MICHELANGELO NETWORK POSITION PAPER
FOR 6th R&D FRAMEWORK PROGRAMME

Motivations for actions on innovative systems within the 6th Euratom Framework Programme

The limitation in fossil fuel reserves, the concern for the security of energy supply, the threat that unstable energy prices would put on the European economic prosperity and the consequences of greenhouse gas emissions on the global climate, are major incentives for developing energy sources free from any fossil fuel burning. In that perspective, nuclear energy may be a major asset in the energy mix of the 21st Century, for complementing other energy sources free of greenhouse gas emissions, but with limited resources (hydro-electricity) or adapted to scattered uses more than to urban and industrial intensive uses (solar and wind energy).

In order to keep the nuclear industrial option open in the 21st Century, solutions must be found to the challenges of market and societal acceptability presently faced by nuclear energy:

- *Market acceptability*
  - The competitiveness of nuclear energy is challenged by the technical progress of other energies and by increasing regulatory and fuel back end requirements,
  - In the presently deregulated electricity market, the needs and constraints of the utilities are quickly changing,
  - The present nuclear systems can only satisfy the needs of a limited fraction of the energy market (only large plants for electricity generation), which dooms the global economic and environmental benefits brought by nuclear energy to be very limited.
- *Societal acceptability*

  The concerns about the safety, the nuclear waste issues and the proliferation risks are currently refraining further development of nuclear energy in many countries.

The present industrial nuclear plants are highly competitive and safe, but, as they are already widely optimised, innovative approaches are necessary for satisfying new requirements and still bringing improvements in the performances. Such innovative approaches are possible, because there is still a large potential for the development of nuclear technologies, but this potential can be transformed into industrial reality only through a continuous and powerful R&D effort.

This is the approach promoted by DOE in United States, with the Generation IV initiative. Together with the development of a close partnership with Generation IV, Europe should preserve a sufficient autonomy so as to keep its strong position in the nuclear technology and industry. In this respect, actions within the 6th Euratom Framework Programme are of crucial importance to respond in time to the demand of new power plants, which can be anticipated over the next three decades due to the end of lifetime of many existing plants. If the European industry misses this opportunity, further opportunities of deployment of new nuclear technologies may not come before long, owing to the long operating life cycle of power plants. Moreover, as the development of nuclear systems indeed requires long lead-times and investments (manpower, infrastructures) that no single country can afford any longer, the R&D of the Framework Programmes, federating and complementing the efforts of individual partners, has a key role for giving to the European nuclear R&D a critical size.

The proposed innovative approach in nuclear R&D

Actions on "innovative systems " within the 6th Framework Programme are of particular importance:

- to **address societal issues relevant to nuclear power**, including safety, sustainability, proliferation resistance, radioactive waste management, as well as **societal needs** beyond electricity generation (hydrogen as substitute fuel for transport, potable water through sea water desalination, process and district heating),
- to **maintain the nuclear competencies** at the best possible level to optimise the operation of existing facilities and to provide the environment to develop the next generation of workers in the nuclear industry,
- to **preserve common references on nuclear issues** between European countries and to keep the nuclear option open in the member states of the Union,
- to **favour R&D programmes in Europe on advanced technologies** likely to stimulate attractive spin-offs for both the nuclear and the non-nuclear industries,
- to **provide the European nuclear industry with sufficient information and technical basis on innovative systems** within a context of increased international competition,
- to **establish appropriate R&D projects and networks in Europe** on scientific issues and key technologies needed for future nuclear energy systems, and to take advantage of similar international initiatives (Generation IV and others).

The approach proposed by MICHELANGELO Network is basically converging with the approach that emerges from the GENERATION IV roadmap, with some specific recommendations related to the European situation:

- The European R&D on innovative approaches must not be focused only on the issues concerning the health and environmental impacts of nuclear energy, but also on the competitiveness issues, which may otherwise push nuclear energy out of the market. Therefore Europe should not dedicate most of its nuclear R&D effort only to the waste issues and in particular to the development of partitioning and transmutation technologies, but also to the development of technologies for future competitive nuclear energy sources.
- It is important to have a balanced research strategy taking into account the experience of the industry and the research on existing industrial systems and the innovative approaches, which are necessary for the long term renewal of nuclear energy, and not to oppose the R&D supporting the present nuclear industry and "evolutionary" approaches and the R&D meant at proposing "revolutionary" solutions for the future. It must indeed be realised that

- The future of nuclear energy depends as much on the safe and competitive continuation of the operation of the present systems, which still need R&D support, as on innovations, likely to suppress in the longer term off-site consequences of severs accidents, even though hypothetical, on health and environment.;
- The feedback from operational experience is a guarantee of improvement of the safety and a source of continuous improvements, on which the development of future systems should build..
- The future systems will not reach full sustainability at once with a revolution of the technology, but rather progressively, by a *step by step* progress. Market needs cannot wait the long term "ideal" systems. They will be addressed by systems with an improved satisfaction of sustainability goals, but still imperfect. Moreover such medium term innovative systems will demonstrate on an industrial basis part of the technology, which will be used in further steps. What must be considered is their potential for satisfying market needs in the medium term, while keeping a high potential for further developments in line with an improved compliance with sustainability criteria.
- The history of nuclear energy is not linear from Generation I to Generation IV systems, but a much more complex evolution. In particular Generation II and III systems will still be in operation for most of the Century and will coexist with Generation IV systems. This coexistence and the synergies between these different types of systems have to be taken into consideration when imagining the future of nuclear energy.
- As the present plants and their evolutionary successors will still be in operation for most of the Century, they will probably undergo partial innovations for the renewable equipment: fuel, I&C, safety systems, etc. These innovative components can in turn be seed design options for a next generation of innovative reactors, which will be designed in such a way that the maximum benefit can be taken from these partial innovations, which often cannot be the case in the environment of an existing reactor.

* The search for a better satisfaction of the goals of sustainable development should not be focused only on the reactors, but should be enlarged to the whole fuel cycle and innovative approaches should be used for various aspects of the cycle (fuel front end, fuel design, reprocessing, etc).
* Several types of systems might be needed for the future deployment of nuclear energy, because the needs are not the same for different types of countries (industrial or developing countries, countries with large fossil fuel resources or not, etc), for different utilities, or possibly for different industrial end users interested in other types of applications than the electricity production. Even in a given fuel cycle strategy, different missions (producing electricity, satisfying the energy needs for other types of applications (district heating, desalination, industrial process heat, hydrogen production, etc.), transmuting wastes, etc) cannot be faced by a single system but by different types of systems coupled in a synergetic way.
* The right balance should be found in the European R&D between developments with likely industrial applications in the medium term and longer term developments with more uncertain prospects for industrial applications. For a relatively early industrial deployment of some of the innovative concepts, all the technologies

needed for the design and licensing of industrial concepts should be made available as soon as possible, while for much longer term and uncertain applications, the R&D should be focused on the key feasibility issues.

- For long term developments, the options should not be frozen too early (lessons should be taken from the past fast breeder development). In particular for transmutation, for which a possible industrial deployment should not be expected before several decades, R&D should not be focused too early on a single solution and ithe potential of different critical systems should be studied as well as the feasibility of accelerated driven systems.

The objective of this document is therefore to recommend actions for the 6th Framework Programme of the European Commission for an R&D support to innovative approaches on nuclear systems selected by MICHELANGELO Network for their high potential in keeping the nuclear option open in the 21st Century. For each of the systems recommended for further developments, the following aspects are considered:

- the time scale for the industrial deployment, taking into account the market needs and the amount of R&D associated,
- the key feasibility issues for each type of promising system,
- the possibility of getting a European R&D partnership with a critical size,
- the possibility of a European partnership to Generation IV in specific areas that could benefit from it,
- the "centres of expertise" necessary for satisfying the R&D needs for innovative approaches,
- the appropriate use of the new instruments of the 6th Framework Programme.

Proposals for the 6th R&D Framework Programme

R&D priorities do not only depend on the impact on economic and societal aspects of future nuclear systems, but also on the time needed to implement new solutions, which in turn depends on the market perspectives and on the size of the corresponding R&D effort. The likelihood of successfully bringing to the market a new nuclear system must be assessed through a pre-evaluation of the key technological and economic issues that pertain to the specific concept before launching a full scale development effort of this concept.

When an early industrial deployment is anticipated (within approximately a decade), a systematic technology development in the frame of a large integrated project could be considered for the 6th Framework Programme. Otherwise, for longer deployment periods (e.g. 15 to 20 years) the R&D effort has to be focused on the key feasibility issues and on the long term development of the base technologies through targeted projects.

1. Water Cooled Systems

Innovative fuel for Water Cooled reactors - Existing light water reactors and their evolutionary successors will still remain in operation for at least the first half of this century. For such a long period, evolutions in the fuel technology will most likely be needed to improve the overall safety, the competitiveness of the fuel cycle and the utilisation of natural fissile resources, as well as to minimise the production of radioactive waste.

The proposal is to have **targeted projects** addressing different evolutions of the potentialities of the fuel like:

- very high burn-up
- tight lattices (for high conversion cores)
- actinide burning
- robustness for severe accidents.

Super Critical Water Cooled Reactor concept - The concept, which can allow the design of much smaller and compact systems for the same generated power, has a large potential for increasing the thermodynamic efficiency of light water reactors and therefore their economic competitiveness.

The proposal is to have a **targeted project** focused on the key technologies and feasibility issues:

- cladding material for temperatures up to 650 °C
- corrosion of materials (including stress corrosion cracking)
- core neutronics (3D coupled neutronics-thermal hydraulics codes at high temperatures), thermal hydraulics aspects, heat transfer phenomena at supercritical water conditions
- optimisation of plant safety systems satisfying the European Utilities Requirements (EUR) and accident analysis
- option of hardened neutron spectrum.

Addressing these key technological issues will help to maintain the necessary European expertise in both nuclear and fossil power plant technologies.

2. Gas Cooled Systems

***Thermal High Temperature Reactors* -** There are good prospects for an early deployment (by the end of the present decade) of a renewed generation of thermal neutron high temperature gas cooled reactors (HTRs) with modular design and direct Brayton cycle conversion:

- there are already two projects of industrial prototypes (GT-MHR and PBMR) involving large international partnerships likely to be put in operation by 2010 or earlier,
- modular HTRs are already making a step towards the goals of sustainable development, with their inherent safety features, which practically prevent any severe degradation of the fuel in accident conditions,
- it appears that there is a market for modular HTRs, which can be competitive even for a limited power generation, both in the deregulated market of electricity of developed industrial countries, where they can satisfy the need for a marginal increase of the production capacity (e.g. in the United States, some utilities already indicated their interest), and in many developing countries, where they are adapted to the demand and to the capacity of the electric

network,

- the technology of modern modular direct cycle HTRs relies on the past industrial experience on HTRs and on the modern gas turbine technology,
- the key feasibility issues are being presently examined in depth in the 5th Framework Programme and in other foreign research programmes (USA, Russia, Japan, China) with which close co-operation is being established.

Moreover, in the longer term, the gas cooled reactor technology has a high potential for further developments (design optimisations, higher temperature, use of thorium cycle, deep actinide burning, hardening of the neutron spectrum…), which can improve the competitiveness of nuclear energy, open new market areas for nuclear energy (hydrogen production, potable water through sea water desalination, industrial process heat and district heating) and lead, step by step, to a full satisfaction of the goals of sustainable development.

The proposal is:

- to continue the effort initiated by HTR-TN to develop the full set of technologies needed for the design and licensing of modular direct cycle HTRs in Europe by the end of the decade,
- to start the exploration of the different above mentioned paths for further developments.

Presently the (European) HTR Technology Network (HTR-TN) already plays a key role for co-ordinating and integrating the cluster of HTR projects of the 5th Framework Programme. It is proposed to strengthen the integration of the HTR R&D in the 6th Framework Programme by consolidating the development of the basic HTR technologies (physics, fuel and safety) in an **integrated project** presented by the HTR-TN partnership. In addition, there are clear synergies between this project and other R&D areas such as:

- fuel back end, including partitioning and transmutation (behaviour of the irradiated fuel in geological disposal conditions, "deep burn transmuter" concept, gas)
- hydrogen technologies
- non nuclear energy technologies (turbine, compact heat exchangers)
- material research.

Tools have to be found and projects have to be organised for developing such synergies with improving collaboration across different fields.

Gas Cooled Fast Reactors - Gas cooled fast reactors, which offer high sustainability features through a most efficient utilisation of the fissile resources and a minimum production of long-lived radioactive wastes, can either be the object of an autonomous **targeted project** following the overall technological review undertaken within the 5th FP, or can be part of the integrated project of HTR-TN. In any cases, a close connection is to be established between both activities on thermal and fast gas cooled reactors to maximise the benefit for both projects.

3. Non conventional systems

Molten salt reactors and gas core reactors appear to be promising in terms of sustainability, but require an extensive and sustained R&D effort before any possibility of industrial application. The nature of the possible activities within the 6th Framework Programme is to be accordingly adjusted.

Molten salt concept - The candidate missions associated with the concept are :

- electricity generation
- minimisation of waste and heavy nuclide inventory (on-line waste burning)
- breeder potentialities (thorium cycle)

The proposal is for a **targeted project** concerning key issues of these concepts such as :

- corrosion of metallic materials by fission products (Te for example)
- reprocessing and salt chemistry issues (in partial connection with Partitioning and Transmutation activity)
- acquisition of reliable thermo-chemical data for molten salts
- phenomenology of corrosion products transport (chemical, thermal-hydraulics aspects and calculation tools)

Gas Core Reactor - The two main issues of this concept concern the materials behaviour (very high temperature) and the physics analysis. There will probably be R&D activities on these topics in the GENERATION IV or NERI framework.

The proposal is at least to assess these main issues through a technological survey which could be organised by the MICHELANGELO Network.

4. Liquid metal reactors

Maintaining the expertise on sodium cooled fast reactors is most likely a subject to be addressed within the framework of existing collaboration agreements in Europe (United Kingdom, Germany and France) and beyond.

Discussions on lead and lead-bismuth technology revealed that:

- lead bismuth, even if of interest for the programme on ADS, will hardly compete with power reactors producing electricity at low cost, due to the scarcity and cost of bismuth, and to the issue of polonium generation, which prevents plant simplification and makes maintenance more difficult;
- pure lead remains a candidate for innovative power reactors, provided that materials, which resist to the corrosive molten lead environment, be found and that the issues inherent to liquid metal technologies be overcome (ISIR especially). This issue can be dealt within the framework of the ADS programme, within the 6th Framework programme, extended to include basic research on materials for pure lead at higher temperature than for the Pb-Bi eutectic.

Germany and Italy plan to extend the current test campaigns on heavy metal coolants to include experiments with pure lead.

Last, some basic and generic aspects of advanced spent fuel treatments, which are essential for fast reactors of any type and are also crucial for developing a sustainable and proliferation resistant nuclear energy, may be considered as a candidate topic, if supported by a sufficient number of organisations. This whole area could be suitable for a network of excellence.

5. Co-generation and other heat applications

Desalination process - As a continuation of the action EURODESAL of the 5th Framework Programme, there is a need to demonstrate the efficiency of new coupling processes with a nuclear reactor:

- the world demand for integrated nuclear systems producing water and electricity at competitive costs is likely to increase considerably,
- the aim of a demonstration plant is to show that innovative desalination technologies, especially those based on exploitation of the waste heat from innovative nuclear reactors (e.g. the Candesal Advanced Reverse Osmosis process) can be operated in an environment simulating as much as possible the nuclear industrial conditions,
- it must be shown that the coupling between a nuclear reactor and the desalination process does not raise concerns as regards safety and possible radio-active contamination,
- individual components and technologies are proven, but their integration is not.

The recommendation is thus to support such an integrated demonstration experiment and to find the proper frame to support the demonstration project.

Some interface issues like the development of an intermediate heat exchanger and the study of tritium permeation should be handled within the HTR-TN programme as generic interface issues, common to several non-electricity applications, in particular hydrogen production.

6. Hydrogen production

The industrial demand for hydrogen (H_2) is growing rapidly, mainly to convert heavy high-sulphur crude oil into transportation fuels (gasoline, kerosene, diesel). As the sources of high-grade low-sulphur crude oil are exhausted, it is necessary to refine heavy crude oils that require more hydrogen to produce transport fuels. The hydrogen is made from refinery still bottoms (components of crude oil) and natural gas. There would be a clear benefit in terms of security of energy supply, economy and environmental impact to reduce or even suppress the dependence of hydrogen production on natural gas.

Therefore the market of hydrogen is not only the prospective market of the "hydrogen economy", which would substitute for the present hydrocarbon economy, in particular with the use of hydrogen for transport in fuel cells, but also the present expanding hydrogen market of petrochemistry.

The objective would be to enter this market with nuclear energy as soon as possible and therefore in a first step to use existing technologies for hydrogen production (natural gas reforming or electrolysis) in order to minimise the development length. The major challenge of this first step is to find acceptable solutions to the safety issues of the coupling of a nuclear and an hydrogen plant.

In a second step, hydrogen could be produced through thermochemical water splitting, which is expected to be really competitive with that generated through natural gas reforming, with the advantage of being free from CO_2 emissions. Furthermore, it will remain practicable when natural gas resources will be exhausted.

The investigation of hydrogen generation systems likely to be coupled to high temperature nuclear electricity and heat sources (thermochemical cycles, electrolysis) can be addressed within an **Integrated Project** of the 6th Framework programme, including performance and economic assessments against other generation means, component technology, and safety issues. Other aspects such as the coupling to the reactor, materials (corrosion and high temperature aspects) and intermediate heat exchangers technology, could be handled as new topics covered by the HTR Technology Network (HTR-TN).