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Summary

This analysis identifies the gaps in industrial infrastructures and competences for R&D which need to be bridged prior to licensing, construction and operation of an HTR demonstrator. Emphasis is given to existing industrial infrastructure and R&D competences in Europe.

Based on the valuable results of the German HTR development program up to the late 1980s, significant progress has been made by several European FP5-7 R&D projects which obtained further leverage through the collaborative participation of European organizations in international projects (NGNP, PBMR, HTR-10…) and in GIF. The most outstanding examples are in the areas of fuel production, quality control and qualification under irradiation, the qualification and coding of high temperature structural materials and new graphite grades (incl. through irradiation testing), component development (e.g. turbomachines, heat exchangers), helium technologies and licensing-relevant modelling (e.g. reactor physics, thermo-fluid dynamics, mechanics, tritium transport, source term calculations, system code integration). In addition, significant improvement was achieved in understanding the market and end-user needs so as to design a power plant accordingly. The European System Integration studies in ARCHER and in NC2I-R, the ANTARES and SC-HTGR projects performed by AREVA and several other industrial designs worldwide reflect this development.

The state of R&D infrastructure is reflecting the available budget and has shown its flexibility. Due to the time gap between the last running HTR and the HTR "revival" in 1999, some facilities had been shut down, mothballed or refurbished to support other projects and developments. A number of them could be recovered and have produced significant results. Examples are the facilities for fuel production (CEA), quality assurance (AREVA), irradiation and post-irradiation examination (JRC, NRG) and safety testing (JRC) or the large-scale facilities to simulate air and water ingress accidents (FZJ). The situation is similar for graphite qualification.

What should not be underestimated is the time and effort required for qualification. Assuming that the currently ongoing international collaboration towards fuel and materials (metals, graphite, composites) qualification are confirmed successful, there is still work ahead in view of licensing related to computer codes and to large-scale test facilities for the qualification of components and subsystems. These include steam generators, heat exchangers, the Reactor Cavity Cooling System, circulators with magnetic bearings, isolation valves, control rod mechanisms, instrumentation and others. Specific qualification test rigs will be needed like the Helium Test Facility built in South Africa for the PBMR program. Comparable large-scale Helium loops are not currently available in Europe.

In parallel to the design efforts, the supply chain for components must be analysed and, where necessary, rebuilt. An example for components no longer available off-the-shelf is the optimized helical coil tube bundle steam generator: while design tools are available in Europe, there is no active supplier worldwide with the required manufacturing capability.

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1 Introduction

Several HTR demonstrators have operated in Europe, therefore a significant amount of know-how and industrial competences have existed in Europe. New regulations and technology, however, require additional or new qualification procedures and skills. Therefore, this document aims at identifying the gaps in industrial infrastructures, and competences for R&D which are required for the construction and licensing of an HTR demonstrator which is recognized as the next step before market deployment.

The first focus will be on existing industrial infrastructure and R&D competences in Europe. Where gaps are identified and relevant competences are known to exist elsewhere in the world, these are addressed as possible alternative or backup solutions.

The demonstrator that is currently foreseen within NC2I-R is based on a number of requirements derived from market needs, input from the industry, HTR programs from the past and current regulatory requirements. It is in line with the strategies of the Generation IV International Forum, the NGNP Industry Alliance in the US, the Nuclear Cogeneration Industrial Initiative in Europe and with the GEMINI collaboration. One of the main requirements for the demonstrator specifications is that the design itself must be based as much as possible on validated concepts and proven technology to reduce the number of gaps. . A distinction is made between gaps related to a near-term demonstrator and to a longer term development, the Very High Temperature Reactor.

The gap analysis ensues other work done within NC2I-R and through the cooperation with GIF. It considers the priorities identified in the VHTR status paper from GIF [1], and is based on task 2.2 (mapping exercise,[2]) and task 4.4 (demonstrator specifications,[3]). The first is a mapping of all HTR technology capabilities which currently exist, the latter lists the required needs for a demonstrator. This gap analysis can be used to establish cost estimations for NC2I, and identifies gaps in R&D and industrial infrastructure and competences for upcoming RD&D.

1.1 Demonstrator specifications

As a first step towards a European HTR design for nuclear cogeneration, a number of functional specifications for an HTR demonstrator have been defined. Task 4.4 has elaborated general specifications for a European HTR demonstrator [3]. These can be summarized as follows:

- The European HTR shall possess **inherent safety features**, even without emergency cooling. This implies absence of radioactivity release which would call for a large Emergency Planning Zone. The passive reactor coolability and the ceramic core tolerating high temperatures are favorable for collocation with industrial sites and public acceptance.
- The demonstrator design should prove the **economic viability** of a follow-on commercial plant. Such a commercial HTR plant should be competitive without government support. In the European context, a minimum power level of about 200 MWth is required. This means that smaller concepts like HTMR, Xe-100, and StarCore (see chapter 4) would need to build several modules per site with the concomitant economic penalty.
- The technical concept should use **proven technology** as much as possible to shorten the licensing process and ensure early deployment. Therefore, the design should largely be based on existing HTR experience with a top cycle temperature of approx. 750°C and employ a conventional steam cycle for producing process steam up to 600°C.
- The requirements towards the **supply chain** & **skills** should be such that high quality of the manufacturing and construction can be assured.

Additionally, a more detailed list of design requirements is listed in the report [3]. These requirements are for a large share focused on the potential customer needs with respect to output requirements of the HTR - Nuclear Heat Supply System (HTR-NHSS), which in turn determine the requirements on components, material properties and selection of fuel.

Further, the specification on inherent safety features implies that the power level should be limited to approx. 250 MWth for a pebble bed design and 625 MWth for a prismatic block design. For increased safety, it is recommended to design at least two barriers between the primary helium loop and the process steam.

Considerations with respect to the distribution between heat and power generation are based on user requirements and heat and electricity price forecasts. In the design requirements report [3] it is concluded that an increase in energy prices favors heat over electricity. Furthermore, flexibility in the heat/electricity ratio would be a welcome feature allowing to iron out demand/supply mismatches of large fractions of renewable electricity generation without having to perform power cycling of the reactor itself.

1.2 History

The content of this report is based on a number of input documents from the NC2I-R project, in addition to earlier studies that have been used as input. Since the early developments in the 1960’s, a number of high temperature reactors have been built and operated around the world, varying from test reactors to industrial prototypes. A significant amount of the development took place in Europe, from the Dragon reactor in the 1960’s to the THTR that operated in the second part of the 80’s. It can therefore be assumed that most of the competences to build and operate an HTR are, or at least have been available in Europe. A number of companies involved in for example the building of the THTR is indeed still active in the field and still develop their products. Due to the time gap between the last running HTR and the start of new HTR R&D in the early 2000's, however, some facilities were shut down, mothballed or refurbished to support other projects and developments.

Also the regulatory requirements, if they are available, change continuously. Today, a demonstrator needs to comply with the new European Directives on Nuclear Safety and Waste. Operational feedback from previous projects results in recommendations for design improvements and operational methods. The design therefore determines the necessary competences in the field of R&D and the required industrial infrastructure for the manufacturing of systems and components.

A large number of gaps that were identified at the early 2000’s when the first EU Framework Programmes on HTR technology started, were successfully addressed in the RAPHAEL and ARCHER projects. Their focus was mainly on the R&D in support of HTR technology, but also industrial competences were reviewed and developed for a number of critical systems such as the Intermediate Heat Exchanger and Steam Generator technology. A number of R&D facilities were refurbished or even built specifically for the purpose of HTR development.

The most recent EU Framework Programme 7 project ARCHER produced a technology gap analysis based on the THTR design, a large one-vessel reactor, which is outside the scope of NC2I-R because it does not comply with the size and safety requirements. The current gap analysis focusses more on the available industrial or research entities that could play a role in delivering the required systems and components for a modular inherently safe demonstrator reactor [4]. Nevertheless, the ARCHER Technology Gap Analysis [5] has produced valuable hints:

Component	Technology Gap
Reactor vessel	none (for concrete pre-stressed RPV)
Steam generator & heat exchangers	Steam generator inspection Tube sheet design and behavior
Core structure	Qualification of new graphite Minimization of bypass flows
Blowers	Bearings (magnetic vs. oil lubrication) Orientation (horizontal vs. vertical)
Fuel handling system	Recycling vs. once through Performance at elevated pressures, temperatures, and burn-ups
Reactivity control system	Diverse shutdown systems Testing and qualification of in-core control rods (if needed)
He Purification system	Design improvements depending on today's regulatory requirements
Core design	Development of an integral HTR modelling package Validation of existing core models
Graphite dust	Filters & Effect of flushing Development of a separation concept minimizing contamination Development of simulation models (formation, activation, transport, deposition, remobilization) Prevention of dust formation
Air & water ingress	Development of simulation tools and their validation
Regulatory framework	Collection and analysis of regulatory requirements and industrial standards
Economical aspects	Economics of scale with respect to investment costs Design optimization with respect to economic aspects (e.g. integral system design vs. separate vessels for core and heat exchanger/steam generator)
Supply chain	Re-establishment of the (European) supply chain

Table 1-1: Technology Gap Analysis from ARCHER Project for a THTR-type High Temperature Reactor

The design of a High Temperature Gas-Cooled Nuclear Reactor shall be developed as a standard design which could ideally be built in any European country foreseen for deployment, with minimum changes.

2 Industry and Infrastructures

In order to reach the plug-in process heat market which is the fastest, easiest and most effective application of HTR for nuclear cogeneration, technical risk for a demonstrator should be minimized. The target for the demonstrator is thus a plant capable to deliver process steam up to 600°C. The following subsections outline the requirements for such a plant.

2.1 Components

2.1.1 Reactor Pressure Vessel

Reactor Pressure Vessels can be fabricated in Europe and also outside of Europe. Design studies in the US for VHTRs at high outlet temperatures have indicated that engineering solutions will allow the use of traditional LWR pressure vessel materials for the high temperature range. The suppliers identified in the mapping exercise [2] include AREVA Le Creusot as a possible European supplier and a number of suppliers outside of Europe, in China and Japan.

The exact capabilities of suppliers might depend on size and diameter of the requested RPV. When dimensions reach beyond current standard RPV's, suppliers might be limited. The dimensions of for example a 600 MWth HTGR would require new and larger tooling. Additionally, waiting lists for forged vessels are generally long, due to a shortage of suppliers and an increase in vessel demand. This is obviously linked to the demand side of the NPP construction, and it might be assumed that production and competences will increase with increasing demand. It should be noted here that if the primary helium pressure is reduced (incurring efficiency penalties), some regulators allow the use of pressure vessels made from welded rings. This pressure vessel can be delivered by several other manufacturers worldwide.

2.1.2 Steam Generator and BOP

Aiming at a maximum steam temperature of 600°C the steam cycle can be considered technically ready. A number of suppliers for helium heated steam generators were available in Europe such as Sulzer and Balcke-Dürr. Design tools are still available, however, even the former manufacturers cannot easily produce such components today so that some new development will be required. Other BOP components such as turbo-generators, superheaters, re-heaters, de-aerators or condensors are available off-the-shelf if the live steam conditions are similar to those of commercial coal fired power stations.

2.1.3 Intermediate heat exchanger

The fabrication of the intermediate helium-helium heat exchanger was demonstrated in the past by several companies, and more recently in the ARCHER project [6]. Within this project, supplier AlfaLaval designed and fabricated a mock-up of a plate-type heat exchanger of Alloy 800H, which was successfully built. Full scale fabrication should be demonstrated however, including all recent developments, and testing of the IHX needs to be performed for licensing purposes.

For a longer term VHTR application, further research is needed for enhancement of the heat exchanger system and the qualification of SiC-based structural materials in order to provide the higher primary He temperatures required to attain acceptable efficiencies in a helium Brayton cycle instead of a steam cycle.

2.1.4 Other components

For all other major components such as the circulator, hot gas duct, isolation valves and control rods and drives multiple suppliers were identified within Europe. The possible gap does not seem to be the ability to design and fabricate the components, but since practically all items are custom designed and built (which is inherent to such a large system) the alignment of all suppliers is essential. While ageing experts are still available, this is not considered a major hurdle but rather an attention point for a demonstration project as a whole.

2.2 Fuel and Materials

2.2.1 Fuel Fabrication

Adequate HTR fuel quality has been achieved reproducibly worldwide, although it is still on laboratory scale. In Europe the fuel for previous HTR programs was fabricated by NUKEM but these facilities and production lines are sold or mothballed and would require significant effort to be restarted. Internationally however, several suppliers are fabricating fuel close to industrial scale, for example at Babcock & Wilcox in the US for the AGR program, and INET in China for the HTR-PM demonstrator. Some smaller fuel production capability is available in South Africa, Japan and Ukraine.

Producing HTR fuel on industrial scale requires fuel factories with full qualification and licenses. Depending on whether existing industrial HTR fuel manufacturing capacity can be used (China, US (partly), South-Africa (partly)), an early "build or buy" decision is required for either establishing fuel manufacturing capability in Europe, or buying fuel from internationally established suppliers.

In both cases, the existing or newly fabricated fuels requires qualification for licensing, which is discussed in the next chapter under the R&D requirements.

2.3 Materials

2.3.1 Graphite

Graphite suppliers that were involved in the production of the THTR material operate in Germany such as SGL, but also GrafTech in France or Toyo Tanso in Japan are capable of supplying the required quantities. In addition a number of suppliers exist worldwide that are either already able to supply qualified graphite, or are in the progress of qualifying their graphite at the moment. The same applies for most structural materials.

In case a European supplier is selected, the graphite would require further study and qualification, which is discussed in more detail in chapter 3.

2.3.2 Composites

When looking at the development of a long-term VHTR, there is significantly more development to be done. High temperature alloys (Ni alloys, ODS steel) or ceramic composites (SiC/SiC, C/C) require significantly more effort to be developed, and current components are not produced on an industrial scale. For instance, ODS versions of 9% Cr steels are difficult to obtain on the market and not always exhibit reproducible properties. These materials would benefit from the lower temperature range as well, but are not essential to be developed. This can rather be seen as innovation within the current design, and would only be of interest if they could reduce risk or cost, which from today's perspective is not the case.

2.4 Gaps

Thanks to the former German HTR development program and the more recent EU projects, there is significant but not always sufficient infrastructure and know-how present in Europe.

Significant progress has been made by a several European FP5-7 R&D projects which obtained further leverage through the collaborative participation of European organizations in international projects (NGNP, PBMR, HTR-10…) and in GIF. The most outstanding examples are in the areas of fuel production and qualification, the qualification and coding of high temperature structural materials and new graphite grades (incl. through irradiation testing), component development (e.g. turbomachines, heat exchangers), and helium technologies.

In addition, significant improvement was achieved in understanding the market and end-user needs so as to design a power plant accordingly. The European System Integration studies in ARCHER and in NC2I-R, the ANTARES and SC-HTGR projects performed by AREVA and several other industrial designs from Europe and worldwide reflect this development. Additionally in parallel to the design efforts, the supply chain for components must be analysed and, where necessary, rebuilt.

However, much of the know-how is tightly linked to an ageing population of experts and laboratories which need a continuous source of funding to maintain and develop their expertise.

Apart from technology gaps, there is also a competence gap with regulators who are rarely exposed to licensing requests for innovative, non-water cooled reactors. The OECD/NEA has recently recognized this issue and created a "Group for the Safety of Advanced Reactors" which involves regulators from several countries.

2.4.1 Long term gaps

In several countries, e.g. in Japan and South Korea, the costs of natural gas are up to 4 times as high as currently in the US. At the same time, these countries produce large amounts of CO_2 (e.g. from steel production) and need to curb their emissions. For these countries, nuclear hydrogen production is a much stronger motivation to support the VHTR concept than in Europe or in the US where the biggest market is in the area of process steam.

At higher operating temperatures, the key developments concern the selection and qualification of materials for the components and the fuel particles that can maintain the required mechanical properties and corrosion resistance. Some possible candidates for components in VHTR environment have already been identified (high performance Ni base alloys, Oxide Dispersion Strengthened Steel (ODS), ceramics, SiC-SiC composites, etc.). For fuel, some possible solutions have also been explored (e.g. the use of UCO instead of UO_2 or the substitution of the SiC coating layer by a ZrC layer, although this was not successful due to high temperature plasticity and insufficient lifetime in repository conditions). The investigations performed until now would only be a start of a larger program on material qualification for VHTR applications. However, industry to produce these materials on an industrial scale is not yet available.

If in the short term applications the cogeneration HTGRs would simply substitute conventional cogeneration plants to provide steam to conventional steam networks, as mentioned above, this is no more the case for higher temperature processes: new materials and heat transport fluids are required calling for new types of heat exchangers. These would again need extensive design efforts, testing and qualification before being available for licensing and deployment.

To accelerate the development of VHTR, some more effort could also be invested in superheating options to reach the temperature level required by the end user. Examples are fossil, electric or compression superheating which would allow maintaining easily acceptable HTR temperatures in the reactor itself whereas the very high temperature issues are concentrated on few non-nuclear components [7].

3 Research & Development

R&D in support of a High Temperature Reactor Demonstrator has a focus on material qualification and safety demonstration. Based on the lessons learned from the historical projects, and the regained interest in the HTR technology in the start of the millennium, a number of key areas were defined. These areas focussed on tribology and corrosion, fuel and material qualification and component testing. A significant effort was put into these topics via the European Framework Programmes RAPHAEL and ARCHER.

Based on the requirements [3], a set of needs can be determined to achieve the necessary scope of a demonstrator project. The requirements as defined in a way that general requirements can be met, details on a component level are not relevant for R&D infrastructures, since one of the design requirements is that the system will be based on proven technology. New kinds of bearings, materials or other components are therefore excluded for the initial demonstrator, but can be addressed for a VHTR.

For the proven technology, several topics can be addressed which are described in more detail in the next paragraphs.

3.1 Computer codes

As the tools used in past projects have become obsolete, a significant effort has been performed in the last 15 years to adapt modern codes to HTGR needs. In most of the areas (reactor physics, CFD, structural mechanics, safety analysis, fuel performance) modern tools are now available for HTGR design and bugs in old codes could be fixed. But the validation of these new tools for HTGR applications is still to be completed. In the case of safety analysis, the models have not only to be qualified, but new models have to be developed: there are too large discrepancies between experimental data and predictions of the models inherited from past projects for these models to be acceptable for licensing. This means that modeling efforts for licensing need to be accompanied by an experimental effort at relevant scale.

3.2 Component testing

Depending on the chosen configuration of the demonstrator, e.g. Direct Steam Cycle, Indirect Process Heat Supply, Hybrid, etc., there is a need for an Indirect Heat Exchanger. Development of the component has already been initiated in the ARCHER project, but further development and qualification is required for full scale application.

The experience on very high temperature tests gained so has disclosed that the technical solution of material problems require further efforts in longer-term projects.

Practically all other components are in a mature technology state. Depending on the configuration and exact final use in the nuclear system, safety and performance will need to be demonstrated in a high temperature helium loop. Components such as the steam generator, the reactor cavity cooling system, circuit valves or circulators will need to be tested in representative environments.

While the previous European HTR experience is a significant asset for demonstration, innovation should not be excluded as long as it brings clear benefits, does not induce additional risks in the project and does not jeopardize its schedule. In particular R&D in the following fields could be beneficial:

- Use of composites for control rod cladding with the aim to avoid frequent replacements that were considered in past projects using control rods with metallic cladding.
- Improvements in reactor instrumentation, poorer in HTGR than in other types of reactors, could clarify margins to be used for improved safety and/or performance.
- Use of magnetic bearings for the primary circulator could avoid the introduction of carbonated impurities in the primary circuit, in which there are carburization risks on some materials.
- Development of high-fidelity validated (multi-physics) code systems has the potential of reducing unnecessary conservatisms in the system design thereby contributing to the economics of the commercial reactor.

3.3 Tribology and corrosion

Several parts of an HTR are subjected to relative motion under load, and wear protecting materials are needed. Within the scope of investigation programs in Germany the available wear resistant materials and coatings were compiled and, after a selection phase, subjected to wear tests under different loads in an artificial HTR-environment. Also aging tests were performed in order to gain information about the interaction of the partners in a temperature range where diffusion controlled processes will occur. Thermal cycling tests provided information about bonding strength and sensitivity to cracking and spalling.

There is significant experience in Germany with the ADI and KVK experimental set-ups [8]. Results from tests in these facilities have identified a number of suitable materials to be used in different temperature ranges. Currently, no comparable setups are available in Europe but significant material knowledge has been gained. Unless there is a need for development of new materials, similar facilities at higher temperatures might be required for the development of the VHTR.

With respect to graphite dust production and mobilization, a number of facilities are operational in Europe to study and address these issues [9], which have been used and demonstrated in the ARCHER project. Corrosion issues were also studied in the same project, where a significant effort was put on the test and understanding of graphite corrosion [10]. Several other material test facilities in Europe still are available such as high temperature helium loops and oxidation testing facilities as described in the mapping exercise [2].

3.4 Fuel qualification

From the demonstrator requirements it is stated that:

"*Reference fuel shall be Tri-Isotopic (TRISO) coated particle fuel, LEU-based (UCO or UO_2) with an enrichment limited to <20.0% (in mass) and with a peak burn-up limited to 20% fissions per initial metal atom (FIMA).*"

This is based on the extensive knowledge base on TRISO particle based fuels, which was developed in the 1970's in Germany.

Although significant effort has been devoted in EU projects to develop HTR fuel manufacturing and to qualify this fuel in representative operating conditions including irradiation, safety testing and post-irradiation examinations, a very expensive and long program would still be needed to qualify fuel from an upscaled industrial process. Such a program would likely be on the critical path for a demonstration project. But the US is currently running a very successful fuel development program with UCO TRISO fuel such that an international procurement for the fuel of the demonstrator should be considered (likely in the frame of the GEMINI partnership).

Another program that is running is the qualification of the Chinese HTR-PM reactor. The qualification project is currently ongoing in Europe, with irradiation in the High Flux Reactor completed by NRG in 2014 and post irradiation accident testing in the KüFA facility in 2016 by JRC-ITU. Summarizing it can be stated that although there is currently no qualified HTR fuel manufacturing capability available in Europe, the qualification capabilities exist, but need to be performed on the very fuel that is produced at industrial scale and is intended for use in a demonstration reactor.

Even if the development of fuel manufacturing and qualification can be bypassed through international partnership, benefit should be taken from the leadership Europe acquired in innovative non-destructive methods for fuel manufacturing quality control. These processes are essential for safety and cost reduction and should be continued, as a European contribution in the frame of an international collaboration for fuel procurement.

Another item to be addressed regarding the fuel is that “the HTR shall include a Fuel Handling System to remove and replace fuel from the reactor core, prepare new fuel for use in the reactor core and store spent fuel”. Currently the technology is not in operation but should be developed in parallel with the final design of the core configuration. Currently there is a significant development on this point with the design and construction of the HTR-PM that includes a fuel pebble handling system [11]. However, it is unclear to which extent this technology will be available for use in a Western demonstrator. If the demonstrator is a hexagonal block design, a completely different system for fuel shuffling would be needed.

3.5 Material R&D

A similar situation as for fuel can be applied to the graphite that will be used in the HTR demonstrator core. Due to the unique behaviour of graphite during irradiation the characterization of the very graphite that is intended to be used is essential, and qualification is required. A significant program is being executed in the United States, and a number of graphite suppliers are available, also within Europe. The type of graphite and required qualification depends however heavily on the chosen concept such as block or pebble-bed. When the final design is being fixed, and a supplier is identified, qualification of the graphite should be performed. Facilities capable of performing graphite qualification exist in both Europe and the United States.

Some points that should be addressed are related to the graphite internals:

- Methods for internals design taking into account uncertainties in their deformation during operation should be developed (in particular for bounding the core bypass)
- Oxidation data in normal and accident conditions should be complemented
- Dust formation and transport should be better understood and modeled.

3.6 Safety analysis and demonstration

The list of facilities that were found in the mapping exersice of existing R&D Facilities in Europe [2] shows that many experimental installations are already available to support the development of an HTR prototype, building on synergies with gas fast reactor projects and fusion technology. In particular, most of the separate effects tests could already be performed in existing facilities. For fuel qualification, irradiation qualification and safety testing can be performed in Europe and in the US.

However, for the qualification of the main reactor components important for safety or pertaining to the confinement barriers (isolation valves, heat exchangers, steam generators, control rod mechanisms, etc.), specific test rigs will be needed, like the helium loop built in South Africa for the PBMR program. Experience was present in Europe with the KVK loop in Germany, but this know-how and expertise would need to be re-established.

To go forward in the concept development, experimental facilities should be selected after the development of an HTR prototype design including the definition of its heat production and cooling performances (e.g. the performance of a passive Reactor Cavity Cooling System). Given this data, the plant designer will have to test the technical solutions required by cogeneration, like the systems which would dampen the specific transients (load following, loss of heat delivery system, etc.) or the isolation devices. On a case by case basis, experiments might also be necessary to qualify the protections envisaged to cope with the external hazards induced by the vicinity of the end-user industry (effects of chemicals on electronic systems, sensitivity of detection systems, fire resistance, etc.). Methodology and criteria defined for the industry would need to be developed and/or updated.

3.7 Coupling

HTR technology has reached a high technology readiness level with several test and prototype reactors built and operated in a number of countries and a demonstrator currently under construction in China.

Process heat technology is mature and industrially applied: high temperature applications with fossil fuel, low and medium applications also with nuclear heat supply.

However, the effective coupling between the reactor and the process heat end-user needs to be demonstrated and confirmed, e.g. in terms of safety and reliability. With respect to technology no significant gaps are to be expected, but licensing may turn out a challenge. This issue, can only be addressed when the site for the demonstrator is located, and the involved regulator identified.

3.8 Design and System Integration Capability

The last detailed design for an HTR was performed in Europe in the mid-1980s. More recent designs were not developed beyond the conceptual design stage. Much of this design capability must be assumed to be retired today thus making it likely that there is a gap already or in the near future. From what could be observed in the PBMR project and in HTR-PM is that in certain cases the rationale for different design options was forgotten, lost or not properly documented in the past.

Design and system integration work has been performed in Europe mainly by nuclear vendor companies. Such work is also beneficial to provide guidance and momentum for future R&D, demonstration and deployment. It would deal with the full reactor and the balance of plant, i.e. it would include electricity generation and end-user processes, and their interfaces with the reactor.

Process-specific R&D gaps need to be filled to adapt the enduser and the nuclear heat source to each other with regard to temperatures, power levels, and operational pressures. Heating of chemical reactors by helium is a departure from current industrial practice and needs specific R&D and demonstration. The development of an intermediate heat exchanger, ducts, valves and associated heat transfer fluid are needed to provide process heat to end-users.

The HTR balance-of-plant is determined by the specific application, which can be process heat, electricity production or cogeneration. A variety of process heat applications were studied already many years ago to understand the technical needs of the specific process, to evaluate potential reactor and balance of plant configurations, and to provide an economic assessment of using an HTR in a specific application. In these process heat applications, all components have to be developed and qualified for their operating conditions and expected lifetime. Failure mechanisms such as creep, fretting, and ratcheting have to be studied in detail, precluded with design, and demonstrated in component tests. Steam generation options for electricity and/or process heat are technically ready. They combine the high efficiency of an HTR and the maturity of steam turbines used in fossil power plants. This is a near term, low risk, large market and high performance option for the HTR. Design, manufacturing, operation, in-service inspection of steam generators requires more efforts and feedback from previous operation experience. Supercritical water conditions could further increase the efficiency of a steam cycle HTR while supercritical CO_2 power conversion systems may also deserve some attention.

A helium Brayton cycle requires approximately 250 K higher working fluid temperature for reaching the same efficiency as a steam Rankine cycle. Therefore, Brayton cycles are mainly of interest for long term VHTR options with significantly increased outlet temperature or when the use of steam is excluded. Some key components such as recuperator, helium turbine, and IHX would then require more R&D. Some heat transfer fluids other than steam or helium could be envisaged to drive certain end-user processes. Of particular interest would be liquids e.g. molten salts because they would allow operation at low pressure. Circuit components would then need to be designed for such specific applications.

3.9 Development of a licensing framework

Since the THTR, no new HTR has been licensed in Europe since the mid-1980s. While most of the limited regulator capability in Germany has retired by now, the TÜV has been involved in the licensing process of more recent projects overseas, namely PBMR and HTR-PM. This capability would need to be maintained in the country where a demonstrator will be built. As this is currently not known, there is indeed the risk that the regulator is not in a position to develop a stable licensing framework for HTR and nuclear cogeneration. An additional difficulty is that in some countries the nuclear regulator and the regulator of a process heat end-user (e.g. a chemical plant) are not the same. Coordination between them is thus a fundamental necessity.

3.10 Cost Savings

Cost saving is a cross-cutting necessity but was not yet identified as such in the R&D projects performed until now. An example would be fuel production where the reduction of the scrap rate, automation and simplification of the many involved subprocesses hold a clear technical and economic optimization potential.

Detailed economic studies have been performed for both electricity production and process heat applications by several GIF members. The US results suggest that modular VHTRs are competitive with new LWRs for electricity production. For process heat and co-generation applications, the VHTR can be competitive with conventional combined cycle gas turbine systems producing steam and electricity when the cost of natural gas is higher than 8 US$/MMBtu. Carbon taxes may reduce this threshold. Currently the cost of natural gas varies widely across the world. Thus, the economic viability depends largely on the financial and regulatory climate in each individual country. The inherent safety features of VHTR may benefit the economics index indirectly. Similar to certain other small and medium sized reactor concepts, the VHTR can also take credit for lower infrastructure requirements such as easier integration in weaker electricity grids, lower cooling requirements, and proximity to industrial sites and agglomerations.

After having established the technical feasibility of essential elements of a near-term VHTR, specific R&D could be devoted to making the system more attractive for investors, in other words make it cheaper (lower CAPEX), reduce the financial risk (e.g. by standardizing components, shortening construction and licensing), strengthen the effect of the “economy of replication” versus “economy of size”, and accelerate deployment and return on investment without compromising safety and performance. The claim that an nth-of-a-kind system will be x% cheaper than a firstof-a-kind is certainly correct and important, but it must be much better quantified and substantiated so that potentially critical areas can be improved and investors be convinced.

3.11 Fuel/Graphite waste minimization and recycling

HTRs and other graphite-moderated reactors produce a significant amount of waste from used fuel and irradiated graphite. Different pathways for waste minimization can be envisaged:

- Waste volume reduction of used fuel: HTR fuel consists to very significant parts of carbonaceous matter (matrix graphite, coatings); although HTR fuel is already a stable waste form, depending on the local repository policy, these materials could be separated for separate disposal;
- Recycling of coated particle fuel would go a step further; it is useful for recovery of U from production scrap and mandatory for closed U-Pu and Th-U fuel cycles, symbiotic fuel cycles and for transmutation ("deep burn"); however, the HTR demonstrator is envisaged to work with an open uranium fuel cycle; depending on the fuel cycle policy in the countries of deployment, HTR fuel reprocessing is likely to be considered a long-term option for larger VHTR fleets;
- Decontamination and recycling of irradiated graphite: this has been studied at lab-scale in the FP6 CARBOWASTE project; irradiated graphite is an issue specifically in Europe with strict repository regulations and large quantities of irradiated graphite to be disposed of from other graphite-moderated reactors. Further work on this subject would not only help solve an existing short-term waste management problem but also facilitate future use of graphite as moderator in HTRs;

3.12 Energy system integration

One of the potential advantages of an HTR system for nuclear cogeneration is its capability to integrate in an existing energy system with fossil and variable renewables. As variable renewables obtain increasing parts of electricity generation, the capacity to compensate for their unavailability will further grow in importance. Some topics should be developed to more clearly illustrate to investors and policy makers the usefulness of nuclear cogeneration beyond local cogeneration supply:

- Design of nuclear cogeneration systems with the built-in capability to iron out demand-supply mismatches in the electric grid by varying the fraction of heat and electricity generation.
- Analysis of integration options with other electricity/energy sources in a local/regional/national energy system. This may e.g. impose design features which enable load following or system services such as frequency stabilization, blackout start-up capability etc.
- Assessing the system performance against Energy Union policy goals in Europe (e.g. CO_2 emission reduction, energy security, industrial development, economic benefits, strategic objectives etc.)
- Cost/b
- enefit/impact/risk analysis and optimization options

3.13 Gaps

In this paragraph the gaps that are identified in the previous section are summarized. Most items are not considered a major hurdle, but need to be performed for the design and built of a demonstrator. The used components in that demonstrator need to be qualified, and since they are usually custom built items, this qualification still needs to be done. Several loops are available in- and outside of Europe, but with different specifications. Whether these current loops would suffice to demonstrate operation against current standards needs to be evaluated when the final design of components is known.

In addition to the items from the table above there are a number of innovation items that could be pursued, but are not essential for deployment of the demonstrator. These should only be considered as long as there is a clear benefit to the project and they do not increase significantly the risks and/or jeopardize the schedule. Examples of these are the development of composites which could be used for the control rod cladding.

R&D Area	***Gaps for Demonstrator***	***Gaps for future VHTR development***
Computer codes	• Validation of updated codes in support of licensing • Modelling of source-term (dust formation and transport)	• Validation of updated codes • Modelling of source-term (dust formation and transport)
Components	• Component qualification in large scale facilities	Development and qualification of IHX High temperature ceramics (SiC-SiC, C-C)
Tribology and corrosion	None	Large scale facilities to measure wear and friction might be required
Fuel	• Fuel is available, but needs qualification	Development and qualification of high temperature fuel.
Material R&D	• Graphite qualification • Some focussed R&D on oxidation in accident conditions	Additional effort will be required for high temperature materials such as ceramics, but also graphite properties at high temperature
Safety analysis and demonstration	• Large scale loop for component testing • compliance of plant design with new Nuclear Safety Directive	effect of high T on safety
Coupling	• Demonstration and licensing	
Design and System Integration	• Demonstrator design and test program	
Development of a licensing framework	• analyze existing licensing framework for suitability to license HTR demonstrator for cogeneration	
Cost Savings	• optimize fuel manufacturing processes	
Fuel/Graphite waste minimization and recycling	• qualify decontamination and recycling of irradiated graphite • Compliance with new Nuclear Waste Directive	evaluate direct disposal vs. reprocessing for symbiotic fuel cycles
Energy system integration	• trade studies on different options to combine NC with fossil and RES	

Table 3-1: Gaps for short and long term deployment

4 Conclusions

A good deal of the European industrial infrastructure to build HTR for nuclear cogeneration is in good shape. Some of the rich history of HTR development in Europe is still available, but probably not for much longer. The supply chain for components and materials is to be re-established before starting a demonstrator project.

The same applies to a lesser extent for the R&D infrastructures. Due to the time gap between the last running HTR reactor and the initiation of the new demonstrator projects, some facilities are shutdown, 'mothballed' or refurbished to support other projects and developments. But also a number of facilities have already been taken back into operation during the HTR revival of the last decade, which took shape in, amongst others, the European Framework programmes that focussed on the R&D on graphite behaviour, component testing and safety demonstration.

Also some focussed R&D might be required to update knowledge and components to the most recent standards, but they cannot be seen as stumbling blocks that might jeopardize the deployment of an HTR demonstrator in Europe. What also needs to be addressed is the qualification of materials and fuel up to the latest standards and the compliance of the plant design with the European directives for nuclear safety and waste.

The same applies for the qualification of the main reactor components which are important for safety or pertaining to the confinement barriers (isolation valves, heat exchangers, steam generators, control rod mechanisms, etc.). Specific test rigs will be needed, like the helium loop built in South Africa for the PBMR program. Comparable large scale Helium loops are currently not in operation on the same scale as in the past.

4.1 Gaps for long term development of VHTR technology

With the aim of reaching higher operating temperatures in order to access new market segments, in particular hydrogen production through high temperature water splitting processes, the key developments concern the selection and qualification of materials for the components and the fuel particle coating layers that can keep in such VHTR environment the requested mechanical properties and corrosion resistance. Some possible candidates for components in VHTR environment have already been assessed (high performance Ni base alloys, Oxide Dispersion Strengthened Steel (ODS), ceramics, SiC-SiC composites, etc.). For fuel, some possible solutions have also been explored, although with a negative result (substitution of the SiC coating layer by a ZrC layer). But the investigations performed until now are only the initial phase of a large program that should result in the qualification of materials required for VHTR application. The Research community in Europe, in collaboration with others should have a clear focus and collaboration for these developments. During the selection and qualification of the appropriate materials, also the industry should be involved to develop industrial scale fabrication and supply routes of the materials and components, since production of these materials on a large scale is not yet available.

Finally, instead of running after extreme temperatures, the development of tricks and new processes with lower operating temperature is an alternative to the development of a VHTR thus potentially accelerating deployment of this technology [7].

5 Acronyms and definitions

Acronym	Definition
ADRIANA	FP6 Project on GenIV mapping
ARCHER	FP7 Project on HTR technology
EC DG RTD	European Commission – Directorate General for Research and Technological Development
GFR	Gas cooled Fast Reactor
HTR	High Temperature Reactor
IHX	Intermediate Heat Exchanger
NC2I-R	Nuclear Cogeneration Industrial Initiative – Research Project
NHSS	Nuclear Heat Supply System
PBMR	Pebble Bed Modular Reactor – South-African HTR project
RAPHAEL	FP6 Project on HTR technology
RPV	Reactor Pressure Vessel
THTR	Thorium High Temperature Reactor
VHTR	Very High Temperature Reactor

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