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Secondary System Specification

J. Ruer (Saipem)

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Advanced High-Temperature Reactors for Cogeneration of Heat and Electricity R&D
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Summary

This document describes the main specification of the secondary system, which supplies the heat to the conventional industry end-users.
Steam is the energy vector between the HTR and the end-users. In the view of the potential integration of a HTR demonstration unit within an industrial complex, it is proposed to consider a steam quality equivalent to the steam delivered by conventional boilers, with a temperature of 550°C.
An annex provided by Empresarios Agrupados provides an analysis of the safety aspects.

Approval

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Contents

Scope

This document presents an analysis of the heat consumed in the conventional industries.

It appears that large quantities of heat are already exchanged between industrial actors in the form of steam.

In the view of a potential integration of a demonstration HTR unit within an industrial complex, it is proposed that the nuclear plant delivers to the consumers steam of a similar quality than the steam produced by conventional boilers, at a maximum temperature of 550°C.

Appendix 1 written by Empresarios Agrupados (EA) provides an analysis of the safety requirements for the coupling of the nuclear and the industrial plants, together with the option schemes.

Appendix 2 written by Akademia Gorniczo-Hutnicza im. Stanislawa Staszica w Krakowie (AGH) focuses on coal liquefaction technologies and hydrogen production processes. The option to increase the temperature with heat pumps is discussed.

Appendix 3 written by Saipem is a short introduction to the treatment of boiler water.

1. INTRODUCTION

The HTR unit is a nuclear plant which must be designed and operated according to rules which are highly specific to this type of energy production system.

On the other hand, the so-called conventional industries must comply with different standards, following the type of feedstocks, processes and products. The safety aspects are sometimes very stringent, for example in the case of chemical plants. However, none of these industries have a reason to obey nuclear related aspects in their operation.

In order to make it possible for the conventional industry to take advantage of the nuclear heat, it is required to design a system able to transfer the heat from the nuclear plant to the conventional ones.

2. HEAT DEMAND IN THE INDUSTRY

The Industry consumes large quantities of heat to operate many different processes. A previous study (EUROPAIRS) made a survey the heating power required and of the temperature range for various industries. Table 1 summarizes the main information gathered, which can be discussed as follows:

- Many applications can be satisfied with a temperature level of 550°C or less. In most cases, we can notice that water is present somewhere in the system, either in the process feedstock (drying), either in the heat supply (steam). Of particular interest in this table is the case “steam as utility for industrial complex” which corresponds to high thermal powers. Indeed, in large complexes, one can find many different consumers, which require heat for distinct process operations. Each individual unit may have a rather low consumption, but the complex as a whole represents a large power, which justifies the mutualisation of the heat delivery in a local power station. The heat is distributed within the complex by a network of steam lines. In most cases, the power plant attached to the complex supplies electricity in addition to steam.

- Between 600°C and 700°C, few consumers are found. The analysis of the table shows that some applications correspond to the production of hydrogen via membrane steam reforming and high temperature electrolysis. These are niche markets to date. However, if the use of hydrogen as an energy vector increases in the future, the corresponding heat demand should expand markedly. In fact, the penetration of hydrogen in the energy landscape will depend on the achievable cost of hydrogen production. Because the elaboration of hydrogen requires a lot of energy, the cost of the energy source will have a major impact. HTR technology may very well play an important role in the successful development of the hydrogen economy.

- Between 700°C and 1000°C, the similar observations can be drawn. Here, the future is represented by the chemical routes for hydrogen production. If HTR (VHTR) proves able in the future to generate the heat at the temperature levels required at an affordable cost, they could again become important players.

- Above 1000°C, the heat is used for the processing of solids (metals, ceramics, cement, etc.) and is obtained by firing combustible fuels or by electrical heating. This is beyond the HTR direct capabilities. However, we can note that electricity produced partly by nuclear reactors today is largely used in metallurgy. Good examples are the arc electric furnaces in steelmaking, or aluminium electrolysis.

Table 1: Industrial Heat Demand – Source: EUROPAIRS Project

TEMPERATURE\POWER	10 -150 MWth	150 - 500 MWth	500 - 1000 MWth	> 1000 MWth
100-250 °C	Refinery Distillation Steam (heating, process, electricity)	Paper Steam (drying)		
	Steel making (process, electricity)	Water desalination Steam (drying)		
250-550°C	Refinery Distillation Superheated Steam (heating, process)	Soda ash Steam (drying)	Steam as utility for indutrial complex	SAGD Steam (process, electricity)
600-700°C	Petrochemicals (styrene…) Reaction enthalpy			
	Hydrogen Membrane steam reforming			
	Hydrogen High temperature electrolysis			
700-1000 °C	Olefine products Reaction enthalpy			
	Methane Steam reforming (syngas) Reaction enthalpy			
	Coal gasification (syngas) Reaction enthalpy			
	Oxygen Membrane gas separation			
	Hydrogen Very High temperature electrolysis	Hydrogen Chemical water splitting		
> 1000 °C	Lime Kiln Burner Solid reaction	Cement Burners Solid reaction		
		Ore sintering Solid reaction		
		Coke making Solid reaction		Steel Blast furnace Solid reaction

3. HIGH TEMPERATURE REACTORS AS HEAT SOURCE

The HTR is basically able to generate heat at a high temperature. The HTR described by Westinghouse in Appendix A of the deliverable D11.31 delivers hot helium at the reactor outlet at a temperature of 700°C. The cooling gas must however exchange the heat with a secondary fluid, in a steam generator. Live steam at 530°C and a temperature of 190 bar is produced.

These parameters are quite similar to the live steam produced in conventional boilers for power plants and many industries. For example, in conventional coal-fired power stations, the steam enters the high pressure turbines at 550°C. In contrast, in nuclear PWR plants, the steam temperature is limited to 315°C.

It is very important to emphasize the fact: The 550°C temperature level commonly considered in the design of the conventional steam boilers matches fairly well with the specification of the HTR secondary steam generator (530°C)

The spirit of the ARCHER Project is to prepare the road towards a future industrial size demonstration. The aim is to initiate a demonstration as early as possible, to gain experience in the HTR technology, and to obtain relevant data in terms of potential benefits of nuclear process heat for the industry.

When it is desired to introduce a new component, like a HTR, into an already existing system, it is necessary to analyse in depth all aspects of the problem. In general, the most efficient way to conduct such a study is to select a specific example, a case study. It was therefore decided to use this methodology in the ARCHER project.

The selection of the case study was governed by the following considerations:

- The industrial demonstration should correspond to a reasonable HTR size, typically 500MWth
- The temperature of the heat source must be compatible with both the presently feasible HTR technology, and the end-user facilities.
- The heat from the HTR must be easily supplied to the end-user units, with as little modification as possible to the existing plant infrastructure and to the operation practices.

It appears that a large industrial complex is advisable, for the following reasons:

- The heat requirement in large complexes are much higher than 500MWth (Power of the reactor described by Westinghouse). Therefore, the HTR unit would cover only a part of the local heat consumption, leaving place for the conventional heat sources, as back-up facilities or load-following units, and reduced impact on the operation practices. This should relieve potential acceptance difficulties from the end-users.
- The heat is produced in a power plant which houses the boilers of the whole complex. The heat is distributed between the various process units by a steam network.
- The heat load varies along the time. It is typically higher in wintertime than in summer, so that a single nuclear unit cannot pretend to satisfy all the needs. The power plant operates a different number of boilers along the year.
- The power plant of large industrial complexes always includes a cogeneration unit. Process heat is generally speaking consumed at a temperature of about 260°C, while it is perfectly feasible to produce the heat at a much higher temperature level (e.g. steam at 550°C). The integration of steam turbines makes it possible to take advantage of the exergy flow between 550°C and 260°C to produce mechanical power and electricity. The electrical energy can be consumed within the plant, or sold to the grid, depending on the circumstances, contributing to the financial balance of the complex.

In the frame of the ARCHER project it was decided to utilize data provided by different end-user industries to specify the characteristics of the energy transferring medium between the

HTR and the industrial plants. The most comprehensive set of data was provided by PROCHEM of Poland, already handed over during the course of the EUROPAIRS project.

The plants described by PROCHEM use steam as the energy carrier between the different units. Steam was identified as the obvious heat transfer medium if HTR energy is introduced in the conventional industries, with a minimum of modifications in existing plants operating well established industrial processes.

The information made available by PROCHEM forms the basis of the case study discussed in Appendix C of Deliverable D11.31. The main teachings are:

- Steam is mostly used at 3 different pressure levels , high pressure (about 30 bars – 260°C), medium pressure (about 16 bars – 220°C), low pressure (about 4 bars – 200°C)
- The steam is mostly generated in a dedicated Power and Steam Station, at high conditions (about 130 bars – 540°C). The steam is first expanded in turbines to produce electricity, then admitted into the different pipe headers.
- The steam is frequently in direct contact with the products
- Most of the steam condensates are discharged into the environment, only a fraction returns to the boilers water preparation plant
- A large part of the steam consumption is linked to heating of equipment and infrastructures which must be maintained at a sufficient temperature in winter. As a result, steam consumption is markedly reduced in summer
- Stable steam conditions are most frequently compulsory for a safe and smooth operation. Sudden interruptions may lead not only into production problems, but also into emergency measures. For this reason, the power plant always maintains several boilers into operation, with at least another one in standby mode ready to take-over.

The specifications of the required steam is derived from this case investigation. See next paragraph.

It must be recognized that many industrial processes will take advantage of heat delivered at a much higher temperature than 530°C. Examples are found in the production of hydrogen and coal liquefaction.

A particular reference is made to Appendix 2 „Towards High Temperature Uses” and the Deliverable D12.11 ”Nuclear-Assisted Coal-to-Liquid Gap Analysis”.

There is no doubt that once the HTR technology becomes accepted in the industry, additional process units will progressively take benefit of nuclear power.

However, in the frame of the ARCHER Project, temperatures uses beyond 530°C were considered as a more remote target, not to be pursued for a first demonstration, for the following reasons:

- Higher temperatures are not readily feasible with the available HTR technology and would require additional development in several areas, like intermediate heat exchangers.
- Heat transfer at very high temperature requires a different medium, and this needs a complete technological development on its own,
- The industries requiring very high temperatures (e.g. Hydrogen manufacture) are not largely developed for the moment, so that potential sites for an industrial scale demonstration could not be available for a HTR demonstration.

4. STEAM SPECIFICATIONS

The HTR cogeneration plant should deliver steam for heating of process units at 2 different pressure levels:

High pressure circuit (HP)

Steam pressure: 31 bars

Steam temperature: 260°C

Medium pressure circuit (MP)

Steam pressure : 16 bars

Steam temperature: 220°C

Low pressure superheated steam can be produced locally via pressure let-down

Saturated steam can be produced locally via water injection

Radioactivity level

The level of radioactive contamination of the steam must be low enough so that no protection measure against radioactivity is required for the end-users, nor for the consumers of the final products manufactured by these plants. This is in particular the case for the tritium content of the steam.

Steam is produced from water which must be treated in order to avoid operating problems of the boilers. See appendix 3.

APPENDIX 1

SAFETY ANALYSIS AND REQUIREMENTS ON THE COUPLING OF THE NUCLEAR AND INDUSTRIAL SIDES

AND COUPLING OPTIONS SCHEMES

Attachment : Document 092-243-F-M-00001 issued by Empresarios Agrupados

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Document No: **092-243-F-M-00001**	Issue: **1**
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ACRONYMS

ARCHER: Advanced Reactor for Cogeneration of Heat and Electricity R&D

HAZOP: HAzards and OPerability study

HRSG: Heat Recovery Steam Generator

HTR: High Temperature Reactor

IHX: Intermediate Heat Exchanger

SG: Steam Generator

1. INTRODUCTION

The aim of the SP1 of the ARCHER project is to study possible ways of designing a nuclear cogeneration plant, made of:

- A nuclear facility, composed by one or several High Temperature Reactors (HTR) that will generate electricity and heat.
- An industrial facility that has a high demand of high pressure steam, and that could hence take advantage of the heat generated by the nuclear facility to produce steam.

The present document is a contribution to D11.11, and it presents the coupling concept selected for the cogeneration plant (in Section 2) as well as an overview of the major topics related to its safety (in Section 3).

The specificity of the ARCHER project is that the nuclear and the industrial plants are interconnected, and hence the aim of the present report is to highlight the safety topics that could arise from this interface, in order to take them into account in the early stages of design. A detailed safety study of each one of the facilities shall be conducted in further phases of the project (for the HTR facility this will form part of its licensing process, and for the industrial facility it will be done according to the current good practices and industrial standards).

2. COGENERATION SCHEME USING A HTR

The objective of this section is to present and justify the concept selected for the nuclear cogeneration plant. Two concepts are presented:

- The first one uses only a Rankine cycle as secondary loop (concept similar to PWRs for example).
- The second one uses Brayton cycles so as to take advantage of the high temperatures of the primary fluid.

Both options respect the safety principle of using three circuits, in order to have one intermediate circuit between the possibly contaminated He of the primary circuit and the steam to be delivered to the industrial end user.

Since the objective is to present conceptual cycles, several simplifications have been made in the diagrams presented hereafter, for example:

- The primary circuit is only represented by one HTR and one Steam Generator, while in reality several reactors and steam generators are likely to be used.
- In the steam/water cycles, the feedwater heaters do not appear in the diagram and only one turbine extraction is represented while more might be needed in reality.
- The tertiary circuit is represented as a closed circuit, while in reality it is likely to be an open circuit: steam will be provided to the end user and approximately the same amount of demineralised water will be returned by the industrial user for steam production (part of the steam is foreseen to be used directly by the end user in its chemical process, thus contaminating the steam).

2.1 OPTION 1: COUPLING THROUGH A RANKINE CYCLE

The cycle proposed here is close to the mature technology of currently operating reactors (like PWRs). The heat produced in the HTR is transferred through He/water Steam Generators to a secondary circuit (Rankine cycle) to produce electricity. Steam for the end user is produced in a tertiary circuit: reboilers use steam from the secondary circuit (turbine extraction) to heat the water fed by the industrial user and produce steam. This scheme is represented in Figure 2-1 hereafter.

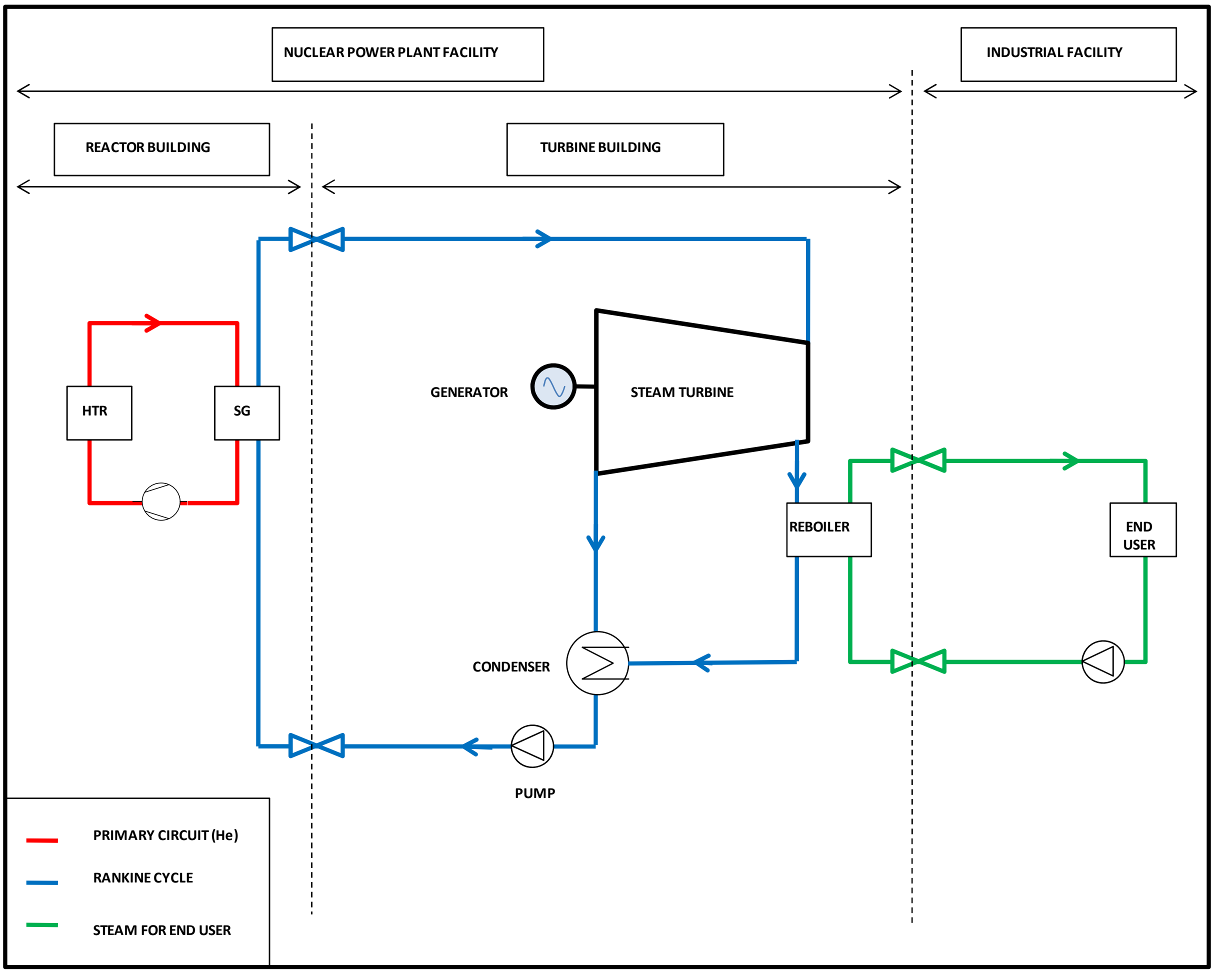

Figure 2-1: Coupling using a Rankine cycle

2.2 OPTION 2: COUPLING THROUGH A BRAYTON CYCLE

2.2.1 Direct Brayton cycle

In the direct Brayton cycle, the He of the primary coolant of the HTR serves as the working fluid: after having been heated in the reactor it expands in the gas turbine. It has to be noted that conventional gas turbines currently used in the industry (designed to expand air) cannot be used effectively with helium under these conditions and that specific turbine models have to be designed for this particular application.

The He gas at the outlet of the turbine is then cooled in a Heat Recovery Steam Generator (HRSG) where the remaining sensible heat contained in the gas is used to produce steam in a steam/water cycle (as in a traditional combined cycle).

Steam for the industrial user is generated in reboilers as in Option 1.

This cycle is represented in Figure 2-2 hereafter.

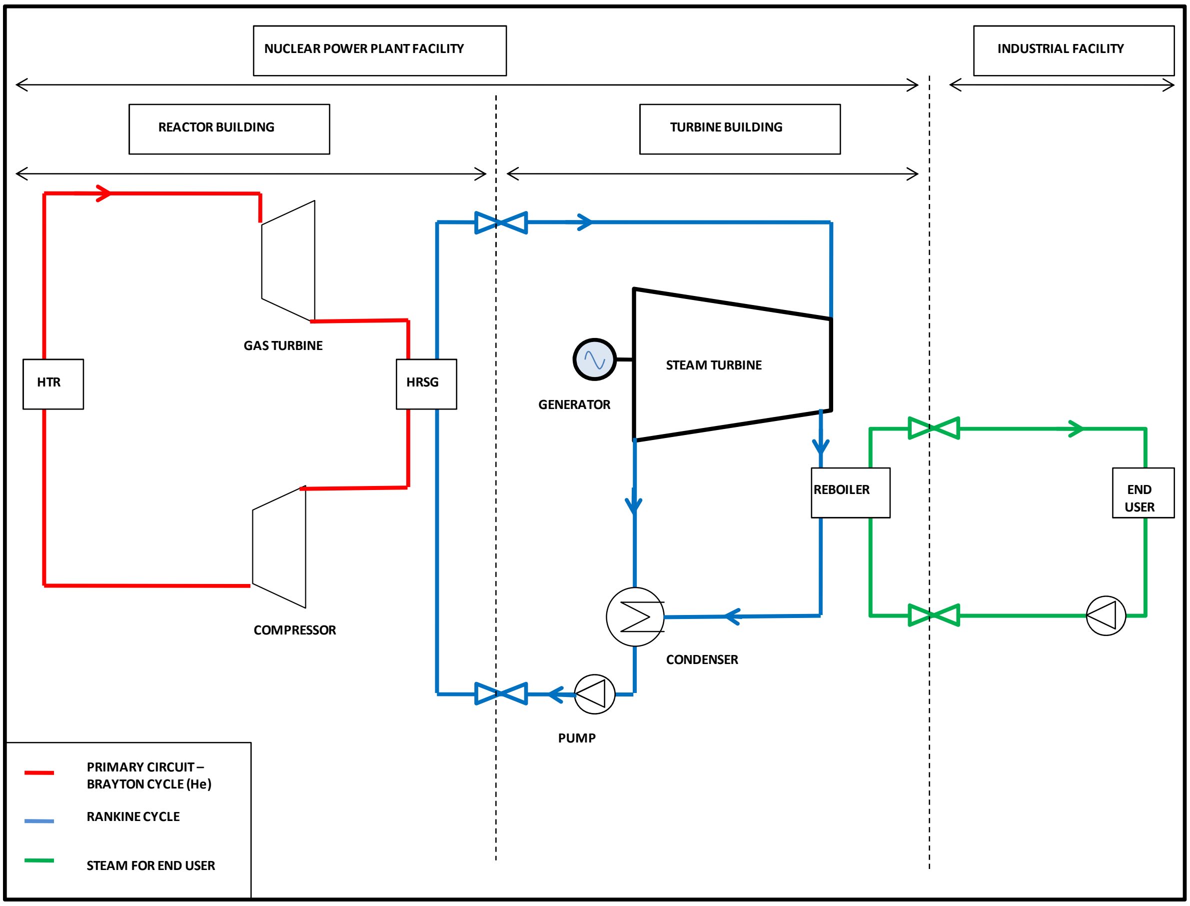

Figure 2-2: Coupling using a direct Brayton cycle

2.2.2 Indirect Brayton cycle

In the indirect cycle (presented in Figure 2-3), the coolant in the primary circuit circulates first through the reactor and then passes through an He/air Intermediate Heat Exchanger (IHX) to heat the secondary cycle.

It has to be noted that the use of an IHX is disadvantageous as far as the thermal efficiency of the cycle is concerned, but enables to use a traditional gas turbine (mature technology).

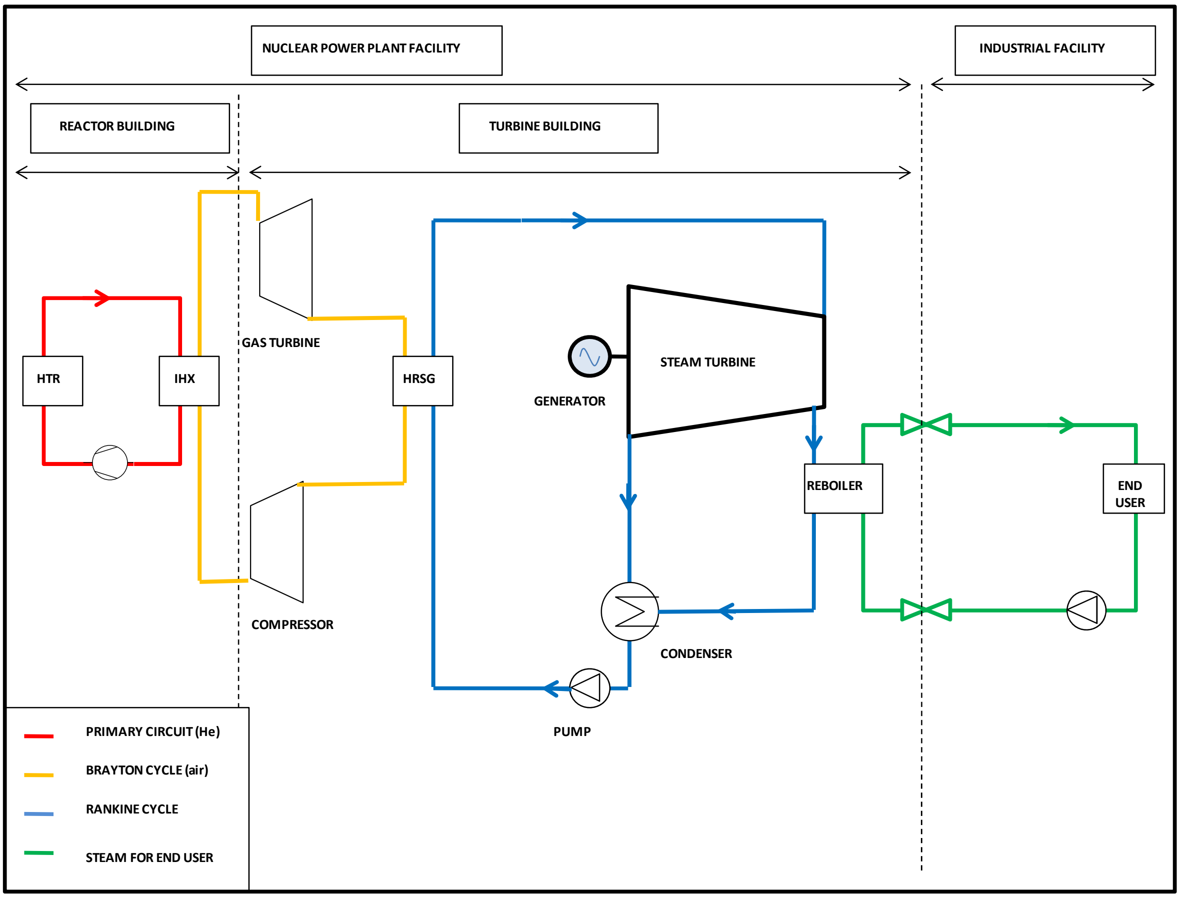

Figure 2-3: Coupling using an indirect Brayton cycle

2.3 COUPLING SCHEME SELECTED

Even if considerations regarding the efficiency of a Brayton cycle that would use a HTR are merely theoretical (because the thermal efficiency of either the IHX or the helium gas turbine are just hypotheses) the use of a Brayton cycle would theoretically provide a better thermal efficiency to the cycle than using just the Rankine cycle since it makes better use of the high temperature generated in the HTR core.

However, for the ARCHER project, the Option 1 has been selected for the two following reasons:

- Its main components are considered to be “mature technology” (only the He/water steam generator would require limited development) which makes it easier as far as the estimation of a realistic heat balance is concerned (the thermal efficiencies of well-known components could be assessed based on experience).
- Since the end user selected for the ARCHER project (PROCHEM) does not require steam at temperatures higher than 320 ºC, taking advantage of the high He temperature at the outlet of the HTR core was not considered a priority.

3. SAFETY ASPECTS OF A HTR COUPLED WITH AN INDUSTRIAL END USER

This Section presents the main safety aspects related to a nuclear cogeneration plant.

3.1 SAFETY TOPICS RELATED TO EACH FACILITY

This purpose of the present document is to focus on the interface between the nuclear and the industrial facilities, since it is the specificity of the ARCHER project.

As far as safety issues specific to each facility are concerned, each industry has a long experience about the main risks related to its activities and the ways to prevent them. Those topics will be covered in the respective designs of each plant as follows:

- The safety of the HTR reactor (e.g. reactivity control, transients, incidents and accident scenarios, defence in depth…etc) will be addressed in the safety analysis report during the licensing of the plant.
- Regarding the industrial plant, the usual risk studies (e.g. HAZOP) will be conducted in order to provide a safe design, according to the best current practices in the industry.

3.2 TRITIUM CONTAMINATION

The main possible impact of the HTR reactor on the industrial facility is the radioactive contamination of the industrial process, especially by tritium.

3.2.1 Tritium production

Tritium (symbol T or ^{3}H) is a radioactive isotope of hydrogen. It is produced in the core of the HTR as a ternary fission product of the U-235 and by activation of the lithium (present in the graphite components) and boron (present in the control rods). Additionally, the He-3 isotopes present in the helium coolant also produce tritium by activation, and this is a significant source of tritium in HTR reactors.

The tritium produced in a fission process will be retained within the fuel particle and it would only escape to the primary coolant in case the fuel coating is damaged. On the other hand, the T produced by activation of He-3 is already in the primary coolant, and the T produced in graphite can rapidly diffuse through the graphite components into the coolant.

3.2.2 Tritium contamination outside of the primary circuit

Primary to secondary coolant:

From the He primary coolant, a fraction of the tritium could escape directly to the containment (but this fraction is expected to be rather small in comparison to the other pathways) or to the secondary coolant through the steam generator tubes.

Secondary coolant to atmosphere:

From the secondary coolant to the environment the paths for tritium are:

- From the deaerator to the condenser via the vents of the deaerator.
- From the condenser to the stack and to the atmosphere, through the vacuum pumps of the condenser vacuum system.

Moreover, leakage in the primary circuit purification system could also occur.

Secondary coolant to industrial fluid:

From the secondary, a fraction of the tritium can pass to the industrial fluid through the tubes of the heat exchangers.

Summary:

The paths of tritium contamination outside the primary circuit are illustrated in Figure 3-1 hereafter.

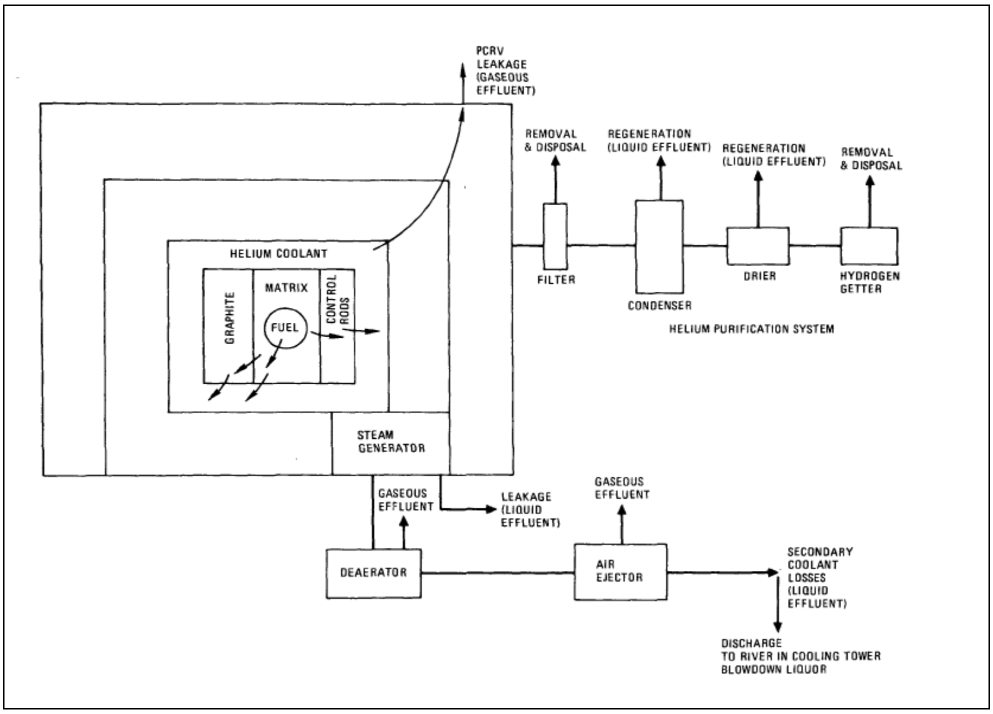

Figure 3-1: Paths of tritium contamination outside the primary circuit

3.2.3 Limiting the tritium contamination

The main ways to limit the tritium contamination are:

- The use of a gas purification system in the primary circuit
- Limiting the use of potential tritium source in the primary circuit (e.g. the use of borated graphite)
- Using an intermediate circuit between the primary coolant and the industrial fluid, purified by a sweep gas flow, would provide an additional barrier. If oxygen or steam is added to the sweep gas, a fraction of the tritium will be bound as tritiated water and no longer be able for permeation.

The issue of tritium contamination is a central safety topic within the design of a HTR cogeneration system and will thus be addressed more in details in further phases of the project.

3.3 IMPACT OF THE INDUSTRIAL USER ON THE HTR FACILITY

3.3.1 Transients in steam consumption by the industrial user

As far as the thermodynamic cycle of the nuclear facility is concerned, the interface between the industrial user and the nuclear plant are the steam extractions from the turbine used in the reboilers to generate process steam for the industrial plant.

The steam consumption of the industrial plant has thus a direct impact on the thermodynamic cycle of the nuclear plant, since it determines the amount of thermal power to be removed from the secondary circuit by the reboilers.

The impact on the primary circuit of a sudden variation of the heat removed by the reboilers depends on many factors (among them, the thermal power fraction of the total cycle that is removed through the reboilers) and would have to be studied in detail in further phases of the project.

3.3.2 Contamination of the nuclear facility by the industrial facility

The industrial user shall ensure the purity of the condensate supplied to the reboilers since in case of a tube failure in a reboiler, the secondary loop of the nuclear plant could be contaminated by chemical products from the industrial side. This type of requirement exists for example in district heating application, either with nuclear plants or conventional thermal plants.

3.3.3 Possible hazards in the industrial plant

During the site licensing process of a nuclear facility, among the external events to take into account in the design of the nuclear facility are the hazards caused by the industries in the vicinity of the plant.

In order to obtain a site permit for the nuclear plant it is likely that the location of the industrial facility, especially the distance between the nuclear plant and the industrial facility will be an important topic.

In case the industrial end user would be a hydrogen production plant, the distance requirements are likely to be stringent (due to the potential consequences of a hydrogen explosion).

4. CONCLUSIONS

The coupling scheme selected for the cogeneration plant of the ARCHER project is to connect the primary He circuit of the HTR to a Rankine cycle. This coupling might not provide the best theoretical thermal efficiency of the cycle, but it has been chosen because it only uses mature technologies (components of the Rankine cycle have been used for decades) and this cycle is thus the more likely to be used in the first HTR cogeneration demonstration plants.

Apart from the safety issues related to the nuclear and the industrial facilities separately (to be addressed in their respective designs), the peculiarity of the ARCHER project are the issues arising from the interface of these two facilities. The main topics that have been identified in this report are:

- The contamination of the industrial process fluid by radioactive nuclides, especially tritium.
- The impacts of the industrial plant on the nuclear facility: variation in industrial steam consumption leading to possible transients in the nuclear plant, possible contamination of the secondary circuit by the tertiary circuit, and hazards that could occur in the industrial plant (explosion, fire…)

5. REFERENCES

1) ”A Review of Tritium Behavior in HTGR System”, B.W.Gainey. San Francisco : General Atomic, 1976.

2) “Nuclear Energy for Hydrogen Production”, Karl Verfondern, Forshungzentrum Jülich.

APPENDIX 2

SECONDARY SYSTEM SPECIFICATION

TOWARDS HIGH TEMPERATURE USES

Attachment : Document issued by AGH

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Advanced Reactor for Cogeneration of Heat & Electricity-R&D

Secondary System Specification

Towards High Temperature Uses

M. Kopeć (AGH), J. Cetnar (AGH)

1. Introduction

The high temperature nuclear reactor can serve as an excellent, emission-free source of technological heat for various industrial applications, partially described in the frames of the EUROPAIRS Project. It has been identified that the heat market is most significant at two temperature ranges: low to medium (100-550°C) and very high (>1000°C). The solutions proposed in that project can significantly facilitate applications of the nuclear heat source in case of technologies where the temperatures below 550°C are required. Simultaneously, the temperatures in the second range, which would be interesting e.g. for metallurgy, are considered to be too high even for the very high temperature nuclear reactors. The range between medium and very high temperatures (550-1000°C) was not identified as really desirable, but in fact these temperatures are used in conventional coal liquefaction and hydrogen production processes. However, both conventional technologies suffer from large CO_2 emissions and this is probably the main obstacle in a world-wide production of synthetic fuels.

In this report we focus on the use of nuclear heat only for these two applications, and the aim is economically acceptable production of liquid fuels from coal with eliminated or at least very much reduced CO_2 emission. Two general coal liquefaction methods, namely indirect coal liquefaction (ICL) and direct coal liquefaction (DCL) will be shortly described. Because both ICL and DCL require large amounts of hydrogen, the most promising options of hydrogen production will be presented as well. Also in this case the analysis will be aimed at elimination of CO_2 production by coupling with the nuclear heat source.

The general configuration of considered nuclear heat delivery system is based on results of EUROPAIRS project, where the steam loop for long distance heat transport is proposed and the resulting temperature of medium retrieved at the final chemical plant is around 550°C. This solution allows for almost immediate application of proven technologies and materials. Conventional steels used in the long distance transport loop instead of very expensive high temperature materials, would significantly reduce installation costs. But, the temperature of medium delivered to the chemical plant (~550°C) is too low for synfuel or hydrogen production, where at least 850°C is required. In this situation some part of delivered heat will require additional temperature increase. This can be done for example by means of the high temperature heat pump working in reverse Brayton cycle. Such a pump, driven by an external energy source, consists of a high temperature gas turbine, high temperature compressor, and appropriate heat exchangers. It can be expected that the most critical part of this device will be the high temperature compressor. It should be noted that the compressors available presently on the market are used to increase pressure, not temperature.

Alternatively to the heat pump, the temperature at the chemical plant can be increased by more conventional methods, like combustion of coal or gas (or oxycombustion). In this case the CO_2 generation will be only significantly reduced but not completely eliminated. However, this compromise solution can be relatively easy implemented.

2. Secondary system specification

2.1. Conventional coal liquefaction

Coal liquefaction, also referred to as coal to liquid (CTL) is a conversion of bituminous or sub-bituminous coals to a liquid fuels like gasoline or diesel. Although this technology is generally more expensive than producing fuels from crude oil, it is potentially very attractive as the coal reserves are more than ten times more abundant, and are more evenly distributed than oil reserves. Conversion of coal to liquids is done by increasing the hydrogen to carbon ratio from H/C ~0.8 (typical bituminous coal) to H/C ~2 (final hydrocarbon fuels). This result can be achieved either by rejection of carbon or by addition of hydrogen. The first method is known as the indirect coal liquefaction (ICL), the second one as the direct coal liquefaction (DCL).

In the ICL (Fig. 1), coal is gasified to form a mixture of H_2 and CO (syngas) which after adjustment of H_2/CO ratio and removal of sulfur and CO_2 is converted to hydrocarbon liquids in a Fischer-Tropsch synthesis unit. The indirect liquefaction has substantially lower efficiency than the direct one (40-45% vs 60-65%), but less complicated processes are involved. The capital costs of ICL plant are generally higher, but 60-80% of them is connected with syngas production and cleaning. ICL can be used for production of a number of various high quality ultra-clean products: conventional fuels like petroleum and diesel, alternative fuels like methanol and dimethyl ether (DME), synthetic waxes and lubricants or chemical feedstocks.

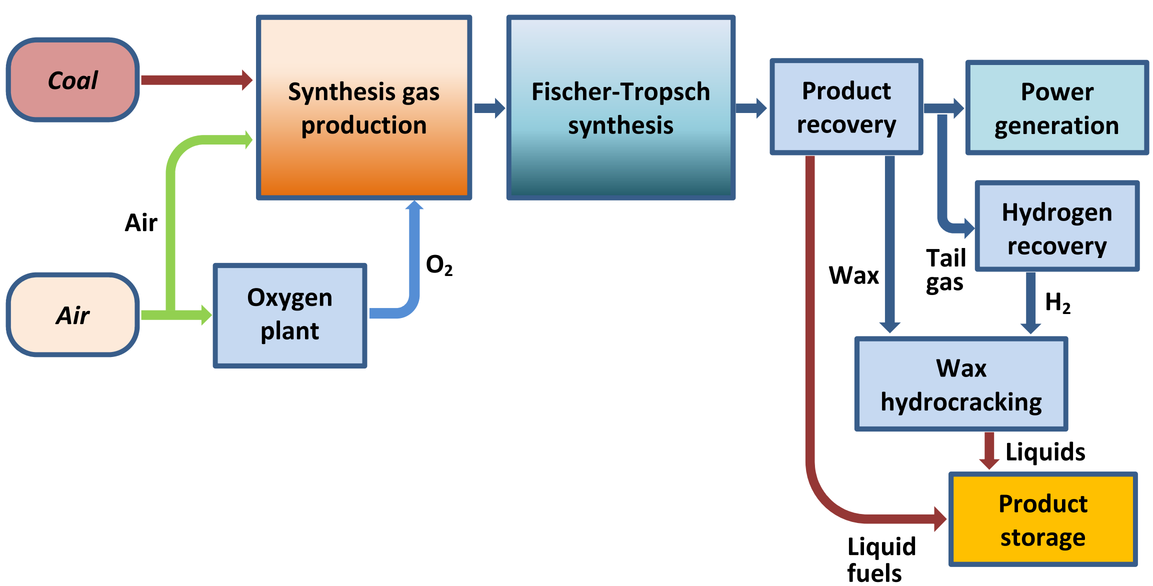

Fig. 1 Indirect coal liquefaction process

In the DCL (Fig. 2), hydrogen is added to crack the coal structure to hydrocarbon liquids. Direct liquefaction works by dissolving the coal with a special catalyst in a solvent at high temperature and pressure and reacting it with hydrogen. This process is highly efficient, but the liquid products require further refining to achieve high grade fuel characteristics.

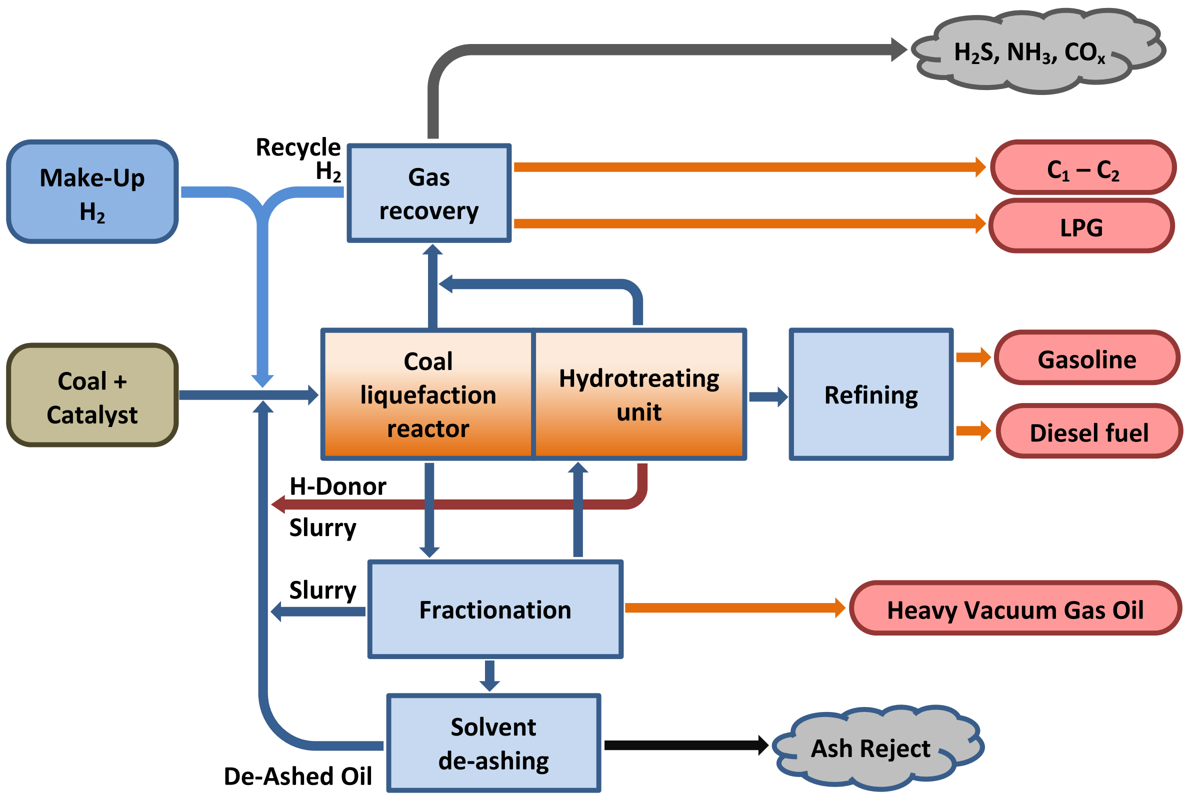

Fig. 2 Direct coal liquefaction process

Hydrogen is needed in the DCL process both to make synthetic crude oil and to reduce the oxygen, sulfur, and nitrogen present in the coal feedstock. The energy consuming hydrogen production step is responsible for big CO_2 emissions and significantly influences both capital and operating costs. In the classical direct liquefaction process hydrogen was produced by gasification of coal.

There is also the third method, called Hybrid Coal Liquefaction which combines ICL and DCL improving the overall efficiency. Both methods are used simultaneously and hydrogen retrieved from the tail gas leaving the Fischer-Tropsch synthesis (ICL) is directed to the hydrogenation process (DCL). The raw ICL and DCL products are blended together and refined using hydrogen from FT unit. Beside the improved efficiency this method allows for more flexible setting of the final product.

From these two basic methods only ICL has been implemented in a big commercial scale, whereas the implementation of DCL has been abandoned for many years. In the last decade some new projects (DCL and ICL) have been launched in China. However, the world-wide deployment of the conventional CTL is limited by production economics and by huge CO_2 emissions. Converting coal to transportation fuels results in ~7-10 times as much CO_2 being emitted, compared with converting crude oil. It is expected that these problems can be solved by the use of a high temperature nuclear heat source.

2.2. Hydrogen production

Hydrogen is already a significant chemical product. Current world production is not precisely monitored, but is estimated at around 45 million tons, or 500 million Nm^3, per year. Ammonia and methanol production is by far the largest consumer of hydrogen, accounting for 58% of global consumption. Petroleum refineries accounted for the next 37%, and 5% was used in other applications, like: hydrogenation of processed foods, thermal treatment of metal components, production of glass or semiconductors, space propulsion etc. It is commonly expected that in near future hydrogen will play important role as an environmentally friendly energy carrier. Finally, the perspectives of all coal-to-liquid technologies depend on the progress in new, emissions-free hydrogen production methods.

Hydrogen can be produced from different feedstocks, by variety of processes:

- **natural gas**
  - steam methane reforming
  - partial oxidation
  - autothermal reforming
  - thermal decomposition of methane
- **liquid hydrocarbons**
  - partial oxidation
- **coal**
  - various gasification processes
- **biomass**
  - various gasification processes
- **water**
  - alkaline electrolysis
  - polymer electrolyte membrane (PEM) electrolysis
  - high temperature electrolysis
  - thermo-chemical water splitting
  - photo-electrolysis (photolysis)
  - photo-biological production (biophotolysis)

The first commercial production technology, dates from the late 1920s, was the electrolysis of water for pure hydrogen production. In the 1960s, the industrial production of hydrogen shifted slowly towards a fossil-based feedstock, which is the main source for hydrogen today. At present, about 96% of hydrogen is made from fossil fuels: 48% from natural gas, 30% from liquid hydrocarbons and 18% from coal. Unfortunately, this gives rise to huge carbon dioxide emissions: depending on the feedstock, each tonne H_2 produced gives rise to 7-11 tonnes of CO_2. Electrolysis accounts for only 4%.

Natural gas is an important resource for near-term hydrogen production – it has a high hydrogen-to-carbon ratio so it emits less CO_2 compared to other hydrocarbons. It offers also the lowest production costs comparing to other feedstocks. Due to concerns about a limited supply the natural gas is not considered a long-term option, but recent developments of shell gas technology as well as discoveries of huge shell gas fields may change this point of view.

Coal is an attractive feedstock due to its natural abundance and low, traditionally stable prices. Coal gasification is an established technology used in hydrogen production today, but additional technical and economic considerations for capture and storage of CO_2 will be necessary. Due to the lower ratio of hydrogen to carbon, which in natural gas is 4:1 and in carbon is 0.8:1.8, the hydrogen produced from coal is almost twice as expensive as from natural gas. Higher are also emissions of CO_2 and other pollutants such as SO_2 and CO.

Biomass feedstocks are unrefined products with inconsistent quality and poor quality control. The production methods vary according to crop type, location and climatic variations. But, being the renewable feedstock, it is considered as attractive due to favourable CO_2 balance.

Water would be the most desirable source of hydrogen, virtually unlimited and almost equally distributed all over the world. Providing non-combustion energy source it also would allow for emission-free hydrogen production. Unfortunately, at present the costs are significantly higher than for other feedstocks.

Production Technique	Efficiency [%]	Estimated price [$/kg$H_2$]	Scale	Status	Major Advantages	Major Disadvantages
Steam Methane Reforming	83	1.4 – 4.0	large	mature	- High efficiency - Proven technology - Economically justified	- Emission issues - Limited long-term natural gas supply
Partial Oxidation of Methane	70 – 80	~2xSMR	large	available R&D required	- High efficiency - Economically reasonable	- Emission issues - Limited long-term natural gas supply
Autothermal Reforming of Methane	71 – 74	~2xSMR	large	mature	- Proven technology - Economically reasonable - Lower reactor costs than SMR	- Emission issues - Limited long-term natural gas supply - Lower efficiency than SMR
Membrane Methane Reforming	70 – 80	no data	small	R&D	- Lower temperatures - Easier gas separation	- Emission issues - Membrane costs - Small scale
Coal Gasification	63	1.0 – 2.5	large	mature	- Proven technology - Abundant feedstock - Economically justified	- Emission issues - Lower efficiency than SMR
Low Temperature Electrolysis	25	3.7 – 6.5	small	available R&D required	- Proven technology - Excellent feedstock - No emissions	- Low efficiency - Expensive
High Temperature Electrolysis	30	3.7 – 6.5	small	R&D	- Excellent feedstock - No emissions - Better efficiency	- Low efficiency - Material issues
SI cycle	30 – 50	2.0 – 8.0	small	R&D	- Excellent feedstock - No emissions	- High temperature - Aggressive reagents - Material issues
HyS cycle	40 – 50	2.0 – 8.0	small	R&D	- Excellent feedstock - No emissions	- High temperature - Aggressive reagents - Material issues
Cu-Cl cycle	40 – 50	1.5– 8.5	small	R&D	- Excellent feedstock - Reasonable temp. - No emissions	- 3-phase reactions - Aggressive reagents - Material issues

Table 1. Summary of hydrogen production technologies

A comparison of the presented hydrogen production methods is provided in the Table 1. Currently only the methane and coal based technologies are used for the large scale hydrogen production. Only 4% of hydrogen come from the low temperature electrolysis. The comparison of hydrogen prices is difficult since there is strong dependency on the feedstock as well as the electricity cost. Simultaneously, the hydrocarbon based technologies emit huge amounts of CO_2 but, at present, this fact is not reflected in the hydrogen price. Another difficulty arises from the comparison of technologies working in different scales. It should be also observed, that the price depends also on such parameters as the required purity or pressure. Finally, many of presented technologies are currently under intensive R&D and the price estimations may be inaccurate.

The most important technological parameters of presented methods are collected in the Table 2. In case of methods based on natural gas or coal, the energies shown do not include expenditure for CO_2 sequestration. From the other hand, the electric energy is produced with efficiency ~33%, and due to that the real energy required in electrochemical processes is higher than the one shown in table.

Production Technique	Thermal energy [MJ/kgH$_2$]	Electrical energy [kWh/kgH$_2$]	Total energy [MJ/kgH$_2$]	Temperature [°C]	Pressure [MPa]
Steam Methane Reforming	170	–	170	850 - 900	0.2 - 0.3
Partial Methane Oxidation	180	–	180	1150 - 1500	2.5 - 8.0
Autothermal Methane Reforming	185	–	185	850 - 1000	0.2 - 1.0
Membrane Methane Reforming	150	–	150	400 - 600	0.2 - 2.5
Coal Gasification	225	–	225	800 - 1500	3.0 - 8.0
Low Temperature Electrolysis	–	56	102	80 - 100	at. - 2.5
High Temperature Electrolysis	85	38	154	800 - 850	0.2 - 0.6
SI cycle	284	–	284	750 - 850	0.2 - 0.4
HyS cycle	119	43	274	750 - 850	0.2 - 0.4
Cu–Cl cycle	140	17	171	450 - 550	atm.

Table 2. Basic technical data of hydrogen production technologies

2.3. Nuclear heat delivery system

Although the coolant temperature on the HTR outlet can be as high as 850°C (in case of VHTR even more), it would be very difficult and expensive to use it directly as a source of a process heat. It must be taken into account that in a real situation the reactor usually will not be located near the end-user plant. In such a case the hot helium would have to be transported over a long distance. Beside the high cost of helium, the material issues at these temperatures would require use of very expensive materials, increasing dramatically the cost of installation. Mainly due to these reasons, following the results of EUROPAIRS Project, it has been proposed to reduce the outlet coolant temperature and apply another configuration with an intermediate heat exchanger and a steam generator.

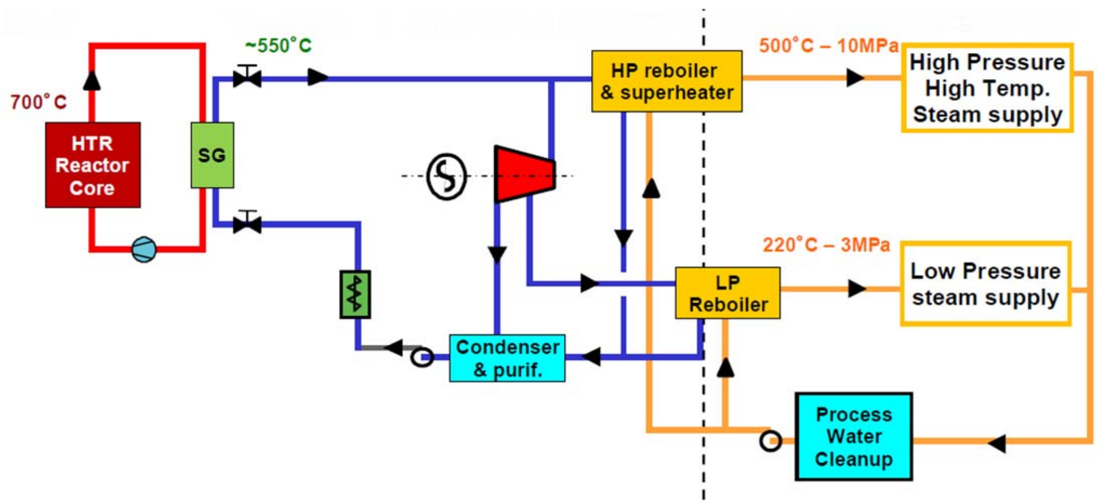

Fig. 3 System configuration proposed in EUROPAIRS Project

Transporting steam (at lower temperatures) rather than helium can be done relatively easy, as the technology required is ready to use and costs of both coolant and materials would be much lower. In this case the nuclear island would generate steam and send it into a steam transportation network towards the end-user's plant. The configuration with an intermediate heat exchanger simultaneously prevents from transportation of tritium produced in HTR improving the radiation safety. In general case the steam consumption by the end-user plant may vary, and due to this it was also considered to use a steam turbine driven generator for electricity production in order to adjust the heat supply to the demand. Such a cogeneration system with electricity as a by-product would have better overall efficiency.

The main features of the cogeneration plant proposed as a result of the EUROPAIRS Project are shown below:

- The HTR is preferably 600 MWth reactor, with a hot helium temperature of 750°C.
- The steam is delivered at 550°C maximum, preferably generated via 2 intermediate loops in order to minimize the tritium level in the steam going to the end-users.
- The turbine for power production is preferably linked to the intermediate steam loop.

This solution eliminates most of the problems associated with transport of a high temperature heat over a relatively long distance, but unfortunately these temperatures are insufficient for the existing coal liquefaction or hydrogen production technologies. Due to that the temperature of medium at the end-user plant must be increased to at least 850-900°C.

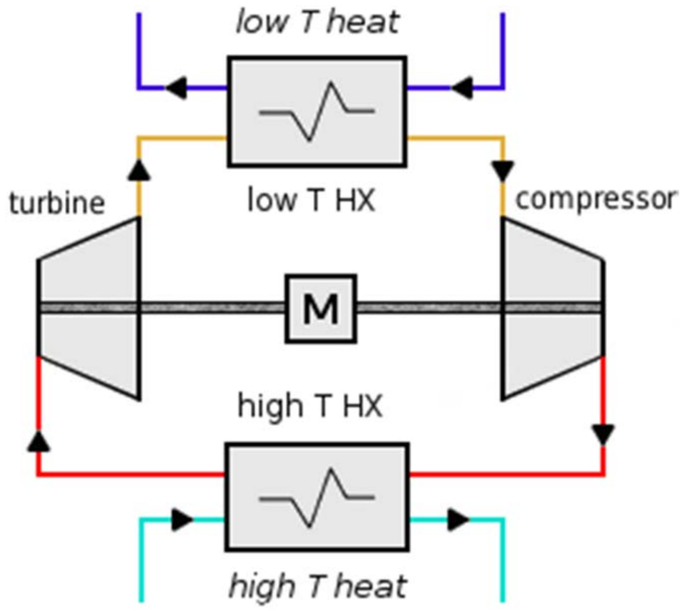

Fig. 4 External driven heat pump

The required high temperature heat could be provided by a conventional electrical heater, but in such a case the final efficiency would be limited by the low efficiency of electricity production (up to 40%). Much better results can be obtained with a heat pump working in the reverse Brayton cycle (Fig. 4). When the externally driven heat pump is used to provide heating, less high-grade energy is required for its operation, than appears in the released heat. In the simplest case the working gas (medium) is heated at a low temperature in the low temperature heat exchanger (low T HX) and compressed, increasing its enthalpy. Both mechanical work delivered to the compressor and low temperature heat are converted into high temperature heat, subsequently passed to the further processes in the high T HX with a coefficient of performance higher than 1. The medium expands in a turbine delivering a part of work used by compressor – the rest must be provided by an external source. For this purpose can be used another turbine working on the same shaft, driven by steam leaving the low temperature heat exchanger (Fig. 5). The efficiency of combined Rankine and reverse Brayton cycle expressed as the ratio of high temperature power to the reactor thermal power depends on assumed working conditions. For the required process temperature of 950°C it can be theoretically as high as 66% (when all losses neglected). In real conditions it will be lower, but still significantly higher than compared to direct heating case.

Another configuration may be preferable when the instantaneous heat consumption in final processes may vary. In this case a steam turbine power generation unit may be included in the steam loop with the heat pump driven by an electric motor (Fig. 6). The surplus of energy between the HTR output and the end-users heat consumption will be transformed into electricity fed to the grid. The nuclear plant is therefore a real cogeneration plant which delivers steam and electricity as a by-product. Although the efficiency will be here slightly lower comparing to the a heat pump directly coupled with a steam turbine, the cogeneration work with variable heat to electricity proportions can offer more flexibility.

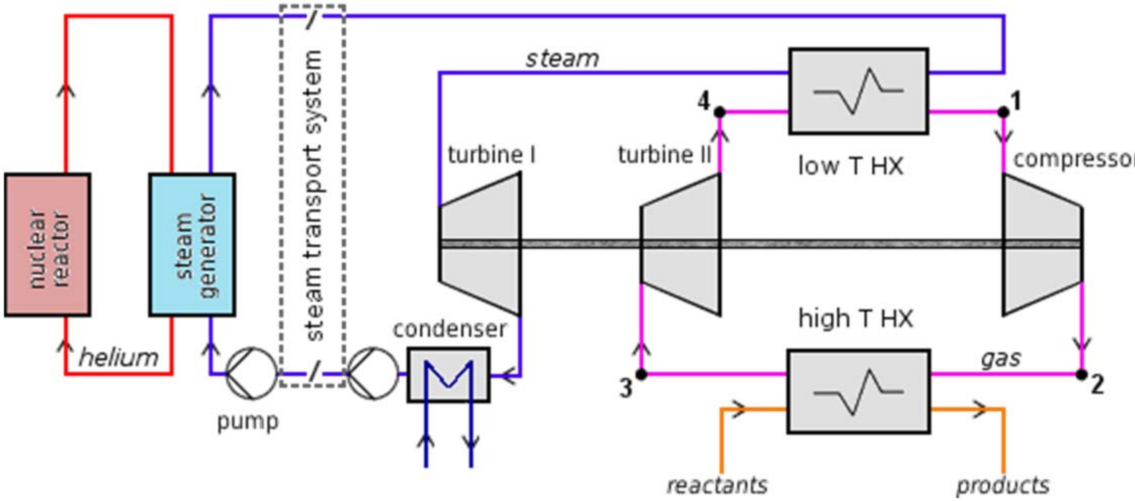

Fig. 5 System with a heat pump driven directly by a steam turbine

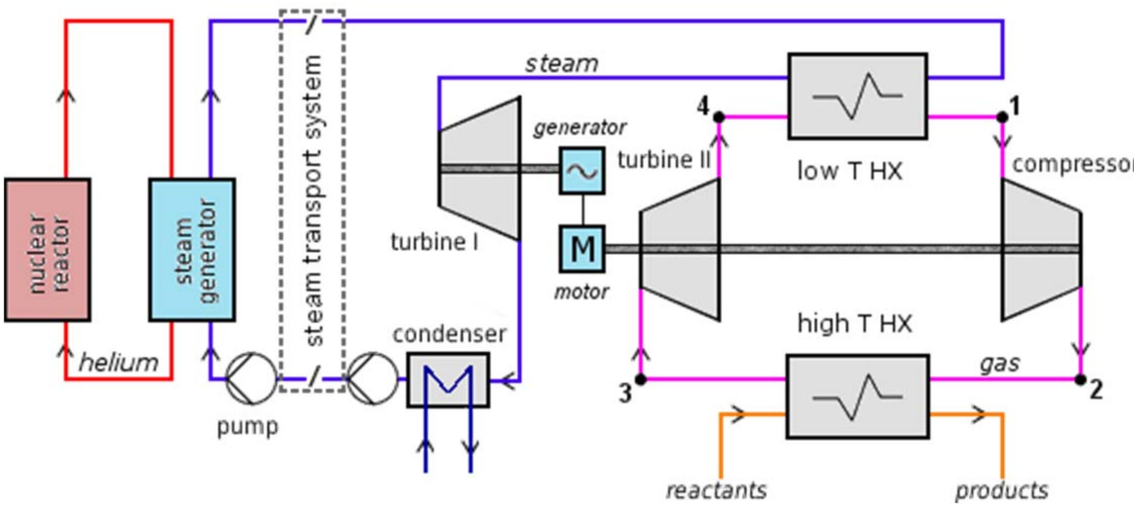

Fig. 6 Cogeneration system with a heat pump driven by an electric motor

In chemical processes considered in this report usually a few reactions (sometimes only one) require high temperature conditions, while the other can be run at lower temperatures. Due to that, only some fraction of process heat must be delivered in a narrow high temperature range. When this fraction is larger, it is possible to apply additional recompression units with high temperature heat exchangers. The system gets more complicated, but – depending on the actual process requirements – it may be economically justified.

The final configuration chosen for the planned cogeneration laboratory will be determined taking into account both results of thermodynamic analyses as well as technical feasibility studies performed in frames of on-going research project.

Conclusions

The high temperature nuclear reactor can serve as an excellent, emission-free source of technological heat for various industrial applications – among them for the nuclear assisted coal liquefaction. This application, however, requires temperatures higher than 550°C i.e. the temperature available directly from the steam loop. In this situation special heat pumps must be used to increase temperature of the most demanding chemical processes. The flexible cogeneration system, capable of producing electricity as a by-product, following the demands of the heat consuming chemical plant, may look like in Fig. 6.

At the moment, the required temperature elevation can be done by means of mechanical heat pumps, but details of design always depend on requirements of high temperature chemical processes. Heat delivery in a narrow temperature window would require additional compressor/HX units, complicating the system design and increasing its cost. The compressors driven directly by steam turbines offer higher efficiency than the ones driven by electrical motors, but in cogeneration systems the latter configuration would allow for better flexibility. It would be also preferable in complicated systems with additional recompression stages.

In case of difficulties with implementation of the high temperature heat pumps, where the material issues can be expected, some alternative solutions offering significant reduction of CO_2 emissions should be considered. The conventional methods based on a clean coal or gas combustion (oxycombustion) may be used to increase the temperature of the most demanding chemical processes above 550°C. It is worth noting that such a compromise solution can be relatively easy implemented.

APPENDIX 3

WATER TREATMENT FOR STEAM GENERATION

1. WATER IMPURITIES

Steam is produced in the steam generators attached to the nuclear reactor or in boilers. Water is continuously fed to these units to maintain the water level. Any impurities introduced in the boilers along with the water and which do not boil off with the steam concentrate in the boiler water and may lead to some problems, briefly reviewed hereafter.

The raw water used to feed the boilers may be surface water (from rivers or reservoirs) or ground water (from sources or wells). The type and quantities of impurities may differ largely, so that the treatment required to obtain the proper water quality for the boilers vary in a large extent.

Common impurities in water are:

a) Suspended solids

Mud particles, organic matter, oils, etc. They are removed by decantation and filtration

b) Dissolved solids

Calcium and magnesium carbonates and bicarbonates:

The bicarbonates like e.g. $Ca(HCO_3)_2$ are more soluble than the carbonates (e.g. $CaCO_3$). In a boiler, the temperature provokes the dissociation of the bicarbonates and can lead to the formation of a scale of carbonates encrusting the inner face of the water tubes which hinders the heat transfer. The presence of such compounds is called hardness.

Calcium sulphate ($CaSO_4$):

It is less soluble at high temperature than at room temperature. It may form a scale which cannot be removed by acids.

Iron oxides:

Iron oxides may be found in the raw water, or are formed by oxygen introduced in the steam circuit. In this case, the presence of iron oxides results from the corrosion of the metal. The oxides can be fully oxidized Fe_2O_3, but more frequently Fe_3O_4 because of the low concentration of oxygen in the boiler water.

Chlorides:

The chlorides (e.g. NaCl) are very soluble, but the salts introduced with the feed water accumulate in the boiler. When the concentration is too high, corrosion problems may occur.

Total Dissolved Solids (TDS):

The total amount of dissolved solids is called TDS. The dissolved solids tend to make steam bubbles more stable, failing to burst as they reach the water surface. When the effect is marked, foam occurs, wet steam leaves the boiler, and a carryover of the suspended solids may contaminate other equipment in the steam circuit.

The amount of TDS is controlled by monitoring the electrical conductivity of the water.

c) Dissolved gases

Oxygen:

Oxygen is always dissolved in raw water. It is highly corrosive, and causes a corrosion of the boiler metal.

Carbon dioxide:

CO_2 is dissolved in raw water and may also be released by the dissociation of the bicarbonates under the influence of the high temperature. It combines with water in the condenser where the temperature is reduced, lowering the pH and making the condensate aggressive to many metals.

2. WATER TREATMENT

Feed water and blow down

In a close-loop circuit (typically in a power plant equipped with steam turbines working with a condensing cycle) the condensates are returned to the boiler, and the losses are limited.

In most process industries, the condensates are not recovered, and the boilers must be provided by as much feed water as steam produced.

The amount of impurities increases progressively in the boiler water. The severity of the problem depends on the quantity of make-up water, the purity of this feed, and the acceptable level of contaminants in the boiler water, which is related to the steam characteristics.

When the amount of solids is too high, a part of the boiler water inventory is replaced by a quantity of make-up water (blow down). The make-up water must have a lower content of impurities than the level admissible in the boiler water.

Filtration

The raw water must first be separated from the suspended solids. A clarifier eliminates by settling most of the solids. This can be combined with the addition of coagulant if required. The clarified water is then filtered on sand filters or other filtering systems. Hard raw water may be pre-treated by an addition of lime in order to precipitate a fraction of the carbonates in the filtration step and to reduce the burden of the subsequent softener or demineralization units.

Softeners

Water intended for low-pressure boilers may be treated in a softener, where calcium and magnesium ions most likely to cause carbonate and sulphate scale are substituted by sodium. Water softening may prove sufficient in combination with addition of phosphates in boilers operated at a low temperature, but not in the case of intermediate or high pressure boilers.

Phosphates

Sodium phosphates can be added to the boiler water. They buffer the pH and minimize its fluctuations. Phosphates precipitate calcium and magnesium into a soft deposit rather than a hard scale. They form a sludge which is removed from the boiler during blow down operations.

Demineralization

For high pressure boilers, the water must be demineralized. The demineralization step includes a treatment in a cation exchanger, where the cations (Ca^{2+} , Mg^{2+} , Na^{+} , etc.) are replaced by H^{+} ions, followed by an anions exchanger where OH^{-} ions displace the anions sulphate, chloride, carbonate, silicate, etc. The cations exchange resin is regenerated by a solution of H_2SO_4 or HCl and the anions exchange resin by a solution of NaOH.

After the cations exchange step, the pH level of the water is low. This is an appropriate condition to remove most of the CO_2 in a degasifier, where the water is contacted by a flow of air to strip out the gas. The degasifier is therefore installed between the cations and the anions exchangers.

Reverse osmosis

When high water quality is desired, reverse osmosis is used on an increasing basis. It is used in combination with demineralization polishing units.

Oxygen control

The oxygen dissolved in the soft feed water is removed in a deaerator. The water is preheated to boiling temperature and the oxygen is stripped by a flux of steam.

The remaining oxygen is eliminated by an oxygen scavenger, sodium sulphite, hydrazine, ammonia, or various organic compounds which are added to the deaerated feed water.

Corrosion protective filming agents

Filming amines may be used to form a protective layer on the condensate piping.

3. BOILER WATER QUALITY

The water contained in a boiler must have a certain quality, which depends on the operating temperature and pressure. The higher the temperature, the lower the admissible contents of impurities.

According to the American Boilers Manufacturing Association, the TDS is for example 600 ppm maximum for a low pressure boiler, 300 ppm for an intermediate pressure one, and less than 90 ppm for a high pressure boiler. Similarly, the content of chlorides should not exceed respectively 100ppm, 30 ppm, 20 ppm.

The pH of the water is maintained within a range corresponding to the passivity of iron (9.5 to 11). The oxide Fe_3O_4 formed by the reaction of iron with water at high temperature gives a stable layer which protects the metal from further corrosion.

The feed water is treated in order to keep the requested boiler water impurity levels, while minimizing the need for blow down discharges.

See Figure 1 for a simplified water treatment diagram.

Figure 1 : Simplified diagram of a boiler water treatment