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RAPHAEL: The European Union's (Very) High Temperature Reactor Technology Project

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***Abstract** – Since the late 1990, the European Union (EU) was conducting work on High Temperature Reactors (HTR) confirming their high potential in terms of safety (inherent safety features), environmental impact (robust fuel with no significant radioactive release), sustainability (high efficiency, potential suitability for various fuel cycles), and economics (simplifications arising from safety features). In April 2005, the EU Commission has started a new 4-year Integrated Project on Very High Temperature Reactors (RAPHAEL: ReActor for Process Heat And ELectricity) as part of its 6th Framework Programme. The European Commission and the 33 partners from industry, R&D organizations and academia finance the project together.*

After the successful performance of earlier HTR-related EU projects which included the recovery of some earlier German experience and the re-establishment of strategically important R&D capabilities in Europe, RAPHAEL focuses now on key technologies required for an industrial VHTR deployment, both specific to very high temperature and generic to all types of modular HTR with emphasis on combined process heat and electricity generation. Advanced technologies are explored in order to meet the performance challenges required for a VHTR (900-1000°C, up to 200 GWd/tHM).

To facilitate the planned sharing of significant parts of RAPHAEL results with the signatories of the Generation IV International Forum (GIF) VHTR projects, RAPHAEL is structured in a similar way as the corresponding GIF VHTR projects.

I. INTRODUCTION AND OBJECTIVES

In the context of worldwide depletion of fossil fuel resources, uncertainties of supply, and CO_2 reduction objectives, Europe invests into R&D to ensure the viability of nuclear fission as a future energy option. Continuing the work initiated by several smaller EU-supported projects since 1998, the European High Temperature Reactor Technology Network (HTR-TN) has proposed the RAPHAEL Integrated Project and put together a consortium of 33 partners from 10 European countries for its execution. With a budget of 19 M€ (including 9 M€ from the EU Commission) and a duration of 4 years, RAPHAEL addresses the viability and performance issues of an innovative system for the next generation of power plants, the Very High Temperature Reactor (VHTR), which shall supply both electricity and process heat.

At present, nuclear fission produces almost exclusively electricity, which, however, accounts for only a fraction of the energy consumed worldwide (cf. Fig. 1). To reduce the dependence on fossil fuel supply, future nuclear systems will need to generate both electricity and process heat, e.g. for the production of secondary energy carriers like hydrogen or synthetic hydrocarbon fuel. RAPHAEL addresses heat and power applications in consistence with the objectives of sustainability and safety of next generation power plants and goes beyond the characteristics of current HTR reactor designs with pebble bed cores, e.g. HTR-Modul, HTR-10 and PMBR.

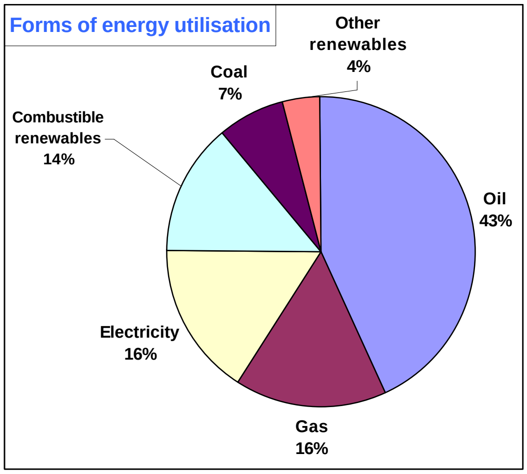

Figure 1. Forms of energy utilization worldwide

Because it produces heat at very high temperature using a smaller reactor with a very robust safety concept, the VHTR system addressed in RAPHAEL enables a wider range of competitive applications than conventional light water reactors. These applications include small to medium-sized electricity production or process heat generation e.g. for CO_2-free hydrogen production, for chemical processes (oil refining, fertilizers etc.), and the use of waste heat for lower temperature applications such as desalination or district heating. The VHTR also features inherent safety, waste minimization approaches, fuel cycle flexibility and cost effectiveness – all key assets regarding public acceptance of nuclear fission and its positive impact on the economy, the environment, and the security of energy supply in Europe and elsewhere.

Finally, the development of such a power plant is expected to create spin-offs in areas such as high performance materials and components with benefits to other industry sectors.

II. PROJECT STRUCTURE

As significant parts of RAPHAEL may be shared with the signatories of the GIF VHTR projects, RAPHAEL is structured into 8 sub-projects in a similar way as the corresponding GIF VHTR projects.

1. **Material Development:** Based on results from the earlier EU projects HTR-M and HTR-M1, the objective is to test and select candidate materials for the un-cooled pressure vessel, graphite internals, and parts in highest temperature conditions. The modeling of properties and the set-up of design code procedures for new materials are tackled. More specifically, for the reactor vessel creep tests on irradiated mod. 9Cr1Mo steel at high temperature are performed as well as non-irradiated creep and other tests on large-scale and welded specimens. Carbon composites for control rods and other reactor internals as well as advanced materials for heat exchangers are tested. The irradiation behavior data of graphites will be completed to full fluence levels and for a wider temperature range, accompanied by the development of microscopic models for the prediction of property changes under irradiation. Finally, guidelines and procedures for design codes are proposed covering graphite, carbon base materials and advanced alloys.

2. **Component Development:** Following the earlier HTR-E project, innovative technologies for the main components are being developed, taking into account requirements for competitiveness, safety and acceptability. This concerns in particular the intermediate heat exchanger, which shall enable both safe high-efficiency power conversion and process heat applications. Issues are thermo-mechanical resistance, lifetime, maintenance, and behavior in case of failure. Work focuses on indirect cycle applications with conceptual designs of critical key components as the target such as heat exchangers and gas circulators. Tribology and corrosion phenomena between graphite and metals as well as between graphites and other ceramics are under investigation.

3. **Fuel Technology:** Based on the results of the EU projects HTR-F and HTR-F1 the objective is to produce sound TRISO coated particle fuel capable of withstanding VHTR requirements (burn-up > 160,000 MWd/tHM, coolant temperature 900—1000°C,). The R&D thus focuses on the understanding of failure mechanisms and on determining the limits of state-of-the-art fuel, as well as on potential further performance improvements. Experiments comprise fuel tests up to very high temperature and burn-up including modeling, safety tests to qualify the fuel in accidental conditions, fabrication of advanced fuel with potentially higher performance, and behavior of irradiated fuel in representative disposal conditions.

4. **Core Physics:** Pursuing earlier work within the EU projects HTR-N and HTR-N1, the general objective is the code validation for reactor physics and safety analysis in view of licensing through comparison with experimental data for both pebble bed and prismatic block type designs. This comprises modeling of hot

full power conditions, transients and high burn-ups against experimental data from the AVR reactor, from the isotopic analysis of pebbles irradiated to very high burn-up in the HFR Petten in the frame of a previous EU project, and, if possible, from HTR-10 as foreseen in a cooperation agreement between INET and HTR-TN from 2001.

5. **Back-end of the Fuel Cycle:** Preliminary tests performed in earlier EU projects will be completed and confirmed. The barrier functions of coated particles embedded in a graphite matrix or in other back-fill materials will be tested, and advanced coatings (ZrC) and alternative kernels (UCO) will be studied. Failure mechanisms will be identified and the geochemical modeling will be improved.

6. **Safety:** Previous work in the HTR-L project will be pursued owing to the obviously strong impact of safety requirements on reactor design. A safety approach accepted by Safety Authorities is under elaboration taking due account of existing licensing frameworks, and the required analytical tools are being qualified for various cases including direct/indirect power conversion, U or Pu fuel, combined heat and power generation, and hydrogen production. The applicability of existing system codes will then be extended and adapted in the fields of CFD and component modeling including in transients. Extensive long-term validation efforts and benchmarking exercises have started. The knowledge on radioactivity source terms and transport will be refined in view of later detailed modeling and code development of chronic and accidental radioactive release. This will be done through the analysis of past operating experience and experimental results, and by performing dedicated tests. An air ingress event experiment is under preparation to better understand and quantify the involved phenomena.

7. **System Integration:** Preliminary feasibility assessments of VHTR plants coupled to hydrogen production processes are being performed. For this purpose, reference concepts and performance data for such a plant will be provided in a first step by industrial partners who are involved in industrial prototype development. The capability of current prismatic block and pebble bed designs to deal with the specified operating conditions will be investigated and potential design improvements and R&D needs will be identified. The continuous integration of technical findings from other sub-projects will enable trade studies of selected reference plant concepts.

8. **Project Management:** This sub-project supports the coordinator and covers classical project and quality management tasks, the administrative and financial management as well as public relations. These activities are key to the success of the project, its visibility and appreciation by the public and cornerstone for any future strategy. Together with the coordination of training and education activities within the other sub-projects, (e.g. in the form of so-called Eurocourses, topical workshops) this sub-project shall foster understanding of the growing needs for nuclear power in general and for the technology of the VHTR in particular.
   The overall coordination is performed by AREVA. Day-to-day business is dealt with at the *Executive Board* level that also proposes decisions to the *Steering Committee*. The main orientations of RAPHAEL are reviewed, discussed and decided by the *Steering Committee* members from all 33 participating partners. The organization chart of RAPHAEL is shown in Fig. 2.
   The project is setting up two Advisory Groups to ensure the relevance of the performed work. One is the *Industrial Users Advisory Group* comprising several high level executives from major potential users of this reactor type, ranging from utilities to chemical industry. This group shall advise on the project strategy and main technological orientations. The other is the *Safety Advisory Group*, comprising the IAEA and representatives of European and extra-European Safety Authorities. This group shall review in particular the safety approach addressed in the project in view of future licensing.

III. INTERFACES WITH OTHER EU PROJECTS

RAPHAEL together with additional national contributions to this technology develops tight links with related EU projects to maximize synergies. The well-established European High Temperature Reactor Technology Network HTR-TN serves as the platform for the coordination of the various projects.

Crossed specifications, regular interface meetings, balanced exchanges of results, and joint participation of several partners are key to mutual benefit with the following projects:

Materials: contributing with ExtreMAT to the development of advanced materials under extreme conditions.

Hydrogen production: cooperation with HYTHEC (HYdrogen THErmochemical Cycles) towards the coupling of a VHTR with high temperature hydrogen production process.

Gas-Cooled Fast Reactor: developing synergies with GCFR in the development of materials, components and fuel with this other GIF concept.

Two other projects on waste management including graphite and fuel were proposed and, if approved, will generate further synergies.

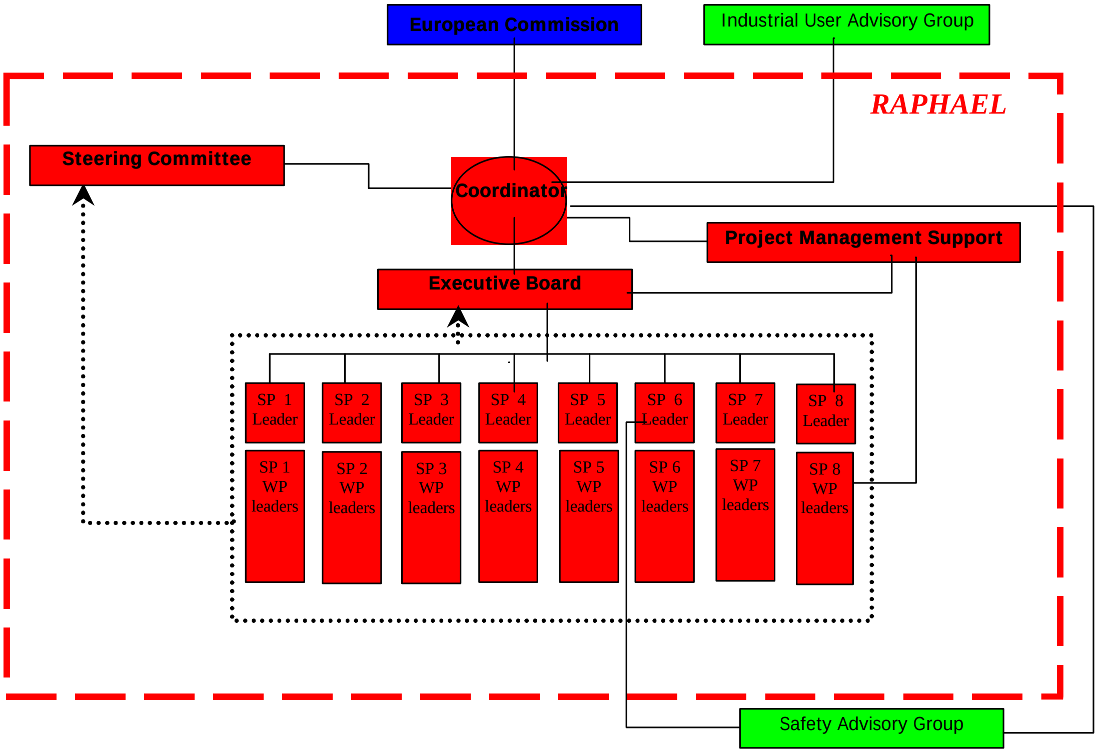

Figure 2. RAPHAEL organization chart

IV. INTERNATIONAL COOPERATION

Significant parts of the RAPHAEL project are proposed as EURATOM contributions to the Generation IV International Forum (GIF) projects on VHTR for which the contractual terms are currently being discussed.

Cooperation with Russia is organized via the International Science & Technology Center (ISTC).

Cooperation with the OECD's Nuclear Energy Agency (NEA) has started, as well as participation in related IAEA benchmarks.

V. PROJECT CONSORTIUM

The RAPHAEL consortium is characterized by its wealth in diverse and complementary expertise. Within the consortium, 20 of the organizations had already participated in the 9 earlier related EU projects and most of them since 2000 in the European HTR Technology Network (HTR-TN). Seven other partners not previously involved in EU projects have joined HTR-TN and begun to participate informally. Their involvement in RAPHAEL corroborates the thriving interest in this type of technology in Europe and helped the related projects gain further momentum.

The consortium unites diverse and complementary expertise:

- Nuclear engineering companies such as Ansaldo Nucleare (Italy), Empresarios Agrupados (Spain), NNC (UK), Serco Assurance (UK) and VUJE (Slovakia) together with the two world leaders in the field, BNFL and AREVA Framatome-ANP, provide their experience in design and licensing, necessary for focusing the R&D on the actual needs of industrial applications, for assessing the R&D results, and for establishing an accepted safety approach.
- Leading companies in the fuel cycle, COGEMA, BNFL, AREVA Framatome-ANP (world leader in nuclear fuel manufacturing) as well as Belgonucléaire (with experience in manufacturing HTR fuel) join their know-how in fuel design, fabrication and fuel cycle technologies.
- The European utilities EdF and Tractebel, provide their experience in operating nuclear reactors and focus RAPHAEL on utility requirements.
- Most of the European nuclear research organizations feature long-standing expertise in various

technologies: CEA (France) which together with AREVA Framatome-ANP and EdF performs the largest national HTR/VHTR R&D in Europe, FZJ (Germany), NRG (The Netherlands), PSI (Switzerland), SCK-CEN (Belgium), VTT (Finland), NRI Rež (Czech Republic) and the European Commission's Joint Research Centre (JRC) provide their research capabilities and strategically essential test facilities such as material test reactors, hot laboratories or test loops.

- Six universities and engineering schools are based in different countries: Delft University of Technology (The Netherlands), École des Mines de Nantes (France), University of Stuttgart and the University of Applied Sciences Zittau-Görlitz (Germany), University of Pisa (Italy), and the University of Manchester (UK) provide RAPHAEL with highly specialized technology contributions, a fundamental science basis, and ensure the lion's part of education and training.
- An independent consulting company, STEP (France) contributes its know-how in international project management.

Most of the partners are providing unique and specific contributions:

- FZJ and AREVA Framatome-ANP offer their huge experience of several decades of HTR development in Germany and can therefore additionally advise on the use of resources and time, and against embarking on unnecessary R&D.
- AVR GmbH, the company that ran the AVR test reactor in Jülich, is now involved in its decommissioning and adds 21 years of AVR operating experience to the consortium.
- NNC supplies the large experience of design, materials, licensing and operation of the British gas-cooled graphite moderated reactors.
- The European Commission's Joint Research Centre makes available unique hot cell equipment and irradiation facilities for fuel and materials through the HFR Petten, which since the 1970s played a key role in the German HTR fuel qualification program.
- Two out of four major worldwide graphite manufacturers, SGL and UCAR/GrafTech, which were already actively involved in the identification of suitable graphite grades in earlier EU projects, provide an essential added value in a strategically important area.
- The unparalleled experience of AREVA Framatome-ANP, as the leading manufacturer of large nuclear components worldwide, is essential for a reactor requiring very large and thick reactor vessels.
- Specialized industrial partners invest their unique competence for key components: Jeumont, a subsidiary of AREVA Framatome-ANP, manufacturer of the coolant pumps of French PWRs, design gas circulators, and Société de Mécanique Magnétique (S2M), an SME, is a world leader in the field of magnetic bearings.
- Specialized research institutes grant top level expertise: the Institut Européen des Membranes (IEM), involved in the development of sophisticated membranes, develops innovative methods for helium purification; the Von Karmann Institute, in turn, performs the thermo-fluid dynamic design of the gas circulator.

In conclusion, the consortium is not only capable of leading RAPHAEL to its ambitious goals, it also has the full potential of developing an HTR/VHTR to industrial maturity in the future.

VI. CONCLUSION AND OUTLOOK

RAPHAEL is the European project for the development of very/high temperature gas-cooled reactor technology and is well embedded in a network of related R&D and industrial projects, e.g. French AREVA's ANTARES project and contributions to the South African PBMR.

While strong international cooperation is explicitly encouraged and carried through within international and bi-lateral cooperation, RAPHAEL also maintains and builds European leadership in selected areas of technology.

RAPHAEL is the stepstone project for a VHTR demonstrator. Whether this will be a purely European machine or not, its development implies a change in scale of the effort that industry is unlikely to achieve without a major synergetic approach supported by the EU. The 7th EU Framework Programme (2007-2013) is expected to see the design of this demonstrator, with the perspective of commercialization of first VHTRs around 2025.

Further information can be retrieved on http://www.raphael-project.org.

ACKNOWLEDGEMENT

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