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Authors : FUTTERER Michael (JRC) , Ferry Roelofs, Norbert Kohtz, Patricia Cuadrado Garcia, Dietrich Knoche, Derek Buckthorpe

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Guidelines and Prioritization for Nuclear Cogeneration System Integration

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Michael A. Fütterer (JRC), Ferry Roelofs (NRG),
Norbert Kohtz (TÜV Rheinland), Patricia Cuadrado Garcia (EA),
Dietrich Knoche (Westinghouse), Derek Buckthorpe (Manchester University)

	For the Authors	Reviewed by	Verified by	Approved by Unit Head
Name	M. A. Fütterer	E. D'Agata	K. F. Nilsson	P. Hähner
Date	7/1/2015	7/1/2015		
Signature				

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Author(s)	Michael A. Fütterer (JRC), Ferry Roelofs (NRG), Norbert Kohtz (TÜV Rheinland), Patricia Cuadrado Garcia (EA), Dietrich Knoche (Westinghouse), Derek Buckthorpe (Manchester University)
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Summary

This document describes the rationale for R&D on nuclear cogeneration and details which type of R&D that needs to be performed in the short term to enable demonstration of nuclear cogeneration by the mid 2020s to capture early market opportunities and, in further steps, to maximize the benefit from this technology from an energy policy point of view (e.g. in terms of energy security, climate change mitigation, re-industrialization) and economy.

Some of the main findings of this report are also issued as a section of the Strategic Research and Innovation Agenda of the European Strategic Nuclear Energy Technology Platform (SNETP), the recent update of Gen IV systems (Progress in Nuclear Energy) and in recent ARCHER deliverables. Some of the suggested R&D orientations had been integrated also in the TWINS project proposal submitted in September 2014 to the first Horizon 2020 call.

Approval

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0					
1		M. Fütterer (JRC) 7/1/2015	M. Fütterer 7/1/2015	F. Roelofs	S. Knol (NRG)

Distribution list

Name	Organisation	Comments
P. Manolatos	EC DG RTD	
All technical participants	ARCHER	
Steering Committee members	ARCHER	

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1 Introduction to Nuclear Cogeneration

Nuclear cogeneration relates to the co-production of heat and electricity using a nuclear reactor. Fossil fuels are today by far the main source of heat for European industry, transport and households. The production of heat with nuclear technology is a major innovation that can open a new and significant market potential for nuclear systems, whilst providing a significant contribution to European strategic energy policy in terms of curbing CO_2 emissions and increasing security of energy supply.

This report was written as Deliverable D12.31 for ARCHER SP1 on System Integration, some results of which are presented in [1].

1.1 Rationale

Although European industry has achieved impressive emission reductions in recent years, fossil fuel combustion to provide heat to the processes of European energy intensive industries corresponds to an annual emission of 720 Mt CO_2. This represents around 20% of Europe's CO_2 emissions. This is more than the 470 Mt CO_2 emitted every year to generate the electricity consumed by these industries. At the moment, there is no energy technology able to reliably and affordably replace natural gas fired cogeneration, which is the reference technology.

Energy is vital to EU industries and accounts for a significant share of the production costs of EU energy intensive industries, with for instance 8% for chemicals production or 22% for pulp & paper making. European industry represents a large contribution to European economy and generates essential products for our everyday lives. To maintain and strengthen this position in Europe ("re-industrialization" and avoidance of further "carbon leakage"), a competitive low-carbon technology is needed. Nuclear cogeneration can be the feasible innovation to meet that requirement.

Additionally, short-term opportunities for households such as district heating, and desalination to solve fresh water shortages, and long-term opportunities for reducing fossil resource usage in transport by generating synthetic transport fuels via nuclear powered hydrogen production, add a significant market, energy security and carbon emission reduction potential.

The EUROPAIRS project has analyzed in depth the European industrial heat market. The vast market potential for nuclear cogeneration was highlighted, most recently in Europe (EUROPAIRS project [3]) and in the USA (MPR Associates [4]), cf. Table 1.

Region	**Heat market estimation**	**Of which produced by cogeneration**
Europe [3]	3 000 TWh/y	800 TWh/y
USA [4]	3 600 TWh/y	1100 TWh/y
Rest of the world	N/A: order of 10 000 TWh/y	N/A

Table 1: Heat market by region [3], [4]

Various nuclear reactor technologies could each meet a part of the market demand as shown in Table 2.

Reactor type	Max. required steam/heat temperature	Relevant applications	Minimum temperature range needed	Comment	Total heat market
Water reactors	250°C	District heating	70-130°C	Seasonal, nuclear already used	700 TWh/y (≈ 80 GWth)
		Desalination	100-130°C	High growth expected, nuclear already used	
Fast breeders	450°C	Pulp & Paper	100-250°C	High load volatility, nuclear already used	
High temperature reactors	550-650°C (secondary steam) < 750°C (secondary gas)	Oil refining	500-550°C		1 000 TWh/y (≈ 114 GWth)
		Chemicals	500-550°C		
		Fertilizers	500-600°C	Largest H_2 application	
Very high temperature reactors	1000°C	Hydrogen	750-850°C	Sector expected to grow, in particular with new applications in transport, energy, energy storage and Carbon Capture and Utilization	1 300 TWh/y (≈ 148 GWth)
		Other applications	>1000°C	Other sectors could be envisaged for nuclear pre-heating (e.g. lime, aluminium, iron & steel, high-temperature O_2 production, glass)	

Table 2: Heat market per type of nuclear reactor technology [5], [3], [6]

1.2 State-of-the-Art

Nuclear cogeneration is already a reality. As of 2006, 1700 reactor years of experience had been accumulated worldwide, mainly for waste heat valorization from water-cooled reactors. In Europe, more than 1 000 GWh of low-temperature heat was produced in 2006 in Bulgaria, Czech Republic, Hungary, Romania, Slovakia and Switzerland.

Water-cooled reactors have an extensive operational experience, including in low-temperature cogeneration. Only limited R&D would be required to accelerate further deployment for low-temperature applications. It would mainly revolve around the coupling, and supporting and securing the safety/licensing connected to coupling a nuclear system to a conventional production process.

Low temperature cogeneration from a fast neutron reactor was proven in one Kazakh plant (BN-350) for water desalination. Significant development is, however, needed before cogeneration application can be considered for low and medium level temperature applications. As time progresses and fast reactors are further developed, the obstacles for fast reactor cogeneration applications will diminish.

High temperature reactors provide significant perspectives for medium and high temperature cogeneration applications. The HTR technology builds on the developments in the UK and in Germany in the 1980s, re-established and revived in several national and European Framework Programme projects from the year 2000 onwards, of which the ARCHER project (2011-2014) is currently ongoing.

The coupling between end-users and HTR for high temperature cogeneration has yet to be developed. The EUROPAIRS project has established direct contacts between the conventional process industry and the nuclear community and has developed key performance indicators. It has also identified operational envelopes for the coupling and assessed the general licensing aspects on dedicated case studies (hydrogen, oil refining). Additionally, the establishment of an HTR demonstrator coupled to industry has been regarded essential by the industry partners in EUROPAIRS, namely to enable market breakthrough by risk reduction and the more reasonable deployment horizon of demonstrator follow-ups.

The ARCHER project provides technology R&D in support of demonstration, in which both fundamental research and direct applications are combined. This basis should be further extended in strategic directions, to minimize demonstrator risks, by securing the licensing framework especially.

National projects are supporting the European R&D. For instance, the Polish project HTR-PL was launched in September 2012 to strengthen the national scientific and technical capacities for the HTR programme in Poland. It gathers universities, research institutes (covering nuclear, fertilizer and coal processing R&D fields), an engineering company, a power plant operator and an energy intensive company. The German project SYNKOPE was launched in August 2012 and elaborates nuclear-assisted coal-to-liquid process scenarios. Additionally, the German project STAUB-II launched in August 2012 is to work on HTR safety, including experiments in a newly built helium test facility.

Since October 2013, the new NC2I-R project is structuring the European public and private R&D capabilities for delivering a nuclear cogeneration demonstrator fully meeting the market needs, in support of the Nuclear Cogeneration European Industrial Initiative. Following the reference EUROPAIRS project and in close collaboration with ARCHER, national projects (e.g. Polish HTRPL, German SYNKOPE), non-EU HTR programs (US, China, South Korea, South Africa) and Generation IV International Forum, NC2I-R will bring a decisive contribution to prepare for a successful, low-risk and rapid European nuclear cogeneration demonstration for Europe’s industry. In view of demonstration, NC2I and the US NGNP Industry Alliance have recently launched the GEMINI initiative [1], a new collaborative effort between Europe and the USA to advance on demonstration and deployment of High Temperature Reactor Technology for nuclear cogeneration.

1.3 Main Design Options for HTR

TRISO coated fuel particles with their high thermal and chemical reistance and excellent retention capability for fission products are the basis for the benign safety performance of HTR ([9], [11], [10]). These coated fuel particles are then embedded in a graphite matrix to form either spheres ("pebbles") or rodlets ("compacts") which are inserted in graphite blocks. HTR cores can then be designed as pebble beds or as prismatic block cores which both have been built and operated successfully in the past. At present, two operational test reactors represent these designs, namely the HTTR (prismatic block-type) in Japan, and in China the HTR-10 (pebble bed) and the twin reactor HTR-PM (pebble bed) power plant under construction. The typical power rating for modular HTR has been evaluated between 200 and 600 MWth producing helium with a conservative core outlet temperature of 750°C to generate live steam of about 550°C, similar to current conventional steam cycle technology in fossil-fired power plants. Helium outlet temperatures of 950°C have been tested and maintained for long periods of time both in the AVR (Germany) and in the HTTR (Japan). A updated summary of the global status of HTR development is given in [12].

The HTR design allows a high degree of flexibility in terms of power rating and temperature. Passive cooling features can be implemented in modular designs roughly below 250 MWth for pebble bed reactors and below 625 MWth for hexagonal block type reactors, but these values are only approximate and depend on the reactor geometry (e.g. surface versus volume ratio) and design (passive coolability). These power limits are different due to differences in helium pressure drop between pebble and block cores. If these power limits are respected, they result in inherent safety characteristics which include passive cooling capability, limitation of fuel temperature in case of accidents and efficient containment of radioactivity in the TRISO fuel particles, complemented by chemically inert helium coolant. These inherent safety features were demonstrated several times in test reactors in the US, Germany, China and Japan.

The different design options for High Temperature Reactors as the heat source for nuclear cogeneration applications have been described in extenso in several books and publications, e.g. in [5], [2], [4], [6].

To be highlighted are in particular the following options for which we list selected pros and cons (not comprehensive) which in some cases are a matter of continued debate, e.g. the licensability of certain design features:

1. **Pebble vs. Hexagonal block:**

	Advantages	Disadvantages
Pebble	• lower fuel temperature * • optional continuous fuel shuffling • shorter and potentially less frequent outages (multi-annual cycles conceivable) • optimized fuel use • no burnable poison required (no excess reactivity)	• higher pressure drop → inherent safety requirements call for smaller modules and higher blower capacity • higher graphite dust production • tends to higher He leakage (from pebble recirculation system)
Block	• lower pressure drop → inherent safety requirements call for larger modules and lower blower capacity	• more frequent and longer outages for fuel shuffling

* due to lower temperature difference between fuel and coolant in the core (under the assumption of a core assembly design limiting core bypasses). Control of max. operational fuel temperatures becomes important with increasing hot gas temperatures, not so much with steam generation at 750°C hot gas temperature.

2. **Cylindrical vs. annular core:**

	Advantages	Disadvantages
Cylindrical	• simplicity	• higher temperature peaking
Annular	• lower temperature peaking • reduced max. fuel temperature in case of DLOFC • for pebble bed: improvement of nuclear shutdown from outside the core	• requires dynamic or fixed central graphite column (complex structure for pebble bed, replacement during lifetime required; easier for block type cores) • higher flow bypasses to the active core (cooling of central column, for pebble bed also at core-reflector interface)

3. Metallic pressure vessel vs. Pre-stressed concrete vessel:

	Advantages	Disadvantages
metal RPV	• modular approach possible (incl. "snowball" financing option through staggered deployment)	• expensive • global forging capacity is bottleneck for deployment • benefit of modularity is yet to be proven (economy of replication, simplification, standardization) • requires careful design of cross duct vessel between reactor pressure vessel and steam generator vessel • size limitation to approx. 7 m diameter
PCRV	• would allow higher reactor powers in a single unit than metal RPV and thus allow economy of scale, albeit losing some inherent safety features • economy of scale is established • feedback from AGR reactors in UK • Continuous monitoring of pretension of cables and/or In-Service Inspection possible	• Long-term behavior of concrete under irradiation • high ground load requires strong basemat support • difficult to design and license (codes for AGR design still valid?) • break before leak approach may need new demonstration • long construction time, little shop fabrication possible

4. BOP options: Steam generator vs. IHX vs. Direct Brayton Cycle:

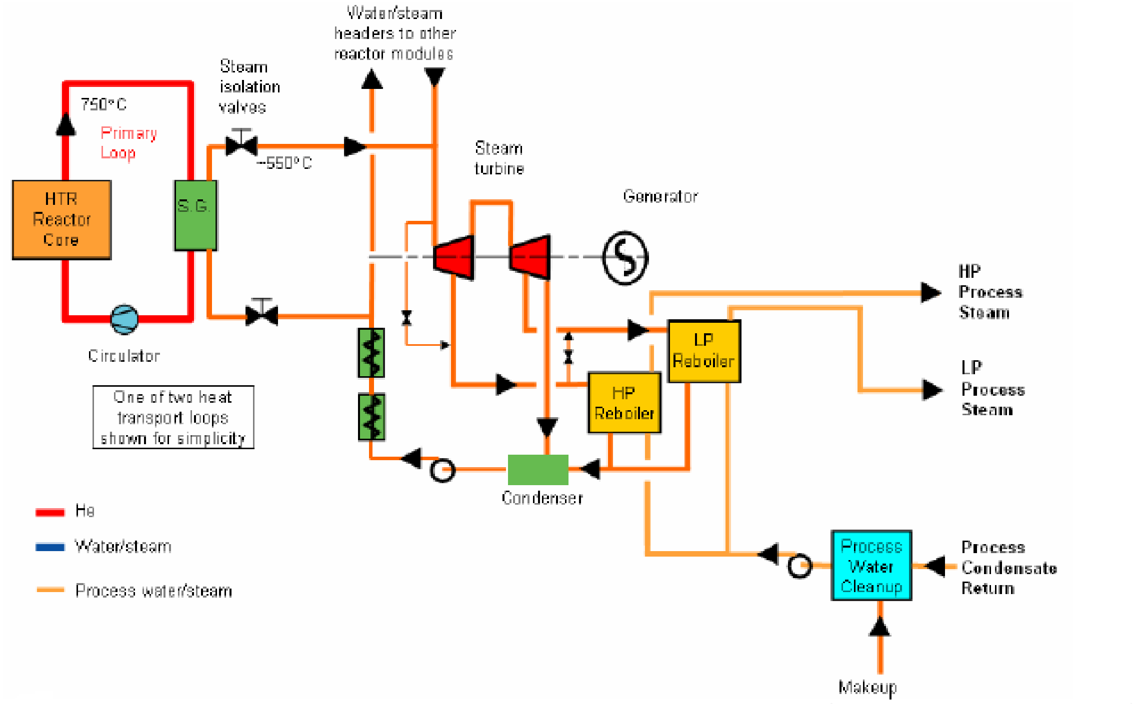
	Advantages	Disadvantages
Steam Generator	• can handle up to 600°C live steam temperature • proven design • allows use of steam turbine as topping or bottoming application	• requires measures to minimize graphite steam reaction • weak supply chain
IHX	• excludes water ingress from secondary circuit	• highly loaded component • requires significant primary pumping power (additional circuit) • supply chain weaker than for SG
Direct Brayton cycle	• excludes water ingress under operational conditions	• only apparently simple power conversion system requiring novel components (He turbine, compressors, coolers, recuperators) • for electricity generation only, combination with IHX for process heat application possible • requires significantly higher temperatures than steam cycle to reach same efficiency • no existing supply chain

There is ample documentation on a large variety of options for nuclear cogeneration applications. These can be classified into:

1. **Short term:** indirect cycle, steam production 550-600℃ (current coal fired power plant conditions as reference), power split depending on demand; this short term option represents today the by far largest portion of the target market; make use of 40-100% load following capacity as demonstrated in THTR for energy system integration;
2. **Mid term:** switch to secondary heat carriers other than steam (e.g. molten salt, liquid metals as employed today in Concentrated Solar Power Plants) which can also be used as temporary energy storage fluids to facilitate load following and grid services; if market requires, follow materials development towards higher temperature applications in fossil-fired plants;
3. **Long term:** 950℃ or beyond (primary side) requires change and thus development of structural material for applications such as thermo-chemical H_2 production and other high temperature processes

Taking into account the favorable safety characteristics of HTR, the coupling of an HTR to a conventional process has to respect the different licensing procedures and constraints. A negative impact of the nuclear energy source on the industrial process side and vice versa must be avoided.

During the PNP project in Germany, a large number of flowsheets were produced to adapt the power conversion equipment to end-user requirements. Indicative for the large design flexibility, a recent simple example as proposed by AREVA for the US demonstrator project NGNP [13] is shown in Figure 1. Here, primary He coolant heats a secondary steam generator which provides live steam to a turbogenerator set for electricity generation. Steam is bled from the turbines at different pressure/temperature levels and used to produce tertiary process steam in reboilers flexibly adapting to end user demand. A multitude of other configurations is possible depending on the heat/steam conditions required by the end-user and depending on the desired fraction between electricity and process heat. Adding to flexibility, a turbogenerator can be used also as a topping or as a bottoming application. It is furthermore possible to build in a certain degree of variability to modulate the electricity/process heat fraction, e.g. due to variations in daily or seasonal demand such that the cogeneration system can also deliver grid services (e.g. electric load following).



Commercial process heat cogeneration facility – Basic configuration (AREVA proposal for NGNP)

Figure 1: Schematic view of an indirect cycle with a SG as heat transport system to a secondary system for heat cogeneration applications [13]

Within Task 1.1.3 of ARCHER, D11.31 [17] has integrated work on nuclear heat source, power conversion system and end user requirements. In order to achieve this task, the coordinated work of several participants was required:

- Westinghouse provided a detailed description and input data for two nuclear heat sources (Pebble Bed High Temperature Reactor) [14], [15];
- ALSTOM proposed a conceptual design of a secondary cogeneration plant and performed a parametric analysis proving satisfactory performance results and flexibility to allow for seasonal changes in steam demand;
- SAIPEM gathered data from an industrial end user (an oil refining and petrochemical complex) and presented it in the "PROCHEM Case Study Data"; the requirements on steam supply (flow-rate, temperature, pressure, seasonal stability, back-up needs etc.) were indicated; the nuclear source can only pretend to cover a part of the local heat demand, because offgases must be incinerated anyway, and backup boilers are required; revamping of an existing refinery with a nuclear cogeneration plant would require a complete redesign of the Power and Steam station; the corresponding investment must find its justification through sufficiently attractive benefits.
- Using the input data mentioned above, Empresarios Agrupados proposed a model and a thermal heat balance of cogeneration plant that would combine a Westinghouse HTR reactor, use a secondary circuit similar to what ALSTOM proposed, and deliver steam and electricity to the industrial end user described by SAIPEM.

The work performed serves as a valuable illustrative example to identify difficulties to be expected in system integration. Although this work represents no commitment to any of the used technical solutions, the exercise provides an example, using real end user data (an oil refining and petrochemical complex) of how an HTR could be used in a cogeneration plant, which was one of the objectives of WP 1.1 of the ARCHER project.

Further improvements of the consistency of this analysis could be performed in the future. E.g. the ALSTOM analysis assumes steam delivery only at two distinct pressures, whereas SAIPEM indicates that a typical oil refinery would need steam often at three different levels and with very high reliability. Also, the ALSTOM study assumes full condensate return whereas SAIPEM indicates that condensates in a refinery are usually discharged to the environment, which is only possible in areas where enough make-up water is available. Finally Empresarios Agrupados emphasizes the mismatch between the energy demand of the oil refinery and the delivery from the nuclear heat source. The study confirms that matching a nuclear heat source to industrial end-users is in principle feasible, but specific features need to be considered for a re-design, e.g. the necessity to flare off-gases from a refinery. It was also pointed out that while nuclear cogeneration mainly competes with gas-fired cogeneration the biggest benefit is obtained when replacing coal firing. Technically, few difficulties are expected. However, the economic benefit and financial risk would need careful analysis.

2 Challenges: Research, Development and Innovation

Nuclear cogeneration is a technology innovation with a potentially major positive impact on European energy policy, supporting CO_2 curbing, increasing security of energy supply, and strengthening the position of European industry, which represents a key economic asset in Europe.

Specifically the HTR features high efficiency potential due to elevated primary coolant temperatures and a very high level of inherent safety characteristics. These features make the system particularly appropriate for the process industry (e.g. chemistry) or other high temperature applications for which a very efficient and CO_2-free energy source is in principle a favorable low-carbon alternative to fossil fuel but which is as yet an economic unknown for these industries.

The R&D outlined in this document is directed towards bringing this innovation to the market via the shortest routes.

- Low temperature cogeneration requires minor R&D, which revolves around licensing, coupling technology, and safety.
- Medium to high temperature cogeneration focuses on high temperature reactor technology regarding its favorable characteristics and very large deployment potential. Demonstration supports this goal, and the required R&D can therefore be summarized by the topics licensing support, safety demonstration and (evolutionary) technology advancement. Very important is the support which R&D can provide by maintaining and strengthening the nuclear fission knowledge base, by developing and establishing the R&D infrastructure that can bridge the transition from technology innovation to implementation.
- Very high temperature reactor technology is a major innovation with a longer term development required, together with alternative fuel cycles. Demonstration is a prerogative, but the development would span such a long time that, assuming that the perspective can be substantiated, these developments should be initiated in the short term.

This section summarizes the R&D efforts that would stimulate and facilitate the implementation of nuclear cogeneration. First, generic items are named that are of importance for all nuclear systems in cogeneration mode. Then, a pathway towards demonstration and deployment of nuclear cogeneration using HTR technology is listed. Finally, R&D is outlined that would enable maximized benefit from nuclear cogeneration technology. Although this is considered long term at this stage, it is recommended to initiate such work early, thus enabling the strengthening of specific long-term deployment scenarios and applications.

2.1 Generic R&D

The following nuclear cogeneration R&D subjects are generic, as they are relevant for all nuclear systems operating in cogeneration mode. However, their importance and relevance depend strongly on the nuclear system envisaged, and the process it is connected to. These mainly relate to safety and licensing but also to the exploitation of existing LWR for purposes of growing importance (e.g. seawater desalination):

- Tritium transport reduction to secondary and tertiary systems (only required for high temperature cases):
  - Tritium permeation barriers
  - Coolant chemistry and purification technology
- Impact of process transients on cogeneration supply unit, and vice versa:
  - Coupled system code development and validation
- Coupling technology including energy buffering:
  - Coupling component development and qualification
  - Coupling material selection and performance qualification
- Adaptation of existing LWR and future SMR to meet strongly growing demand for district cooling and seawater desalination in arid countries

Non-cogeneration specific R&D for large water-cooled reactors, water-cooled small and medium-size reactors (SMR) and for fast neutron reactors is referred to in the SNETP/SRIA [16] chapters associated to these technologies.

2.2 Pathways towards Demonstration and Deployment

Demonstration is required for a breakthrough of HTR technology in the cogeneration market. Such a demonstrator should make maximum use of proven technology with minimized R&D requirements. Owing to R&D and market studies carried out in EU projects such as ARCHER or NC2I-R, the demonstrator specifications have converged to an intrinsically safe steam cycle HTR operating at 700-750°C for the purpose of process steam generation up to 600°C. US market studies came to similar specifications. To enable further strategic decisions on functional and technical specifications and to properly prepare and facilitate licensing of a demonstrator, the main design options have to be frozen. Some of this work is envisaged to be performed by a new project, possibly as part of the international collaboration between NC2I and the Next Generation Nuclear Plant Industrial Alliance (NIA) in the US (the "GEMINI Initiative" (http://www.gemini-initiative.com). The list below summarizes main development gaps. Input to this list was provided by the technology gap analysis which was performed based on the industrial knowledge and experience of the THTR which is described in ARCHER deliverable D12.11 [17].

- Design options: Define the functional and technical specifications for a demonstrator based on market needs, technical capabilities, safety and licensing requirements, cost reduction through design optimization.
- Safety requirements and assessments: Establish safety requirements for different European countries and evaluate safety options proposed for a demonstrator.
  - Accident modelling (air and/or water ingress)
    - Thermal-hydraulic and fuel performance code development and experimental validation for accidents and transients
    - Integral safety testing: water and air ingress experiments such as NACOK and safety tests under irradiation
  - HTR earthquake response (graphite core and component vibration analysis), identification of suitable countermeasures, e.g. design innovation to minimize loads on supports, flanges and connectors;
  - Behaviour of graphite dust including fuel element performance, filters, flushing, separation concepts, and development, testing and validation of simulation tools.
  - Response of nuclear heat source to transients from heat sink and vice versa (coupling impact);
- Licensing Support
  - Agreement on internationally applicable stringent safety standards for HTR
  - Renewal and adjustment of the past German and US HTR licensing processes to new standards
  - Support the development of European design codes and standards to cover HTR
  - Fuel and graphite back-end: waste volume reduction, graphite decontamination and recycling, and compatibility of HTR waste with final repository conditions
  - Source term determination (fission product transport)
  - Development of a probabilistic licensing approach with regards to HTR fuel and core components
  - Development of a system integration approach for the HTR system, and of the coupled system, and apply this to actual application cases
  - Develop, prepare and perform the material and fuel characterization and qualification process
- Graphite internals: Develop specifications for graphite component design to achieve the required component performance. Ensure availability of graphite properties including under irradiation.

- Components: Define specifications for the critical components, conduct a supply chain analysis to identify systems and component supplier capabilities in Europe, the US and third countries, identify instrumentation and perform validation tests.
  - Helium technology (purification, primary system sealing, pumps, circulator)
  - Material behavior in a helium environment (tribology tests, helium loop, helium flow erosion/corrosion)
  - Development, testing and qualification of diverse shutdown systems.
  - Hot gas duct design: determination of thermal stratification loads
  - (Digital) high temperature Instrumentation and Control for online system performance and behaviour monitoring and analysis
  - Fuel and graphite hardening against air and water ingress
  - Heat exchanger and system design to minimize air and water ingress
  - Fundamental understanding of HTR fuel performance and behavior by appropriate (separate effect) irradiation tests and modelling efforts, to determine:
    - Material properties and behavior under irradiation
    - Fission product transport and diffusion
    - Manufacturing impact on fuel performance
  - Adopt the fundamental knowledge regarding HTR fuel behavior, develop and validate a mechanistic fuel performance code, including transient behavior and severe accidents
- Roadmap towards demonstration: Identify potential demonstration sites, study the integration of nuclear cogeneration on such sites as well as in existing energy grids, plan the demonstration program.
- Communication and international relations: Use and enhance international collaboration on HTR demonstration, assess opportunities for high temperature nuclear cogeneration worldwide
- Market and economic analysis to identify best demonstration and deployment opportunities and to corroborate a business case
- Development of a strategy to complete the innovation chain
- Preparation of a mature business case to approach private investors
- Identification and use of funding and financing opportunities for an HTR demonstrator

The main conclusions of the technology gap analysis provided in [17] are given below:

- Many of the identified gaps address (economic) efficiency rather than safety issues
- Some gaps address improvements in analysis tools (either experimental techniques or simulation approaches)
- The main gaps are related to economic performance and re-establishment of the supply-chain including the know-how.

It is recognized that progress in the technology development of nuclear cogeneration with HTR will not automatically lead to a favorable market pick-up. It is recommended to more systematically address all elements depicted in the SWOT Analysis provided and graphically presented in Figure 2 [8]. Strengths must be maintained, opportunities be seized, weaknesses and threats be removed or countered by strengths and/or opportunities. The SWOT Matrix taken from [8] presented in Figure 3 will support this process. A few examples can be given here:

- The identified weakness of communication on nuclear safety concepts to the public could be countered in some respect by the strength of using robust passive safety systems in an HTR.
- The threat of unstable public and political support could be countered by opportunities like volatility of prices for natural resources, CO_2 emission reduction policies, and the increasing public awareness of the drawbacks of all energy sources.
- The relatively high construction costs, economic uncertainties for end-users, and competition with other resources promoted by EU incentives, could be countered by the proven experience, the fuel economy, the potential for modularization, and the high efficiency of the system, but also by the large potential heat market, the volatility of the prices of natural resources, and the CO_2 emission reduction policies.

- The threat of having to compete with existing reference technologies for cogeneration, will be countered by the opportunity of reaching the end-of-life of these same facilities.

While technical challenges can be addressed with R&D, others (e.g. strategic, economic, legal & social) require a number of complementary approaches beyond R&D to complete the next steps in the innovation chain. For this purpose, the partners in NC2I will in the future have to tap into the resources of their companies other than scientific and technical. If this should prove inconclusive, it is recommended to seek professional advice from specialized consultancy companies on the best possible ways forward.

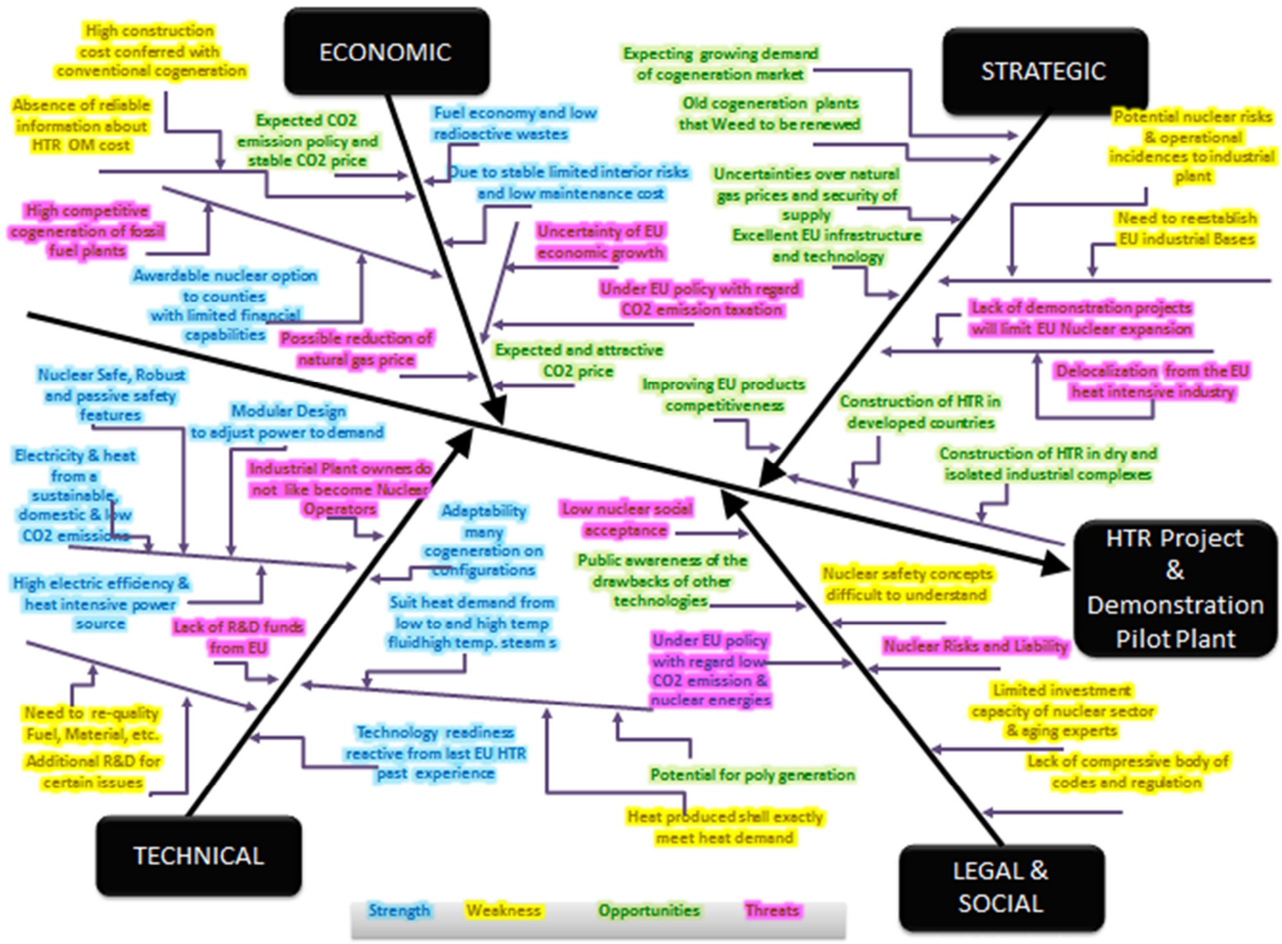


Figure 2: Schematic view of the SWOT approach [8]

Strengths	**Weaknesses**
- **Robust passive safety systems** - **Proven experience** - **Fuel economy** - **Waste stability** - **Modularization potential** - **High Efficiency** - **Low carbon source of energy** - **Reliability of heat supply**	- **Existing knowledge and experience retiring** - **Requalification of fuel, materials, components** - **Need to re-establish industrial basis** - **High relative construction costs** - **Nuclear risks affecting industrial plant** - **No up-to-date European licensing framework** - **Communication of nuclear safety concepts to public**
- **Large potential heat market** - **Volatility of prices for natural resources** - **CO_2 emission reduction policies** - **European nuclear industry** - **Potential for cogeneration** - **Public awareness of drawbacks of all energy sources** - **End-of-life for existing cogeneration plants**	- **Unstable public and political support** - **Existing reference technologies** - **Economic uncertainties for end-users** - **Process heat users do not wish to be nuclear operator** - **Restrictive nuclear policies** - **Co-location with industrial sites complicates licensing** - **Competition with other resources promoted by EU incentives**
Opportunities	**Threats**

Figure 3: SWOT Matrix [8]

The main conclusions of the SWOT analysis presented in [8] are summarized below:

- The large potential market for cogeneration forms an opportunity for the low CO_2 emission HTR technology.
- There is a large European knowledge and experience base
- The energy from an HTR is affordable, reliable (both with respect to security of supply and with respect to safety), and clean (low carbon technology) which fits the European energy policies.
- Heat provision with an HTR is flexible (a large range of pressures and temperatures can be achieved).
- An HTR fits very well in small grids which are typical for many regions where heat intensive industrial complexes are located.
- Nuclear safety concepts are difficult to explain to the public at large. Apart from that, nuclear risks and liabilities are hindering deployment of any nuclear project.
- The European energy supply and policy is divided and differentin each member state.
- A consistent and up-to-date regulatory framework is lacking.

2.3 R&D towards Deployment and Long-Term Market Opportunities

Beyond demonstration, the potential of nuclear heat sources can be further broadened by appropriate R&D. Of particular relevance is research in the following areas:

- Increased primary coolant temperature (950ºC) for enhanced efficiency and broader application perspectives:
  - Development and qualification of suitable structural materials including codes
  - Fuel behaviour and performance, and potential improvement to maintain HTR safety margins
  - Coordination with non-nuclear projects on hydrogen production technologies
- Alternative fuel cycles to stretch fuel resources, to minimize waste and to optimize cycle length: cf. related SNETP/SRIA section on Fuel Cycles;

2.4 R&D Infrastructure: The Bridge to Deployment

Besides the essential competences and experience of experts involved in HTR development (a critical asset for the whole nuclear sector), major investments are needed in modern experimental infrastructure and facilities to enable the above R&D to be performed adequately. The following facilities are essential:

- New irradiation facilities for the investigation, characterization, development and, ultimately, validation and qualification of HTR fuels and materials. Accident testing requires development of novel and specific irradiation test facilities and equipment. Additionally an in-pile helium loop is needed to assess material behaviour under representative primary coolant flow and irradiation conditions.
- Out-of-pile testing facilities such as accident tests (NACOK, KORA), helium loops (HELOKA, HEFUS)
- Modern hot cells with heating tests (KÜFA) and state-of-the-art PIE possibilities to enable the generation of the appropriate data for code development and validation, and to increase the fundamental understanding of material and fuel behaviour.
- Fuel manufacturing laboratory, also able to handle transuranics.

These facilities serve two purposes: on the one hand they are essential for appropriate R&D to be performed, on the other, they form the basis for the design, licensing and operation of a demonstration project.

The steps towards demonstrator construction go partly beyond R&D and are therefore considered beyond the scope of the SNETP SRIA [16], but they are closely tied, and therefore shortly mentioned here. As the EUROPAIRS roadmap has shown, the following items were identified as critical for the establishment of a supply chain for a demonstrator:

- HTR fuel pilot plant, or qualified fuel delivery from an external supplier
- Manufacturers and suppliers, and the appropriate qualification and quality assurance fitting HTR technology and licensing requirements for:
    - Reactor pressure vessel (most critical)
    - Other components, such as heat exchanger, graphite, circulator, hot gas duct, core structure, steam generator, civil engineering

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4 Annexes

Annex 1 – Document approval by beneficiaries' internal QA

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Fill involved beneficiaries as appropriate (mandatory for Milestones and Deliverables, but optional for other document types)

#	Name of beneficiary	Approved by	Function	Date
1	JRC	E. D'Agata	Reviewer	
2	JRC	P. Hähner	Unit Head	
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