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Work programme for establishing the coupling between industrial processes and (V)HTR systems

Deliverable D3.2

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End-User Requirements fOr industrial Process heat Applications with Innovative nuclear Reactors for Sustainable energy supply

EUROPAIRS project – Grant Agreement no. 232651

End-User Requirements fOr industrial Process heat Applications with Innovative nuclear Reactors for Sustainable energy supply

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Summary

This report describes a work programme towards establishing a (V)HTR system connected to an industrial process in the form of roadmaps at various levels of detail. This has been established in the EUROPAIRS 7th Framework Program. Elaborating an appropriate work program and accompanying roadmap was Task 3.2 in the EUROPAIRS Description of Work, and has made use of the other deliverables in the work program, and the discussion between the partners involved.

This deliverable is public and intended for communication purposes. Considering the complexity, and the many uncertainties involved, the roadmaps presented can only be considered a starting point for an elaborate work program. Further development and detailing is recommended by the stakeholders involved in the development and market introduction of the technology, to which this deliverable and underlying roadmaps will be made available.

Revisions

Rev.	Date	Short description	First author	Task leader	Work package leader	Coordinator
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Distribution list

Name	Organisation	Comments
Panagiotis MANOLATOS	*EC DG RTD*	
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EUROPAIRS D32: EU Work Programme for Establishing the Coupling between Industrial Processes and (V)HTR Systems

The EUROPAIRS Roadmap representing the HTR Deployment Strategy

Confidential

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1 Introduction

This report describes a work programme towards establishing a (V)HTR system connected to an industrial process in the form of roadmaps at various levels of detail. This has been established in the EUROPAIRS 7th Framework Program. Elaborating an appropriate work program and accompanying roadmap was Task 3.2 in the EUROPAIRS Description of Work, and has made use of the other deliverables in the work program, and the discussion between the partners involved.

Three roadmap levels will be presented, in which one is a detailed roadmap for the first-of-a-kind or prototype of the HTR system to be deployed as an electricity and steam supplier for bulk chemical industry. This medium term market opportunity that allows for relatively quick deployment of virtually existing HTR technology has been identified as a key starting point, especially in Europe and the US.

The longer term perspective is the demand for clean hydrogen, related to innovative steel making processes, coal to synfuel application, and other end user industry innovations, that provide a huge potential for clean hydrogen from a clean nuclear source. The second roadmap makes use of the detailed roadmap for the prototype, and especially takes into account the risks and critical paths identified in the prototype roadmap, but includes the broader perspective, for example, the next steps, R&D requirements for longer perspectives to open up, international cooperation as a main driver for licensing and cost reduction.

The third roadmap is a high-level roadmap, only depicting the global approach to establishing the route towards large scale application of HTR systems, via the industrial initiative and the chemical bulk industry opportunity as the drivers. This roadmap is intended for communication of the strategy to be adopted for successful implementation of HTR systems, based on current assumptions. The industrial initiative is a key and central point of this strategy, and as both the initiative and the strategy are carried forward by the Sustainable Nuclear Energy Technology Platform, this roadmap is named the SNETP Roadmap.

This deliverable is public and intended for communication purposes. Considering the complexity, and the many uncertainties involved, the roadmaps presented can only be considered a starting point for an elaborate work program. Further development and detailing is recommended by the stakeholders involved in the development and market introduction of the technology, to which this deliverable and underlying roadmaps will be made available.

The Excel-based roadmapping freeware has been used, i.e. the Roadmapper’s Workbench, developed by Albright Strategy Group.

2 Assumptions

Most of the information provided in this document assumes knowledge regarding HTR systems, and specifications of the energy provided is known to the reader. For more information reference is made to [EUROPAIRS report HTR systems by Viala].
The roadmap originally targeted a schematic of a work program to come to establishment of a demonstration project and further steps. During the course of the program, it became clear that an elaborate work program, to finetune HTR system design to end user specifications, should be avoided to meet the stringent end user deployment horizon: HTR systems should be available in 10 years time for end user industry to be able to commit to anything.

Based on the assessments of the industrial applications for which HTR could be suitable on the short to medium term, and the characteristics of HTR systems, the following preliminary technical assumptions have been made, as background for the roadmap:

- HTR should be considered in first instance as a replacement for current fossil fuel based industrial energy infrastructure.
- In this market (mainly bulk chemical industry) the energy products delivered by the energy supply system are steam at various pressures and temperatures, and (in many cases) electricity
- Developing new industrial processes and subsequently new (very) high temperature nuclear reactors is considered too risky and too long term for a first step, and is therefore not taken into account for the prototype, which should focus on short to medium term demonstration. Additionally, these advanced developments are expected to rely on a developed HTR market, at least in Europe.
- Economic viability, reliability and availability (these items are coupled) are key requirements for the end-user industry. Next to loss of production, unexpected heat supply interruption can damage installations and can require extensive time and cost consuming restart operations. To maximize reliable heat supply continuity, a number of options can be considered, which could be more or less suitable, depending on the case under consideration:
    - Redundancy, i.e. multiple HTR units per site, could be considered, which leads to moderately sized HTR systems. For industrial site requirements which are expected to be in the range of 600 MWth to 1000MWth, an appropriate HTR unit power level could be approximately 300 MWth. The larger the HTR unit, the less market share can be covered reliably by HTR redundancy. Larger units are not excluded but this should be accompanied by a significant portion of the energy generated to be adopted for electricity production.
    - Next to being economically advantageous, electricity production increases flexibility in heat supply. Combined with the requirement of heat supply in the form of steam, a (conventional) steam cycle coupled to the primary nuclear cooling system as secondary or tertiary cooling system seems the most appropriate. This means that moderate primary coolant temperatures (750°C) are sufficient.
    - Apply 'off the shelf' technology as much as possible to minimize risks and deployment duration.

- Especially in a strategy where fossil fuel energy infrastructure at industrial sites is replaced, the existing energy infrastructure based on fossil fuels can potentially be maintained to ensure heat supply is guaranteed also in case HTR outage is inevitable. This relates especially to low maintainance cost options focused on steam supply such as gas- or coal-fired boilers.

The Europairs roadmap will be based on establishing a prototype, in line with current-day technical and licensing standards and Europairs industry specifications, to replace existing fossil fuel based energy supply systems. In what way heat supply reliability can be guaranteed will be determined as soon as the application and specific end user demands have been selected. This can be done as soon as site and application and end user have been selected.

One of the conclusions from the economic study and the market study is that HTR is hardly economical in case it is adopted solely for electricity production, and that using the high temperature heat from an HTR system is both a necessity and an opportunity.

Additionally, the preliminary conclusions from the economic study performed in EUROPAIRS have shown that the total power of the system should be maximized to optimize economic attractiveness of the system. HTR maximum unit size is approximately 630 MWth, above which the typical inherent safety features of HTR systems are lost, and economic impact of the active safety systems that are subsequently required are considered detrimental for HTR technology viability.

On the other hand, average heat demand of typically large industrial sites in Europe ranges from 400 MWth to 1000 MWth. Establishing adequate heat supply reliability by redundancy for these typical site sizes would require relatively small sized HTR systems.

The optimization of maximizing HTR system unit size for economic attractiveness versus minimizing HTR system unit size for market attractiveness has not been finished within EUROPAIRS, and requires more elaboration. It has been added as a specific and critical decision point in the roadmap.

3 International Framework

3.1 International Cooperation in the field of (V)HTR

Many initiatives for HTR development are ongoing and planned worldwide. More detailed information is provided in [EUROPAIRS report HTR systems Viala]. The main developments are, in summary:

- China: HTR-10 test reactor operational, and HTR-PM (2x250 MWth pebble bed twin unit) under construction. The HTR-PM is a two unit pebble bed type high temperature reactor based on the German HTR-modul design. The main target of the system is electricity production.
- US: NGNP (Next Generation Nuclear Plant) R&D project targets the establishment of a Very High Temperature Reactor (VHTR) for hydrogen production. In parallel, US end user industry targets an HTR for steam and electricity production. Interested US industrial stakeholders

have been organised in the US Alliance. A EUROPAIRS-US Alliance meeting has taken place as part of the Europairs project.

- Japan: HTTR test reactor is operational, further optimization developments are ongoing to achieve very high coolant temperatures, accompanied by R&D to establish a hydrogen production process. Currently a strong cooperation with Kazakhstan is ongoing. The aftermath of Fukushima, and potential consequences on the Japanese nuclear program and ambitions are unknown at the time of writing of this report.
- Republic of South-Korea: NHDD design is under development and a Korean Industry Alliance is established. The application focus at this time is HTR for energy supply to steel making processes.
- Republic of South-Africa: HTR program (PBMR) has stopped. A large amount of experience and knowledge is currently maintained, and coupling to international activities is targeted, with a focus on developing applications of HTR technology in industrial context. RSA is involved in the EUROPAIRS project and the EU ARCHER project.

The EUROPAIRS-US Alliance meeting that took place in Paris 13-14 October 2010, has shown that there is a large agreement to the approaches and goals of the end users on either side of the ocean. To alleviate the financial burden of large investments required for a prototype, and to facilitate the establishment of a global technical and licensing framework for HTR technology, international cooperation especially with the US could be of mutual benefit.

Cooperation with other international HTR activities is established at R&D level mainly via the (V)HTR Generation IV International Forum (GIF). Especially considering end users operate their plants globally, the global licensing and technology basis required would be facilitated by international cooperation. This cooperation is especially useful in case a similar approach and (first) application for HTR technology is foreseen.

3.2 International Trends

Based on the limited horizon for any end user commitment, the plug-in market is the most sensible and safe first step for HTR nuclear cogeneration market deployment. The plug-in market has been defined by the EUROPAIRS HTR market study (ref. LGI), and represents replacing current fossil based energy infrastructure with HTR technology, in majority for chemical bulk industry. This market has been identified as the most accessible option within end user industry investment horizon:

- Volatility of fossil fuels impact end user industry economic reliability to a large extent. A less volatile alternative would be beneficial
- The fossil fuel infrastructure requires replacement within the next decades, which offers an opportunity for alternatives
- Current infrastructure could be conveniently replaced, without much impact on the industrial process infrastructure (‘plug-in’)

- Heat in the form of steam is required, which can be achieved with moderate coolant High Temperature Reactor, which can be achieved with current-day technology, minimizing time and costs for R&D, and allowing HTR technology to be achievable within the maximum horizon for end user commitment

The first step of entering the plug-in market can however be justified even more if the potentially very large application possibilities of HTR systems are taken into account, after the initial demonstration steps have been taken.

The end users in EUROPAIRS have identified a number of developments or trends, for which HTR systems would be excellently fitted to contribute as clean energy supplier. These trends are for example:

- making more efficient use of carbon resources: coal to liquid, CO2 recycling
- advanced steel making processes, CO2 reduction opportunities
- hydrogen production for transport fuel

All these relate to hydrogen production as the main product produced by HTR systems. For these cases HTR should possibly no longer be regarded a heat and electricity supplying system, but as a large scale hydrogen production system, as proposed by Dr. Fick (NWU, RSA) during the EUROPAIRS open workshop.

This is in line with the vision pursued in Japan, and the R&D efforts for NGNP in the US (in parallel to the US Alliance target). EUROPAIRS learns as well that in Europe hydrogen production could be a major HTR application opportunity in the longer term. However, it can only be reached by demonstrating HTR technology robustness to end users, within their commitment time frame.

4 R&D Requirements

4.1 Developments

Within EUROPAIRS, the following major R&D developments have been identified, both considering the prototype, and considering the medium term future (from 10-20 onwards) to support longer term industry opportunities. This is a non-exhaustive list of items:

- Fuel performance code experimental validation. Although fuel performance codes have been developed in the past, the fundamental understanding of HTR fuel behaviour, and subsequent performance modelling has not been adequately achieved, although proper performance of HTR fuel is beyond doubt, as elaborate experimental and qualification programs has shown in the past. Separate effect experiments are needed to retrieve the right data to make the steps from empirical towards physics based modelling. This would allow fuel performance to be extrapolated to other boundary conditions, and guide efficient development of other HTR fuel types.
- Advanced safety testing to support licensing, such as air and water ingress testing, also under irradiation conditions. Both for fuel elements and structural materials such as graphite and high temperature ceramics.
- Alternative coolant R&D. Although helium has some preferable characteristics as high temperature coolant in a nuclear reactor, it is very volatile (leakage issues), potentially scarce in the future, and has a low heat capacity. Alternatives such as molten salt, or supercritical CO_2 can be considered as well, which would require significant R&D to be able to confidently introduce these options.
- High temperature material and component development
- Coupling technology development: nuclear systems have not been connected to conventional industrial processes before, and specialized coupling technology could be required.
- medium temperature hydrogen generation techniques. One partner specifically has brought in expertise related to the innovative membrane reforming process, by which hydrogen is formed at relatively low temperature (i.e. 700°C), but with adequate efficiency. The HTR prototype system could in that case be converted to a hydrogen production plant, without major adjustments.
- Tritium, which is formed in the nuclear system, mainly in the control rod system and the fuel, could diffuse through heat exchanger/steam generator boundaries, by which secondary coolant could become contaminated. Tritium is from that point of view considered of major impact on licensing feasibility and end user acceptability. Although tritium contamination was

to a large extent tackled in the German HTR programs, for example by primary coolant purification systems, and oxide coating barriers on heat exchanger piping, special attention should be given to this aspect, especially with increasing temperatures. R&D on increased tritium barriers, advanced primary system purification, and design changes to fuel and/or control rod systems is recommended.

- Both from tritium, but potentially also to facilitate safety case licensing an intermediate coolant circuit, in between the primary coolant side, and the process tertiary coolant side, is recommendable, in case it does not negatively influences system economics too much.
- In case high coolant temperatures are required, to enable very high process temperatures, for example for hydrogen production, new advanced HTR fuels are required. The state of the art HTR fuel (TRISO fuel following German design) performs very adequately for operational temperatures up to 1200°C (corresponding approximately to 900-1000°C average primary coolant temperatures). However locally, temperatures could be higher, for example depending on coolant flow patterns, or fuel loading or burn-up asymmetry. For coolant temperature beyond 850°C, advanced fuel types should be developed, that do not show the permeability problem SiC has shown in recent experiments. The main candidate for that seems to be ZrC coated fuel particles, for which significant R&D and optimization is required.
- Make use of the high temperature alloy expertise built up in conventional industry. The current HTR system designs rely on materials developed, tested and qualified decades ago. Conventional industry has already many years of good experience with advanced alloys, that perform well under higher temperatures. Nuclear industry could make use of this experience, although even materials with decades of experience in conventional industry will require qualification following nuclear standards.

4.2 Infrastructure Requirements

The following essential testing and research infrastructure is required in support of the above R&D points, but also for the qualification of fuels and materials, and to support licensing and modelling validation. It is specifically mentioned, as the expenditures for establishing or maintaining the infrastructure are significant. Of course, the infrastructure needs to be accompanied by appropriately skilled and experienced scientists and engineers:

- Fuel manufacturing laboratory
- Safety testing facilities (NACOK type)
- Irradiation facilities (material test reactors with HTR fuel and material irradiation expertise)
- Post irradiation examination equipment and facilities (for example Küfa, Kora and Imga)

5 End User Involvement

Without consumers of the energy supplied by HTR systems, there is no market, and there is no viability. Committed end user industry, and utilities as operator and sellers of the energy generated, are key for the technology to become established.

EUROPAIRS is the first step in connecting the nuclear community to non-nuclear industry, which has been successful so far. Next steps to strengthen this relation and ensure a mutual commitment to get HTR technology established can be:

- Subsequent European Framework programs, continuing from Europairs, further strengthening the relation, with focus on business modelling, site selection, fixation of system specifications, solution of potential feasibility issues. In short, covering all aspects that need to be addressed for end users and utilities to gain confidence in the potential of the technology.
- Create a European organisation, in which end user industry, nuclear vendors and utilities combine their efforts in developing and taking the next steps in making HTR technology mature. A first step has been taken by the creation of the Associated Industry Network connected to EUROPAIRS, which is being developed into an organisational entity, that is fully independent and self-sufficient, at the time of writing. A construction like in the US (the US Alliance) is targeted.
- The prototype system is a first of a kind, which is much more costly than subsequent systems. This first financial hurdle exists for any new technology, but for this case, considering the time and the risks involved, it is too much to bear justifiably by industry. Within Europe a financial framework is present to enable new energy technologies to overcome these initial hurdles in terms of (financial) risks, i.e. the so-called Industrial Initiatives in SET-plan framework. End user participation is essential for this type of construction to succeed, but SET-plan Industrial Initiatives also provide an opportunity for end users to take advantage of the technology first, with acceptable (financial) risk.
- To ensure risks and costs for subsequent systems following the prototype are not negatively influenced by repetitive licensing procedures, and the fact that end users generally operate sites worldwide, a generic and global HTR licensing approach should be envisaged. This could be one major motivation for strong international cooperation between end users, and it is therefore specifically added to the roadmap, to stress the importance of both the international framework and the broad end user involvement required.

6 Roadmap

6.1 Prototype Roadmap

For the prototype a specific detailed roadmap has been set up, which is described in summary in tabular form in Appendix A. It is the basis for prototype aspects and planning in higher level roadmaps such as described in the next section of this chapter.
The roadmap has been constructed by estimating time, costs and risks of all aspects of the prototype, and counting backwards from a targeted commissioning date in 2020.

The general conclusions from the detailed prototype roadmap are:

- a 10 year framework from establishing an Industrial Initiative to commissioning of the prototype is very tight
- Total prototype costs are in the range of 2 to 3 billion Euro
- The following technical risks have been identified as of major importance for costs and planning:
    - Vessel ordering: waiting lists for forged vessels are generally long, due to lack of suppliers and an increase of vessel demand. To mark this in the roadmap, a milestone has been added where vessel design has to be finished, and the vessel has to be ordered, to be in time for construction, and the target commissioning deadline in 2020.
    - Fuel manufacturing on industrial scale: although adequate HTR fuel quality has been achieved reproducibly worldwide, it is still on laboratory scale. Producing HTR fuel on industrial scale requires HTR fuel factories to be established, and a full qualification of the fuel produced. Depending on whether existing industrial HTR fuel manufacturing capacity can be used (China, US (partly), South-Africa (partly)), a decision has to be made quite early for either establishing fuel manufacturing capability in Europe, or buying HTR fuel from internationally established suppliers. This ‘build or buy’ decision has been added as a key milestone.
- The following essential decision points have been identified, which determine the start of all subsequent phases of prototype development:
    - The system specifications have to be fixed before the final design phase can be finalised. Therefore a ‘fixed system specifications’ milestone has been added to the roadmap
    - The above milestone is accompanied by knowing for which application, and at what location the prototype will be established. For this the milestone ‘site selected’ has been added, which coincides with the fixed system specifications milestones.

The milestones are considered essential, and have been transferred from the detailed prototype roadmap to the higher level roadmap described in the next section.

6.2 Deployment Roadmap

The assumptions and items behind of the deployment roadmap have been addressed in separate section. Each section starts with a table in which the roadmap item is further detailed, with name, description, and timing added. In case required, additional text has been added, to explain the assumptions, and relations to other activities.

6.2.1 European Framework

EUROPAIRS I	2010	2012	Current program
ARCHER	2011	2015	EU framework program: HTR R&D in support of demonstration
HTR R&D program in support of prototype and longer term perspectives	2013	2021	Technical programs supporting prototype and (longer term) applications

Considering R&D and dedicated strategic coordination actions for HTR development, European Framework programs can be envisaged to support for example generic R&D, attract national funds, include national R&D infrastructure, and strategic first steps, for which investment by industry is premature, not aimed at construction sufficiently direct, or not justifiable for industry in any other way.

EUROPAIRS has already played a key role in achieving contacts between the nuclear community and non-nuclear industry. The industrial initiative task force in SNETP intends to strengthen this bond, and take next steps in terms of site evaluation and selection, business modelling, prototype financing, fixing system specifications, detailed market study as a basis for longer term perspective, etc.

ARCHER is a generic HTR R&D program, in support of demonstration of HTR technology by early prototype. The program focuses on specific topics that would support a demonstrator project, and requires an effort early to ensure delay is avoided as much as possible. The topics are system integration in which the nuclear system and its non-nuclear application in process industry are assessed intergrally, safety experiment and code validation as a basis for licensing, fuel and waste form investigation as a basis for representative fuel and waste performance assessment, material testing and selection, component manufacturing, testing and selection, and education and training.
Subsequent programs could take these subjects further, in preparation of the prototype and the longer term perspective of advanced HTR technology development, and by proper knowledge dissemination maintain and broaden the solid basis of HTR technology in Europe. A non-exhaustive list of R&D items to be considered has been presented in the previous chapter.
Especially the latter requires emphasis: maintaining the knowledge base, and to ensure it is sufficiently disseminated to new generations of scientists and engineers is a prerequisite for the technology to be further developed in Europe. A significant work force is required, for the prototype, and of for the next steps. For this reason alone, European framework programs are imperative to ensure the technology and accompanying competence is maintained.

6.2.2 International Aspects

Preparation phase	2008	2014	
Prototype Collaboration	2014	2031	
Global Licensing Approach	2022	2024	Generic Licensing Approach
Fossil fuel alternative for Chemical bulk industry	2015	2031	European organisation of end user industry established
Coal to Liquid	2020	2031	Requires HTR technology enhancement and subsequent R&D
Synfuel / Hydrogen	2020	2031	
Advanced Steel making	2025	2031	

International cooperation is currently focused on the R&D level via the Generation IV International Forum (GIF). For the prototype and subsequent steps, international cooperation on industry level is envisaged to alleviate financial burden and risk, and to target appropriate systems with accompanying global licensing framework to support HTR nuclear cogeneration deployment, globally.

Additionally international trends in process industry are included. These trends do not represent a current market, but provide perspective on large scale processes that are currently under development and are motivated by expected fossil resource scarcity and subsequent price increase/volatility, and CO2 reduction targets, both as general industry policy, and potentially imposed by authorities. These trends have been identified by the end user partners in EUROPAIRS, and also provide a guide and justification for R&D efforts in parallel to viability demonstration of HTR technology by establishing a prototype.

6.2.3 HTR Prototype – Industrial Initiative

Pre-Conceptual Designs	2000	2012	History
Conceptual Design	2012	2014	2 year duration assumed
Detailed Design	2014	2017	3 year duration, ends 1 year before end of civil engineering
Civil Engineering	2015	2018	3 year duration, ends 1 yr after start construction
Fixed System Specifications	2014		Critical milestone
Site Evaluation & Selection	2012	2014	start EUROPAIRS II, end detailed design
Site Preparation	2016	2018	2 year duration, starts 1 year before construction
Site Selected	2014		Critical Milestone
Construction	2017	2020	3 year duration assumed, starts one year before end of site preparation
Commisioning	2020	2022	Follows construction
Operation	2021	2031	Arbitrary end date

Based on the detailed roadmap for the prototype a higher scale roadmap has been set up for the prototype. In Europe the prototype project can potentially be funded in a public private partnership construction in SET-plan framework as an industrial initiative. Therefore the entire prototype project is an industrial initiative until commissioning, and is presented as such.
For the industrial initiative end user participation is a prerequisite, and the European nuclear technology platform (SNETP) has set up a task force, to set up the initiative and submit to the SET-plan. A number of critical issues, and major milestones have been identified specifically from the prototype roadmap and transferred, as they to a large extent determine progress. It also clarifies the

general conclusions that establishing a prototype within 10 years from now, provides a very tight schedule.

6.2.4 Process Heat

Transport System	2014	2017	Detailed design
Distribution System	2015	2017	Starts 1 year start after start transport system, 2 year duration assumed
Construction	2017	2020	Construction

The coupling of the nuclear unit to non-nuclear process industry is not trivial, and is therefore separately addressed. It is however strongly site and industry specific, and can only start after a site has been selected. Generic coupling development is considered part of ongoing R&D activities, recommendable in international collaboration with direct end user participation.

6.2.5 Commercial HTR Market Deployment

Site Preparation	2024	2026	Starts 2 years after start HTR Proto
Construction	2025	2028	Starts 1 year after site prep starts
Commissioning	2028	2030	Follows Construction
Operation	2029	2031	Follows Commissioning
Towards N-of-a-Kind	2027	2031	Arbitrary timescale

After the prototype has been established, subsequent systems are targeted to replace fossil fuelled cogeneration infrastructure in chemical industry. For now, a modular approach is assumed, in which the market is penetrated by system duplication, but systems optimized to take full advantage of international trends mentioned earlier is certainly not excluded. Although the plug-in market by itself can justify HTR technology, these medium to long term trends in industry requires large scale CO2-free energy (or hydrogen).

6.2.6 Licensing

Reactor	2015	2018	Starts 1 year after start construction
Safety Analysis Report	2014	2017	Starts 1 year before reactor license
Environmental Assessment	2014	2017	Starts at site evaluation, 1 year before reactor license
Process Heat Application	2015	2018	Starts with Reactor license
Generic License	2022	2025	Starts at the end of prototype construction

A licensing framework for HTR systems is not existing at this moment, and will therefore need to be established. Licensing a nuclear reactor is not trivial, and coupling the reactor to industrial processes brings even more and new licensing aspects to be taken into account.

In the German HTR program, a licensing procedure has been developed to a large extent, and this is for example used as the licensing basis in China. For the nuclear system this can be the starting point, to be extended to locating the nuclear system at or near an industrial site and coupling the system to industrial processes. Preferably this is done in or supported by international cooperation, pulling together resources and expertise worldwide, by which a more or less global licensing framework can

be established. This is especially relevant considering the fact that the end users of HTR cogeneration operate plants worldwide, and a similar licensing approach for each site, independent of location, would be highly preferable.
Therefore not just licensing of the prototype, but also generic licensing, in international cooperation framework is added to the roadmap specifically, to highlight its importance. Part of the international cooperation could be the IAEA, which has been in the process of drawing safety guidelines for new reactor systems, which could also be directed more specifically to cogeneration with HTR systems.

6.2.7 Economics

Business Model	2010	2018	Development of a business model incorporating interests of vendors, utilities and en users, To be finalised before construction
Market Strategy	2010	2014	Market strategy also provides input for (generic) system specifications and needs to be finalised before start the conceptual design is fixed.

Economic viability of HTR technology is, of course, imperative for success. This is a combination of the construction costs of an HTR system, a modular approach (duplication of systems, reducing construction costs of subsequent systems), the market perspective, the business model of the operator/utility, energy costs for the end user, and many other factors that determine cost, price, and potential uncertainties that could jeopardize economic viability of the technology.

A start has been made in EUROPAIRS-I, but next steps are planned to be taken in the industrial initiative task force, where business modelling, detailed market studies, site selection, market introduction and penetration strategies will be developed, as a basis for solid economical assessment of HTR system deployment, in direct cooperation with end users.

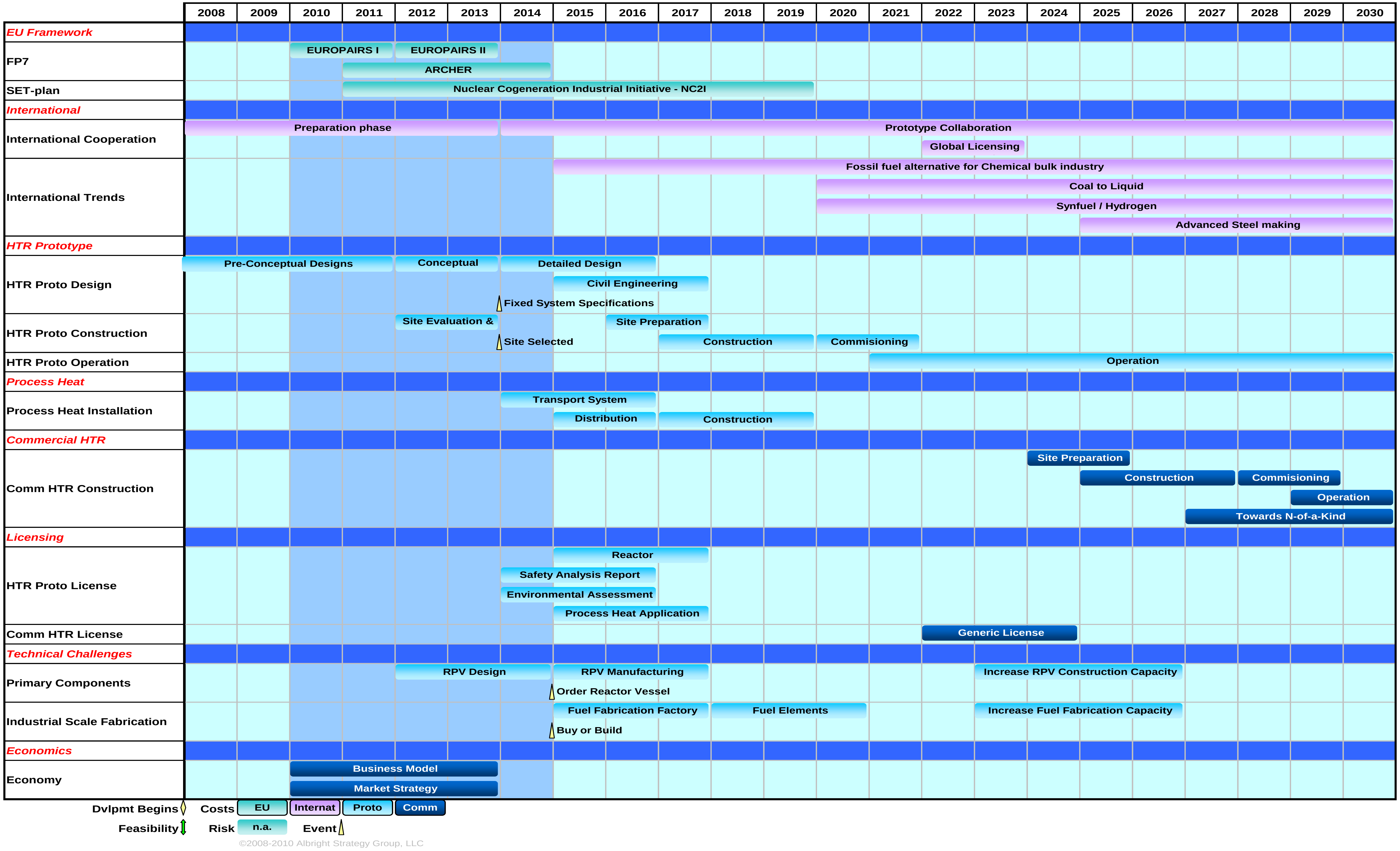
6.2.8 Challenges

RPV Design	2012	2015	yr end after start detailed design
RPV Manufacturing	2015	2018	3 year duration assumed (including waiting time)
Increase RPV Construction Capacity	2023	2027	Starts 2 year after prototype construction ends
Order Reactor Vessel	2015		Critical Milestone
Fuel Fabrication Factory	2015	2018	3 year duration assumed, fits between qualification/prototype commissioning, and buy or build decision in 2015
Fuel Elements	2018	2021	yr duration, start 1 yr before irradiation
Increase Fuel Fabrication Capacity	2023	2027	Starts 2 yr after prototype construction ends
Buy or Build	2015		Critical Milestone

The challenges are derived from the detailed prototype roadmap, and are transferred because of their importance and impact on global prototype planning.

6.2.9 Roadmap overview

A visual representation of the deployment roadmap has been shown in the image below.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SET-plan
Nuclear Cogeneration Industrial Initiative - NC2I
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International Cooperation
Preparation phase
Prototype Collaboration
Global Licensing
International Trends
Fossil fuel alternative for Chemical bulk industry
Coal to Liquid
Synfuel / Hydrogen
Advanced Steel making
HTR Prototype
HTR Proto Design
Pre-Conceptual Designs
Conceptual
Detailed Design
Civil Engineering
Fixed System Specifications
HTR Proto Construction
Site Evaluation &
Site Preparation
Site Selected
Construction
Commisioning
HTR Proto Operation
Operation
Process Heat
Process Heat Installation
Transport System
Distribution
Construction
Commercial HTR
Comm HTR Construction
Site Preparation
Construction
Commisioning
Operation
Towards N-of-a-Kind
Licensing
HTR Proto License
Reactor
Safety Analysis Report
Environmental Assessment
Process Heat Application
Comm HTR License
Generic License
Technical Challenges
Primary Components
RPV Design
RPV Manufacturing
Increase RPV Construction Capacity
Order Reactor Vessel
Industrial Scale Fabrication
Fuel Fabrication Factory
Fuel Elements
Increase Fuel Fabrication Capacity
Buy or Build
Economics
Economy
Business Model
Market Strategy
Dvlpmt Begins
Costs
EU
Internat
Proto
Comm
Feasibility
Risk
n.a.
Event
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7 SNETP Roadmap

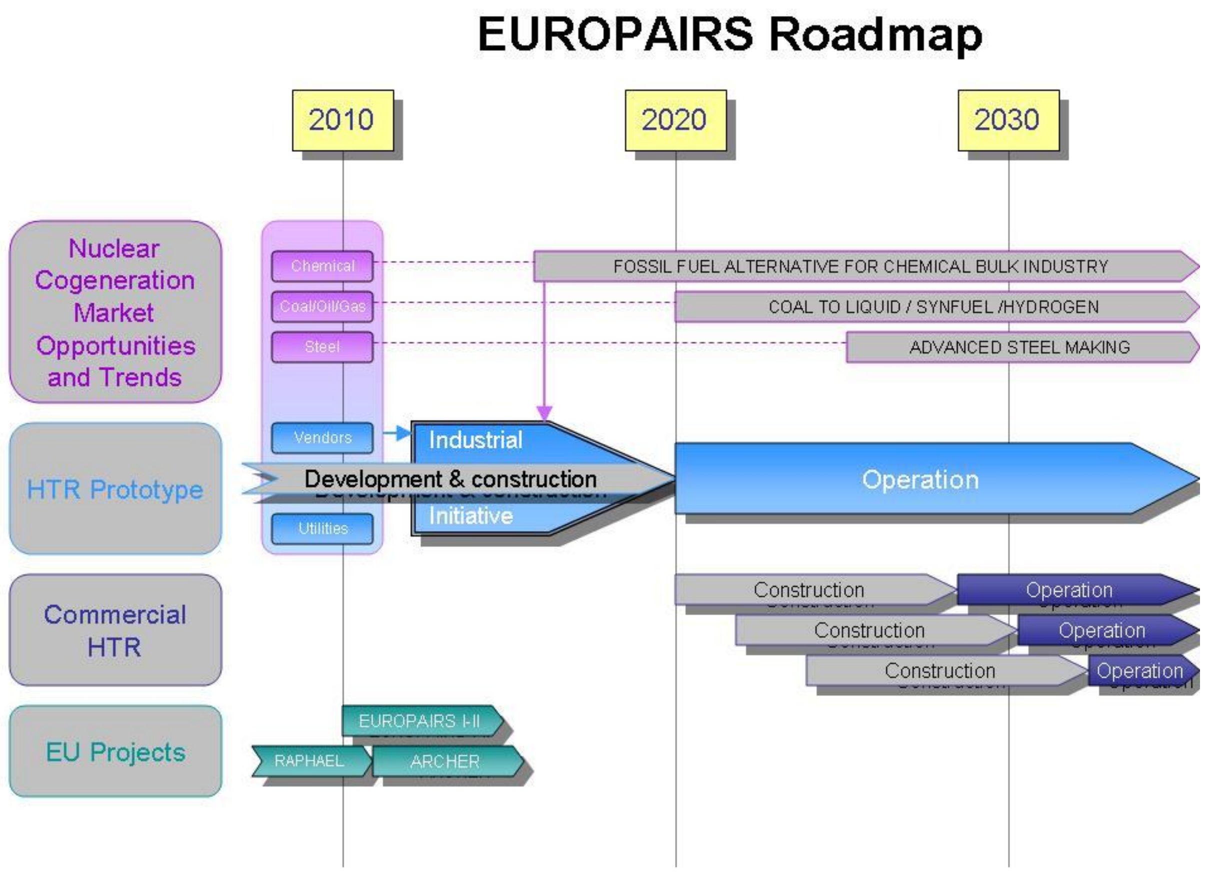
The high level roadmap is intended for communication purposes, and highlights the most relevant and important aspects of HTR nuclear cogeneration deployment, but avoids potentially distracting details. However, all planning and timing aspects rely fully on the underlying detailed roadmaps.

For this roadmap, it has been assumed that the following aspects are essential to convey:

- End user involvement, timing and organisation
- Timing of the prototype, connection to the Industrial Initiative
- International Cooperation, timing and organisation
- Subsequent steps, in relation to international trends and opportunities
- European framework programs and R&D required

These global items have been derived from the detailed roadmaps, and the result has been depicted in .

This EUROPAIRS roadmap provides the essential steps from now to HTR market deployment, in which the trends currently observed, are taken as future opportunities.



8 Conclusions

This deliverable from the EUROPAIRS program has taken the information available and generated in EUROPAIRS to elaborate a work program, in the form of three roadmaps, at different levels of detail:

- The prototype roadmap, representing the main aspects of a prototype project
- Based on the prototype roadmap a broader scope has been represented on a more global level in the deployment roadmap, in which also international cooperation, market opportunities, market introduction and penetration are included
- Based on the deployment roadmap, a simplified roadmap for communication purposes has been derived, in which the most important strategic aspects have been included. The roadmap is intended to provide a strategic overview, that can be used for example in SNETP framework, to present the Nuclear Cogeneration Industrial Initiative

This deliverable is public and intended for communication purposes. Considering the complexity, and the many uncertainties involved, the roadmaps presented can only be considered a starting point for an elaborate work program. Further development and detailing by the stakeholders involved in the development and market introduction of the technology is recommended. This deliverable and underlying roadmaps will be made available for that purpose.

Appendix A

Detailed Prototype Roadmap

The roadmap consists of different levels.

- The first level (yellow rows) indicates the main elements of the roadmap, e.g. ‘Reactor’, ‘Fuels’, etc.
- The second level (first column) indicates the secondary elements of the roadmap. These are subdivisions of the main elements which are indicated at the first level. Such elements may be e.g. ‘fuel qualification’ and ‘fabrication’, which are both subdivisions of the main element ‘Fuels’.
- The third level (second column) indicates the various development elements. They belong to a certain secondary element of the roadmap, e.g. ‘irradiation’ and ‘safety tests’ both belong to the second level element ‘fuel qualification’.

The third level elements of our roadmap, allow us to indicate three types of information.

- Time, provided by start and end year
- Budget estimate for the total development
- Risk involved.

Additionally there are of course dependencies between the various activities, which are elaborated in the final column.

All the information can be translated into a visual roadmap, but the level of detail, makes an overview complicated. It has been decided that the detailed protoype roadmap is set up from the third level items mentioned above. The most important items, and critical aspects have been translated to the deplyment roadmap, which is fuly in line with the prototype roadmap, but provides a more simplified, and communicative format.

In case a visual representation is required, this can be required, but requires an A2 format to be able to distinguish all aspects.

HTR Prototype		Begin	End	Funds	Risk	Dependency
HTR Proto Design	Pre-Conceptual Designs	2000	2012	<50K	Low	Long History
HTR Proto Design	Conceptual Design	2012	2014	<100M	Low	Follows Conceptual Design
HTR Proto Design	Detailed Design	2014	2017	<500M	Low	Ends 1 yr before end of civil engineering
HTR Proto Design	Civil Engineering	2015	2018	<20M	Low	Ends 1 yr after start construction
HTR Proto Construction	Site Evaluation & Selection	2012	2014	<250K	Low	Start with EUROPAIRS II, ends with detailed design
HTR Proto Construction	Site Preparation	2016	2018	<500M	Medium	Starts 1 yr before start construction
HTR Proto Construction	Construction	2017	2020	<500M	Low	Starts after Civil Engineering
HTR Proto Construction	Commissioning	2020	2022	<100M	Low	Starts after construction
Process Heat		Begin	End	Funds	Risk	Dependency
Process Heat Installation	Transport System	2014	2017	<20M	Medium	Parallel to HTR Prototype Detailed design
Process Heat Installation	Distribution System	2015	2017	<5M	Low	Starts after transport system
Process Heat Installation	Construction	2017	2020	<100M	Low	Construction parallel to HTR Prototype Construction
Licensing		Begin	End	Funds	Risk	Dependency
HTR Proto License	Reactor	2015	2018	<5M	High	Starts 1 yr after construction
HTR Proto License	Safety Analysis Report	2014	2017	<5M	Low	Starts 1 yr before reactor license
HTR Proto License	Environmental Assessment	2014	2017	<1M	Low	Start with site evaluation, 1 yr before reactor license
HTR Proto License	Process Heat Application	2015	2018	<1M	Medium	reactor license
Economics						
Economy	Business Model	2010	2014	<5M	Low	EUROPAIRS II
Economy	Market Strategy	2010	2014	<5M	Low	EUROPAIRS II
Primary System						
Primary Components	RPV Design	2012	2015	<5M	Low	Ends 1 year after start detailed design
Primary Components	RPV Manufacturing	2015	2018	<100M	High	Duration includes waiting time
Primary Components	Piping	2014	2017	<20M	Low	Part of Detailed design
Primary Components	Hot Duct	2014	2017	<20M	Medium	Part of Detailed design
Primary Components	Blower	2014	2016	<100M	Low	Ends 1 year before end detailed design
Primary Components	Steam Generator	2014	2017	<100M	Medium	Part of Detailed design
Primary Components	Helium Purification	2014	2017	<20M	Low	Part of Detailed design
Primary Components	Shutdown System	2014	2017	<20M	Low	Part of Detailed design
Primary Components	Fuel Handling System	2014	2017	<20M	Medium	Part of Detailed design
Primary Components	Graphite Reflector	2014	2017	<5M	Low	Part of Detailed design
Primary Components	Seals	2014	2017	<5M	Medium	Part of Detailed design
Secondary System						
Secondary Components	Piping	2014	2017	<20M	Low	Part of Detailed design
Secondary Components	Compressor	2014	2017	<20M	Low	Part of Detailed design
Secondary Components	Turbine	2014	2017	<500M	Low	Part of Detailed design
Secondary Components	Generator	2014	2017	<100M	Low	Part of Detailed design
Secondary Components	Recuperator	2014	2017	<20M	Low	Part of Detailed design
Secondary Components	Electrical Equipment	2014	2017	<5M	Low	Part of Detailed design
Secondary Components	Water Intake & Rejection	2014	2017	<5M	Low	Part of Detailed design

Fuels						
Fuel Qualification	Irradiation	2019	2021	<20M	Low	Starts after HTR fuel manufacturing
Fuel Qualification	Safety Tests	2021	2022	<20M	Medium	Starts 1 year before prototype start
Industrial Scale Fabrication	Fuel Fabrication Factory	2015	2018	<500M	High	Assumed to take 3 years
Industrial Scale Fabrication	Fuel Elements	2018	2021	<100M	High	Assumed to take 3 years, Starts 1 year before irradiation
Materials						
R&D and Selection	Metals	2014	2016	<250K	Low	
R&D and Selection	Ceramics	2012	2015	<250K	Low	
R&D and Selection	Graphite	2012	2015	<250K	Low	
Material Qualification	Metals	2016	2018	<5M	Low	2 year duration starts after selection
Material Qualification	Ceramics	2015	2018	<5M	Medium	3 year duration starts after selection
Material Qualification	Graphite	2015	2018	<5M	Medium	3 year duration starts after selection
Codes & Standards	Metals	2015	2018	<1M	Low	2 year duration starts after selection
Codes & Standards	Ceramics	2015	2018	<1M	Low	3 year duration starts after selection
Codes & Standards	Graphite	2015	2018	<1M	Low	3 year duration starts after selection
Coolant	Gas Coolant	2000	2012	<50K	Low	History
Analyses	Section Heading					
Analysis	Neutronic	2011	2015	<1M	Low	Archer
Analysis	Thermal Hydraulic	2011	2015	<1M	Low	Archer
Analysis	Structural	2011	2015	<1M	Low	Archer
Analysis	PRA	2014	2016	<250K	Low	Starts 1 year before SAR ends
Safety Analysis	Safety Analysis Code	2012	2014	<250K	Low	Starts at start SAR
Safety Analysis	Gas Coolant	2014	2016	<50K	Low	Starts 1 year before end SAR
Safety Analysis	Dust Transport	2012	2017	<1M	Medium	Ends at end SAR
Safety Analysis	Water & Air Ingress	2012	2017	<1M	Medium	Ends at end SAR
Safety Analysis	Thermal Fatigue	2012	2017	<250K	Medium	Ends at end SAR
Safety Analysis	Decay Heat Removal	2014	2017	<1M	Low	Ends at end SAR
Safety Analysis	Source Term	2014	2017	<250K	Low	Ends at end SAR
Safeguards						
Proliferation	Proliferation Resistance	2015	2017	<50K	Low	Starts 2 years before start construction
Physical Protection	Physical Protection	2014	2018	<50K	Low	Start at detailed design, ends with civil design
Waste						
Disposal	On-site Storage	2015	2018	<5M	Low	Parallel Civil engineering
Disposal	Final Disposal	2000	2027	<50K	Low	Separately developed, outside current scope