POTENTIAL APPLICATIONS FOR NUCLEAR ENERGY BESIDES ELECTRICITY GENERATION: A GLOBAL PERSPECTIVE

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Energy supply is increasingly showing up as a major issue for electricity supply, transportation, settlement, and process heat industrial supply including hydrogen production. Nuclear power is part of the solution. For electricity supply, as exemplified in Finland and France, the EPR brings an immediate answer; HTR could bring another solution in some specific cases. For other supply, mostly heat, the HTR brings a solution inaccessible to conventional nuclear power plants for very high or even high temperature. As fossil fuels costs increase and efforts to avoid generation of Greenhouse gases are implemented, a market for nuclear generated process heat will be developed. Following active developments in the 80's, HTR have been put on the back burner up to 5 years ago. Light water reactors are widely dominating the nuclear production field today. However, interest in the HTR technology was renewed in the past few years. Several commercial projects are actively promoted, most of them aiming at electricity production. ANTARES is today AREVA's response to the cogeneration market. It distinguishes itself from other concepts with its indirect cycle design powering a combined cycle power plant. Several reasons support this design choice, one of the most important of which is the design flexibility to adapt readily to combined heat and power applications. From the start, AREVA made the choice of such flexibility with the belief that the HTR market is not so much in competition with LWR in the sole electricity market but in the specific added value market of cogeneration and process heat. In view of the volatility of the costs of fossil fuels, AREVA's choice brings to the large industrial heat applications the fuel cost predictability of nuclear fuel with the efficiency of a high temperature heat source free of Greenhouse gases emissions. The ANTARES module produces 600 MWth which can be split into the required process heat, the remaining power drives an adapted prorated electric plant. Depending on the process heat temperature and power needs, up to 80 % of the nuclear heat is converted into useful power. An important feature of the design is the standardization of the heat source, as independent as possible of the process heat application. This should expedite licensing.

The essential conditions for success include:

- Timely adapted licensing process and regulations, codes and standards for such application and design
- An industry oriented R&D program to meet the technological challenges making the best use of the international collaboration. Gen IV could be the vector
- Identification of an end user (or a consortium of) willing to fund a FOAK

KEYWORDS : HTR, VHTR, Process Heat Application, Hydrogen

1. INTRODUCTION

1.1 Potential Applications for Nuclear Energy Besides Electricity Generation: a Global Perspective

Energy demands can be broken down into five major sectors for analysis :

- Electricity (widespread low voltage distribution and concentrated high voltage distribution, as well as industrial applications).
- The home, essentially widespread but with some areas of concentration (e.g. large residential areas); needs include electricity (non-replaceable but scope for much progress in terms of energy efficiency, e.g. lighting) and heat.
- Transport (road and rail, the latter being mostly electric in Europe, but not everywhere – far from it). Intense energy needs, both in terms of volume and weight.
- Industry, with two main types of demand: substitutable and non-substitutable electricity, and heat.
- Finally, a "negative" demand from power saving "opportunities".

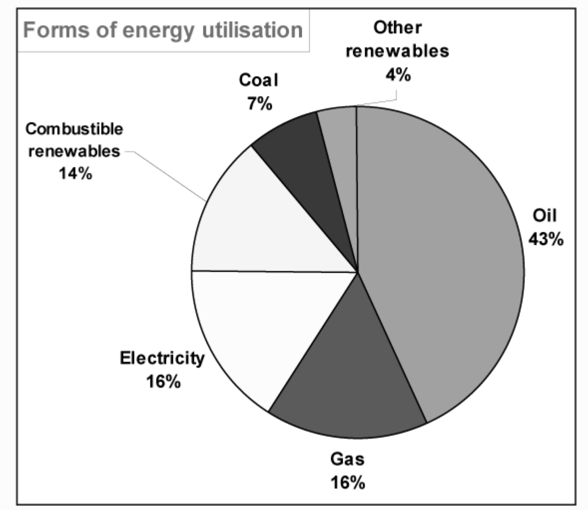

Fig. 1. Forms of Energy Utilisation Worldwide

The change in energy demand depends on two main factors: demographics and economic development. Energy demand is set to rise steeply over the coming decades, but will not be homogenous either in terms of quantity or quality.

Given this demand, energy generation (see fig.1) sources are facing three major constraints. These are not new, but have grown even more acute in recent years:

- Pollution (local, around power generation or transformation plants, and global – notably greenhouse gas emissions and the associated climate change).
- The gradual depletion of natural resources (both "real" in the sense that the amount of resources actually or potentially available is dwindling, or "economic" where access to existing resources is too expensive for the general financial capacities of developing economies, particularly in areas such as the Indian subcontinent, Asia, South America and Africa.
- The issue of energy independence is starting to be seen as increasingly important in a world where, in future decades, access to energy will be a geo-strategic challenge.

One of the prime concerns of Sustainable Development is how to find energy resources given these constraints. In this context, we need to look at possible responses, and what role nuclear power could play.

Civil nuclear power was originally developed to generate electricity. Its successes and mistakes are well known, as are the conditions for the accepted and acceptable development of this type of energy on a global and widespread scale.

Nuclear could therefore be one solution for generating electricity. Unfortunately, given the challenges that the electricity generation industry is facing from the forecast changes in demand, this cannot be the only solution, if only due to the time it takes to set up a large-scale nuclear generation facility. A country starting "from scratch" would need around fifty years realistically before it could generate a significant amount of nuclear power.

The greatest challenges for Sustainable Development might lie in other areas of energy consumption, and nuclear power could provide a solution for other applications than just electricity generation.

Before going into further detail on this point, we should stress the importance of the role that renewable energies will play, particularly in "widespread" applications. The home is certainly the main sector where energy savings and the use of renewable sources can make inroads (mainly solar power for heating applications and all domestic heating requirements).

Transportation of goods and people clearly represents the biggest challenge, due to its economic importance and the impact it has on lifestyles and therefore social organization. Innovative solutions are therefore needed, to act within global and local constraints.

One long-term solution could be a society powered by hydrogen, an idea heavily championed by the current US administration. However, many difficult obstacles must still be overcome, including:

- How to generate H_2 without producing CO_2 (or at least in greatly reduced quantities for an equivalent amount of energy generated), and also make the best use the O_2 produced in the case of water decomposition.
- How to store H_2 in economical weight and volume conditions.
- How to transport H_2.
- How to convert H_2 into energy, e.g. fuel cells.

Nuclear could be at the forefront of generating H_2 without producing CO_2, either through electricity and electrolysis (cold alkaline or via high temperature membranes), or – in the longer term – by generating very high temperature heat to thermo-chemically decompose water.

While awaiting an "all-hydrogen" society, we can imagine intermediate stages involving the production of synthetic fuels:

- Using innovative carbon liquefying processes
- Using natural gas liquefying processes.
- Using processes to enrich fuel oils with H_2, such as shale or bitumen sand. — NB: CO_2 quantities release (e.g. per passenger km) depends greatly on the processes used.
- Using biomass. — NB: The last option raises valid questions on land development, but could enable us to maintain balanced net CO_2 emissions.

In any case, adding H_2 into the transformation processes improves the CO_2 balance. In the same way, using the (CO_2-free) heat generated by nuclear power also considerably improves the overall CO_2 balance.

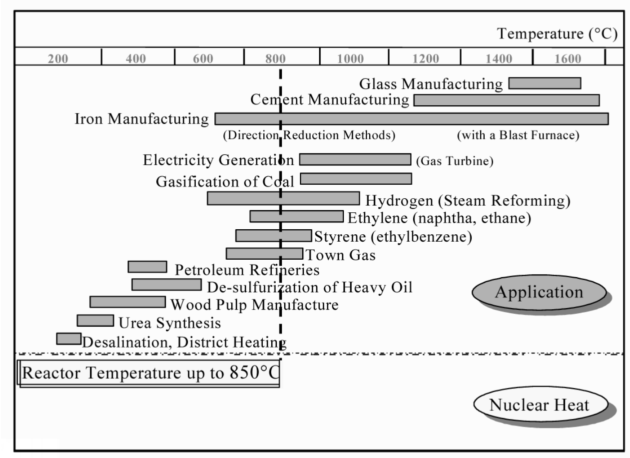

Fig. 2. Temperature Range of Main Large Scale Industrial Heat Uses

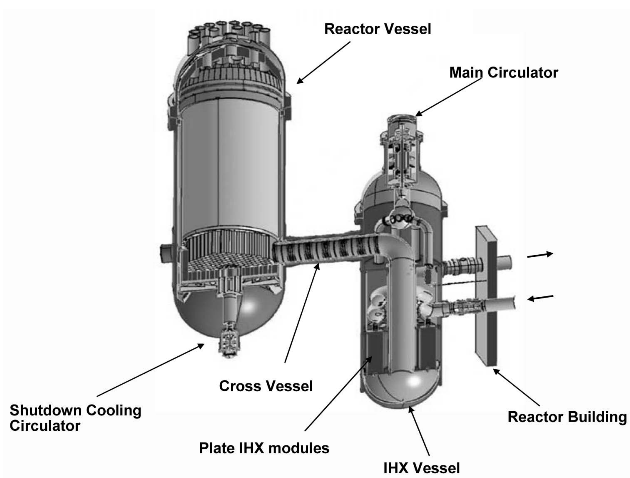

Fig. 3. ANTARES, a Flexible Concept for High, Medium and Low Temperature Heat Applications and Power Generation

Finally, given that coal and biomass are much more widely worldwide spread resources than oil or natural gas, this wide-scale production of synthetic fuel will be a means of easing geo-strategic tension surrounding energy supply.

The last sector with high energy demands is industry, which uses both electricity and heat. (See fig. 2)

Again, this is an area where nuclear can play an important role, providing high temperature heat – and in the future very high temperature heat – possibly while also co-generating electricity. The required technologies have gone beyond the stage of merely demonstrating their technological and scientific feasibility; the demonstration reactors built in Germany and the US have enabled us to pinpoint the operating principles, safety analyses and technological solutions that need to be further enhanced.

These reactors, called High (or Very High) Temperature Reactors are:

- Helium-cooled under limited pressure (typically 5 to 7 MPa) with input temperatures of ~400°C and output temperatures of ~800°C.
- Neutrons moderated by graphite.
- Fuelled by particles (UO_2 nucleus, D~0.5mm) those are coated (by vapor deposition in a gaseous phase on a fluidized particle bed) by layers of graphite of varying density, to absorb volatile fission products, and by a sealed layer of silicon carbide. These particles are agglomerated in “compacts” that are either spherical (D~5cm) or cylindrical (D~1cm, H~5cm) in shape.
- Intrinsically safe in nature, enabling the reactors to behave spontaneously in a safe manner, needing no short term intervention by operators or active safeguard systems in particular in the event of a total loss of the normal core cooling means. In the event of a partial or total loss of cooling in the core, the reactor – rather than relying on control rods – spontaneously and very slowly falls back over several hours or days to a stable safe state. The measures that an operator would need to take to return to normal operating condition could then be taken without urgency.

Figures 3 and 4 illustrate as an example the HTR concept proposed by AREVA which links the nuclear heat source to a combined cycle power conversion system through an intermediate heat exchanger (IHX). Depending on the process heat application temperature, process heat can be extracted from the power conversion system at different places.

Nuclear power, used either to generate electricity or to provide industrial heat, could therefore be part of the solution to the problems facing the planet. The nuclear solution is safe, economical, locally environmentally-conscious (given its extremely thorough and controlled waste management), and CO_2-free for better global environmental preservation.

However, like all forms of cutting edge technology, nuclear power would require a number of appropriate measures to be taken for it to be deployed in a more widespread manner globally, in countries other than those where it already exists:

- Technological control and understanding (mining, enrichment, reactors, spent fuel treatment and recycling, waste management, operating safety and nuclear safety) by all industrial, administrative and political players.
- Controlled training within the organized branches, and initial and ongoing training resources.

- An independent nuclear safety authority, with a clear and solid skills base grounded in industrial reality and greatly concerned by the conditions of industrial success (of course we cannot put a price on safety, but it can come at a cost that could completely undermine the economic stability of the industry).
- A sustainable political willingness to ‘go the distance’ in terms of setting up the industrial structure needed and properly addressing the political issues such as non proliferation, control of sensitive nuclear materials, and the political and societal long-term waste management choices from among the existing technical solutions that have been validated scientifically and experimentally.
- Access to uranium and the supply of reactor cores, including their treatment after irradiation, under satisfactory conditions of supply security and safety – both economically and in terms of proliferation control.

We need to examine this last point more closely, as like all natural resources; the planet does not have endless uranium supplies.

Most nuclear powered countries today, with the exception of Japan and France, use so called open fuel cycles where the spent fuel is considered a waste. However, such a fuel usage strategy is not sustainable in the long term if nuclear power is to expand. Indeed, the spent fuel contains valuable material, plutonium that can be recycled as new fuel together with some uranium in the form of MOX (Mixed Oxide). Recovering plutonium to recycle it is used in Japan and France in so called closed fuel cycle, thereby saving substantial natural uranium resources and decreasing the final waste volume and more importantly the radio toxicity.

For the long term with a significant nuclear share of the power market, the open cycle is not sufficient for a sustainable economy. The majority of present day reactors use a very small part of natural uranium, only the isotope U235 which represents 0.7% and a very small proportion of U238 which represents the remaining share of natural uranium. In order to optimize the use of natural uranium, one must convert the U238 into fissionable material thereby expanding by 2 orders of magnitudes the usable resources. This is feasible with breeder reactors which use a fast spectrum of neutrons to convert U238 into plutonium at a rate larger than their own consumption. This type of reactor has been built and its fuel efficiency usage demonstrated in several countries. Due to their slightly higher cost, breeder reactors are not widespread but they are bound to take a substantial share of the market when natural uranium resources become scarce.

The renaissance of nuclear power – of which we can already see tangible signs in the US, various European countries, China, India, South Africa and South America – will require a widespread strengthening and development of industrial capabilities, as well as new global “governance” of these industrial activities (non-proliferation control, sensitive technology and nuclear equipment export control, supply security, etc.).

To conclude this introduction, the resurgence of nuclear power can only come about with a new generation of skilled engineers with the right theoretical training and solid industrial experience, and who are capable of successfully completing projects of this size in a context of international competition in which “nuclear” countries – including Korea – have sought-after expertise but can also offer innovative solutions by actively contributing to the associated essential research.

2. ANTARES: READY FOR THE COMBINED HEAT AND POWER MARKET

Most of the systems selected in the Generation IV roadmap [1] are fast reactors aimed at addressing sustainability goals by minimising the long term risk of short supply of fissile resources, as well as authorizing advanced fuel cycle including LWR spent MOX fuel burning and minor actinide incineration. But, on top of the concern for security of energy resources, the Generation IV roadmap also addresses the need for other types of applications of nuclear energy than mere electricity generation and identifies the Very High Temperature Reactor (VHTR) as the most relevant system for satisfying this need.

Electricity indeed represents only 16% of the world energy consumption. Even if the role of nuclear energy and renewable energy sources for electricity production is extended, it remains that 79% of the rest of energy uses are obtained from heat produced by burning fossil fuel figure 1 [2]. Therefore in order to address effectively both the security of long term energy supply and the global warming risk, alternatives must be found to fossil fuel burning not only for electricity production but also for heat applications.

Another important result of the Generation IV roadmap, which perhaps did not receive enough attention, is that there is not a single nuclear system satisfying all energy needs: the VHTR and fast reactors have different missions and should not be considered as competing nuclear systems, but complementary ones. Neither should HTR be considered as competitors for LWRs. In fact the merits of each reactor type towards market needs and fuel cycle optimisation should not be assessed separately, but by considering a whole fleet of reactors operated in a symbiotic way. A European consistent strategy for keeping the industrial nuclear option open in the 21st Century should not favour one type of system against the other, but consider the development of several ones as necessary. Now, for selecting the relevant systems and the appropriate programmes for developing those, for determining the right pace for each programme and the balance of the efforts dedicated to the different selected systems, the status of development, the different technologies and the time schedule of market needs should be taken into consideration:

- **Status of technologies**:
  - Even if fast reactor technologies already achieved initial industrial demonstration, drastic innovations are necessary for reaching competitiveness and for developing an improved safety concept. The next step should be the selection of the most appropriate options, examining the potential for innovative options in the well proven sodium technology and exploring the potential of alternative systems, like the Gas Fast Reactor, and then the validation of these options with the construction and operation of a small test reactor.
  - The HTR/VHTR technology benefits from the legacy of past programmes and after the first demonstrations of the modular concept at the level of test reactors (HTR-10 in China and HTTR in Japan), the next step is the demonstration of industrial and economic viability. None of the present projects missed this target, all being aimed at building industrial demonstrators of a few hundreds megawatts.

- **Market needs**:
  - It will probably take some decades yet before the scarcity of fissile resources becomes a strong incentive for a large deployment of fast reactors, though the need of burning spent LWR fuel might accelerate the trend,
  - The heat market and more particularly the industrial CO_2 free process heat market is already a very large market, with a fast development. A competitive HTR/VHTR system really answering its specific needs would certainly succeed in entering this market as soon as developed.

To conclude, the present R&D needs for fast breeder development are base innovative technology developments with a long term perspective of industrial deployment and with an intermediate step of a test reactor, while for the HTR/VHTR the rather near term objective, which is a priority target for industry, is the development of an industrial demonstrator coupled with a process heat application. As the heat market already exists, this early demonstration should be made as soon as possible, that is by the end of the next decade, taking into account the unavoidable length of the developments and qualifications still to be performed.

But the possibility for a nuclear system to meet the specific needs of the heat market is not obvious: if nuclear energy has shown for long its ability to match in a competitive way the electricity market needs (producing about 1/3 of the electricity in European Union and more than 3/4 in France), until now, there has never been any significant breakthrough in the use of nuclear energy for any heat application.

In order to assess the potential of a nuclear system to bring a competitive answer to heat market needs, the characteristics of this market and its prospects for evolution in the coming decades have to be analysed carefully. It is from such an analysis that the performance requirements of future nuclear industrial systems will be determined and not from any technological challenging goal a priori defined, like for example very high temperature or burn-up targets.

2.1 Heat and Cogeneration Market Needs

Nuclear systems can be competitive only above a power minimum threshold, depending on the type of reactor: for LWRs a production of heat of a few thousands megawatts is necessary, but, due to their completely different safety design, modular HTR/VHTRs could likely reach competitiveness for a few hundreds megawatts and anyway should be limited to such power range to keep their inherent safety features that also make them attractive.

As heat cannot be transported on long distances like electricity, there can be prospects for heat applications of nuclear energy only for large scale heat intensive industrial uses, which are anyway always locally limited to a few hundreds megawatts. This is a reason why modular high temperature systems, due to their power range, could be attractive for industrial process heat applications.

Now, in figure 2, the temperature range required in present major large scale process heat intensive industrial uses is shown as well as the range of temperature of the heat source that can be provided by a HTR in the next decades with a reasonable development based on existing technologies and materials [3].

It should be added that prospects for new massive combined heat and electricity uses are likely to emerge in the next decade with the extraction of oil from tar sands, which will require both the injection of large quantities of steam at or above 300°C, 100 bars in the tar seam and large pumping power [4].

The production of hydrogen will be another area with fast growing heat needs: the use of hydrogen which already has a fast growth based on its present uses in refineries and chemical industries, could expand even more rapidly in the next decades, if used as a substitute to natural hydrocarbons as such or as an additive to other types of fuels (up-grading heavy oils or producing synthetic fuels either from coal or gas and even more environmental friendly from biomass).

Steam reforming of methane is presently the main process employed for hydrogen production. Providing the heat required for this process from an HTR instead of burning one part of the gas would allow in a first step saving approximately one third of the natural gas. In the longer term new water splitting processes for hydrogen production allowing fully sparing natural gas and avoiding CO_2 emission might emerge that could substitute the present steam reforming process.

But the present effort of industry for developing HTR/VHTR cannot be based on hypothetical long term trends towards a possible “hydrogen economy”. It should rather rely on the analysis of the present market and its evolution in the next decades. As shown above, there are already many industrial uses requiring temperatures lower that 800°C that open a large field of applications for modern modular HTRs:

- Oil extraction from tar sands,
- Petroleum refineries,
- Chemical plants,
- Hydrogen production by steam reforming for refineries and chemical plants,
- Desalination,
- District heating.

There are also higher temperature industrial applications that are for the time being out of reach of existing or future medium term HTR technologies, but which could in the longer term benefit from the progress of these technologies towards VHTR performances.

Another feature that differentiates the industrial process heat market from the electricity market is the large versatility of the industrial processes to which a nuclear system should provide heat and the wide range of the temperature levels of these processes. In order to have a chance to be competitive, the same nuclear system should therefore be flexible enough to be capable of easy adaptation to different industrial processes with only minor changes.

Therefore, it is clear that industrial heat market needs will be the main driving force for HTR/VHTR development, while there will be less incentives for utilities to turn to new technologies for electricity production still under development, while there are proven safe and economical industrial technologies (as EPR). Nevertheless, if modern modular HTR/VHTR is developed for another purpose, it can also answer some specific needs of some utilities depending of specific local condition (grid structure, power production needs…). Moreover, the energy needs of large industrial platforms often combine both heat and electricity. Therefore the flexibility requirements on future HTR/VHTR must not consider only the needs of different types of industrial process heat applications, but also the needs of electricity generation and combined heat and power production.

2.2 The ANTARES Programme, AREVA Answer to the Growing Indestrial Process Heat Needs

AREVA started the ANTARES programme in 2004, for developing a high temperature commercial reactor, with the following objectives:

- Competitiveness,
- Flexibility for adaptation to the widest scope of industrial energy needs,
- Maximum use of the inherent safety features of modular HTR for simplifying the safety design,
- Possibility of entering the market within a reasonable delay.

The design options of ANTARES (see for example [5]) directly follow from these objectives:

- The indirect cycle is the consequence of the need for flexibility. As illustrated in figures 3 and 4, the relative

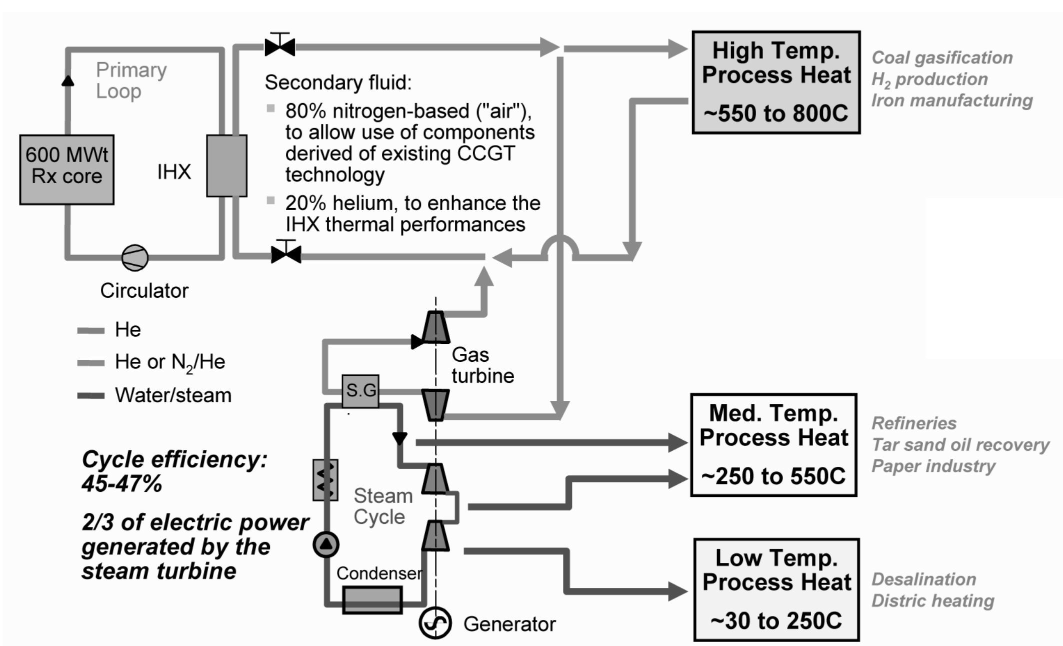

Fig. 4. ANTARES, a Flexible Concept for High, Medium and Low Temperature Heat Applications and Power

decoupling it brings between a primary circuit dedicated to the extraction of the heat generated in the reactor and to the confinement of radioactivity and a secondary circuit using non nuclear technologies, dedicated to the uses of this heat, allows for flexible uses for high, medium or / and low temperature heat applications or / and electricity production.

- The key component of the indirect cycle concept is the intermediate heat exchanger (IHX). A single primary loop design with a single IHX is preferred figure 4 for minimising costs. Several hundreds megawatts have to be exchanged in this component, which should be compact enough to be housed within a pressure vessel. Several compact plate designs are investigated, as well as a back-up solution with a multi-loop tubular IHX figure 5.

- In order to maximise the power generated by the reactor (~ 600 MWth) and therefore the competitiveness, a block type annular core has been selected figure 6, based on the standard SiC TRISO UO_2 particle fuel.
- The economic optimum for fuel cycle cost will most certainly correspond to a very high discharge burn-up, most probably about 150 GWd/tHM, as long as the fuel withstands being operated up to such high burn-up without loosing its outstanding leak tightness, which is the basic condition for using the inherent safety features in HTR safety demonstration.
- In order to minimise the development delay, only materials with already existing industrial applications are selected. For example for the reactor vessel, the Modified 9Cr 1Mo steel (with PWR vessel steel as a back-up solution) and, for the IHX, a nickel base alloy are currently selected. These materials will determine the maximum operating temperature: in the range 400-450°C for core inlet (with 350°C for the vessel back-up solution), about 850°C for the core outlet.

2.3 The Technological Challenges of Modern HTR/ VHTR Development and the Corresponding R&D Needs

Despite the fact that the technology of HTRs has known large developments in the past, in particular in Europe, with the construction and operation of industrial prototypes, significant R&D efforts are necessary for the deployment of modern modular HTRs, not only for going to the next step, the VHTR, with the objective of reaching 1000°C or more.

First of all, as already mentioned, no nuclear reactor has yet been coupled with any industrial process. In order to demonstrate the feasibility of such a coupling and to convince industry that it can work in an effective way, a large size demonstration is necessary. Such a coupling will be a major innovation and making it possible, efficient and reliable should be the central objective of the present HTR R&D effort. Adding at once the objective of a coupling

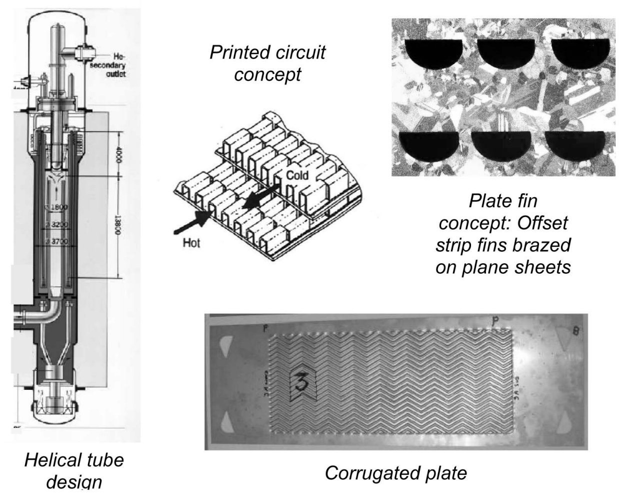

Fig. 5. Different IHX Concepts

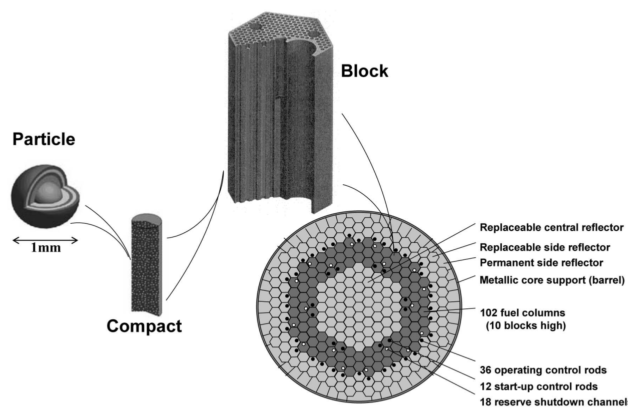

Fig. 6. ANTARES Block Type Core Design

at 1000°C would raise risks that no industrial partner would accept to share before the industrial feasibility of coupling is demonstrated in more reasonable conditions.

One of the key components to make this coupling feasible is a cost effective, high efficiency, compact IHX. The development of such a component is rather challenging: plate heat exchangers such as those which are presently considered for ANTARES are widely used in industry, but they have never been used as component of the primary circuit of a nuclear reactor, and no more with the large size required by the power level of the reactor, with such temperature, thermal and pressure load conditions as those the IHX will meet in a HTR, even without reaching VHTR conditions.

A few other components are beyond existing industrial experience, like the helium circulator in the primary loop, large helium valves and the hot gas duct.

All these components must be tested, first in order to select the design options (e.g. selection of the plate concepts considered for the IHX) and then to qualify the design. The first tests for directing the design towards the most appropriate solution can be made on small mock-ups in air, but the final qualification must be made in large test loops, with large size representative mock-ups, in representative temperature, flow rate, pressure and chemical environment conditions. For the ANTARES programme, the selection of the IHX concept will be supported by tests in the low flow rate, high temperature (up to 900°C) air loop CLAIRE of CEA Grenoble, in the large flow rate, low temperature air loop PAT of EdF Chatou and in the low flow medium temperature helium loop HEFUS 3 of ENEA, Brasimone, already operating for fusion needs or in the future HELOKA loop under development in Forschungszentrum Karlsruhe; then the choice of concept will be validated in a 1 MW helium loop, HELITE, to be built in CEA, Cadarache figure 7; for the final qualification, a much larger helium loop will be required with at least a power of 10 MW, which represents a much larger investment.

The selection and qualification of materials is a critical issue for the development of components, not only for the IHX, but also for the vessels and the internals: even if existing industrial materials should be preferred, they will be used beyond their domain of usual application in terms of temperature and chemical environment. The past HTR experience is insufficient: even if the test reactor AVR has been operated during a long period at very high temperature (950°C or even more), the metallic parts of the reactor were kept at much lower temperatures, which cannot be the case when there is an IHX, which is continuously maintained at the core outlet temperature; for all other HTRs operated in the past, the maximum temperature was about 700°C. Many additional data must be acquired on mechanical properties of the materials for components design. Moreover the presence of unavoidable impurities in helium (CO, CO_2, H_2O, H_2, CH_4, N_2…), even in very low quantities, can have a strong negative impact on mechanical properties of metallic materials, for instance through carburisation and decarburisation reactions in the absence of sufficient quantities of oxygen that could create protective oxide layers. These phenomena are particularly critical in the case of the thin IHX heat transfer walls. The behaviour of the IHX wall material regarding the particular environment of the secondary coolant (for ANTARES a mixture of nitrogen and helium) must also be investigated.

Therefore a large programme of experimental studies on interactions of high temperature materials with their specific environment has to be undertaken in order to select the most appropriate materials for operating in HTR environment, to adjust the minor element content of these materials for improving their corrosion resistance and to define the acceptable proportions of impurities in helium (to be controlled by the helium purification system) in order to minimise the impact of these impurities on material behaviour. These tests are performed in dedicated helium loops with very careful control of the atmosphere content, several of them being currently operated in a coordinated way (e.g. the CORINTH loop in CEA Saclay, figure 8) or still under development in CEA, EdF and AREVA.

It should also be mentioned that the past experience on the different types of gas reactors with graphite moderator is not directly applicable to the design of future HTRs as the graphite grades used in the past are no more industrially available. All the characterisations, the tests for determining the graphite behaviour under irradiation and in oxidising atmosphere (normal or accidental conditions) must be restarted for selecting the most appropriate grade, within the present available ones and for acquiring a complete database on the selected grade for design needs.

The second major challenge for the development of modern modular HTRs, after the development of the IHX and the qualification of a material for this component, is the development of the fuel. The fuel for the German MODUL was qualified for operation at 700°C, 80 GWd/tHM and, with such normal operating conditions, it has been shown that, in accident heat-up conditions up to 1600°C, there was no unacceptable radionuclide release. Various experiments provide indications of margins beyond the qualification domain of the MODUL fuel, which could allow envisaging operation in more stringent conditions, even if there are a few indications of increase of radionuclide releases in accident conditions at very high burn-up. The test programme started during the 5th European Framework programme will give valuable information on the actual performance limits of the state-of-the-art fuel. Now for ANTARES and for other present HTR programmes, the required performance includes higher temperature and possibly higher burn-up (850°C and ~ 150 GWd/tHM for ANTARES) than in the past HTR programmes. For that purpose, state-of-the-art technologies for fabrication and quality control of the fuel have been recovered, with a large contribution of the fuel projects of the 5th

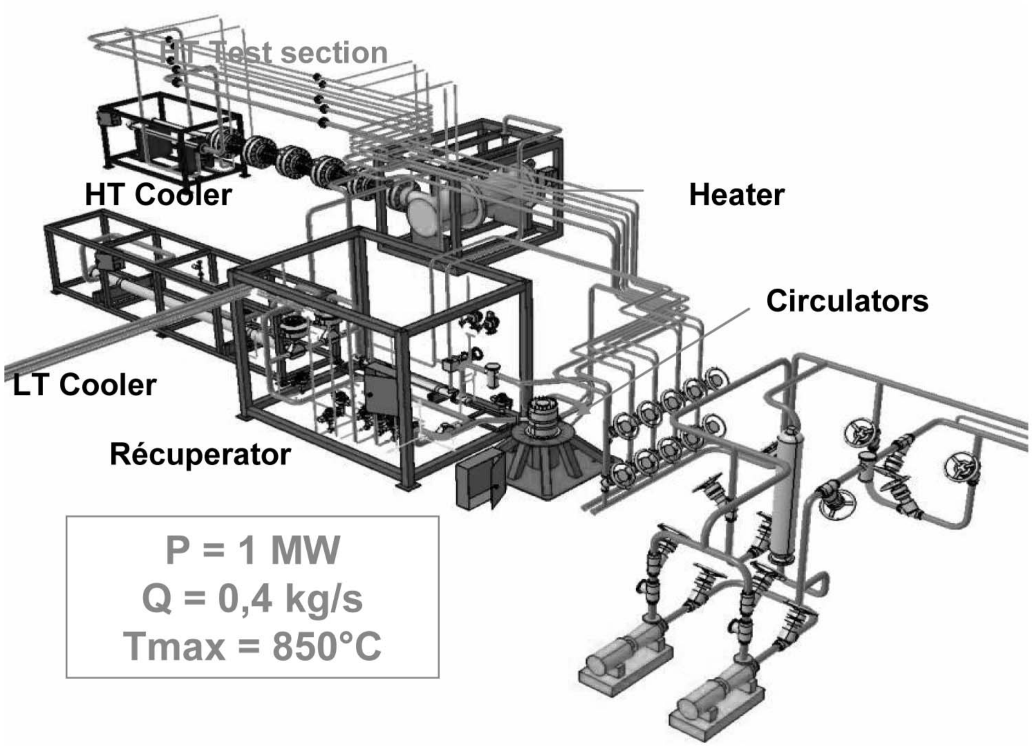

Fig. 7. The HELITE Loop, CEA Cadarache

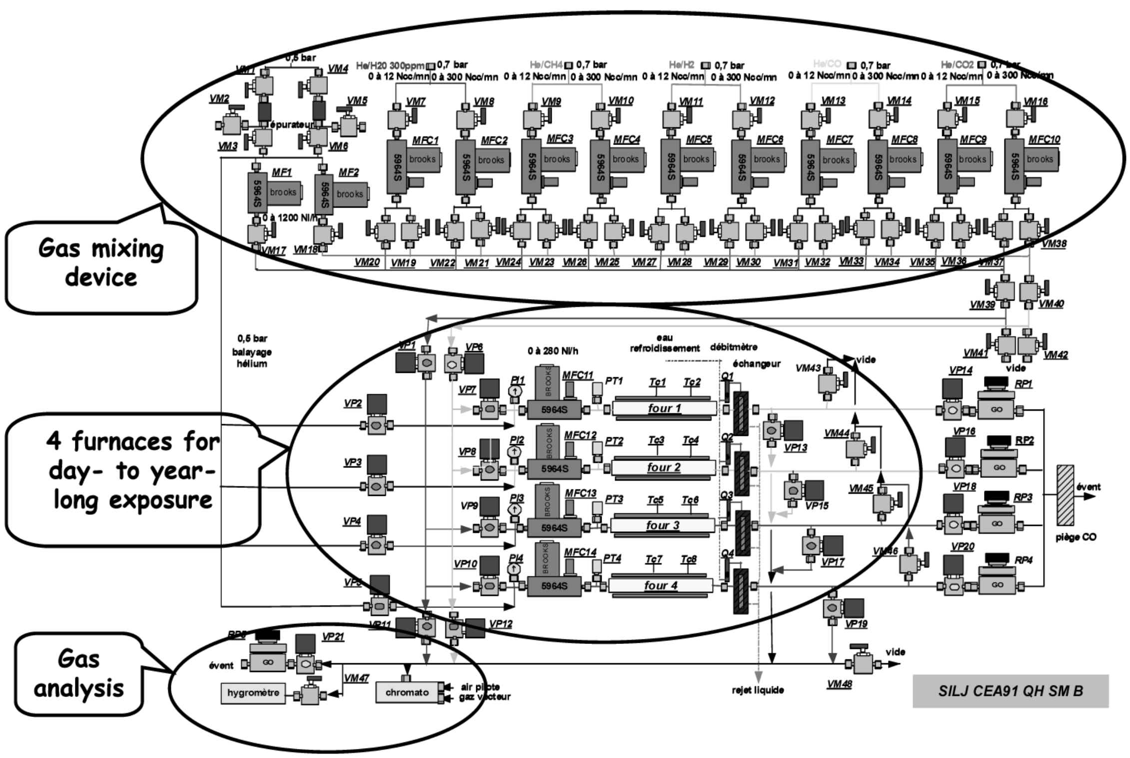

Fig. 8. The CORINTH Loop for Helium Environmental

Framework Programme [6] and they will have to be mastered at an industrial scale and if needed improved in order to produce the high quality fuel required for such operating conditions. A large programme of irradiations, post-irradiation examinations and heat-up tests will have to be performed with dedicated test facilities allowing on line monitoring of fission product releases in order to assess the performances of the fuel and to qualify it for industrial operation and licensing purpose. The HFR irradiation facility in Petten, presently already operational for the HTR fuel tests of 5th and 6th Framework Programmes [6-7] and the irradiation facility (figure 9) under development in OSIRIS (CEA Saclay), will be essential tools for the implementation of this programme, as well as several European hot laboratories.

Last but not least, it has been shown during the last ten years that there are large needs for improvements in the modelling and the qualification of existing computer tools for HTR design and licensing: the reactor physics benchmark organised by IAEA emphasised the fact that most of the tools used by the participants did not predict correctly the first criticality of HTTR and of HTR-10 [8]. This was the beginning of a large international effort for improving the understanding of the HTR physics, which is far from being completed [6]. The new codes have to be qualified and most probably dedicated zero power critical tests will have to be performed for that purpose. The fuel code IAEA benchmark has also shown that phenomenological laws used in the different fuel codes must be revisited [9]. These codes will have to be qualified against fuel irradiation and accident condition test results. The existing Computational Fluid Dynamics codes will have to be qualified through tests on representative mock-ups, in particular for the calculation of several situations that are critical in HTR design (e.g. mixing in the core lower plenum, core by-pass flow, hot gas duct flow, distribution of flow in IHX headers, etc). The knowledge inherited from past HTR developments on radio-contaminant transport, where the temperature and burn-up were lower, might be insufficient for present projects, with more stringent operating conditions. New tests and modelling developments might perhaps be required. Moreover some modelling should be coupled together in order to calculate complex situations where different phenomena interact, and this should be qualified in large integral test loops, like for example the NACOK facility in Forschungszentrum Jülich figure 10 for qualifying the coupling of graphite oxidation modelling and natural circulation modelling. Finally beyond the physical needs of coupling, modern codes should be easily interconnected, by sharing standardised interfaces that allow flexible exchanges of models and data between many organisations involved in cooperative work with different computer tools (for example the 35 organisations contributing in the HTR/VHTR integrated project RAPHAEL of the 6th Framework Programme and perhaps tomorrow an even wider partnership in the frame of GIF). The development of a computer code platform, as started by the project NURESIM of the 6th European Framework Programme is indeed a very useful step in line with this prospect.

Now, beyond the HTR prototype required for demonstrating the feasibility of the coupling between the reactor

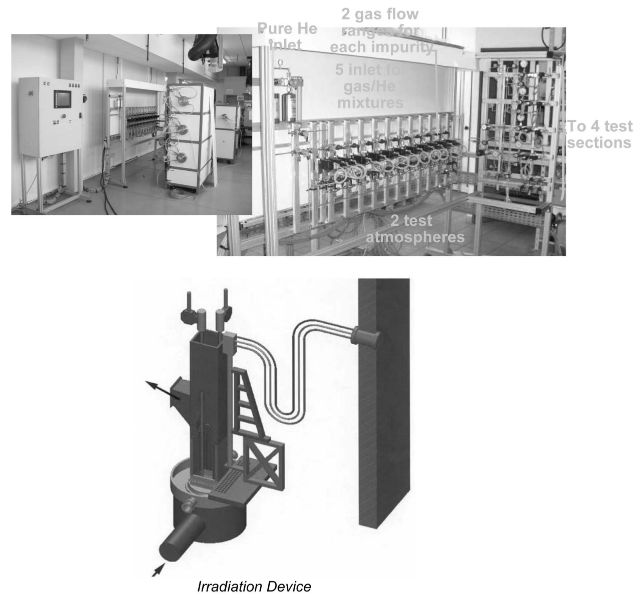

Fig. 9. OSIRIS HTR Fuel Irradiation Facility

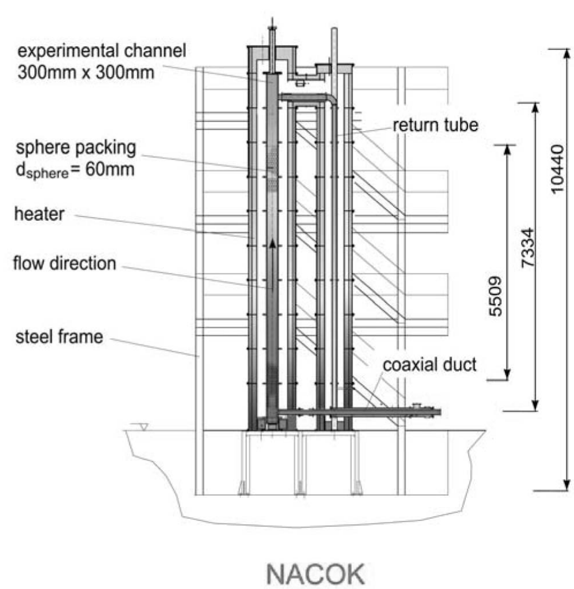

Fig. 10. The NACOK Facility, for Air Ingress Tests

and an industrial process heat application, investigations should be launched on advanced technologies needed for possible longer term evolutions of the system, towards improvements in its cost effectiveness and its capability of addressing other types of applications, e.g. at higher temperature, if there are actual market prospects in this direction. It is clear that the main limits in the performances of HTR/VHTR are imposed by the materials and the fuel. There are needs for R&D on advanced materials with improved performances, like oxide dispersed steels, composites and ceramics. There is also the need to develop innovative designs for the components, in particular the IHX, because there is always the possibility of design innovations that could improve the performances or the cost effectiveness and also because using new materials might impose changes in forming and assembling techniques that could require complete design changes. The search for alternate fuel particles with higher performances is already starting in the 5th [6] and 6th [7] European Framework Programmes with in particular the study of a different kernel composition (UCO) that might result in a slower CO pressure built-up in the particle than with a standard UO_2 kernel and of a new coating layer (ZrC), which remains stable at higher temperature than standard SiC. This R&D should be continued. Improved fabrication and quality-control methods should also be looked for, as well as advanced instrumentation techniques allowing improving the information that can be extracted from inside the reactor in spite of the difficulties caused by radiation and high or very high temperature helium environment.

Nevertheless priorities should be clearly set: first comes the development of the industrial advanced HTR demonstrator, with a top priority to the large R&D needs of this development, then the possible improvements to be introduced step by step in the following generations of reactors.

3. CONCLUSION: THE CONDITIONS FOR SUCCESS

Bringing to industrial emergence a high temperature nuclear system that can address a wide range of the energy needs should be an important short/medium term objective for the future economic prosperity, because it would answer the needs of the already large and fast developing industrial process heat market and would contribute to secure in the long term a competitive and stable energy supply to industry. Moreover this system can also address efficiently the environmental concerns of citizens, because it can contribute to reduce CO_2 emissions in energy production for many process heat industrial applications, beyond those using only electricity.

This relatively short term objective should not be considered as an alternative option in competition with the long term necessary development of fast reactors, but as a complementary one in a consistent strategy for keeping a sustainable nuclear option open in the long term. It should be noted that in case the GFR option is selected for fast reactors, the HTR/VHTR development should be considered

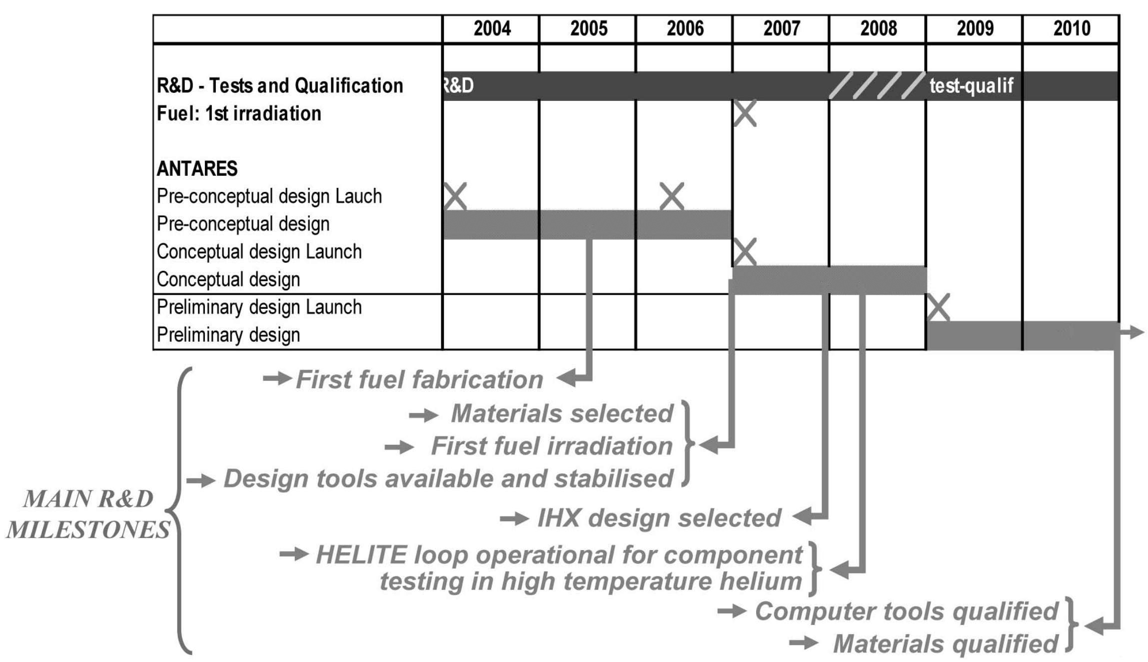

Fig. 11. ANTARES Design Schedule and Main R&D Milestones

as a first reasonable step for the GFR development due to synergies between the two types of reactors that should be systematically used in order to optimise the R&D effort: the development of helium technologies, of components and of high temperature materials, for instance, is necessary for both HTR/VHTR and for GFR.

The key for the emergence of HTRs at an industrial scale is the first demonstration with a prototype reactor coupled to an industrial process heat application before the end of next decade. Due to the important investment and R&D support it requires and to the risks involved in the project, developing and building such a demonstrator requires a strong public funding support and international partnership. This is the case for all present HTR projects, heavily funded by governmental agencies and, for most of them, at the centre of international industrial and R&D networks [10,11]. The large expertise legacies of past programmes, the living programmes world-wide are key assets for the success of a HTR demonstrator project.

For all present HTR/VHTR projects, the schedule can be shorter compared to other Generation IV systems, thanks to the legacy of past HTR developments and industrial applications: a prototype could be operational before the end of the next decade. Figure 11 gives, for example, the short term schedule for satisfying the main R&D needs of ANTARES programme, in relation with the design milestones.

A very important part of the development of a demonstrator is the qualification of the components, the fuel and materials. The qualification requires large test facilities that already exist, but the durability or renewal of which should be secured and new ones that have still to be built (e.g. large helium test loops). A concerted effort worldwide for making available the large test facility infrastructure that the developers of HTR/VHTR (and other Generation IV systems) need, is therefore desirable.

The development of a safety approach taking due account not only of existing licensing frameworks, but also of the very unique safety features of modular HTR/VHTR, allowing simplification in its safety design, is a key factor for competitiveness and therefore success of this type of reactor. A large consensus should be built on this approach.

More generally, an essential condition for the success of the development of a new generation of nuclear reactors is a worldwide consensus on principles, goals and criteria, concerning sustainability, safety and proliferation issues.

Last but not least, when launching projects for the development of Generation IV systems which will continue for more than one decade or even several ones until full achievement, one must take care to keep and develop enough human resources for the whole duration of the projects and beyond, for operating the systems that will emerge from these projects. Since the 80's, the downward trend in many countries in the number of newly educated nuclear engineering specialists rises serious concerns and should lead to new education programs.

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