ANNEX 9: NEA NUCLEAR INNOVATION 2050

R&D COOPERATIVE PROGRAMME PROPOSAL

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TITLE/SUBJECT: High Temperature Industrial Nuclear Cogeneration

This template has been reviewed by

- *NC2I partners*
- *Other members of the PRIME project (NC2I, NGNP Industry Alliance, JAEA, KAERI)*
- *Members of the Generation IV International Forum (GIF) VHTR Steering Committee*

1. **Justification of the selection**

High temperature nuclear cogeneration matches top-level goals

COP21 climate objectives: Following the scenario of the International Energy Agency, meeting the COP21 primary objective to limit the global temperature increase to 2˚C by 2050 would require a quasi-full decarbonisation of electricity generation worldwide (see figure 1), which might be difficult to reach. Introducing in addition non-CO_2 emitting energy technologies in the second sector responsible for the largest greenhouse gas emissions, industry, will increase the chances to meet COP21 objective. Moreover COP21 also considered the possibility to go "well below 2˚C", which would be strictly impossible without addressing industrial emissions.

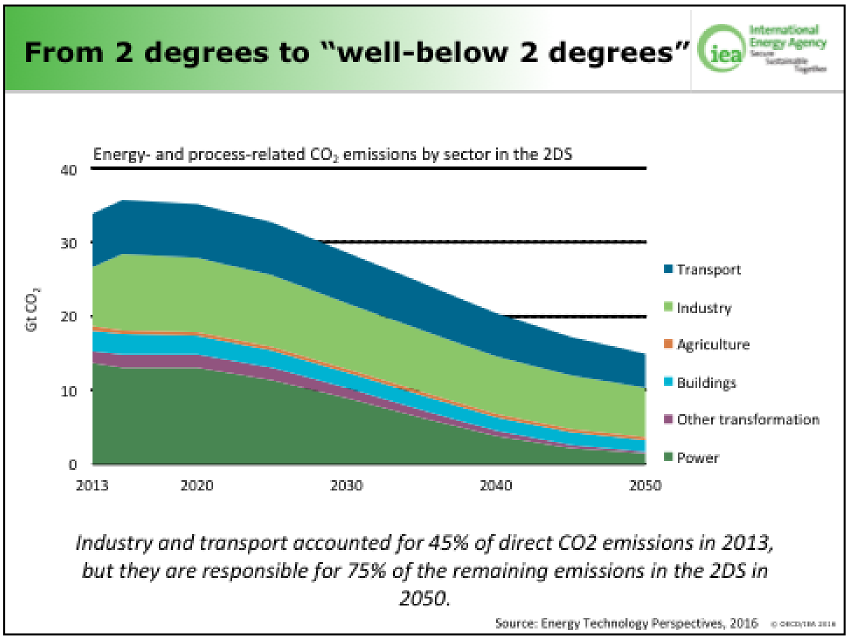

Figure 1: the IEA scenario for 2050

Beyond electricity, the energy needs of industry are process heat needs. The process heat market is very large, requiring mainly high temperature heat, as illustrated in figure 2 for Europe: e.g. just in the range 250-550˚C, the European process heat needs amount to about 87 GWth.

Sustainability of industrial activities: Today process heat is nearly exclusively obtained from fossil fuel combustion. High and unstable prices of fossil fuels, as well as prospects for CO_2 tax, are endangering the competitiveness of industry, which tends to migrate from the most developed countries towards countries with low energy and manpower costs. Moreover the concentration of most of oil and gas resources in regions with high geopolitical instabilities is a vital threat on the security of energy supply to industrial activities in many developed countries, jeopardising their economic prosperity.

<u>A potential nuclear solution to address environmental and economic top-level goals</u>

Nuclear reactors can contribute to address COP21 objectives because they do not emit CO_2. Moreover uranium resources are more broadly distributed in the world than fossil fuel and the dependence of the cost of nuclear energy on the uranium price is low. Nuclear energy can therefore contribute to secure energy supply, providing in addition energy at a competitive and stable cost.

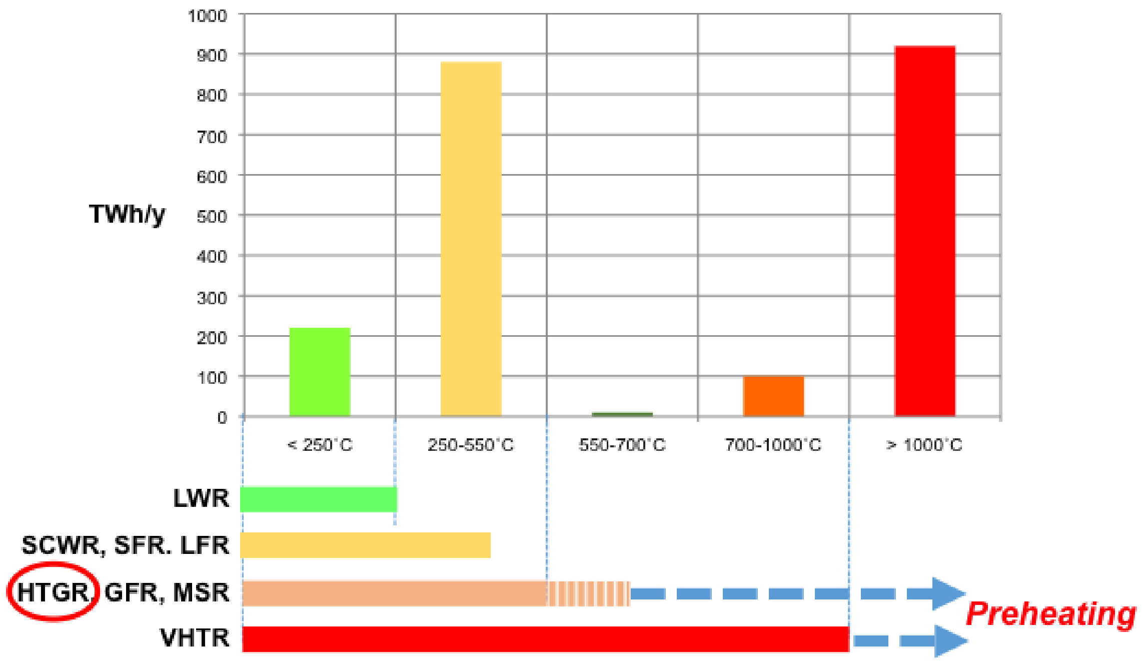

Figure 2: The European heat demand (from Euratom FP7 project Europairs) and the temperature range of industrial applications that can be reached by different types of nuclear reactors

Nevertheless, as shown by figure 2, present LWR industrial reactors can only address a small faction of industrial process heat needs, because they supply low temperature heat (< 250˚C), while most of industry needs are at higher temperature. Several Generation IV nuclear systems, SCWR, SFR, LFR, HTGR, GFR and MSR could, in principle, address part of high temperature heat needs of industry, but HTGR has particular advantages:

- It is the one with the most mature technology and could therefore be deployed earlier, which is decisive, as timing is the critical parameter to get a chance to really contribute to curb the global temperature increase. Of course this first experience of industrial nuclear cogeneration will pave the way for other Generation IV systems to contribute in the longer-term to reduce CO_2 emissions of industry, at the time when they become mature for commercial deployment.
- It covers the widest range of temperature, all the more since HTGR technology has a high potential for evolution in the longer-term, in particular towards higher temperatures (VHTR).

- The specific features of its modern version, the modular HTGR, make it particularly well adapted to industrial process heat needs:
    - Its medium power range (a few hundred MWth), corresponds to the actual needs of most of the industrial sites,
    - Its simple, but extremely sure, intrinsic safety design, is an asset for competitiveness, as well as for making collocation with industrial activities acceptable.

A real breakthrough

Nuclear energy has very rarely been used for other applications than electricity generation, and the rare experiences of nuclear heat supply are only at low temperature. Though HTGR technology is mature, no HTGR has ever been coupled with high temperature industrial process heat applications. ***Getting a first experience of industrial nuclear cogeneration with HTGR will be a major innovation that will open a new and vast field of applications of nuclear energy***.

When the licensing feasibility, as well as the economic and industrial viability of nuclear high temperature cogeneration are demonstrated, the risks on the way to commercial deployment will decrease significantly and therefore investing for supporting this deployment will become much more attractive. Moreover the feedback from the demonstration will allow industry to be ready for such deployment and regulators to streamline licensing of subsequent commercial reactors.

Need for large cooperation and crosscutting activities

International cooperation can accelerate the deployment of high temperature nuclear cogeneration systems by defining a widely shared framework for licensing such systems, by sharing effort for obtaining the experimental results needed for supporting their safety demonstration and by giving access to the few large test facilities existing worldwide (large helium loops, irradiation reactors, etc.), which are needed for qualifying their components.

Moreover beyond a first deployment of nuclear cogeneration HTGR systems for applications below 600˚C using as much as possible proven technologies for minimizing the development time, there is a large potential for HTGR technology to address in the longer term a wider market of industrial process heat applications, in particular (but not only) hydrogen production and other applications beyond 600˚C up to the domain of very high temperatures (800-1000˚C). This will require the development of advanced materials and components (in particular heat exchangers), alternative heat carrying fluids, etc. that are often not specific to HTGR and can be shared with other nuclear and non-nuclear technology developments. Such developments have already been initiated in the international framework of the Generation IV International Forum (GIF).

Finally to get the maximum benefit of nuclear cogeneration, mutual adaptation of the nuclear heat source and industrial processes will be necessary, and this will be possible only through cooperation between nuclear and non-nuclear industrial R&D.

2. **The issue to tackle and objectives to reach**

Modular HTGR technology is a mature technology with a large historical background and present achievements (see section 3). So the competences and the required technical data exist (with a few limited gaps that will have to be addressed) to be able to design a HTGR, to manufacture its components, to build and operate it.

Moreover, in order to minimise the development time, the costs and risks, the first market targeted for initial deployment is the market of industrial sites, mainly in chemical industry, in which steam networks already exist, fed by fossil fuel fired cogeneration plants and / or boilers supplying the steam required by the industrial processes. In this kind of application, no adaptation of the nuclear plant and no modification of the steam network and of the processes are required by their coupling through the steam network. The nuclear plant is just "plugged-in" in the existing steam network in substitution to fossil fuel-fired plant(s) to supply the same quantity of steam at same temperature and pressure.

As nuclear vendors are ready to design and procure HTGRs, as on the other hand the first application target is already identified and finally, as no modification in the reactor or in the applications is expected due to their coupling, what is the challenge?

The challenge is to get a first experience of coupling of a nuclear reactor with high temperature industrial process heat applications. As already mentioned, apart from a few isolated low temperature industrial applications, there is no experience of such a coupling. So going from mere electricity generation to industrial heat supply is an actual revolution for nuclear energy, which, apart from limited R&D to bridge a few residual technology gaps, requires demonstration of

- Licensing feasibility of the coupling of a nuclear reactor with industrial processes,
- Economic competitiveness of HTGR in cogeneration of electricity and steam,
- Ability of the nuclear reactor to satisfy the needs of industrial end-users, in particular in terms of availability, reliability and flexibility.

To consider in particular the licensing feasibility, the very specific safety approach used for modular HTGR, which relies only on its intrinsic passive safety properties and not on the use of costly redundant active or passive engineered safety systems to keep the reactor in safe conditions in any circumstance, has been accepted by some countries, but is not universally recognised. A lot of progress has nevertheless been made through international initiatives (IAEA and GIF) for defining a licensing framework taking into account the specific safety features of modular HTGR and obtaining a large consensus on it, but the regulatory aspects of the coupling of the reactor with process heat applications have not been addressed yet. The licensing framework for modular HTGR should therefore be consolidated and should include this coupling.

A convincing demonstration of the industrial viability of nuclear cogeneration with HTGR cannot be obtained without a comprehensive actual experience including design, licensing construction and operation of a full-scale industrial prototype reactor for steam supply to a steam network.

Choosing for the first application the coupling with a steam network has the merit of minimising the development costs, risks and duration. It will allow providing in the relatively short-term an already significant contribution to the efforts to reduce CO_2 and other noxious emissions, in line with the milestones of COP21 climate objectives, and to provide to countries with low fossil fuel resources a mean to improve the security of their energy supply and the stability of their energy costs. Moreover further progress in HTGR technology, in coupling technologies and in processes themselves will enable, building on this first experience of "plug-in" HTGR cogeneration with steam supply to industrial steam networks, nuclear energy to access in a second longer term step a much larger segment of the industrial heat market, including applications in which heat production is integrated in the process itself, possibly but not exclusively at higher temperature. It is clear that such evolution will not only require progress in nuclear technology, but also in non-nuclear industrial technologies (heat transport and adaptation of industrial processes).

3. **What is done/exist already, who is doing what, what are the means (resources and infrastructures)**

Past programmes

Billions of dollars have been spent in Germany, in the US and in other countries to develop HTGR technology from the 1960s to the 1980s. Test reactors (DRAGON in the UK, Peach Bottom in the US, AVR in Germany) and industrial prototypes (Fort Saint Vrain in the US, THTR in Germany) have been built and operated. Close to the end of this period, a unique safety design has been imagined both in Germany and in the US with the modular concept, which is the basis of modern HTGR design. It enables introducing intrinsic safety in the reactor design, excluding severe core damage. Moreover, the substitution of complex and expensive added-on safety systems by the simple action of natural phenomena, the efficiency of which is inherent to the modular HTGR design, provided a very high safety level, as well as a strong economic asset for competitiveness. But at that time the intrinsic safety of the modular HTGR design was only demonstrated by analysis, with limited verifications by tests only on non-nuclear facilities. This safety concept did not raise any major objections from the German and American regulators, who reviewed preliminary safety analysis reports of the first modular designs (HTR-Module in Germany, MHTGR in the US). Performances and economic viability of the reactors have also been assessed by theoretical transposition of previous nuclear experience. At that time, no modular prototype has been built and operated to verify on an actual industrial experience the real licensing and economic viability of the concept.

A significant part of the experience feedback of these developments is still available in the archives of companies and research centres that have been involved, and large efforts have been made in particular in Euratom Framework Programmes to recover the information and to make it available.

More recently, in the 2000s, the development of modular reactors has been revived in several countries, with the construction and operation of the test reactors HTR-10 in China and HTTR in Japan, and with the design of several industrial prototypes, GT-MHR in the US and Russia, NGNP in the US, PBMR in South Africa, ANTARES in France, GTHTR 300 in Japan. The intrinsically safe behaviour of modular HTGR has been verified by safety tests reproducing real accident conditions in the test reactors HTR-10 and HTTR. International benchmarks have been organised by IAEA and NEA to assess the capability of appropriate nuclear computer codes to predict the behaviour of modular HTGRs in accident conditions.

Present developments

China is constructing an industrial pebble bed prototype based on the modular concept. Its commissioning is expected very soon and it will be the first industrial HTGR based on the modular concept to be operated in the world. It will be coupled with a turbo-generator to produce electricity.

Japan is planning the coupling of its test reactor HTTR, with a very high temperature hydrogen production pilot plant based on the S-I thermo-chemical water splitting process. Korea has also a HTGR programme focused on very high temperature applications.

In North America there are still some design developments (SC-HTGR, Xe-100, Starcore Nuclear,…).

In Europe, Poland officially announced in 2017 its intention to launch a national programme to develop HTGR technology for the supply of process steam to its industry. In the frame of Euraton H2020 programme, a new project, GEMINI+, started end of 2017, with the objective of defining the basis of a European cogeneration HTGR design to be proposed for demonstration in Poland. On the other hand, in UK, in the frame of a competition organised by the government to support Small Modular Reactor (SMR) development, among non-LWR designs, HTGR has been identified as the most promising system for medium-term industrial applications and vendors are presently funded in the frame of the UK AMR programme for planning the development of two HTGR concepts among other advanced systems.

A large range of designs is therefore available for developing high temperature nuclear cogeneration systems. Nevertheless, none of these designs has been used until now for a real demonstration of industrial nuclear cogeneration.

In addition many engineers and researchers are active or have recently been active in HTGR related activities and therefore a large expertise exists today in this area.

Finally most of the key technologies required for HTGR design and licensing are sufficiently mature to be used in industrial projects:

- ***Materials:*** The metallic materials that will be used for the initial demonstration of coupling with an industrial steam distribution network are well identified industrial materials, with already a large experience in nuclear energy and therefore they are included in appropriate sections of RCC-M and ASME codes. For graphite, the grades used in past projects are no more available, but large programmes have been undertaken in several countries to identify appropriate grades for HTGR applications and to qualify them. The results of these programmes are shared in the frame of GIF.
- ***Components and structures:*** The design bases of the key nuclear components (steam generator, circulator, valves, vessel, internals, etc.) have been developed in the past and there is no incentive for major change for the first demonstration using secondary steam cycle, with a core outlet temperature limited to 750˚C. Such components have been fabricated in the past, but the present manufacturing feasibility should be checked carefully for some components with very specific manufacturing know-how (e.g. helical bundle of the steam generator). Maybe some effort of reappropriation of manufacturing technologies should be planned.
- ***The HTGR fuel***, based on TRISO coated particles, which is specific to this kind of reactor, has been developed up to a high quality level in the past German programme. More recently, relying on the German achievements, high quality TRISO fuel has been produced again in

Japan, South Africa, France and China. In the US, the very systematic AGR programme allowed understanding and mastering the parameters that are drivers of fuel manufacturing quality and determine the fuel performance in normal operation and accident conditions. An industrial pilot plant producing high quality fuel on the basis of the results obtained in this programme is operational and the fuel supplied by this plant has been the object of extensive qualification through AGR irradiation campaigns and heat-up tests for accidental behaviour. The whole US fuel programme represents 10 years of efforts, and benefiting from its results for the demonstration programme will allow shortcutting long and hazardous developments. Similar high quality fuel is also produced in China in an industrial facility that delivers the fuel for the two HTR-PM prototype reactors.

- ***Modelling:*** Most of the computer tools necessary for design and licensing of HTGR are available, though a V&V effort should still be needed for some of them. The most noteworthy exception concerns the codes for source term transport calculation, for which discrepancies between calculations and experimental results are important, while large scattering between different experimental results is not even understood. Nevertheless the extremely low fission product releases of HTGR TRISO fuel allows coping with such uncertainties for demonstrating that the reactor complies with regulatory dose limits.
- ***Experimental facilities:***
  - Essential infrastructures for carrying out an HTGR project are large helium loops able to reproduce HTGR thermo-fluid dynamical and chemical conditions needed for qualifying the reactor components. After dismantling of the large helium loops operated in the past in Germany and in Japan, similar facilities have been built in China and in South Africa, but are no more active.
  - The irradiation rigs and safety heat-up test benches used for qualification of the HTGR fuel are also key facilities. For the time being, irradiations with on-line fission gas monitoring can be performed in the reactors HFR in Petten (Netherlands) and ATR in INL (USA) and heat-up tests at JRC Karlsruhe (Germany) and INL.

<u>Longer-term prospects</u>

Critical issues for VHTR feasibility are very high temperature materials and the design of the heat exchangers extracting heat from the primary gas circuit of the reactor:

- Many research programmes have been performed in different countries (US, France, Japan, Korea…) to select materials with mechanical and corrosion performances compatible with very high temperature operation (nickel base alloys, ODS, ceramics, composites), but there is still a lot of work to do for qualification of the most appropriate ones for VHTR application.
- Designing a heat exchanger with good heat exchange performance, acceptable mechanical properties in VHTR conditions and with sufficient compactness for economic viability is a challenge. Investigations performed until now on different designs (in particular compact plate designs) allowed selecting some promising options. Nevertheless, a lot of work is still needed for optimising and qualifying a design for VHTR operation. Moreover, for such a heat exchanger made from very high temperature materials, cost effective manufacturing techniques (assembling, forming, machining) have still to be developed, though some exploratory investigations have already been performed.

In the area of VHTR technologies, one of the most advanced achievements obtained until now is the continuous operation of HTTR at 950˚C during 50 days, thanks to the use, for the highest temperature components of a high performance nickel base alloy, Hastelloy XR.

Beyond technical achievements, the setting up of stable international partnerships is an asset for future developments:

- In the frame of the ***Generation IV International Forum (GIF)***, there is a VHTR Steering Committee and several Project Management Boards dedicated to different technical issues (materials, fuel, hydrogen production and computer code V&V), which are the basis for exchange of R&D results.
- In Europe, a partnership for the development of HTGR technologies has existed since the beginning of the 2000s', first called ***HTR Technology Network (HTR-TN)***, now more focused on heat applications of nuclear energy, thus renamed ***Nuclear Cogeneration Industrial Initiative (NC2I)***: a significant number of industrial and research organisations, as well as higher education institutes participated in this partnership and have organised in a concerted way answers to Euratom calls, getting funding for many HTR related research projects (HTR-N, HTR-L, HTR-M, HTR-E, HTR-C, RAPHAEL, PUMA, CARBOWASTE, EUROPAIRS, NC2I-R and now GEMINI+).
- In the US, a similar organisation exists grouping industry and research organisations, the ***NGNP industry Alliance (NIA)***, meant initially at supporting the NGNP project of DOE, now endeavouring to promote the industrial deployment of HTGR.
- Recently NC2I and NIA decided to coordinate their actions for promoting and supporting the industrial deployment of HTGR for cogeneration under the ***GEMINI initiative***, soon joined by JAEA (Japan) and KAERI (Korea), transforming GEMINI into the ***PRIME project***. The first joint action of PRIME partners has been to submit together the GEMINI+ project proposal. Now PRIME partners are working together to implement the project.
- Last but not least, the action of IAEA for promoting HTGR and its applications through multiple international Coordinated Research Programmes should also be underlined.

4. **What can be done to improve/accelerate, ia through cooperation**

The main action presently initiated for developing industrial cogeneration with HTGR is the Polish programme and the initiatives around this programme taken by NC2I and PRIME to support it.

The development of the demonstration of nuclear cogeneration will be undertaken under an industrial organisation still to be built, including the participation of international partners. Though there are, in such a project, industrial stakes and intellectual property issues that cannot be opened to a large sharing in an international R&D framework, it does prevent the project to be proposed as the reference project for defining R&D needs, adjusting the boundary conditions of R&D actions and their schedule.

There are already many useful data for the demonstration project coming from the existing international cooperation frameworks described in section 3. But until now international cooperation addresses mainly base scientific data and there are 3 R&D areas closer to application, though still pre-competitive, that are not or insufficiently covered, as well as, in addition, a long-term mission of knowledge management:

- Safety and licensing, with two types of actions:
    - The development of an internationally accepted licensing framework that can
        - Take into account the specific safety approach used for modular HTGRs, based on their passive intrinsic safety features.
        - Address the coupling of the reactor with industrial processes using the heat supplied by the reactor.
    - Support of the safety demonstration by producing some still missing experimental data.
- Creating a network of pre-existing large test facilities (in particular, but not exclusively test reactors such as HTTR in Japan, large helium test loops and specific irradiation facilities) that are necessary for addressing R&D and qualification needs both for the first nuclear cogeneration systems and for longer-term developments, and possibly complementing, if necessary, existing ones by new ones created in the frame of international cooperation.
- Making cooperative programmes on these facilities for performing qualification tests required by the demonstration programme and for addressing development and licensing needs.
- Addressing the integration of the nuclear system in its industrial environment (industrial process heat applications, heat storage and connection to the electric grid, including grid services that high temperature nuclear cogeneration systems can provide thanks to their high thermal inertia) for short-term plug-in applications, as well as for longer-term applications with possibly heat transport at very high temperature.
- In addition to these 3 R&D areas, considering that the deployment of a new generation of nuclear cogeneration plants, as well as the longer-term developments to extend the domain of applications, will last several decades, it is necessary to secure the conservation of the existing knowledge and its transmission to the young generation, thus avoiding in the future the loss of competences presently affecting nuclear industry.

5. **Plan of Actions and necessary means (resources and infrastructures)**

The R&D programme to be elaborated in support of industrial demonstration of high temperature nuclear cogeneration has a real meaning only if its results are produced in due time for the demonstration programme in all its phases of design and licensing, procurement, construction and operation. The timing proposed in the high level schedule of figure 3 is aligned with the Polish demonstration programme.

Safety and licensing

- The first objective is to develop of an **international licensing framework**, which will facilitate the deployment of systems based on same designs worldwide, minimizing adaptations to local regulations that are usually heavily penalising competitiveness of nuclear energy: considering that extensive generic work has already been performed in different contexts (in particular in GIF, IAEA and in Euratom projects), the proposed scope of work should include
    - An assessment of existing licensing experiences of modular HTGR (MHTGR, HTR-Module, HTR-10, HTTR, HTR-PM) and of experiences of nuclear heat supply at low

temperature (already at least partially addressed in the Euratom project NC2I-R) to analyse the lessons learnt from these experiences,

  - The development of a large international consensus in dialogue with regulators through IAEA, MDEP, WENRA… not only including the consideration of specific intrinsic safety features of modular HTGRs, but also the particular issues related to their coupling with industrial process heat applications,
  - The testing of the licensing framework that will be developed on the design proposed for demonstration, to assess its robustness.

- Then international cooperation can very usefully **support the safety demonstration** of HTGR cogeneration plants by providing scientific and technical data still missing in some areas, for instance (but not exclusively):
  - Complementing existing data for computer code V&V whenever these data are still insufficient (e.g. the NEA LOFC project testing the behaviour of HTTR in accident conditions could be a very valuable contribution for validation of computer codes used for HTGR safety analysis),
  - Developing and qualifying the modelling of the source term transport: the radioactive releases from the fuel are very small and well characterized, but they accumulate in graphite structures and plate out on different parts of the primary circuit. Then they can be remobilized and transported outside the plant in case of an accident. Though for the first applications at moderately high temperature, the radioactive releases of the core are small enough to use a very conservative approach enveloping uncertainties in fission product transport phenomena, an improved understanding and modelling of the plate-out and lift-off behaviour of fission products in HTGR structures would facilitate licensing especially for longer-term applications at higher temperatures.
  - Developing appropriate instrumentation, to maximise the benefit of demonstration: past HTGR instrumentation was limited, due to the harsh operating conditions of this type of nuclear system. Therefore it is desirable to take advantage of recent progress in instrumentation technology, including high temperature instrumentation, to get more information from the demonstration plant, in order to optimise the operational margins and performances of future commercial plants and to facilitate their licensing.
  - Developing modern methods for graphite internals design (seismic behaviour, thermal-hydraulics, etc.).
  - Defining solutions for the decommissioning of HTGR and for management and final disposal of specific HTGR waste (fuel and graphite) and producing data for justifying the acceptability of these solutions: the deployment of a new type of nuclear system at large scale can only take place if a credible waste management and possibly recycling strategy for fuel and reactor materials, in particular graphite, are devised. While some trailblazing R&D on specific HTGR waste had already been performed in Europe (in RAPHAEL and CARBOWASTE projects), the selection and industrial qualification of processes for decommissioning HTGR and managing its waste must still be achieved.

- Thorium, as a nuclear fertile material for a future HTGR system, is one of promising options to meet Generation IV requirements for sustainability and economy. Thorium-fuelled HTGR minimizes radioactive waste by reducing plutonium and minor actinides production. Self-sustainable advanced thorium cycle can be revisited in the long-term R&D programme.

The order of magnitude of funding for activities in support of safety and licensing should be about hundred million dollars. It would require continuity of funding for at least one decade, in particular for studies on waste disposal behaviour, which need quite lengthy tests.

Large Test Facilities

The main large test facilities for HTGR development are, on the one hand experimental reactors and, on the other hand, large helium loops able to reproduce physical and chemical operating conditions in the primary system of the reactor.

Reactors

Two types of reactors are necessary: irradiation reactors and high temperature test reactors. Irradiation reactors are needed for the qualification of materials and of fuel. For this purpose, test rigs, in which high temperature conditions are maintained, are introduced in the reactor. For fuel qualification these test rigs are particularly sophisticated, as they do not have only to maintain representative high temperature test conditions, but also to enable on-line monitoring of fission gas releases. There is a very specialised know-how related to the design and the operation of such facilities.

Significant irradiation programmes have been performed in the last 20 years for materials needed in modern HTGR. So these materials are selected and most – if not all data – needed for their qualification are available. The experimental basis for fuel qualification is also available for the fuel produced in the very few production lines existing worldwide (China, US), which will likely be sufficient for the demonstration programme (possibly increasing their production capacity). All this will be sufficient for licensing the first generation of nuclear high temperature cogeneration systems. Therefore it cannot be expected that any additional irradiation will be required in the short-term, but irradiations will be necessary later for qualifying the fuel of new production facilities needed for fuelling the commercial deployment of HTGR cogeneration plant and for developing and qualifying new materials and fuel for higher operating temperatures. This raises the issue of maintaining the know-how of the techniques used for material and fuel irradiations, which, if lost, would require a long development time (see below "knowledge management").

Complementing irradiation, heat-up tests are part of fuel qualification, and the very specific know-how needed for these tests, presently existing in JRC Karlsruhe and in INL, should be equally maintained.

On the other hand there are only few irradiation reactors worldwide, especially reactors that can accept fuel irradiation, and these reactors are usually aged and relatively close to decommissioning. Planning for their renewal is vital for being able to achieve NI2050 objectives. The needs for irradiation of HTGR and VHTR materials and fuel should be taken into account in the specifications of new irradiation reactors.

There are presently only two operational high temperature test reactors in the world, HTR-10 (pebble bed core) in China and HTTR (block type core) in Japan. They are particularly useful for the safety demonstration of modular HTGRs and several safety tests have been undertaken on each of these reactors, as already mentioned above. Maybe additional tests could be desirable (to be identified). In the case of HTTR, additional very useful contributions to NI2050 can be envisaged, due to the fact that it can be operated at very high temperature and to the fact that a coupling with a very high temperature thermo-chemical unit of hydrogen production is planned:

- Demonstration of very high temperature operation can be beneficial for long-term evolution of HTGR industrial cogeneration and HTTR can be a test bench for providing data on equipment and materials behaviour at very high temperature in representative conditions,
- The feedback from the experience of a real coupling with an industrial process heat application can be beneficial for the preparation of the Polish demonstration programme.

So an international contribution to the future HTTR programme through NI 2050, in particular for hydrogen production, is strongly recommended. But HTTR is presently stopped for the licensing review required after Fukushima accident. A restarting of HTTR is highly desirable.

Helium loops

Even using past qualified designs, performance and safety behaviour of components, as fabricated presently, should be verified in helium loops providing HTGR representative conditions (steady state and transient temperature, pressure and flow rate conditions, as well as chemical environment (helium with impurities)), all the more since optimisation of 30 to 40 years old component designs will likely be considered, requiring a renewed qualification.

A few helium loops have been constructed recently but their present operability and accessibility for international programmes should be clarified: a test loop has been used in China for qualification of HTR-PM components, another one has been erected in South Africa, in the frame of the PBMR project. Could these loops, if still operable and accessible, provide appropriate conditions for the needs of the demonstration programme? This should be investigated. Otherwise, the development of a new loop of 10 to 20 MW, which would be required for qualification needs, represents an expense of $100M to 200M. It should be noted that a smaller loop, SUSEN, which could be useful for preliminary tests, is in development in the Czech Republic.

<u>Integration of Cogeneration HTGR in their industrial environment</u>

- Even if, for the first process heat applications, the coupling of the nuclear reactor with industrial processes is envisaged through simple “plug-in” of the reactor systems on existing steam networks, additional benefits could be drawn from the integration of such nuclear systems in their global industrial environment: an HTGR operating in nuclear cogeneration mode has the advantage, compared to other types of nuclear power plants, that it can perform load following by dynamically switching between heat and power production, while operating at full capacity. Moreover high thermal inertia is another asset of this type of nuclear system, especially when operated in cogeneration mode, thermally coupled with a heat distribution network and industrial processes, which increase this inertia. These features are particularly advantageous when an increasing share of intermittent renewables in the energy mix requires more flexibility for avoiding instabilities of the grid. ***Hybrid Energy Systems (HES)***, which are combinations of energy production sources using different technologies (nuclear including HTGR cogeneration systems, conventional thermal plants, renewables) and, if required, additional heat storage capacities, can be a solution to adapt easily the production of energy (both electricity and heat) to the load demand. Cogeneration of electricity and hydrogen with HTGR can also be a way to store energy. The technical and economic viability of these approaches will need to be demonstrated and could be included as an objective in the demonstration project.

- In the longer term, ***extending the nuclear process heat market to a larger scope of industrial applications*** will necessitate additional technology developments, which will require close cooperation with process heat users' industries, as they do not only imply progress in nuclear technology, but also significant evolutions of industrial processes:
    - Whether at higher temperature or even in the temperature range considered for the first demonstration, there are many industrial processes that are not coupled with a steam network, the heat generation being closely integrated in the process itself. Bringing heat to the processes through convective heat transfer from a hot fluid will likely require adaptation of the processes themselves and of the components that shelter these processes.
    - The development of very high temperature reactors is rather challenging, but a possible alternative, could be to modify processes, to operate them at a lower temperature adapted to the use of present reactor technology. An example of such evolution is the recent development of a membrane process for steam-methane reforming, which allows obtaining a sufficient efficiency in hydrogen production in the range 600-650˚C instead of 850-900˚C in the present industrial process.
    - When the supply of heat at a temperature above 600˚C is needed, no efficient industrial heat transport technology is available on distances from a few hundred meters to a few kilometres. The development of such technologies includes the search for appropriate heat carrier fluids, for materials compatible with these fluids and for appropriate components of the heat transport system. Alternative solutions, in particular the Adam and Eve process that has been developed in Germany, which allows carrying only cold fluids, should also be investigated.

Knowledge management

The experience of past HTGR developments shows the difficulty of keeping the detailed know-how and experience on long periods of time, as well as the consequences that losses of precise information can have on the duration and cost of new developments.

A systematic effort of knowledge conservation and transmission to young generation should therefore be undertaken, as the final target for the developments considered in NI2050 is more than 30 years ahead. This effort can take different forms:

- Development of databases and document repositories organised in such a way that the information can be retrieved easily not only by experts involved in the creation of the information, but by newcomers in the technology.
- Formalisation of informal know-how, which has often no other repository than expert memory or, for fabrication, specialised workers' manual skills, by at least interviews of those who are depositaries of the know-how, or even by launching R&D to understand the scientific bases of practical skills (a good example is what has been done for fuel fabrication in the US: the domain of parameters that guarantee good fuel quality has been systematically explored,

while previous fabrication developments stuck to blind reproduction of the process first developed in Germany).

- Organisation of R&D programmes not necessarily immediately required for industrial deployment, but needed for keeping key competences that will be necessary for longer-term applications (see the above mentioned example in the area of fuel qualification).
- Finally organising systematically the training of the young generation, encouraging ageing experts to devote time for this mission, immersing PhD students in existing R&D projects…

Top priority actions to be started as soon as possible

- Developing a licensing framework addressing not only the nuclear reactor, but also its coupling with process heat applications,
- Identifying possible R&D actions required for supporting the safety case of the demonstration plant by producing still missing data and defining a plan for implementing them,
- Developing advanced high temperature instrumentation for implementation in the demonstration plant,
- Developing solutions for HTGR decommissioning and specific waste management,
- Developing an international network of test facilities accessible to the demonstration programme for its qualification needs,
- Initiating cooperation with process heat user industries to develop favourable technical and non-technical conditions for the deployment of nuclear cogeneration in these industries,
- Developing a plan for knowledge management and training for supporting the demonstration project and keeping the knowledge for longer-term developments.

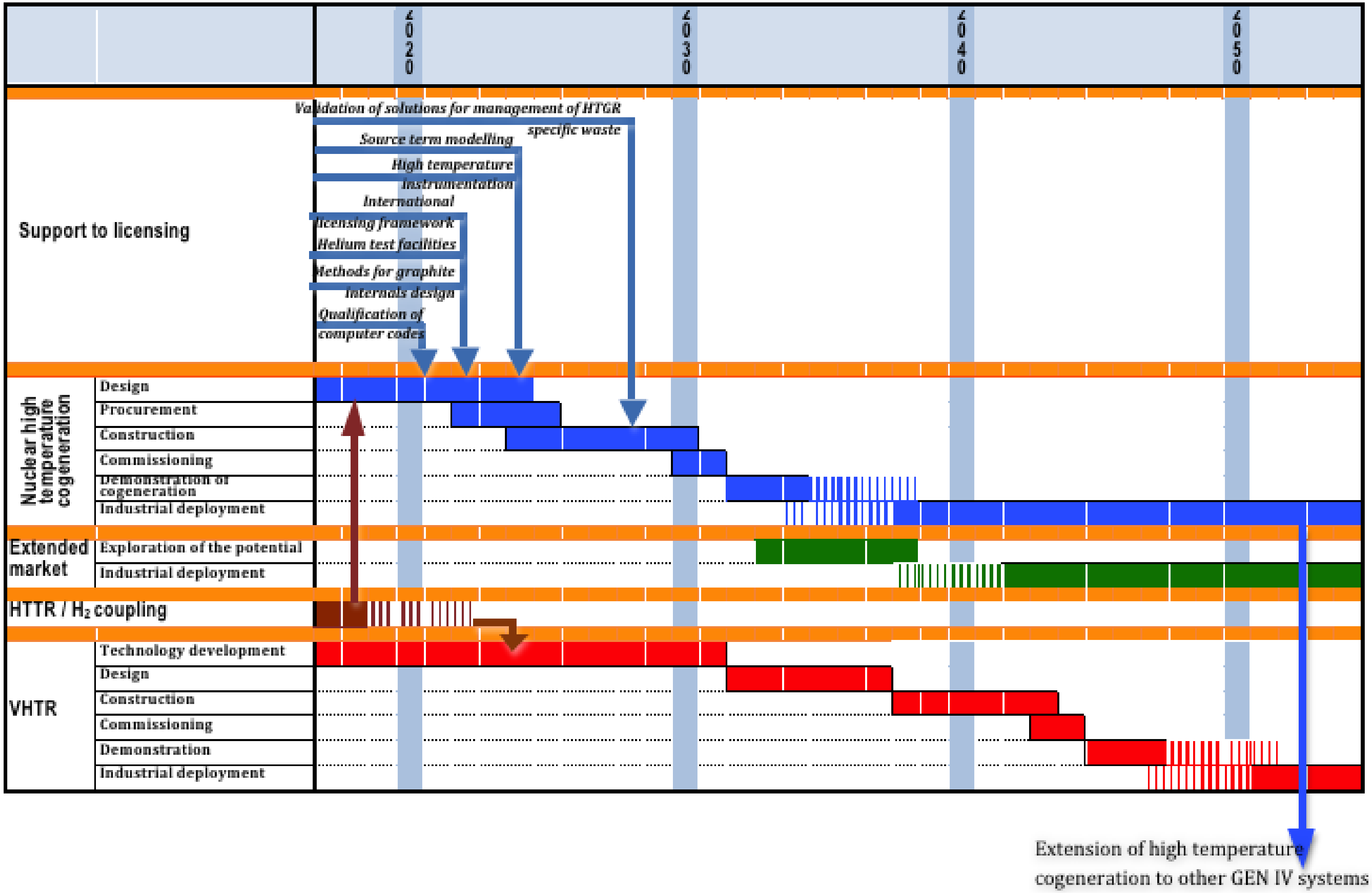

Figure 3: High level schedule for the development of high temperature nuclear cogeneration