End-Users Requirements fOr Process heat Application with Innovative nuclear Reactor for Sustainable energy Supply

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D13: Viability assessment of a (V)HTR system coupled to industrial processes

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Summary

This document presents the results of the task 1.3 of the EUROPAIRS project. The objective of the task is to produce a synthesis of the requirements for coupling a High Temperature Reactor (HTR) with industrial heat processes.

The work is part of work package 1 of EUROPAIRS project, i.e. the "viability assessment" of the coupled system. The synthesis of the requirements is based on the input from other tasks of the project:

- End user processes: characteristics and requirements (task 1.1)
- Nuclear system: characteristics and limits (task 1.2);
- Safety and licensing evaluation (work package 2);

The main results of these inputs are resumed in the document. The reader is referred to the corresponding deliverables for more details.

In parallel to the technological assessment, the document also gives elements for a preliminary analysis of the economic viability of the coupled system. The results of the market analysis (deliverable 131) are used to determine the most promising coupling schemes. Some bases for a comparative assessment of production costs of the HTR and fossil fuel plants are also given (in agreement with deliverable 133). This presentation is for illustrative purpose only since there is not sufficient information available on the costs of the HTR technology at this stage to be more precise.

From the different inputs, a synthesis of the constraints and the expected performances of the coupled system are proposed. The main features of the coupling scheme are discussed: temperature achievable in the different circuits, influence of heat transfer technology, and protective means against contamination releases, match between consumption and production, etc.

The assessment is presented for two time horizons. First, the expectations for a coupled system that would be achievable in the near-term are discussed. Here, "near-term" means that a detailed design of the coupled system should be achievable rapidly to start construction of a demonstrator project within 5 to 10 years. This objective requires that the demonstrator of the coupled system relies only on already mature technologies. Also, it implies that sufficient design margin be taken to avoid potential licensing issues.

Trying to look further into the future, it is discussed what would be the required development to broaden the range of coupling schemes and be able to supply heat to a meaningful part of the industrial heat market. Only developments that would not require (realistically) more than 10 to 15 years are presented ("medium/long term" scenario). Expectations for a longer time horizon are out of the scope of the analysis.

The results of this assessment are used in the definition of a roadmap for the deployment of the HTR technology (task 3.2).

It should be noted that the analysis presented here was done before the Fukushima-Daiichi accident. The consequences of the accident on the nuclear industry and on the HTR technology in particular are not discussed in the document.

Approval

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Abbreviations and Acronymes

ANTARES	AREVA New Technology for Advanced Reactor for Energy Supply
CCS	Carbon Capture System
CEA	Commissariat a l'Energie Atomique
CHP	Combined Heat and Power station
EU ETS	European Union Emissions Trading Scheme
EUROPAIRS	End-User Requirements fOr industrial Process heat Applications with Innovative nuclear Reactors for Sustainable energy supply
EVA-ADAM	Pilot plant erected in Germany (late 70s) for chemical energy transportation system
GFR	Gas Fast Reactor
HP	High Pressure
HTR	High Temperature Reactor
HTGR	High Temperature Gas-cooled Reactor
HTR-PM	Chinese industrial project of 250 MWth pebble-bed reactor
HTSE	High Temperature Steam Electrolysis
HTTR	High Temperature Test Reactor (Oarai,JAEA)
HWR	Heavy Water Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IHX	Intermediate Heat eXchanger
JAERI	Japan Atomic Energy Research Institute (changed name a few years ago to JAEA – Japan Atomic Energy Agency)
LFR	Lead cooled Fast Reactor
LP	Low Pressure
LWR	Light Water Reactor
MSR	Molten Salt Reactor
NGNP	Next Generation of Nuclear Plant (US HTR Project)
NPP	Nuclear Power Plant
O&M	Operation and Maintenance
PBMR	Pebble Bed Modular Reactor (South African HTR Project)
PBMR (Pty) Ltd	Pebble Bed Modular Reactor (Pty) Ltd
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessel
SCWR	SuperCritical Water Reactor
SET Plan	Strategic Energy Technology Plan
SG	Steam Generator
TRISO	TRistructural ISOtropic particle
VHTR	Very High Temperature Reactor

1. Introduction

This document presents the results of the EUROPAIRS project task 1.3 “identification of an operating window for combined system”, which is part of the work package 1“Viability assessment” [1]. The goal is to give a synthesis of the requirements for a High Temperature Reactor (HTR) with industrial heat processes. The focus is on technical aspects of the coupling but some cost assessment is also discussed.

A conventionally coupled system between an HTR and an industrial process can be divided in four parts as depicted in Figure 1:

1. The nuclear zone of a HTR plant, with the reactor, the primary circuit, the heat transfer system and the protecting buildings;
2. The secondary circuit, receiving the heat from the primary circuit. The heated fluid of the secondary circuit can be used to generate electricity in a turbine in parallel to supplying a heat process.
3. The heat transport system linking the HTR heat supply to the industrial site.
4. The industrial facility consuming heat (or making use of process fluid) and electricity.

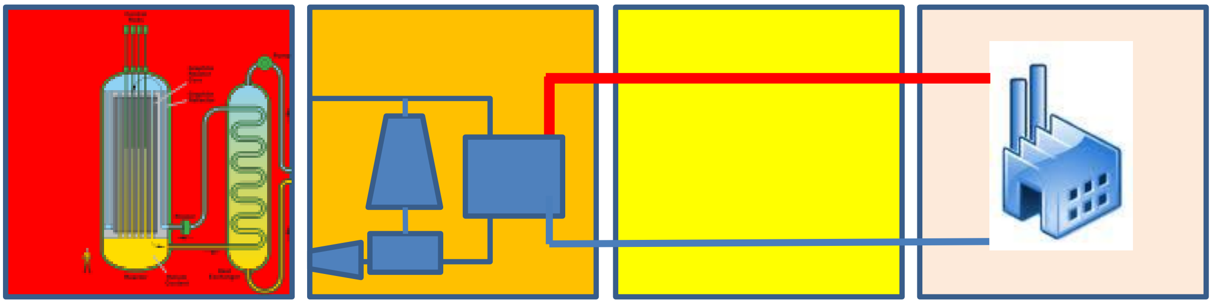


Figure 1 : Schematic view of the coupling of an HTR with an industrial process

The present report is structured as follows. The main results from the heat transport system and industrial process heat requirements [2] and of the heat market survey [3] are summarised and discussed in §2. The main features of the HTR technology and of the characteristics of the primary and secondary circuits [4] are summarized in §3. Certain relevant aspects from safety evaluations [5] are also presented in the section.

In §4, the main aspects of production costs both for conventional process heat production and for the HTR technology are outlined. The assessment gives a qualitative basis for comparison of different scenarios and for a level of costs that would have to be attained by the HTR technology to become competitive.

The identification of potential coupling windows in §5 is separated in a near-term horizon and a medium to long term horizon. Near-term corresponds to the coming 5-10 years. The assessment identifies what would be needed in this time period to put on track the project of a demonstrator coupling scheme between an HTR and an industrial application. The medium/long-term horizon corresponds to a time period of 10-15 years. This is considered to be the time needed to further develop required coupling technologies and be able to supply a larger market with HTR heat supply.

2. Industrial process heat market

The aim of this section is to give an overview of the industrial process heat market. A good understanding of the heat market is necessary for determining the best strategy to develop the HTR technology. In §2.1, the main technologies used in the industry to supply heat to the processes are defined. Also, alternatives for heat transportation are discussed, following the presentation in [5]. Paragraph §2.2 summarizes the results of task 1.1 [2] of the EUROPAIRS project. The purpose of the task was to make a screening of the potential heat processes that could be coupled with an HTR; the analysis relied on the information provided by the EUROPAIRS partners. As presented below, three classes of processes were identified. Paragraph §2.3 gives the main results of the market analysis [3] for assessing the economic potential of the coupling scheme. The market analysis should also play an important role in the selection of the strategy for developing the HTR technology.

It should be reminded that the EUROPAIRS project focuses primarily on the technical limits of the coupling with the heat process. The cogeneration of heat and electricity is also analysed here for the impact it has on the technical (and economic) feasibility of the coupling scheme. Of course, HTR technology is also envisaged for the production of electricity exclusively but this scheme is outside the present scope.

District heating will not be treated in detail in the analysis below, although it is a heat process application with large potential. The reason is that district heating is not strictly speaking an industrial application. Moreover, the temperature requirements for district heating are on the low end of the industrial process requirements (below 200°C) which makes it an application accessible for many technologies (heat recovery systems, geothermic/heat pump, other types of nuclear reactors, etc.). It is not the objective here to compare HTR technology with these low temperature concurrent technologies.

2.1. Generalities on heat supply

2.1.1. Heat sources

Heat supplied to a process can come from different origins. Predominantly, heat is provided from the combustion of a fuel, with the released energy radiated to the surroundings and transmitted to the process medium (liquid or vapour). In chemical processes, the heat can also come from other exothermic reactions that occur during the process. Other industries, such as aluminium production from aluminium ore, use electricity to generate the heat in metal (by the Joule effect) and, eventually, to melt it.

The combustion of fossil fuel and heating with electricity covers practically all industrial process applications. Some specific applications can use other types of heating sources such as heating by induction, by micro-wave or laser but these do not represent a significant market. Heat can also be provided by nuclear energy although to date there are a very few applications of heat processes with heat produced by nuclear energy. District heating and desalination are particular cases.

2.1.2. Direct and indirect heat transfer

Here we shall distinguish two modes of heat transfer: direct and indirect.

Direct heat transfer is when the heat coming from the source is generated within the reactants of the process (from chemical reaction, Joule effect) or when the reactants are directly in contact with the heating fluid (fumes in general). Hence, there is no solid interface between the heat source and the process. This is an advantage because the temperature that can be reached is not limited by the properties of the interface. The walls of the chamber in which the process takes place can be made of refractory materials (typically ceramics) capable of sustaining very high temperature (above 1000°C). In industrial processes, direct heat transfer between the source and the process is carried out in kilns (or ovens), in blast furnaces, in distillation columns, etc.

Indirect heat transfer is when the heat must be transferred from one media to another through a solid interface. This is specifically what a heat-exchanger is made for. The solid interface must satisfy competing requirements:

- It must be a good conductor to limit the size of the transfer surface;
- It must have sufficient mechanical strength at the desired temperature, be resistant to creep and thermal fatigue;
- It must sustain corrosion from the fluids on both sides.

For industrial applications, the heat transfer interfaces are (almost) exclusively made of steel or specific metals alloys. The problem is that metals lose their mechanical resistance at higher temperature and are also more affected by oxidation. This sets a limit on the maximum temperature that can be reached in a process with indirect heat transfer. Typically, with the present technology, the maximum temperature for steels is in the range 500°C to 900°C, depending on the nature of the media on both sides and the steel chosen. Typical types of equipment used for indirect heat transfer in industrial processes are single phase heat-exchangers, furnaces, boilers (steam generators).

Much research has been carried out on ferritic steels to increase the allowable maximum temperature of metal interfaces further. The use of complex nickel based alloys will enable the temperature to be increased further, but they are much more expensive and complex to manufacture. Also, there is hope in the much longer term that heat exchangers with ceramic material will eventually be possible (on an industrial scale) in order to achieve metal interface temperatures greater than 1000°C.

2.1.3. Heat transport / distribution

The content of this paragraph is largely based on information from [6].

On industrial sites, it is often convenient to generate heat or to recover heat in one location on the site, and to distribute or transport it to different consumers on another location (which can several kilometres away for some large sites). The principle is to use a fluid as heat transport media. In general, the fluid is heated by indirect heat transfer (in furnaces, or heat recovery steam generators) and is then sent to the consumer through the pipes of the distribution network. For the consumers, the heat is used either directly, if the fluid can be injected in the process, or indirectly through a heat exchanger.

An objective is to limit the heat losses over the transport network. Typically, heat losses in heat transport networks over several kilometres are limited to a temperature drop less than 50°C. The heat transport media can be gases, liquids and chemical cycles. They are briefly described below.

<u>Gas heat transport media</u>:
The most widely used heat transport media in industrial facilities is steam. It is cheap and the large latent heat of vaporization of water is advantageous for many applications. It should be noted that steam is not only used for heating, but also to supply mechanical work to the facilities (drive turbo-pumps, create vacuum…) or be part of the reactants. Steam is however an oxidant agent, with increasing reactivity as the temperature increases limiting its use to under 600°C with current steels. Other gases, such as nitrogen, carbon dioxide, or helium, may be good alternatives to steam, but in practice, they are currently only used for specific applications.

Liquid heat transport media:
The advantage of liquids over gases is that the former can have better heat transfer properties and larger heat capacity per unit of volume. Hence, the required heat exchange surfaces and the transport pipes can be much smaller than for gases. Water is the usual choice below the temperature of vaporization (for example, for district heating). At temperatures up to 320°C, oil is sometimes used, particularly in refineries. Silicone oils can be used at slightly higher temperatures as can some of the synthetic organics. Above 400°C, molten metals or liquid salts are good candidates. Liquid fluoride salt is sometimes used in chemical industry because of its high boiling point and positive reaction properties with water and air. However, important technical challenges remain with liquid salts: risk of freezing, corrosion issues, interaction with environment in case of leakage, design of heat exchangers, risk of clogging [7].

Chemical heat transmission systems:
Another principle to transport heat is to make use of reversible chemical reaction. This is sometimes referred as "Chemical Heat Transmission Systems". On one side of the transmission system, heat is used to drive an endothermic reaction, reactants are transformed into products of reaction (generally gases) while absorbing heat. The reaction should be rapid, as complete as possible and have high reaction enthalpy to limit the quantity of reactants/products. The products must be sufficiently stable to be transported in the transport pipes to the consumer site. On the other side, the inverse reaction takes places, releasing the energy that was stored. A catalyst is generally required on both sides of the transmission system.

One of the limitations is that the endothermic reaction is improved by increasing the temperature of the reaction, while the inverse exothermic reaction is facilitated if the temperature is decreased. Another source of losses arises from the need to regenerate the catalysts. Currently, the overall efficiency of a chemical transmission system is not sufficient to compete with other heat transport media. The temperature drop between the heat given to the reactants and the heat recovered at the end is larger than the heat losses of a fluid heat carrier over several kilometres. Moreover, the implementation of such a cycle presents other technological issues (purification of compounds due to incomplete reactions, risk of reaction with water or air, toxicity, etc.).

In fact, the principle of reversible reaction is similar to the use of heat to produce chemicals and synthetic fuels. The difference is that for synthetic fuels the production and the consumption are expected to be completely independent (instead of a closed system). Figure 2 shows an illustration of a plant using the reversible reactions involved in steam reforming as a means of energy transmission. A summary of the studies that have been realized on this principle is given in [6]. Also a review of current research trends in this field is given in [8].

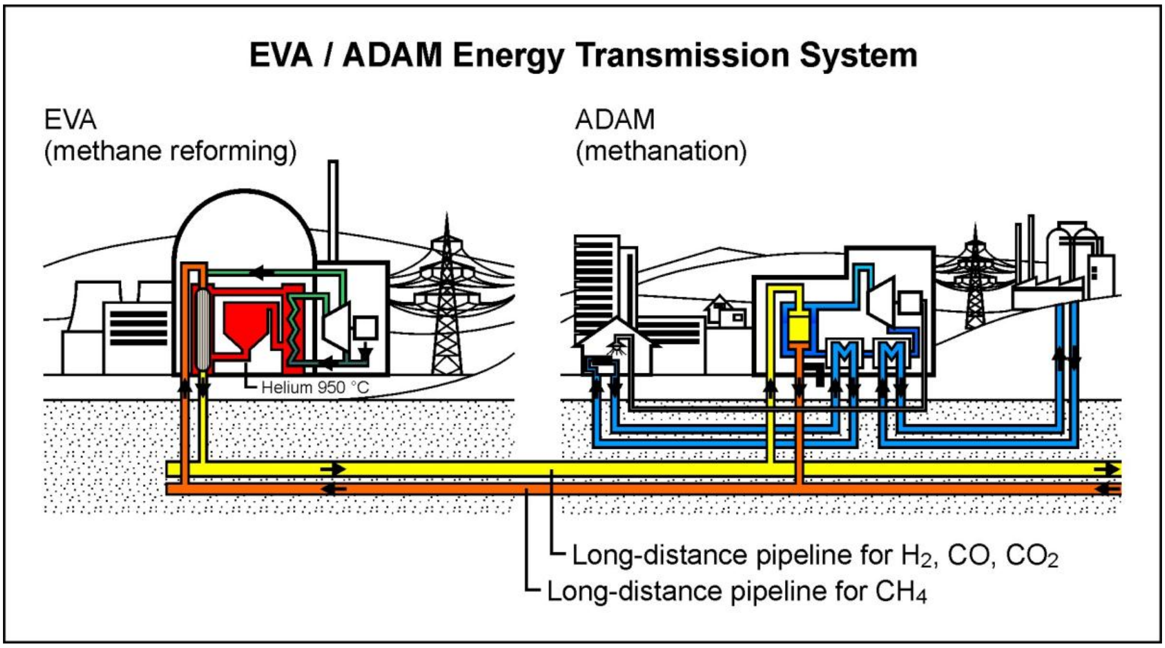


Figure 2: Schematic view of EVA-ADAM pilot plant with steam methane reforming [6]

2.1.4. Heat process temperature

A heat process generally requires specific amounts of heat at different temperatures. The maximum temperature of the process is not necessarily representative of the needs if the process already consumes heat at lower temperature. A distinction is made between “sensible” heat and “latent” heat.

The term “sensible heat” is used when the effect of the heat absorbed (released) by the reactant or the products is to increase (decrease) their temperature. Sensible heat at low temperature is in general easy to provide with heat excess from higher temperature processes.

The term “latent” heat is used for the heat transfer that comes from a chemical reaction or a change of state. As latent heat can be transferred at constant temperature, it is sometimes used to control the temperature of a process. Water-steam transition is the best example of latent heat because it has many applications in the industry (see section 2.2.1). Above 22 MPa, the transition between water and steam is smooth, with no associated latent heat. It corresponds to the range of super-critical steam. The application of latent heat of water is only possible below the critical water temperature, 374°C. In practice, applications of latent heat are well below 300°C.

2.1.5. Cogeneration

Cogeneration is the combined production of electricity and process heat supply. It is often an efficient way of making use of the energy in the heating media (which is generally steam). One application of cogeneration is in a bottoming cycle (Figure 3) when the high temperature steam is used for the heat process and the recovered heat at lower temperature is used for electricity production.

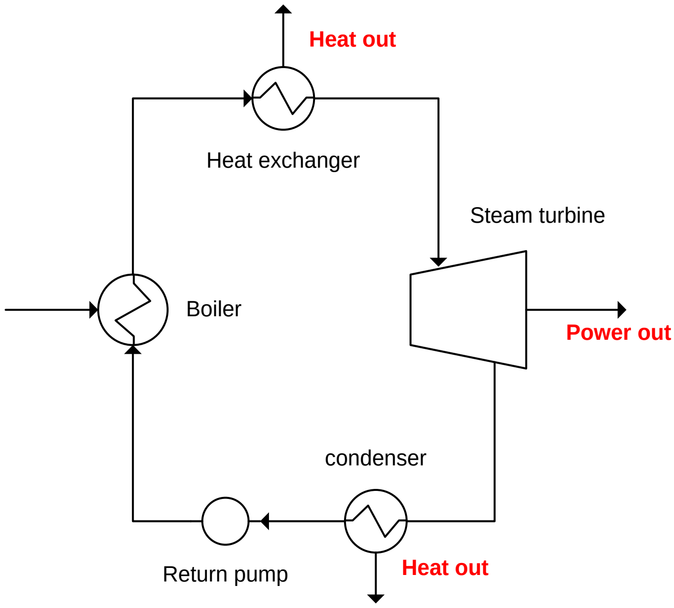


Figure 3: Cogeneration in bottoming cycle [2]

At low temperature, the efficiency associated with electricity generation is low and it is not always worth the additional investment. Other applications which require large amounts of heat at low temperature (<200°C) are desalination plants, district heating, fish farms, greenhouses… These are good candidates for synergies with industrial heat processes.

The inverse configuration is also possible. When the heat-process requires heat at moderate temperature (typically below 400°C), it is efficient to use cogeneration in the form of a topping cycle (Figure 4). Electricity can be generated using a gas turbine (Brayton cycle) and the exhaust gases leaving the turbine used as heating media for the heat process (also known as a combined cycle). In the same way, steam produced in a boiler can generate electricity in a backpressure turbine, and then be used for a heating process.

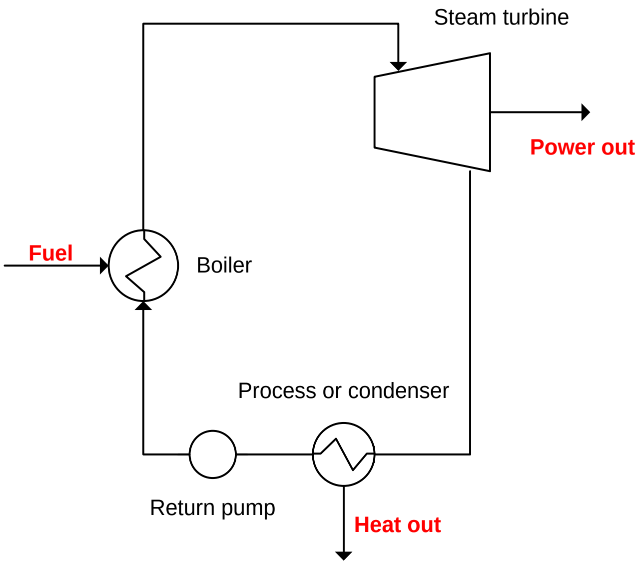


Figure 4: Cogeneration in topping cycle [2]

2.2. Screening of energy consuming processes

The EUROPAIRS project gathers 13 different end-users (Table 1) who have accepted to share information on the requirements of their main processes.

Table 1 Process heat industries participating in EUROPAIRS

Partner name	Industrial sector
AMEC	Oil sands engineering Cement engineering Paper engineering
Air liquide	Industrial gases producer
Arcelor-Mittal	Steel producer
Fortum	Utilities (District heating)
FZJ	Coal gasification Steam methane reforming
Tractebel Engineering - GDF Suez	Utility Engineering
NWU/PBMR	Synthesis fuel production Hydrogen production
PROCHEM	Refinery engineering
SAIPEM	Oil & Gas engineering
SOLVAY	Soda ash
TECHNIP KTI	Refinery engineering
USG/BEC	Petro chemistry Utilities
ZAK	Ammonia – Fertilizers

The EUROPAIRS partners provided descriptions of their processes and the following operating requirements:

- Operating parameters: temperature, pressure as well as the allowable fluctuations.
- Type of fuel used and average consumption by years (for a given production).
- Valuable by-products such as chemicals, flue gas, steam or hot water…

Table 2 categorizes the different processes described by the partners as a function of their (maximum) temperature and the average power of a plant. The analysis of the processes revealed that there are three large classes of heat processes: the steam class, the chemical class, and the mineral class; the characteristics of each are given below (details are given in [2]).

Table 2: Heat requirements (temperature and power) synthesis [2]

TEMPERATURE \POWER	10 -150 MWth	150 - 500 MWth	500 - 1000 MWth	> 1000 MWth
100-600 °C	Refinery Distillation Steam (heating, process, electricity)	Paper Steam (drying)		
	Steel degassing (process, electricity)	Water desalination Steam (drying)		
	Refinery Distillation Superheated Steam (heating, process)	Soda ash Steam (drying)	Steam as utility for indutrial complex	Steam Assisted Gravity Drainage 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	Carbon monoxyde production		
	Hydrogen Very High temperature electrolysis	Hydrogen Chemical water splitting		
> 1000 °C	Lime Kiln production	Cement production		
		Ore sintering		
		Coke making	Metallurgical processes	

2.2.1. Steam Class

The first class is called “the steam class” because heat is transported via steam media or heat is used to remove water by vaporization. The temperature of the processes in this class is between 150°C and 600°C. At the lower temperature limit (150°C) already some important applications occur such as water desalination. Steam can be adequately used as a heating media. As explained in the previous section, the latent heat of condensation makes steam a very efficient media that can control the temperature of a process. For this reason, steam is often used below the critical water temperature (374°C). When steam is produced at a higher temperature:

- The heat process is coupled with a topping cycle to produce electricity in steam turbine; More generally, high pressure steam can be required to perform mechanical work (e.g. to drive turbo-pumps, to maintain a vacuum, etc.)
- Steam takes direct part in a higher temperature process, i.e. for stripping in a refinery or more generally as a process reactant.

The 600°C limit is a technological barrier for ferritic steam generators because corrosion affects the resistance of materials at higher temperature. New materials are being developed to sustain 700°C, in particular for supercritical steam power stations.

2.2.2. Chemical Class

The second class is called “the chemical class”. In this class, heat is the driver of chemical reactions and is consumed as reaction enthalpy generally at constant temperature. The required process temperature is typically between 600°C and 1000°C.

At present, heat in the chemical class is mainly supplied by fossil fuel burners and to a lesser extent by electrical heating. The main applications in this class are:

- Production of oil derivatives by processes such as upgrading, cracking, coking…;
- Syngas production by transformation of methane, biomass or coal derivatives. Syngas is at the base of many useful chemical compounds. It appears also in hydrogen production by methane reforming;
- Production of synthetic products: synthetic fuels, methanol, ammonia fertilizers;
- New processes in this class are also being developed for oxygen production or water electrolysis.

The chemical heat class family is complex for several reasons. The first one is the way in which heat is consumed. As heat drives the reaction, the temperature of the heat source must be higher than the reaction temperature. To have a good efficiency (i.e. pure products), it is advantageous to have the temperature as high as possible. The second reason is the complexity of industrial plants in this class of processes. Chemical industry is organized in industrial complexes which benefit from synergies between the different process units. These synergies are realized by the exchange of energy (heat recovery, burnable gases) and chemical compounds. Introducing external heat sources in an existing complex is not simple as it can affect the overall balance of the different processes. Moreover, the economic costs of changes in such complex facilities are important.

A better way to proceed for the coupling with a new source of heat could be the production of intermediate materials such as syngas, hydrogen, and oxygen. These compounds represent a large market for chemical plants and they can be easily transported and distributed to the consumers in the complex.

The chemical class of processes is still undergoing many developments in technology to continue improving the processes, or to use different sources of raw compounds. This can be an opportunity to have parallel development with the coupling of a “non standard” heat supply system such as HTR. It is however clear that supplying the chemical class with a non-standard heat source is more complicated than supplying for processes of the steam class.

2.2.3. Mineral Class

The third class of processes is called “the mineral class” because heat is used to melt solid or to drive reactions between solids. The required temperature is in general above 1000°C. The temperature can be reached in facilities such as blast furnace and kilns by direct heating. These processes produce excess heat at lower temperature. It is usually exploited by cogeneration in a bottoming cycle. The main industrial sectors for this class of processes are: metallurgy, ceramics, cement and glass.
Providing heat at very high temperature is not possible by indirect heat transfer with current technologies. There is potential in some applications for reducing the temperature of the process. For example, steel making is possible at lower temperature than used in a blast furnace as it requires a hydrogen supply to carry out the iron reduction.

2.3. Heat market analysis

This section presents the main results of the heat market analysis that has been conducted in the framework of EUROPAIRS [3]. The objective of this study is to quantify the European heat market and qualify the energy usage in European heat intensive industries. This is used to determine where the highest potential for the HTR technology lies.

As shown in Figure 5 the estimated heat needs in Europe is subdivided in four categories, from which the first two are existing markets while the others are potential markets:

1. Plug-in supply covering all combined heat and power cogeneration plants supplying one or more industrial facilities.
2. Extended heat market covering all boilers and burners operated internally within an industrial facility and/or embedded directly into the production processes.
3. Poly-generation relating to the production of base raw materials such as industrial gases (e.g. hydrogen nitrogen, oxygen) near or within the nuclear plant.
4. Pre-heating market representing the share that could be externalised if a low-carbon, competitive high temperature steam was available.

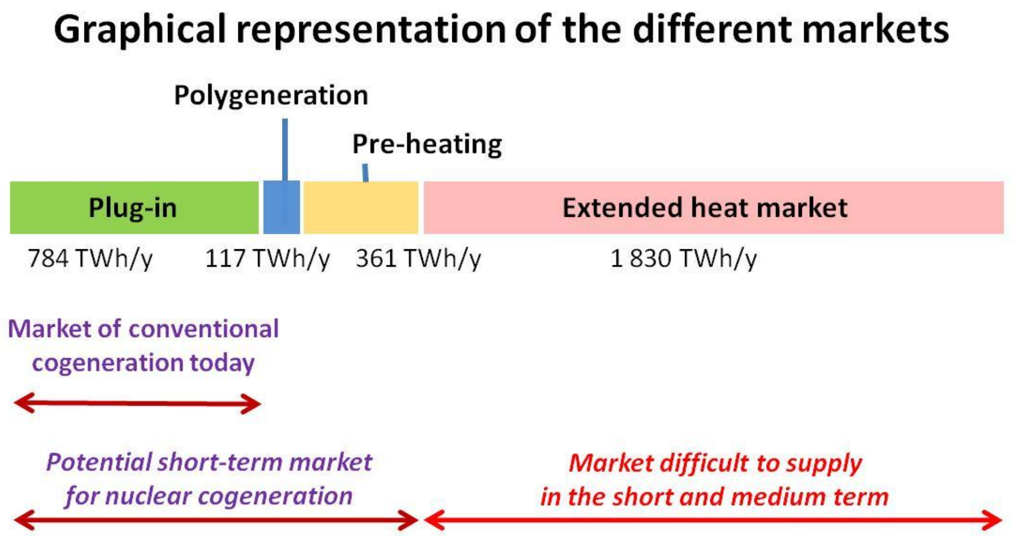


Figure 5: Graphical representation of the European markets for conventional and nuclear cogeneration [3]

From this analysis, important observations are derived; they must be taken into account to decide which coupling configuration should have the priority in developing the technology:

1) The European heat market is large, ranging from 2 529 to 3 091 TWh_{th}/y, or an equivalent 289 to 353 GWth. In comparison, electricity production in Europe in 2007 accounted for an equivalent 381 GWe, which corresponds to about 1000 GWth when produced with fossil fuel power plant having 38% average thermal efficiency.
2) Up to 25% - 30% of the heat market is for external energy in the form of cogeneration, equivalent to 87 to 89 GWth; the remaining 70% - 75% is consumed in embedded process burners and boilers.
3) The heat market is most significant at process temperatures below 550°C (60% to 66% of the heat market) and above 1 000°C (28% to 36% of the heat market).
4) The plug-in market (i.e. cogeneration plants) is restricted to temperatures below 550°C only.
5) The main fuel for cogeneration today is natural gas, and combined cycle gas turbines are the reference technology for cogeneration.
6) The average thermal capacity per site is 34 MW_{th} for the “plug-in” market and 66 MW_{th} for the “extended” market.
7) Each sector has a very specific usage of its internal and external energy which demands a tailored energy supply; large consuming sectors are not necessarily the simplest ones to enter.
8) The distribution of the European heat market by temperature may change in the future with the introduction of new industrial technologies operating at lower temperatures and with pre-heating which would supply a share of the energy consumed in high temperature processes.
9) A competitive, low-carbon production of base raw materials, in particular hydrogen and oxygen, would be welcome by many industries; this would represent an additional poly-generation market.
10) Europe is an attractive market; it has a commercial experience in nuclear cogeneration and good industrial infrastructures with strong companies; and the European energy policy context is favourable to introducing new low-carbon competitive energies.
11) Europe has several industrially dense regions where several customers could be supplied with nuclear steam, electricity and/or base raw chemicals at the same time: Benelux, Western Germany, Northern and Southern France, Northern Italy, Northern Spain and Central UK. Isolated industrial clusters exist in Central and Eastern Europe.

3. Energy supply through High Temperature Reactor

This section focuses on characteristics and technological capacities of High Temperature Reactors (HTR) coupled with an industrial site [4].

Technical information regarding the HTR technology has been provided in deliverable D12 [4]. Over the last years, several nuclear and engineering companies have carried out important developments to design their own HTR concepts. The renewal of this technology worldwide is acknowledged by various projects: HTR-PM in China, GTHTR-300 in Japan, NGNP in the USA, NHDD in Korea. At present, no concept has taken a lead over the others. All HTR designs are facing the same challenge to reach the targeted objectives, namely:

- Very high degree of nuclear safety;
- Supply of high temperature heat (development and qualification of steel or ceramics materials);
- Competitive cost in comparison to current fossil fuels based industry.

3.1. Context

The High Temperature Reactor (HTR) has long been recognized as a promising technology for high efficiency electricity generation and high temperature process heat applications.
Today, HTR is considered the most favourable nuclear reactor technology for heat and electricity cogeneration and coupling with an industrial site. Light Water Reactors (LWR), and among which the most widely spread Pressurized Water Reactors (PWR), are also envisaged for cogeneration but HTR with elevated core outlet temperatures will be able to cover a larger field of industrial heat applications as presented in Figure 6 below. Moreover, developments which would lead to a Very High Temperature Reactor (VHTR) (namely, an HTR capable of supplying heat at temperature well above 800°C) could have a major impact on high temperature process industry.

The HTR technology has a long historical background with several HTR programs with experimental and operational reactors throughout the world. The industrial providers have gain invaluable experience from these past achievements giving them confidence that the technology is mature.

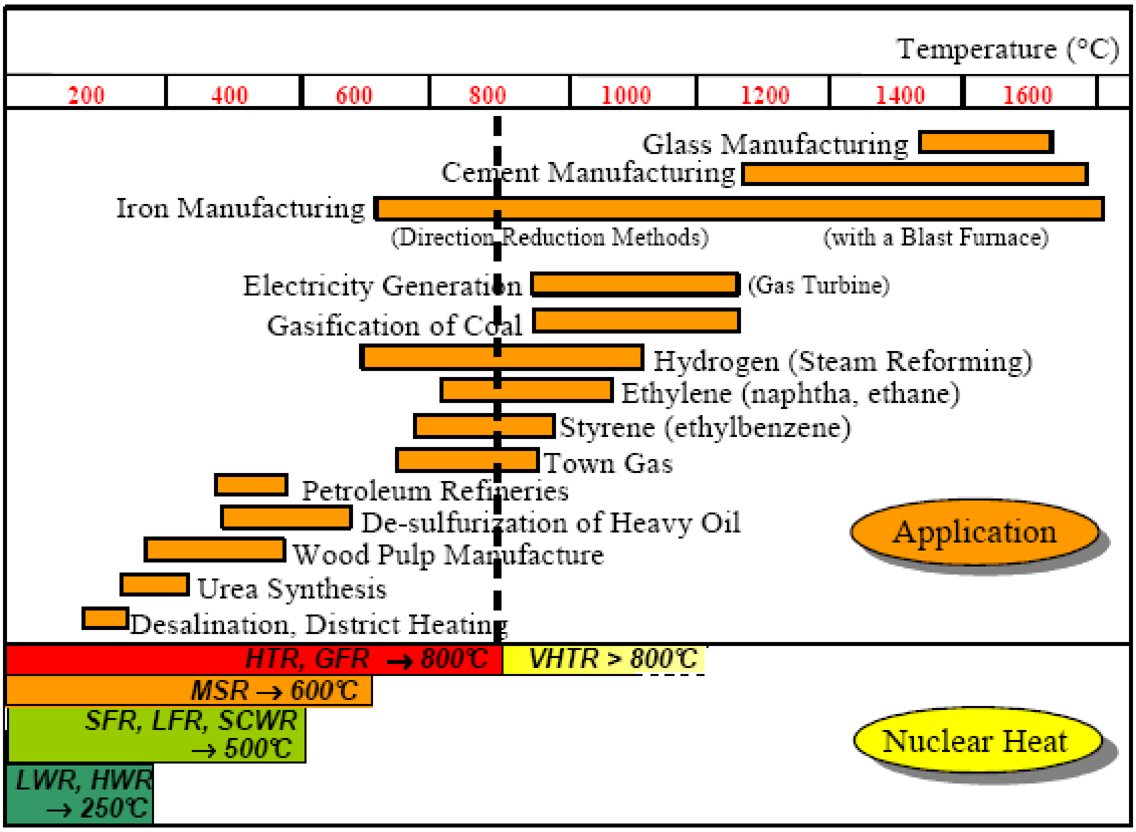


Figure 6: Heat process applications accessible to the different nuclear reactors[1]

3.2. The HTR concept

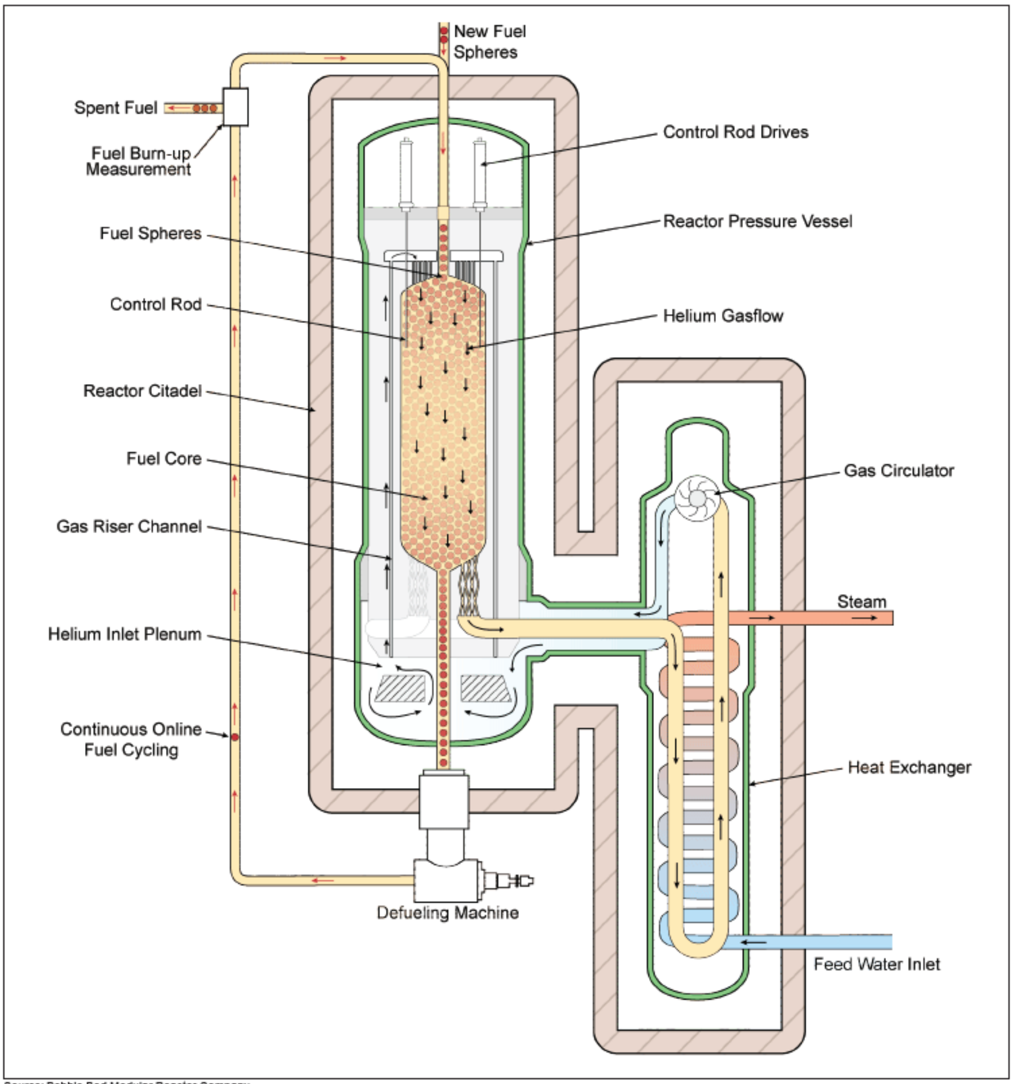
Similarly as with the Light Water Reactor (LWR), the heat in an HTR is generated from the fission of fissile materials (mainly Uranium-235 or Plutonium-239) by thermal neutrons. To be useful for the chain reaction, neutrons emitted after the fission of an atom must be slowed down to the range of thermal neutrons. This is the role of the moderator. In the HTR, graphite is used as moderator. An advantage of graphite is that it can sustain its structural integrity up to (very) high temperature and confine the radioactive fission products. Helium is used as primary coolant to evacuate the heat

[1] Source unknown.

from the fission reaction in the HTR. It presents advantages in that it is inert, has a very small activation cross section (i.e. the probability to be transformed to radioactive elements is very low), and it has very good thermal properties for a gas. The thermal capacity of helium per unit of volume is however much smaller than that of water. So the density of energy transported by the coolant is small in comparison to the LWR. The core power density is also relatively small because of the large mass of graphite it contains. It means that for the same thermal power, the size of the primary equipment of an HTR is much larger than for the LWR.

The schematic view of the primary circuit of an HTR is drawn in Figure 7. The main components of the primary circuit are:

- The reactor vessel containing the core and the fuel. The drawing shows a pebble bed fuel reactor;
- The blower(s) which circulates the helium to cool the core (one per primary loop);
- The heat-exchanger(s) where the heat is transferred to the secondary circuit (one per primary loop). The figure below shows a steam generator as heat exchanger;
- The pipes between the vessel and the heat-exchanger.



Source: Pebble Bed Modular Reactor Company

FIGURE 2
Pebble bed modular reactor demonstration plant reactor

Figure 7 : Schematic view of primary circuit of an HTR (Source: PBMR Ltd)

3.3. Safety Features

Nuclear safety aims at protecting workers, the public and the environment from undue radiation and contamination by radioactive substances [9]. The HTR has the following advantageous safety features:

Very robust fuel particles:
HTR uses TRISO (for TRIstructural ISOtropic-coating) fuel particles, composed of low enriched Uranium kernels (around 0.5mm in diameter), enclosed in a coating with four successive layers (Figure 8). These coatings act as a very robust containment for the radioactive materials, capable of maintaining its integrity to temperatures in excess of 1600°C and in corrosive environment. Another advantage is with regard to proliferation resistance in that it is difficult to reprocess the fuel to extract the plutonium. The particles are also more resistant to fast neutron fluence and allow the fuel to achieve a higher burn-up compared with LWR fuel (note: the burn-up limit is the quantity of fission energy that fuel elements can release without reaching inacceptable degradation of their structural integrity).

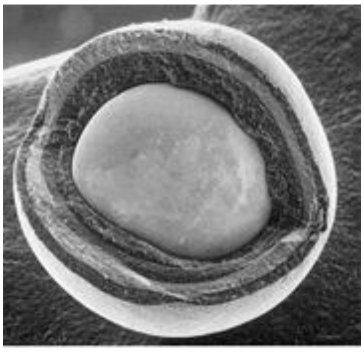


Figure 8 : Microscopic view of a TRISO fuel particle

Large thermal inertia
A second interesting feature for safety is the large thermal inertia of the graphite core. This is favourable as it limits the speed of thermal transients, and therefore gives more time to prevent accidental sequences, and to intervene in post-accidental management. It is expected that the grace period, i.e. the time available before an intervention is required, after a reference accident (such as a. loss of coolant accident) could be 1 or 2 days. In comparison, the grace period for the LWR is generally considered to be 30 min.

Large negative temperature-reactivity coefficient
The power released by the core is controlled by the reactivity of the chain reaction. The HTR concept has the desirable property that adverse conditions (e.g. failure of important equipment) that cause an increase in core temperature automatically reduce the reactivity of the chain reaction, limiting the power further released. This property together with the large thermal inertia and the passive heat removal (see below) allows designing a reactor that remains within acceptable temperature limits during the grace period of any accidental conditions.

Helium as primary coolant
Helium is an inert gas with excellent thermal properties for a gas. It presents no chemical interaction with materials and other gases. It is only weakly inclined to activation through neutron irradiation. The transparency of helium would allow for in vessel inspection (visual, infra-red, LASER) even during reactor operation. These are advantageous properties for a primary coolant.
Nevertheless helium is a source of tritium production in HTR (see §3.5) and it circulates corrosive and radioactive particles generated in operation. Therefore purification systems must be implemented to maintain high purity of helium.

Passive decay heat removal

When the nuclear chain reaction is stopped, the core continues to produce power as the radioactive elements continue to decay. This is called the residual heat. For HTR designed with limited power range (modular concept) the residual heat of the core can be removed passively through the reactor vessel, i.e. by thermal conduction, convection, and radiation. This is made possible because of the relatively low power density, the slim core geometry and the possibility to let the core reach high temperature (in conjunction with the use of a high-temperature alloy for the reactor pressure vessel). Passive heat removal allows the core to be cooled and maintained in a safe state without the need for reliable active safety systems that call for high redundancy. This is favourable not only for the safety but also for the global costs of the technology (see section § 4.2). Active cooling systems could be limited to functions required during normal operating conditions.

Low radiological consequences of accident scenarios

Overall, the inherent safety features of the HTR makes it possible to manage major failures without requiring fast intervention management. The preliminary assessment made by the designers shows that radioactive release consequence of all credible accidents are restricted to the plant site only and have virtually no relevant offsite effect. The consequence is that the nuclear plant boundary can be significantly smaller and the HTR can be located closer to the industrial process than a LWR.

3.4. HTR characteristics and performances

3.4.1. Modular concept

The thermal power of HTRs could in principle be as large as the current LWRs (3000-5000 MW_{th}); however, the feasibility of passive cooling of the core limits the size and the power of the reactor. It is estimated that the maximum achievable power of a reactor depends on its geometry: maximum of 250 MW_{th} for cylindrical core geometry and of 600 MW_{th} for annulus core geometry.

Because of its relatively small power, the HTR is designed as a modular reactor concept. The advantage of small modular reactors is that they can have a high level of factory fabrication that enables a substantial time gain in comparison to field construction of larger reactors. Higher installed power is achieved by combining several modules. It is also clear that the market for HTR modules will not be the same as the market for large reactors producing several thousands of MW_{th} as with the current LWRs.

3.4.2. Components

Core and reactor vessel:

The HTR core is a cylindrical structure mainly made of graphite and housing the fuel elements (pebble or prismatic depending on the HTR design option). The core structure (including the fuel elements and the fuel particles) can maintain their structural integrity up to very high temperature and could be operated in the range 800°C-950°C. The maximal operating temperature is limited by other components (notably the heat exchanger, see below).

Blower(s):

The capacity of the blowers determines the flow rate through the core. The blower capacity required depends on the power of the core, on the cold temperature of the secondary fluid and the pressure drop through the reactor. The higher this temperature, the higher the blower capacity required. In addition, there is a minimum core inlet temperature (about 250°C) that the blower must be able to maintain. This is to prevent the release of Wigner energy building up in graphite (which was part of Windscale accident [10]). The most mature technology for the blower is a design with the motor outside the primary circuit and a leak tight rotating seal. It has been used in the past and its feasibility has been demonstrated.

Heat exchangers:
It is currently not possible to use the primary coolant to directly supply the heat process for different reasons including radioactive graphite dust and tritium content of the primary circuit. Hence, the heat from the primary circuit must be transferred through a heat-exchanger to a secondary circuit (see section 3.4.3 below).

3.4.3. Heat exchange technologies

Three heat transfer technologies have been reviewed within the task 1.2 (see [4] for details): Steam Generators (SG), gas-gas Intermediate Heat eXchanger (IHX), and Molten-salt IHX. The main results of the study are the following:

Steam Generators:
Sub-critical (or conventional) SG is a mature technology already used in past HTR projects and which is in service in most nuclear plants (in PWR of course, but also in CO2-cooled Advanced Gas Reactors for example). The current limits of the technology are the mechanical strength and the resistance to steam corrosion at high temperature. The technology is mature producing steam at 570°C and 17 MPa. On-going research is looking at increasing the operating limits of the technology. It is expected that for the medium term horizon (>15years), temperatures of up to 650°C – 700°C should be achievable. In parallel, the return of experience on super-critical SG should be available from conventional power plants and be adapted to HTR.

Gas-Gas IHX:
The use of an inert gas on the secondary side of the heat exchanger reduces the corrosion issues and allows operation at higher temperature. The technology of IHX has already been demonstrated in HTR modules (tests of 10 MWth mockups). At present, the technology is not considered to have reached the same maturity as SG because there is little return of industrial experience and the degradation mechanism are less well known than with steam generators. Nevertheless, it is estimated that IHX with operating temperature of 750°C-800°C and a lifetime of 10 to 30 years should be available not to far in the future. In the longer term, the technology could probably extent the temperature limits to 900°C with sufficient HX lifetime but that will require important material and design advances. In addition to technical problems, another major issue is the cost of Gas-Gas IHX. Currently, long lifetimes are only achievable with tubular IHX's, which are robust heat exchangers but expensive and of a low compactness compared with very compact plate-fin or printed circuit IHX's. The compact IHX technology however needs more R&D to achieve designs that are of a sufficient lifetime and address issues such as inspection and repair.

Molten-salt IHX:
As an alternative to the gas-gas IHX, the use of molten salt would allow a more efficient heat transfer and a much higher thermal density. Temperature of 800°C in the secondary circuit would be achievable. This technology has however its own drawbacks as discussed in §2.1.3. Corrosion of the heat exchanger by the molten salt is the main issue. Other challenges concern the risk of freezing, the design of the heat exchangers resistant to clogging, and the interaction of the molten-salt with the environment in case of leakage. It would be desirable to maintain the molten salt pressure relatively low. The IHX would then have to resist high differential pressure. Too many unknowns remain to consider the coupling with molten-salt IHX as a potential technology in the near or medium term.

3.4.4. Transient behaviour

The HTR must be able to manage safely three types of transients:

Operational transients:

They are typically startup/shutdown transients and load variations. The frequency, speed and range of operational transients have an impact on the lifetime of the main components. From this point of view, it is advantageous to keep power operation as steady as possible.

Accidental transients:
They occur in the event of a failure of equipment or are triggered by hazard affecting the plant. The safety studies must demonstrate that nuclear safety is guaranteed for envelope scenarios of accidents. It is possible to show that the modular HTR concept is very safe because failure of major equipment (e.g. loss of the blowers, primary leak, and reactivity excursion) can be managed without requiring complex active systems.

Industrial transients:
As a result of the coupling with industrial processes, the HTR must also be able to manage transients triggered on the industrial side (operational or accidental transients): the tighter the coupling, the more impact industrial transients can have on the nuclear side. The choice of the coupling configuration is discussed in §5 (a preliminary analysis of the safety of the coupling between the HTR and the industrial process is performed in EUROPAIRS work package 2 [5]).

3.4.5. Availability and reliability

The availability of a reactor is defined as the ratio between the average power generated by the reactor over a given period (including stops) and its rated power. The availability of an HTR module will mainly be determined by the frequency and the length of planned and unplanned outages. Planned outages are necessary for refuelling (in case of a block fuel reactor), maintenance work or inspections. In parallel, failure of components may lead to unplanned outages which will further reduce the availability of the plant. With several HTR modules combined, the heat supply should remain guaranteed, at least partially, in case of a planned or unplanned outage of one module. This feature is advantageous over a single unit covering the whole heat supply.

The importance of unplanned outage is difficult to predict. Certainly some unplanned outages are to be expected during the first years of operating prototype reactors. But in the longer run, the availability of an HTR module should reach 90-95%. This figure is considered realistic given that there are already LWRs achieving availability close to 95%, and that HTR construction will follow high quality standards common to the nuclear industry.

3.5. Prevention against Tritium released to the coupled system

The content of this section is based on arguments developed in references [4][5][11][12] and [13].

The desirable safety features of HTR technology, preventing important release of radioactivity in accidental conditions, has already been discussed in §3.3. In normal conditions, another safety goal is to prevent tritium (a radioactive isotope of hydrogen) present in the primary coolant from reaching the coupled industrial system. This issue is sufficiently complex to treat it in this dedicated paragraph.

Tritium is produced primarily through reactions in the fuel and inside the control rods, but also from neutron capture reactions with impurities in the coolant and in graphite. The major part of tritium is efficiently contained by fuel coating. Tritium is however highly mobile and will end up in small quantities in the coolant from which it can permeate into secondary cooling circuits and to the outside. Mobility of tritium increases with temperature, so the rate of release in the primary coolant may fluctuate with the reactor temperature regime.

Since the 1970s, ample overview literature was written on the source terms, mobility, and control mechanisms of tritium in HTRs (as well as in tritium generating blankets of fusion reactors). Also, the amount of tritium generated in the reactor can be calculated rather accurately with today's neutron physics codes. There is also substantial feed back from operated plants, in particular Fort Saint Vrain and Peach Bottom in the US and AVR in Germany as well as on HTTR in Japan.

Several methods can be used to act against Tritium releases to the coupled system. Tritium control efforts begin with the limitation impurities in the graphite. Once in the coolant, the permeation outside the primary circuit can be kept low by suitable gas chemistry. The principle is to help convert HT molecules to less permeation-prone molecules (such as water, methane). This can be done by maintaining small amounts of water and hydrogen in the coolant (i.e. "doping" with oxidation potential). The adjustment of the chemistry is used also to keep the heat exchange surfaces oxidized which act as tritium permeation barrier (the permeation can be reduced of more than a factor of 100 with respect to non-oxidised surfaces). Oxide layers are stable with stable temperature. They may have to be restored after temperature transients. An alternative to in-situ generated oxide layers are (expensive) engineered coatings, e.g. aluminizations similar to those used as corrosion protection in gas turbines.
In parallel to the control of the chemistry, tritium releases are limited by purifying the coolant. For this purpose, a slip stream fraction of typically 0.1% of the coolant flow is directed to a gas purification station where impurities are extracted and the gas chemistry is adjusted.
Another principle way to protect from tritium is to separate the coupled heat process from the HTR with a cascade of several cooling circuits (each with coolant purification and possibly permeation barriers). But this exhibits obvious drawbacks with respect to cost, complexity and temperature loss (see discussion in §5).
It can be concluded that today tritium control techniques are well known to minimize tritium contamination to very stringent values, but this capability must be balanced against factors such as loss in efficiency and cost.

As regards to the regulatory imposition, some guidelines on limits of tritium release are defined in the European directive 96/29/EURATOM [25] (member states can yet impose more stringent limits):

- the fluid radioactivity, if exclusively due to tritium, must not exceed 1 GBq or,
- the tritium concentration in the fluid must stay below 1 MBq/g.

But these limits apply only to determine whether the processes fall under declaration exemption procedures or not (declaration to state Authorities). As a minimum objective, the contamination of tritium should respect the ICRP recommendations of 1990 [26] which state that the effective dose yielded to the public by industrial activities must be kept far below the limit of 1 mSv/y. It could be reasonable to demonstrate that the potential dose exposure of worker of the heat process site and on the population exposed to contaminated by-products would not exceed 3% to 5% of the recommended ICRP limit.

4. Economic Assessment

The purpose of this section is to give the main elements that come into play for assessing the economic viability of the HTR technology. The figures given are essentially illustrative and should not be used for decision making purpose. It is not possible to have a detailed assessment of the HTR economics at this stage of the ongoing HTR projects. A more extensive discussion of this economic assessment can be found in [24].

4.1. Process heat costs for concurrent technology

The costs for the heat supply of a process are highly dependent on the specifics of the site. Already for fuel prices, meaningful differences can exist between sites. These differences may originate from the localised nature of the sites (e.g. proximity to terminals or gas network), from terms of contract with suppliers, and from local taxation. More than fuel prices, the costs of heat production for different sites will be strongly influenced by the synergy that can be created between several processes on a site. By-product gases may be recovered to reduce the external feed; excess heat from high temperature processes can be recovered to drive lower temperature processes. Also, each site investment cost is dependent on the way the site has transformed historically.

For these reasons, it is clearly not an easy task to provide a "generic" assessment of process heat costs. Nevertheless, to fix the idea, it is proposed here to give some reference costs for a typical production of steam. Three technologies are compared:

- Production of steam only from gas or coal Steam Generator/boiler;
- Cogeneration of electricity and steam from gas (CHP);
- Cogeneration of electricity and steam from coal power station.

The costs are divided in four parts:

- Investment (taking into account a specific discount rate);
- Fuel;
- Operation and Maintenance;
- Carbon (and other pollutant) emission.

The aim is to compare the costs for producing a quantity of steam equivalent to 1 MWh_{th} supplied to the process. To simplify the reasoning, it is assumed that all technologies would be able to produce steam at the desired conditions and that the electricity produced by cogeneration can be sold as a "by-product" to reduce the heat supply costs.
The following efficiency for converting heat from fuel combustion has been applied:

- Efficiency of boiler/steam generator: η_{th} = 95%.
- Efficiency for cogeneration cycle: η_e of 30% for electricity + η_{th} of 55% for heat (remark: the ratio is assumed fixed).

Table 3 shows some reference for the terms appearing in the calculation. The values for investment and operating costs were derived from IEA energy statistics for 2010 [14]. They should however be considered as illustrative as there may be significant differences from one plant to another.

Table 3: Reference value for investment and operating costs (IEA 2010) [14]

	Overnight investment cost (k€/MW_{th})	Levelized investment at 5% rate (€/MWh_{th})	Levelized investment at 10% rate (€/MWh_{th})	Operating and maintenance (€/MWh_{th})
Boiler / Steam Generator (*)	150	1	2	1
Natural gas – CHP	520	4	8	3
Coal CHP	1200	10	20	5

(*) Illustrative figures only.

The levelized investment represents the energy price that would cover the refunding of the investment (and interests) over the whole plant lifetime.

Table 4 shows some reference value for the price of fuels, electricity and CO_2 emission during the last decade in Europe.

Table 4: Prices – data from European Energy Exchanges (EEX) [15][16]

	Prices observed during previous years			CO_2 factor (ton CO_2/MWh_{th})
	average	Historical high	units	
Natural Gas	16	33	€/MWh_{th}	0.200
Coal	10	17	€/MWh_{th}	0.350
Electricity	55	80	€/MWh_e	-
CO2 on European trading market	18	30	€/ton CO_2	-

The data for CO_2 emission costs refers to European Union emission trading scheme (EU ETS), a mechanism created in 2005 [17]. After reaching a historical maximum in 2006, the prices for emission permits collapsed below 1 €/tCO2 in 2007. Changes made in the trading scheme phase 2 (2008-2012) and phase 3 (after 2012) should correct the shortcomings of the first phase. The price is now more or less stabilized around 18€/tCO2.

From these data, it is possible to evaluate the costs for producing 1 MWh_{th} from one of the technologies with the following formula:

$$C_{1MWhth} = I_{\%} + OM + F + E – S,$$

where

$I_{\%}$: Investment cost for a specific interest rate.

OM: Operating and maintenance costs.

F: Fuel consumption cost, which is computed by the price of fuel for 1 MWh_{th} divided by η_{th}.

E: Cost of CO_2 emission in EU ETS system, which is computed by the cost of 1 ton CO_2 emission permit, times the CO_2 factor of the fuel, divided by η_{th}.

S: Money earn from selling the electricity produced by cogeneration at the market price.

With this formula, the production of 1 MWh_{th} of steam from the different technologies and different scenarios can be calculated. The results (illustrative only) are given in Table 5.

Table 5: Costs of different scenarios for producing 1 MWh_{th}

Technology	Investment rate	Prices	Emission scheme	Cost in € for producing 1 MWh_{th} steam
Boiler	5%	Coal, avg	No	1 + 1 + 10/0.95 = 13€
Boiler	5%	Coal, avg	Yes, avg	1 + 1 + (10 + 18x0.35)/0.95 = 19€
Boiler	10%	Coal, high	Yes, high	2 + 1 + (17 + 30x0.35)/0.95 = 32€
CHP - gas	5%	Gas, avg	No	4+3+(16-0.3x55)/0.55 = 6€
CHP - gas	5%	Gas, avg	Yes, avg	4+3+(16+18x0.2-0.3x55)/0.55= 13€
CHP - gas	10%	Gas, high	Yes, high	8+3+(33+30x0.2-0.3x80)/0.55 = 38€
CHP – coal	5%	Coal, avg	No	10+5+(10-0.3x55)/0.55 = 3€
CHP – coal	5%	Coal, avg	Yes, avg	10+5+(10+18x0.35-0.3x55)/0.55 = 15€
CHP - coal	10%	Coal, high	Yes, high	20+5+(17+30x0.35-0.3x80)/0.55 = 31€

As stated previously, it is very difficult to have a precise estimate of costs in a generic manner; moreover, predicting how the prices will evolve in the next decade is far from obvious. Currently, for fuel prices stabilised around their averages and a CO_2 trading scheme that applies for all production, there is not much difference between the technologies. Production costs are estimated around 16€/MWh_{th} with the average fuel, electricity and CO_2 taxation prices over the last years. Given the limited gap between the technologies, political incentives are required for industries to switch from existing boiler to a more energy-efficient cogeneration production.

What is also apparent is that if the taxation mechanism for CO_2 emission is to prevail and if the fuel prices are to increase and stay at a high level in the future, this can only lead to a drastic increase of heat production costs.
It is expected that gas prices will increase more rapidly than coal because reserves of coal are much larger. In this case, the production of heat with coal could be the leading technology in the future, at a cost around 30-40€/MWh_{th}. If CO_2 costs are to further increase, it could become more advantageous to switch to Carbon Capture and Storage (CCS) technology to avoid emissions costs, although the technology is said to increase the production costs by 30 to 60%. The CCS could be the concurrent technology of HTR in the long term if prices of gas are to increase much faster than coal prices.

4.2. HTR technology cost assessment

The economics of new nuclear power plants is very complex. The total cost of generating power via nuclear energy is generally separated in four contributions:

- Investment cost including construction and financial interests;
- Operating cost, including buying the fuel and running the plant;
- Cost of waste disposal from the plant;
- Cost of decommissioning the plant.

Quantifying some of these costs for a new design of reactor such as the HTR is difficult as it requires making many assumptions on the future. Costs from HTR research reactors do not give neither an attractive image because they are much larger (by kWh generated) than the costs of a mature industrial realization. In China, HTR-PM project is expected to demonstrate the economic potential of Nth-of-its-kind modular HTR. It is however too soon to rely on the information available from this project as the two-module plant is only starting its construction phase.

It should be also noted that HTR technology is to play a role on market inaccessible to (large) LWR, with higher process temperatures and smaller capacity production needs. Large reactors require large electrical grid and they are not well suited for many regions in the world where the electrical grid is too sparse. Furthermore, the extremely low radiological consequences that an accident on an HTR would generate allow it to be sited where the consumers are located rather than in remote locations. Distance between a facility and an HTR can be smaller than with, for instance, a PWR, the heat transport costs are thus less important.

4.2.1. LWR reference costs

Many studies have tried to assess the cost of electricity generation with a nuclear reactor, and with LWRs in particular [18][19][20]. Presently, there is no consensus between the studies, mainly due to the fact that very different values are stated for the complementary costs such as waste disposal and dismantling. Also, there is debate on the amount of public funding that has been injected to start nuclear industry. The values cited by the different studies for electricity generation with nuclear lies generally between 30€/MWh_e and 80€/MWh_e (or higher from more pessimistic opinions).

The relative costs appearing in LWR electricity production are separated in the following manner:

- Investment: 40-50%
- Fuel: 10%
- Operational and maintenance: 35-45%
- Waste disposal and decommissioning: 5%

From this distribution, it is easy to understand why large uncertainties on the construction costs of new builds have a big impact on the financial viability of a project. The cost for new LWR designs are claimed to be around 1500€ per installed kW_e, although it has been revealed that construction delays could make the costs multiplied by a factor of two or three. This large uncertainty is of course not present when considering current LWR fleets which have already exceeded their pay off time.

As fuel costs amount to only a small percentage of the total costs, variability of the cost of Uranium ore on the market has a limited impact. For example, if the price of fuel were to increase by a factor of three, this would only correspond to a 20% increase of the total costs (according to the distribution given above). Nevertheless, if ore production capacity becomes insufficient for the future, the fuel costs could increase drastically.

As indicated above, there is still large uncertainty on the final costs of waste disposal because the solutions proposed for the long term have not yet been definitively accepted. Concerning dismantling, there is already experience acquired by the dismantling of some plants [21]. It is difficult to compare the costs of prototype dismantling methods with the costs that will ultimately be associated with dismantling of the current LWR fleets.

From these considerations, it is understandable why there is so much debate on the real cost of nuclear energy and on the profitability of new builds.

Let us consider that the costs of electricity production with nuclear reactors is around 50€/MWh_e. A LWR produces steam at approximately 70bars and 290°C. This gives an efficiency of the thermal cycle for electricity production with LWR around 32%. If steam was to be used for heat process application, it would have to be sold somewhere close to 20 €/MWh_{th} to be profitable. This should be a target for competitiveness of HTR in the long term.

4.2.2. Construction costs

In comparison to LWR, the smaller power density of the HTR penalizes the costs. The reactor vessel, reactor internals and potential heat exchanger (SG, tubular IHX, etc.) are proportionally much larger than the corresponding components of a LWR. Overall, the larger power of a LWR contributes to scale economy. It should be noted however that these large components account only for a few percent of the total construction costs so the impact might not be very important [22].

On the other hand, due to the inherent safety feature of the HTR concept, auxiliary systems and I&C systems can be greatly simplified. These systems have a large impact on the costs of LWR. Their simplification for the HTR could compensate the scale economy of LWR.

Another advantage is that an HTR module constitutes a smaller and more flexible investment than a LWR. Standardization and off-site prefabrication should provide for a cheaper and shorter construction time. For a multi-module plant, production and return on investments will start earlier than for a LWR.

Some economic assessments reached to the conclusion that overall economics of a 2×250 MW_{th} modular plant would be more expensive than a single 500 MW_{th} plant but far less than twice the capital cost expenses (see INET assessment for the HTR-PM [22]). Given the advantages that smaller units presents, the modular solution could be judged more attractive depending on the project.

The lifetime of the main components and availability of an HTR have also a significant impact on the overall cost. The targeted plant lifetime of an HTR module is in the range 40 – 60 years, similarly to the current generation of LWRs and other new advanced reactors. It is expected that the main components such as the blowers, SG or IHX will need to be replaced (possibly several times) over the lifetime. The HTR design must be such that these replacements can be done easily.

4.2.3. Heat backup

Due to planned and unplanned outages, it will not be possible to satisfy at any moment the needs of the heat process with a single HTR module. The combination of several supplies is required to guarantee high availability of the heat for the process.

Loss of production during planned outages could be managed with several HTR modules because the outage pattern would be chosen to maintain continuously sufficient production capacity. The total installed heat capacity would have to be higher than the maximum process needs. The use of smaller HTR modules is favourable because it limits the over-capacity. Given the important investment cost of nuclear reactors, it makes sense to operate the HTR modules at the rated power. Electricity cogeneration seems the most rationale solution to make use of excess heat production capacity.

Loss of production due to unplanned outage is more difficult to manage because it can disturb the pattern of planned outages. Here also, smaller modules are favourable since the impact of losing a single module is more limited. More problematic is the risk of losing the complete HTR heat supply (although this scenario is very improbable). Some safeguard conventional heat production units will have to be maintained to ensure that the process installation can not be harmed by HTR supply interruption. This is nevertheless not particular to HTR because all other technologies require back up more or less to the same degree. The back up is then provided by relatively low investment cost technology such as a simple gas fired boiler. The operation costs may be high for the back up but this is not so relevant as the operating hours of the back up will be very limited.

Overall, the optimal size of HTR module as well as the optimal number of HTR and conventional units will have to be determined. A method to do the optimization has been described in [23].

4.2.4. Other costs

<u>Fuel</u>

The design of HTR fuel elements is very different from LWR fuel elements. The HTR fuel technology presents some advantages over the LWR. The global efficiency is improved because of the higher working temperature of the reactor. The HTR fuel accepts higher burn-up (see §3.3 for the definition). Also, design that allows in-power refueling could increase the overall availability of the plant, although a more complex refueling machine would be needed.

There are currently two different fuel designs available, namely UO_2 and UCO. UCO should achieve a burn-up of 70% more than UO_2, which is advantageous on fuel economics. In any case, the fuel cost should be very robust against fluctuations in the Uranium price. Fuel cost will not be the major operational cost of an HTR. A cost somewhere around 5€/MWh_{th} has been estimated by some constructors. To get to this price range, fuel economies of scale will have to be achieved through large fuel production (and reprocessing) facilities that are shared over an HTR fleet.

<u>Operation and maintenance</u>

Over the plant lifetime, operation and maintenance costs can become the dominant term for a LWR. The relative importance of these costs should be similar for the HTR, but experience feedback is needed to confirm this.

<u>Waste and decommissioning</u>

Again, part of costs attributed to waste disposal and dismantling should not be so much different to expectations for LWRs. For the dismantling, feedback from other graphite core/gas cooled reactor could be more helpful, although the size and the design of the reactor could also make a big difference.

Concerning waste disposal, some people claim that TRISO particles would be perfect for long term deep burial. This would reduce the reprocessing cost of fuel compared to LWR fuel. Clearly, it is impossible to give precise estimate of these costs for reactors that are yet to be designed.

4.3. Conclusion

Cost comparison between the HTR technology and conventional heat production units is very difficult due to the limited knowledge of HTR costs, the complexity of assessing costs within industrial sites, and the uncertainty on the evolution of energy markets. It is essentially qualitative arguments that can be drawn from the available information.

There exist many studies comparing nuclear electricity production against other technologies. The results may vary from one study to another but overall there should not be much difference between the technologies within the current fuel market prices. The main economical obstacle for new nuclear builds is the high investment risk that such project represents.

For combined heat and power application (cogeneration), gas is currently often the preferred technology because of the relatively low investment costs. It is however expected that coal will be the leading technology against which nuclear has to compete in the future because the coal prices are not expected to increase as much as natural gas. Nuclear could gain an advantage over coal if costs of CO_2 emission were to increase. Carbon capture and sequestration technology represent also important complementary costs giving a further advantage to nuclear.

To be competitive in the current market, it is estimated that HTR should produce heat at a cost around 20 €/MWh_{th} , i.e. in range similar to the costs of LWR steam production. Considering an increase of fossil fuel prices and CO_2 taxation, the probability that the cost for other technologies will increase to 30-40 €/MWh_{th} in the future is high. This would be a market easier to enter with a new technology. It is however not possible to predict how long it will take to reach that level. In any case, the HTR technology will certainly not be able to compete against the cost of the competition for a first industrial realization. The considerations developed above show that the cost of HTR technology will improve as more experience in the construction of modules and fuel are gained over time.

5. Coupling of HTR with industrial processes

From the analysis of the industrial heat process market and the HTR technology description, it is possible to assess the viability of the coupling. The goal of the present assessment is to identify what is technically achievable and what is the potential for the heat market for two different duration prospects:

Near-term horizon:
Near-term horizon concerns the work that could be done within 5 years from now on a coupling project. It is thought that this period should be necessary to resolved remaining technical and licensing issues in order to be able to elaborate a detailed demonstrator design. The coupling configuration for the near-term objectives should rely on already mature technology.

Medium/long term horizon:
Medium to long term time horizon focuses on the developments that could need another 10 to 15 years and that would allow broadening of the range of coupling schemes (i.e. reaching higher temperatures and tighter coupling configurations). To succeed, the HTR technology will have to be able to reach a market sufficiently large to make a difference on the reduction of CO_2 emission and to become an economically viable alternative to conventional heat supply systems.

Longer term perspectives are out of the scope of the EUROPAIRS project. Hopefully, new materials will be developed to allow heat transfer at very high temperature (>900°C). Also, experience feedback is needed to demonstrate the safety of the HTR concept at very high temperature and with tight coupling.

The two considered time horizons are discussed in detail in the following.

5.1. Near-term

The focus here is on defining possible coupling schemes relying on mature technologies on which the demonstration of coupling an HTR with an industrial process could be based.

5.1.1. Coupling configuration

Many configurations are possible to bring the heat from the HTR module to the final heat process consumer: direct or indirect coupling between the secondary fluid and the heat process, cogeneration, choice of heat transport media, number of modules… Also, safety, flexibility of operation and costs must be taken into account to determine the optimal configuration. Above all, coupling with an industrial process should not lead to a reduction of the level of safety of the HTR concept.

The selection of the configuration will only be possible after a licensing framework is defined. The licensing requirements may lead to exclude for a first realization certain configurations needing more experience feedback.

Protection against contamination:
A first aspect that will be required within the licensing process of the coupling scheme is the guarantee that the exposure of workers on the coupling site and the exposure of public in contact with products coming from the industrial process will always be below the regulatory limit. As discussed in §3.5, tritium is the main potential contaminant in normal operating conditions. The protective means against contamination are needed to bring exposure of the workers under the exposure level of non-nuclear facilities.

In order to protect the heat process from tritium contamination (and a fortiori from other radioactive elements), protective means discussed in §3.5 will have to be implemented in the coupled system: limitation of impurities, retention in core materials, control of fluid chemistry, purification systems, and physical separations. This is illustrated on Figure 9.

The separation barrier is realized by the heat exchangers surfaces. At present, it is expected that for a first realization, the licensing process could require that two separation barriers be present between the primary coolant and the process fluid, even if it can be shown that the tritium content after the first barrier is already very low. This has of course an impact on the temperature available for the process as each heat exchange is responsible for a temperature drop, and moreover it penalizes the overall economic viability of the concept.
The manner in which contamination carried by the coupling fluid will disperse in the consumer products will have to be carefully assessed taking into account the whole life cycle of the products. It is probable that for a first realization, coupling with some processes may not be accepted because of the lack of experience feedback and the fear that contamination reaching the public be underestimated in the design.

In parallel to the protective means, monitoring of the activity in the different loops should allow the detection of any increase of radioactivity release. Isolation valves on the secondary loop will be necessary to stop the contamination with the nuclear site in case of accidents (e.g. rupture of heat exchange surface).

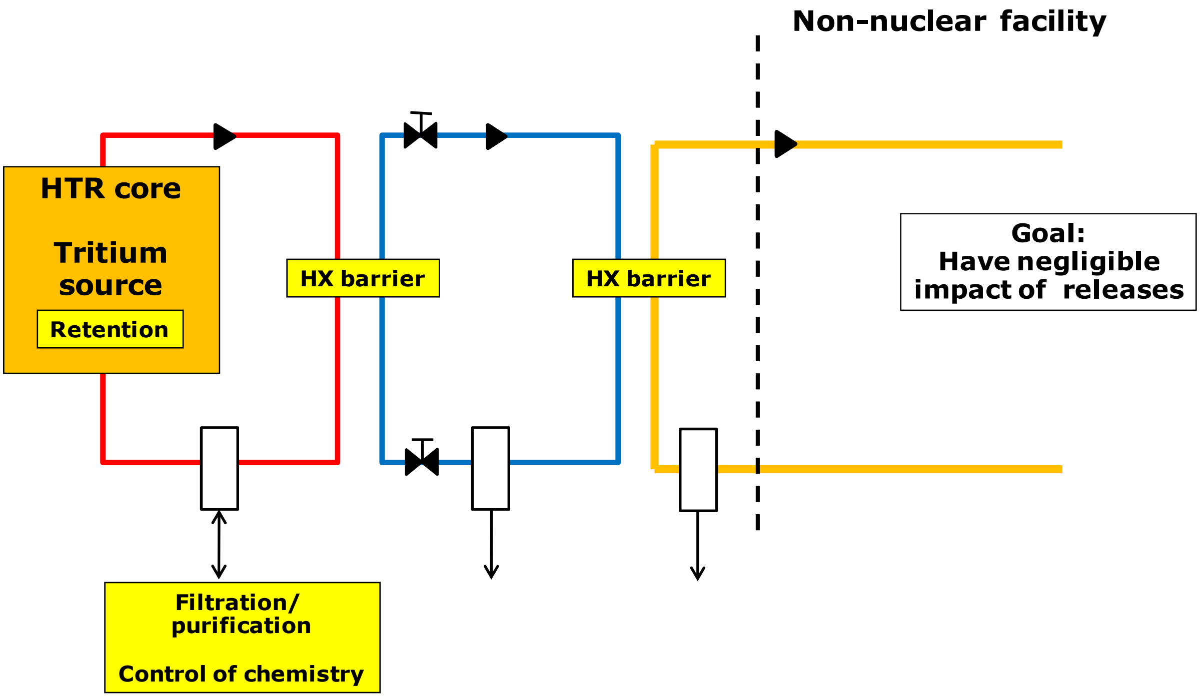


Figure 9: Schematic representation of protection against contamination

Heat transfer technology

If a full-scale demonstrator project was to be started in the near-term, the heat transfer between the primary and the secondary circuits (which is also the first barrier to primary coolant contaminant) would be based on a sub-critical steam generator technology. Other technologies are not sufficiently mature and still very expensive to be proposed for the near-term.

Depending on the tertiary fluid, different secondary to tertiary circuit heat exchanger technology could be imagined. In practice, steam again may be the most natural heat carrier for the tertiary fluid as it is cheaper than other technologies, widely used in the industry and the achievable temperature range covers many existing industrial process needs. The second heat exchanger barrier would then also be a steam generator, but with another design than the one used between the primary and the secondary circuits because the heating fluid is different.

Transferring heat from steam in the secondary loop to generate steam in the tertiary loop can be carried out using a reboiler; however, such equipment would only produce saturated steam limiting the temperature in the tertiary loop atmost to the critical temperature of water/steam. Reaching higher steam temperature in the tertiary loop would require steam/steam HX superheater which is clearly less standard and it would certainly require some development. A liquid heat carrier (oil, fluoride) could also make sense for the tertiary loop, although again this is less standard.

Separation distance

As discussed in the report of the work package 2 of the EUROPAIRS project [5], the proximity of the HTR plant to the heat process site plays an important role in the evaluation of the safety of the coupling scheme. The further apart the HTR to the end-user facility, the lower the risk that an event on one side constitutes a dangerous external hazard on the other. The heat transport media, the chemicals present in the end-user facilities, the risk of leaks and breaks are different aspects that have been analyzed.

Preliminary results [5] indicate that there should not be difficulties to respect the separation distance between the HTR plant and the industrial plant. As long as both plants respect the exclusion distance of one another, the risks induced by the coupling should be relatively easy to tackle. The distance to explosive/toxic material should be the limiting feature. It is expected that a separation distance of 2 kilometres between the HTR modules and the industrial facility would be sufficient in itself for the main explosion risks. This should not present technological obstacle since steam supply network are commonly used for large industrial plant extending over several kilometres. The distance could be shortened with additional protective measure (e.g. erection of a dam).

Transient management and cogeneration

As described in §3.4.4, the HTR will have to be designed to withstand a set of design basis transients which cover both operational transients (power variations, start-up, shutdown) and accidental transients.

Preliminary studies [4] indicate that the transients caused by events on the side of the heat process are less penalizing (for the nuclear safety) than the transients caused by failure of the nuclear systems. Nevertheless, from the point of view of transient management, it is advantageous to have intermediate systems in the coupling which also provides a buffer against the impact of a transient originating from one side of the coupling (HTR or process).

In particular, the cogeneration of electricity in parallel with the heat supply is an interesting way to decouple the nuclear heat production and the heat process consumption. Fluctuations in the consumption can be compensated by the rapid changes in electricity production while the reactor is maintained at optimal steady state conditions, limiting the wearing of main components due to thermal and mechanical cycles. For very fast transients (e.g. loss of heat process), the regulating system should be designed to limit the consequences on the core. This type of requirement is standard for nuclear facilities.

From an economics perspective also, cogeneration looks advantageous as it enables the HTR module to be continuously operated at its rated power (this makes sense for any technology with low fuel costs and high investment costs). The best strategy is probably to have HTR heat production capacity a little over-sized in comparison to normal heat requirements. The excess heat is then used for the production of electricity.

The turbine should certainly be positioned on the secondary circuit to benefit from the higher temperature and thermal cycle efficiency. However, if the electricity production system is shared between several HTR modules, it might also be justified to have a turbine on the tertiary circuit (for design simplicity, or other issues).

For processes requiring lower temperatures than the maximum temperature achievable by the current technology, cogeneration would certainly be performed using a topping cycle, with steam at average to low temperature extracted (by means of a reboiler) for the process.

Number of HTR-modules

It has already been discussed that an advantage of having several modules is to increase the availability of the HTR heat supply. Useful knowledge could be gained from the coupling of several modules in a demonstrator realization. However, the financial risk associated with an HTR demonstrator project should remain within accepted limits. The financial impact for a configuration with several HTR modules should first be assessed.

Proposal

Based on the discussion above, Figure 10 shows a possible (schematic) configuration for a near-term coupling scheme with two HTR modules coupled, steam in the intermediate (secondary) circuit, cogenerating electricity and producing steam in the transport (tertiary) circuit. For the purpose of the illustration, steam is supplied to the process at two different pressure levels.

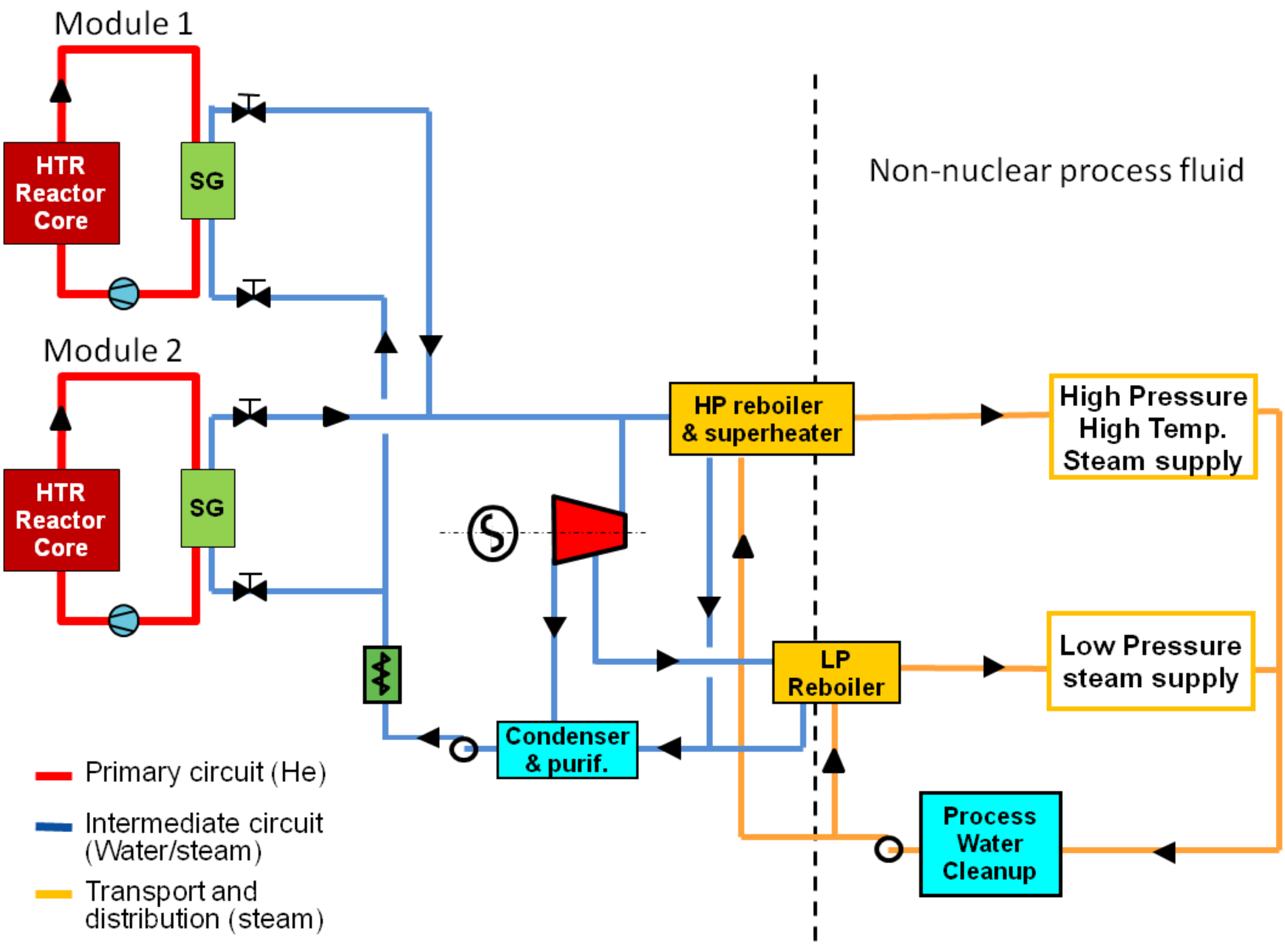


Figure 10: Proposal for near-term configuration of coupling.

5.1.2. Operating parameters

Based on the information in deliverable of task 1.2 [4], it is expected that the limiting operating parameters of the reactor for a near-term realization would be close to the following:

- Nuclear thermal power: max. 250 to 600 MW_{th} depending on the core geometry and, of course, the demand;
- Primary circuit temperature:
  - Core outlet: 750°C
  - Core inlet: a little higher than 250°C up to 450°C.
- Secondary circuit parameters
  - Maximum steam temperature: 570°C
  - Steam pressure: max. 17 MPa

In order to provide the heat process with steam on the tertiary loop at a temperature as high as possible, a type of reboiler-superheater will have to be designed. This type of heat exchanger would probably be responsible for a complementary 30-50°C temperature drop and would limit accordingly the steam pressure in the tertiary circuit to about 10MPa; a more detailed technical economical evaluation would be needed to confirm the values.

The heat losses on the transport line will depend on the length, the size and the insulation of the transport line. Data from the chemical site in Chemelot (The Netherlands) [5] indicate that for a 120 t/h industrial steam transport line over 3 km, the temperature drop over the line is about 30°C and the pressure drop about 1 to 2 MPa.

Finally, the steam is used in the process to heat it. There may be another 20°C gap between the steam temperature and the maximum process temperature. Consequently, the maximum temperature at which the process could be heated should be around 470 - 490°C.

5.1.3. Possible applications

From the discussion of the previous sections, it is obvious that the first applications for which HTR technology will be mature is for coupling with processes from the steam class (see §2.2):

- Applications making use of the latent heat of condensation of steam will be desalination and drying. For such applications, cogeneration in a standard topping cycle with reboilers to generate saturated steam seems appropriate.
- Production of process steam: there should be little licensing issue for process steam application since the steam does not come in contact with the products.
- Distillation process in refinery would also start to be reachable. The acceptability with respect to tritium contamination in the products would have to be assessed.

The maximum temperature available for the process is not sufficient for application of steam at higher temperature (among which the process belonging to the chemical class).

According to the market study [3], the average heat process needs for applications in the steam class are rather in the range 30 MW_{th} to 70 MW_{th}. An HTR with core power in the range 250 to 600 MW_{th} would be too large to supply a single process. Such capacity could of course supply a larger steam network, linking larger sites; the excess capacity would be used to generate electricity. Also, for medium term application, larger modules might be better fitted although this has to be confirmed (see discussion in §5.2). If this is the case, a demonstrator with maximum power capacity would probably be a step in the right direction. On the other hand, smaller modules (40 – 100 MW_{th}) would be better adapted to the needs of the steam class. Regardless of the steam demand, the demonstrator would have to be multi-module to demonstrate steam coupling and control between modules. The financial risk concerning the prototype nature of the project would be reduced with a smaller module capacity. In any case, if the choice of a demonstrator is made for the smaller module capacity, it should still have a design that allows extrapolation to the envisaged optimal commercial size in the longer term.

Applications of the steam class already represent a large market. There are however several limitations to the potential of using the HTR technology for these applications. Indeed, the industry is already highly optimized, with strong concurrent technology used as discussed in §4. High global efficiency is already achieved by cogeneration and an excess of low temperature process heat is often available for steam applications. Moreover, the dispersion of the steam market is not an advantage for nuclear supply because of tedious siting and licensing work needed for each location. In consequence, the steam market that is already accessible to HTR supply in the near-term might not be large enough to represent a very significant CO_2 reduction potential.

5.1.4. Challenges

Significant work is still needed to bring the project of a demonstrator on track. First, licensing and siting aspects, as well as public acceptance, will need to be resolved. It is necessary to determine the best manner to tackle the remaining issues and to be able to convince the safety authorities of the robustness of the concept.

Second, the main design parameters will need to be confirmed (fuel technology, power of a module, detail configuration of intermediate coupling systems…). A detailed technical-economic study will have to be performed to determine the best size of the demonstrator.

To reach these goals, a strong partnership between nuclear and heat process industry is essential. The estimation of the costs of the project will certainly be of great importance to promote this partnership. The demonstrator development stage can be decisive for the HTR technology; if it is a technical success with limited financial exposure, the technology will obviously stir interest leading to a rapid growth.

5.2. Medium/long term

As discussed in the previous sections, HTR technology will be economically viable and present interest for important CO_2 reduction only if it can have access to a sufficiently large heat market. It needs to reach processes other than from the steam class. This section summarizes the potential and the improvements needed for such a development.

5.2.1. Coupling configuration

Some improvements from the proposed near-term configuration are required to bring the technology to other heat processes.

Protection against contamination
Protective measures aimed at limiting the tritium reaching the process are penalizing for the costs and the maximum temperature available for the process. Acquiring better knowledge from the first coupling realizations of operating parameters limiting the release of tritium in the primary coolant and slowing down the permeation rate shall be of prime importance. It may be possible to demonstrate that the stringent requirements on tritium (and other contaminants) release can be achieved with a single physical separation. Experience feedback from a demonstrator project would of course support the demonstration. With a single physical separation between the primary coolant and the process fluid, the requirements on monitoring and isolation systems are increased.

Heat transfer technology
The gas-gas IHX technology has good chance to become the reference heat transfer technology in the medium/long term because it should be the first mature technology to provide heat transfer at temperatures higher than 700°C. To reach this objective, better understanding of the wearing mechanisms is required. Also, the development of a compact IHX with a sufficient lifetime, and limited costs are desirable.

The choice of the gas in the secondary loop is open. Helium is of course a good candidate because of its good thermal properties, but a mixture of helium and nitrogen would make sense also as it would allow the use of compressor/turbine designs similar to those used with combustion gases.

Different configurations can be envisaged for the coupling with the process. One configuration would be to have the process coupled to the secondary circuit by a second IHX. For example, this could be appropriate for processes involving gaseous endothermic chemical reactions.

Another possibility would be to have the heat transfer between the primary and the secondary circuits again based on a steam generator technology, as for the near-term proposal.
If the validity of a single physical separation is proven, the steam could be directly sent to the heat process. With development of steam generator alloys, it is possible that superheated steam at temperature as high as 700°C will be feasible.

Separation distance

It was considered that for a near-term realization, the exclusion distance between the HTR and the industrial site would have to be at least several hundred meters. To benefit from the maximum temperature available in the secondary circuit, it would be advantageous to reduce as much as possible the distance between the HTR module and the heat process; this is even more important at higher temperature because the heat losses during the transport would increase. Furthermore, if the HTR is to be coupled with a process that consumes heat only at high temperature (e.g. latent heat of chemical reaction), the heating fluid could come back still at a medium temperature on the return way, leading to additional heat losses. In this scenario, there would be twice the benefit to have a shorter separation distance.

Safety studies for the coupling scheme will have to determine how shorter coupling distances can be realized within the licensing framework. Under a certain distance, the coupling scheme might have to be considered as a unique entity with a dedicated safety demonstration, rather than two juxtaposed systems as discussed in the report of task 2.1 [5].

Transient management and cogeneration

The discussion given for the near-term configuration is still valid for medium term coupling schemes. It is probable that cogeneration will be interesting both for transient buffering and to maintain the HTR module at rated power. Depending on the process heat requirements, a topping or a bottoming configuration might be more appropriate. With the IHX technology, the secondary fluid is a gas and the electricity will be produced using a Brayton cycle.

For coupling with a process that consumes heat in the high temperature range, another scheme would be to reheat the fluid returning from the process to medium temperature levels. For example, one could envisage that the HTR heats the secondary fluid to 800°C, the process consumes the heat from the secondary fluid down to 500°C, and the secondary fluid is directly reheated from 500°C to 800°C. Albeit thermodynamically appealing, such a scheme would be difficult to handle for the HTR core. The inlet temperature of the reactor would be increased (over 500°C in the example above) and increased blower capacity would be required to reach the same core thermal power as a core with a 250°C inlet temperature. This would also affect the speed of the transients, and potentially leave smaller margins with regard to the safety studies.

Number of modules

Similarly for the near-term, the optimal size of an HTR module and the optimal number of modules for a particular site requires a dedicated technical-economic study.

Proposal

Figure 11 and Figure 12 show two possible configurations for the coupling scheme in the medium/long term. The first proposal is based on a double gas-gas IHX configuration, parallel to a Brayton cycle for electricity generation. The second proposal is based on the production of steam directly sent to the heat process.

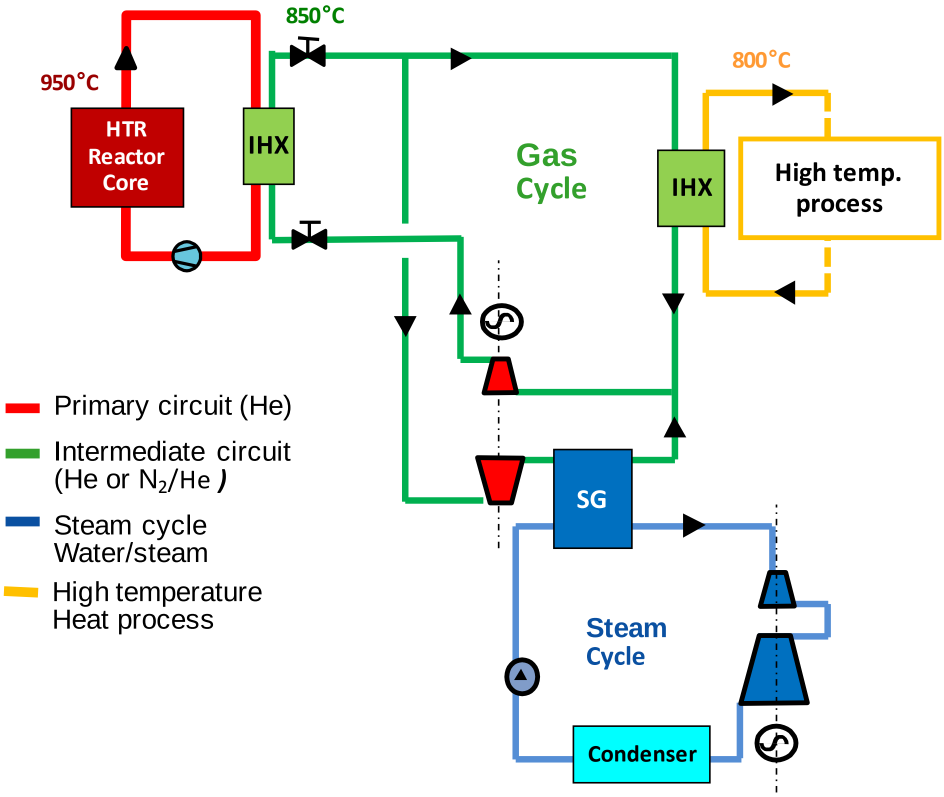


Figure 11: First proposal for medium/long term configuration: double IHX technology for heat process supply and cogeneration by combined gas and steam cycles.

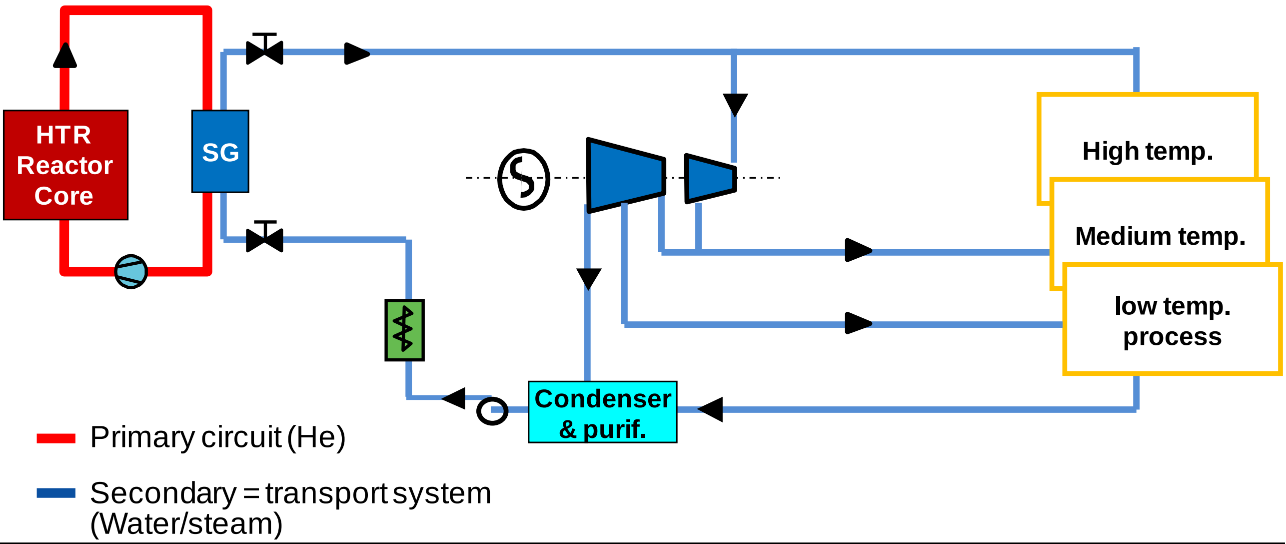


Figure 12: Second proposal for medium/long term configuration: production of steam directly transported to the heat process

5.2.2. Operating parameters

Developments should bring the limiting parameters in the medium-term to the following values:

- Nuclear thermal power: no changes with respect to the values of the near-term horizon, it will remain a maximum of 200 to 600 MW_{th} depending on the core geometry and the fuel design.
- Primary circuit temperature:

    - Core outlet: 850°C to 950°C.
    - Core inlet: higher than 250°C, dependent on the blower capacity and the return temperature of the fluid on the secondary side.
- Secondary circuit maximal temperatures:
    - IHX: the choice of the gas (or gas mixture) for the secondary loop is open (700°C to 900°C, in the longer term)
    - SG (sub-critical or super-critical): 600°C to 700°C.

It is expected that the transport distance could be reduced compared with the near-term realization. In consequence, the temperature drop over the transport system could probably be reduced to a value as low as 10°C.

For a configuration with a second IHX in series to supply the heat process as depicted in Figure 11, a temperature drop of 30°C is assumed (note: this depends essentially on the size of the IHX and the acceptable costs for the equipment). The temperature available for the process in this double IHX coupling scheme could then be around 700°C-10°C-30°C = 660°C in the medium term, and possibly up to 860°C in the longer term horizon.

If instead of the double IHX configuration, a steam generator technology is used to produce steam on the secondary loop (Figure 12) which is sent directly to the transport lines (similar to the near-term proposal but with one less physical separation), the temperature available for the process could then be in the range 600°C -30°C = 570°C, and up to 670°C in the longer term.

5.2.3. Potential applications

With temperatures in the range 600°C to 700°C, the HTR heat supply could start reaching processes from the chemical class:

- Some petrochemical reactions;
- High temperature electrolysis;
- Hydrogen steam reforming.

More processes would become available if the temperature can be further increased. At the same time, developing processes requiring lower temperature is clearly interesting. Some examples are:

- Membrane steam reforming;
- Steel production with advanced processes requiring lower temperature than the standard blast furnace process.

Chemical plants are often very large and complex with synergies between the different processes and, thus, it seems difficult to couple an HTR module directly to existing facilities. A better strategy would be to design the coupling with an HTR dedicated to the production of some basic chemical compounds that have large use in the chemical industry (e.g. syngas, methanol, hydrogen) and are easy to transport.

Based on the market analysis [3] (see summary in §2.3), the current market for the production of base raw chemicals does not seem extremely significant. Nevertheless, if the synthetic fuel is to gradually replace fossil fuels, the market growth perspectives for applications in the chemical class are huge. For this reason, there is certainly a large potential for HTR technology if it is able to be coupled with such processes in the medium term horizon.

Contrary to the steam market, larger HTR modules (200 MW_{th} – 600 MW_{th}) might be more appropriate. The first reason is that the needs for basic chemical compounds could become very large. A second reason is that most chemical processes consume only heat in the higher temperature range, returning large amounts of excess heat at medium temperatures (as discussed in §5.2.1). This “excess” medium temperature heat would probably be suitable to run a bottoming cogeneration configuration.

5.2.4. Challenges

The road is still long before the HTR technology can provide heat at sufficient temperature for chemical processes. Developments are needed to qualify material of gas-gas IHX at high temperatures and to lower the costs in general. Also, there will certainly be much to learn from the coupling scheme by operating a demonstrator, even at lower temperature. The experience feedback might reveal new problems, or might show that some issues have been overestimated.

In parallel to the development of HTR technology and the optimization of module costs, it is important that the process heat industry be involved in the design of the coupling. In particular, it would be valuable to conduct research to assess the interest in bringing existing processes to temperature level that the HTR could attain more rapidly.

6. Conclusions

It is considered that the HTR technology is the most mature nuclear technology that could produce useful heat for industrial processes while further improving on the nuclear safety of the current generation of nuclear reactors. This technology is therefore a potential concurrent to conventional heat production facilities. Coupling of the HTR technology with industrial heat processes is a great challenge because of remaining questions such as the reliability of the technology, the licensing framework to apply, and uncertainties on the economics.

The purpose of this report (Deliverable 13 of the EUROPAIRS project) was to evaluate the prospects for the coupling schemes. The evaluation relied on the information presented in several other sub-tasks, namely the requirements of heat consuming industries (Deliverable 11) [2], the status of HTR technology (Deliverable 12) [4], the analysis of the safety for the coupling between an HTR module and industrial processes (Deliverable 2.1)[5], as well as the market analysis of heat consumption in Europe (Deliverable "Market Study" D131)[3]. Both technical and economic aspects have been taken into account in the present report. The viability assessment of the coupling scheme was considered with respect to a near-term horizon, relying only on mature technologies, and a medium to long term horizon orientated towards markets with high potential.

Assessing the economic viability of the HTR technology is very difficult as there is limited knowledge on costs given that there are currently only experimental HTR reactors operating in the world (deliverable D133) [24]. Also, the costs of fuel and nuclear waste disposal are too complex to assess at this early stage. The first construction of a full scale prototype for the HTR-PM project in China is only just starting; experience feedback from this project in a few years time will be very precious. The other difficulty is that assessing costs for heat production for industrial process is also very complicated and will be subject to high uncertainty in the future. It is expected that fossil fuel prices and CO_2 taxation will be responsible for a significant increase in heat production costs, and it will not be easy to predict whether this trend will change.

Concerning the licensing framework of the coupling scheme, it appears that most risks would be already adequately handled within the existing licensing frameworks. Nevertheless, the regulations will certainly have to be adapted to the HTR technology in order to specify the requirements for the acceptable tritium contamination of the process (and ultimately the products to which the population is exposed). The lack of a dedicated framework plays against the HTR technology, making the choice of the best coupling scheme at this stage complex. It is thought that for a first realization, two separation barriers will be required between the primary coolant (source of contamination) and the process fluid.

From the review of the potential heat transfer technologies presented in Deliverable 12 [4], it appears that steam generator is currently the most mature technology for reliable high temperature heat transfer. Hence, for a near-term demonstrator, the proposal would be to use the heat from the HTR module to generate steam in the secondary circuit at a temperature close to 570°C (which is a current technological limit). A second heat exchange would separate the steam of the secondary circuit from the fluid used as heat carrier for the supply of the industrial process. Steam again appears to be the best choice for the heat carrier fluid. Of course, the successive heat transfers and transport distances would further reduce the temperature available for the process. In parallel to the process heat supply, it looks advantageous to produce excess heat from the HTR module that can be used to cogenerate electricity in the secondary circuit. The electricity would either cover industrial needs or supply the grid.

The proposal for the near-term demonstrator is meant to be alternative to a standard gas-driven combine heat and power station. As stated in the market study [3], the applications that can use externally produced heat represent already a significant part of the market. However, the analysis also shows that there are important barriers to a large deployment of the HTR technology in this market segment, namely because the market is broadly spread using small localized capacity productions, and because there are already other highly competitive technologies at these temperatures. For the HTR technology to provide a substantial contribution to CO_2 reduction, it requires further technological development in order to make it capable of supplying higher temperature processes belonging to the "chemical class". There is a good possibility that the HTR will reach temperatures sufficiently high with the gas-gas heat exchanger technology although it is too early to rely on it (or other non mature technologies) for the demonstration of a coupled system. Generally speaking, it is difficult to predict how long it will be needed to bring a technology to industrial maturity. The prediction of medium to longer term coupling configurations discussed in the document is affected by this difficulty.

The HTR technology will succeed if it can progress step by step in a well defined manner. In this respect, it is of utmost importance that technical and financial risks are correctly identified in order to select the best strategy for the future. The human and financial means allocated to the development of the technology will increase in the same time that doubts can be overcome. As presented in this document, an important step would be to put on track a European demonstrator project for a coupled system, similar to that being developed in China. Achieving this objective would be a major leap for the HTR technology in Europe.

The involvement of both nuclear and heat consuming industries is crucial to determine the best way to proceed as well as to allocate resources most efficiently. The collaboration set by the EUROPAIRS project is an initiative that is certainly going in the right direction. In the future, it would be beneficial to extend this area of partnership around the technology development, inside and outside the European Union.

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