

Nuclear Science

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Independent evaluation of the MYRRHA project
Report by an international team of experts

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NUCLEAR ENERGY AGENCY
Organisation for Economic Co-operation and Development

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Foreword

The MYRRHA project at the Belgian Nuclear Research Centre, SCK•CEN, was started in 1998 and is aimed at the design, construction and operation an accelerator-driven, lead-bismuth-cooled, subcritical, fast-neutron reactor. The project has now reached a point where a decision on its future needs to be taken.

In view of the financial implications, at both national and regional level, of taking the project forward to the construction phase the Belgian government asked the OECD Nuclear Energy Agency (NEA) to organise an independent international evaluation of the MYRRHA project and to advise on what steps should now be taken.

A MYRRHA International Review Team (MIRT) was established, comprising scientists and engineers from France, Germany, Japan, the Netherlands, Switzerland, the United Kingdom and the United States of America. The team met together twice (once in Paris, France at the end of May 2009 and once in Kasterlee, Belgium in the middle of August 2009), held one teleconference and exchanged numerous e-mails.

This document describes the main findings of the MIRT, covering strategic, technical, operational and financial issues. The final chapter contains overall conclusions and MIRT's recommendations to the Belgian government.

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Chapter 1: Introduction

1.1 The MYRRHA Project

The MYRRHA Project, conceived by the Belgian research centre SCK•CEN at Mol, is aimed at constructing and operating an accelerator-driven Multi-purpose, Hybrid Research Reactor for high-technology Applications. Work began in 1998 and a preliminary design with a nominal power of 30 MWth was completed in mid-2002. The design of MYRRHA has continued to evolve and is now for a 57 MWth facility.

MYRRHA is intended to be a flexible, fast neutron irradiation facility, able to work in either subcritical or critical mode. It is currently planned to be in full operation by 2020 and to be operated in its early years as an accelerator-driven reactor system (ADS), to demonstrate/prove the technology required for both the accelerator driver, the spallation neutron source and the coupling between neutron source and reactor core.

Later on, it is intended to run the reactor as a critical fast neutron irradiation facility, decoupling the accelerator and removing the spallation loop from the reactor core. It will then focus on fuel research for innovative reactor systems, materials research for Generation-IV advanced reactor systems and for fusion reactors, together with radioisotope production for medical and industrial uses, as well as other industrial applications, such as Si-doping.

The decoupled accelerator would then become available for fundamental research in nuclear physics and also for neutron science in the areas of complex fluids, crystalline materials, disordered materials, magnetism and superconductivity.

1.2 The commission from the Belgian government

Following the 10-year concept and design development phase of the MYRRHA project, SCK•CEN is now at a point where decisions need to be taken about the construction of the MYRRHA facility. Because of the significant national and regional implications of such work, especially the financial and budgetary ones, the Belgian government asked the OECD Nuclear Energy Agency (NEA) to establish an international group of independent experts to assess the strategic, technical and financial aspects of the project and to report on its conclusions.

The terms of reference for the review, set out for the NEA by the Belgian government (see Appendix 1), contained a set of questions to be answered by the International Review Team.

1.3 The MYRRHA International Review Team

In accordance with the terms of reference for the review, the NEA identified seven persons to serve on the MYRRHA International Review Team (MIRT). They were (in alphabetical order):

| | |
|-------------------|--------------------------|
| Frank Carré | France |
| Jean-Marc Cavedon | Switzerland |
| Joachim Knebel | Germany |
| Paul Lisowski | United States of America |
| Toru Ogawa | Japan |
| Derek Pooley | United Kingdom |
| André Versteegh | Netherlands (Chair) |

The NEA was represented by Thierry Dujardin and Claes Nordborg. The *curriculum vitae* of the review team members and the NEA representatives can be found in Appendix 2.

The MIRT members met physically on two occasions, first at OECD headquarters in Paris, France on 27-28 May 2009 and later in Kasterlee, Belgium on 13-14 August 2009. Representatives from the SCK•CEN and the Belgian government were present on both occasions to present different aspects of the MYRRHA project and to answer questions. In addition to these two meetings, MIRT members exchanged numerous e-mails and held one teleconference.

1.4 Preliminary comments

The review team believes it has obtained a good understanding of the important features of the MYRRHA project, as a result of:

- the excellent documents provided for MIRT by the MYRRHA project team covering, *inter alia*, the design, business plan and R&D programme for the project;
- the equally excellent presentations made by Eric van Walle, Hamid Aït Abderrahim and their staff to MIRT at the OECD headquarters in May and in Kasterlee in August;
- numerous additional documents, presentations and answers to supplementary questions;
- a visit by MIRT to SCK•CEN in August to see for itself some of the current work in BR2 as well as the site proposed for the MYRRHA facility;
- the opportunity that SCK•CEN gave MIRT, whilst visiting Mol, to meet and hear from a wide range of local, regional and national stakeholders in SCK•CEN, with interest in the activities there.

MIRT acknowledges, at the outset of this report, the excellent, world-wide reputation of SCK•CEN and the important benefits it has brought to Belgium, to Flanders and especially to Kempen. We agree that, if MYRRHA turns out as envisaged, the construction and operation of this facility would secure these benefits for SCK•CEN, Kempen, Flanders and Belgium for many decades to come. We note that SCK•CEN itself estimates that the economic activity that would be generated within Kempen from the MYRRHA project would be many EUR billions (~5). However, MIRT does not consider itself competent to check the quantification of such economic benefits, nor to assess their monetary value to the Belgium, Flanders or Kempen governments. Instead, we confine our comments to the MYRRHA project itself.

Chapter 2: Strategic issues

2.1 Accelerator-driven systems and/or lead-bismuth-cooled fast reactor

MYRRHA is expected to be employed for a variety of purposes, including the demonstration of both accelerator-driven reactor systems (ADS) and lead-bismuth-cooled (LBE) fast reactors. These demonstration plans are evaluated in this section, as are some of the technical problems which may be encountered in trying to achieve both in a single project. MIRT considers that a staged approach would be highly beneficial to mitigate these problems.

In Europe, the companies and research institutions that are members of the Sustainable Nuclear Energy Technology Platform (SNETP) have articulated a Strategic Research Agenda (SRA) for the development of nuclear power. This includes exploring partitioning and transmutation (P&T), for reducing the amount of radioactive waste that must be disposed of geologically, as well as the development of ADS technology to allow the transmutation of minor actinides in fuel in high concentration in reactor cores. However, the prioritisation of the many components of the SNETP SRA has yet to be determined. ADS will be assessed alongside other systems with the potential to achieve transmutation at industrial scale and a selection of those systems offering the best industrial prospects will be made in 2012. If ADS were chosen, the technology would have to be demonstrated by about 2020. An experimental accelerator-driven transmutation system (XT-ADS) would then be required with a power of 50-100 MWth: this XT-ADS machine is essentially identical to the MYRRHA facility. In the longer term, a European Facility for Industrial Transmutation (EFIT) is envisaged.

Thus the SNETP states that the XT-ADS/MYRRHA facility is intended to:

- demonstrate the ADS principle and contribute to the longer-term development of minor actinide fuels,
- contribute to demonstrations of the potential of lead-cooled reactor systems (LFR);
- act as a fast spectrum irradiation facility in Europe.

It is therefore important to find a reasonable balance among demonstration, testing and research aspects, to ensure that the requirements each places on MYRRHA can be met.

2.1.1 Accelerator-driven systems

The purpose foreseen for ADS is the “burning” of transuranic elements, particularly the minor actinides (Np, Am and Cm) that place severe constraints on geological disposal of nuclear waste, more effectively and more safely than is achievable in critical reactors. The fraction of neutrons which are delayed in the fission of minor actinides is much smaller than for uranium, with the result that control of a critical core comprising mostly minor actinide fuel is expected to be difficult, yet using few largely-minor-actinide-fuelled reactors may prove more advantageous than distributing minor actinide fuel throughout the whole reactor fleet. ADS can achieve the required control and safely burn the transuranics in a largely minor-actinide fuelled core.

Although the driver fuel proposed for MYRRHA does not contain minor actinides it would demonstrate the essential features of ADS for the first time, that is, the combination of a high-power proton-beam accelerator, spallation source and a subcritical core. The scientific and technological value of this demonstration would therefore be very high if successfully achieved.

The technical problems to be overcome are not trivial. A high-power proton-beam accelerator that meets the project reliability requirements has yet to be developed; the techniques for precise positioning and controlled displacement of the proton beam need to be mastered; maintaining a stable, free surface of flowing lead-bismuth liquid target is also necessary; these are all formidable challenges. These challenges are recognised by the project team and were clearly explained to the review team. Significant advancements have already been made in the FP6 EURATOM project EUROTRANS (EUROpean Research Programme for the TRANsmutation of High-level Nuclear Waste in an Accelerator-driven System) and in the FP7 EURATOM project GETMAT (Generation IV and Transmutation Materials). Success in solving the remaining problems depends on intensive R&D, which will also find its way into the FP7 EURATOM project CDT (Central Design Team) which works on the detailed design of XT-ADS/MYRRHA.

It should also be pointed out that there may be a question of timing, of whether the demonstration of ADS will eventually prove necessary within the time frame proposed for MYRRHA, as Belgian and/or European fuel cycle and waste management strategies evolve. It should also be kept in mind that the successful demonstration of ADS is only part of P&T; advanced fuel cycle technology in which substantial amounts of minor actinides are handled and incorporated into new fuel is also necessary. This is still in a very early stage of development (NEA, 2006).

2.1.2 Lead-cooled fast reactors

Liquid lead or a lead-bismuth eutectic (LBE) are candidate coolants for future fast reactors, the current priority being on lead because of limited global resources of bismuth. Although substantial investment has been made in and experience accumulated with sodium-cooled fast reactor (SFR) technologies, these have experienced operation and maintenance problems due to the coolant being a liquid metal (inspection and repair under an opaque liquid

metal is more difficult than when the coolant is gas or water) and to the high chemical reactivity of sodium. In addition, the relatively low boiling point of sodium (883°C) necessitates careful design to avoid damaging power transients and to ensure reactor safety. The use of lead instead of sodium would solve some of these problems but would introduce others. For example, both erosion and corrosion of structural materials by lead or lead-bismuth can become severe as the temperature exceeds 500°C. The only experience with heavy-metal cooling to date is that of the LBE-cooled submarine reactors of about 150 MWth in Russia, whose development began in the 1950s. Detailed comparisons of SFR and lead-cooled fast reactors (LFR) can be found in the literature (IAEA, 2002).

Coolant temperature is a key parameter in these considerations. Regardless of the coolant material, an outlet temperature above 450°C is accepted as being desirable in a commercial fast reactor, for obtaining good thermal efficiency and hence acceptable unit capital costs. In MYRRHA, the use of LBE instead of lead, limiting the outlet temperature of 400°C, will limit its ability to demonstrate technologies for liquid-lead-cooled reactors but might well allow valuable first steps to be taken in the demonstration of LFR technology. More directly, relevant demonstration steps would need to follow (probably from studies made under the Generation IV International Forum), but the necessary work might be done elsewhere, for example in Russia.

A remarkable design feature of MYRRHA is that the core-support structure is above the core. Since this arrangement seems inevitable for realising both the ADS and LFR modes, the inspection and maintenance techniques used on this part of the reactor must be devised with special care. A staged approach should be considered, where the realisation of the ADS mode is postponed until sufficient confidence in operation and maintenance in the LFR mode is obtained.

2.2 Research and/or commercial services

The Belgian government would like to know which role for MYRRHA should be emphasised, its research and demonstration role or that of providing services, such as testing of reactor materials and acting as a back-up for the production of medical isotopes and Si doping.

As designed, MYRRHA should eventually be able to fulfil many roles, but because it is a very ambitious, challenging and complicated facility the main task in the early years of operation will be to show that it can operate reliably (i.e. with high availability) and safely over long periods. Only when this has been achieved will the supply of routine services become a realistic prospect. Material testing is sometimes fairly flexible in time, but it also often requires very reliable, constant and predicted conditions. It is very hard to say how much time will be needed to reach these conditions, but several years is a reasonable guess.

Moreover, the suitability of fast neutrons for producing medical isotopes and Si doping needs to be verified, as well as the practicability of inserting, maintaining and replacing the neutron moderators that would be needed for those applications that are usually performed in thermal-neutron Material Test Reactors (MTR). In addition, because of the long spent fuel handling times in

liquid-metal-cooled reactors, any medical isotopes produced in MYRRHA are likely to be mainly medium-lived isotopes such as ^{60}Co and ^{14}C rather than the short-lived isotopes (such as ^{99}Tc or ^{99}Mo) which are produced in MTR.

The MIRT therefore suggests focusing MYRRHA initially on research, working progressively towards stable, reliable operation whilst demonstrating the feasibility of a lead-bismuth-cooled fast reactor and of an accelerator-driven system. When this has been done, MYRRHA should be able to provide suitable conditions for testing materials and for making some medium-lived radioisotopes which need a very high neutron flux and can be therefore be used as a back-up for producing other radioisotopes.

2.3 Multi-purpose or focused facility

The rationale for the MYRRHA design derives very clearly from the several goals of the project and the technical specifications that are required to achieve them. Thus:

- The decision to operate as soon as 2020 with a facility comprising three major innovative items (accelerator, spallation target and subcritical core) imposes a requirement to use mature technologies wherever possible. Restricting innovation as far as possible does limit the associated risks, but those remaining are still quite substantial: especially in the coolant, the fuel and the structural materials, all of which are either not yet validated or hard to procure.
- Irradiation of materials by fast neutrons is a critical need of the science and engineering communities developing materials for fission or fusion reactors. Reaching the high fast-neutron flux of 10^{15} n/cm².s (>0.75 MeV) required for accelerated testing of materials requires a fairly high power density in the reactor core, calling for highly efficient heat removal, for which liquid metals are very well suited.
- The in-reactor transmutation of minor actinides requires not only fast neutrons, to cause fission in even-atomic-number isotopes, but also some mainly-minor-actinide fuel, to avoid spreading the difficulties of fabricating fuel containing minor actinides across all fuel. Although it may be possible to use some minor-actinide assemblies in critical fast reactors, additional safety margins and/or large loads of minor-actinide fuel may be sought through operation in subcritical mode, i.e. with a controllable external neutron source, such as the MYRRHA spallation target. The very high neutron flux production of the target is driven by the spallation reaction on heavy nuclei. Spallation is induced by a high current of protons delivered by a high-energy linear accelerator.
- Some of the reactor designs proposed for future generations of nuclear reactors include high performance coolants, among them liquid metals. Technological demonstration of these coolants, especially of heavy liquid metals, is a must, together with the proper fuels and structural materials and requires moderate-power demonstration cores operated in critical mode.

The choice of lead-bismuth as both core coolant and spallation target medium does provide a common answer to these last two issues. However, the synergy between the technical requirements of the other goals is much less evident, and SCK•CEN's proposed multi-purpose approach, with little overlap between individual needs, does lead to a daunting accumulation of technical requirements. The probability of successful operation of all the assembled items at once will be the product of the individual probabilities of success of the different components (assumed independent). As the accelerator, the spallation target and the subcritical core are each innovative and challenging items, one is led to examine risk-reducing alternatives to the reference plan, in which the simultaneous and reliable operation of all items is sought at the first milestone.

Focusing the project initially on one single goal would significantly reduce the risks. For example, one could achieve high fluxes for irradiation services with a reactor in critical mode, without facing the challenges of the accelerator and spallation source at the same time. In contrast, focusing initially only on waste transmutation and ADS demonstration would not reduce the total risk. This goal does require the simultaneous operation of all three major subsystems, although high reliability may not be required in the context of a time-limited experiment.

However, it is the opinion of MIRT that, if the project had to focus on one goal only, the ADS demonstrator would make the most unique contribution to the national and European scientific and technical communities, as well as making the widest use of industrial networks in Belgium and meriting most national, regional and local government support. The technical risk might therefore have to stay high for this reason.

On the assumption that ADS demonstration is the ultimate goal, one could still seek risk reduction by increasing separately and in parallel the performance and reliability of the major elements of MYRRHA. This could mean for instance:

- Progressive increase of the accelerator's proton current and reliability while serving the needs of accelerator-based scientific communities (radioactive beams, proton therapy, proton-based isotope production, accelerator science,...), including of course the development needs for the neutron spallation source.
- Progressive increase of the reactor power in critical mode while serving the needs of irradiation for materials science, as well as for doping electronic materials, medical isotope production.
- Progressive increase of the flux of the neutron spallation source while serving the needs of fast and thermal neutron physics communities,
- Final integration and simultaneous operation of the accelerator, spallation target and reactor (in subcritical mode); demonstration of the ADS concept for the transmutation of minor actinides. This would be undertaken as soon as the above-mentioned items had achieved the necessary performance and reliability.

The above scenario is an illustration of an alternative project strategy that could reduce the technical risks along the path forward and provide useful technical services more quickly. The price to pay for such a strategy is that the assumed overarching goal is the last to be reached, and not the first as in the reference case. One may assume that other paths are possible, filling the gap between the “ADS demo comes first” and the “ADS demo comes last” scenarios, with varying risks levels. In parallel to detailed technical studies and risk reduction strategies on the individual items, a search for lower risk progression paths to the ultimate goal could be profitable.

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International Atomic Energy Agency (IAEA) (2002), *Comparative Assessment of Thermo-physical and Thermo-hydraulic Characteristics of Lead, Lead-bismuth and Sodium Coolants for Fast Reactors*, IAEA-TECDOC-1289, IAEA, Vienna.

Chapter 3: Project and operational issues

3.1 Project management

MYRRHA has made significant innovations in several areas, especially in accelerator and nuclear reactor technology. Individually, the two segments are on the leading edge of their respective fields. That helps to make the project an exciting and attractive endeavour for SCK•CEN but managing it will require a substantial effort, integrating research and development work, design, construction, commissioning and eventual operation.

For mature technologies, large projects often use an experienced engineering procurement and construction company to minimise investor risks. This practice has been highly successful in the past for many conventional projects. The MYRRHA team believes that such an organisation is unlikely to be cost-effective here because of the novelty of the technologies involved. For that reason the project is currently organised with a Central Project Team and an Owner Engineering Team that are both part of a Central Project Management Team reporting to an SCK•CEN Owners Consortium Council that will function as a governing board. As the project matures, the plan is to establish a Facility Operation Team that will work with the Central Project Team to prepare for and lead commissioning and eventually take over operation of the facility. This is a sound approach, but one with many team interfaces that will require substantial management effort to avoid integration problems.

In this regard, there are lessons (Strawbridge, 2005) to be learned from the management of other large technology-intensive projects such as the United States' Spallation Neutron Source (SNS), which had a similar complex interface with regard to:

- 1) project management across organisational boundaries;
- 2) integration of different teams and the good control of the interfaces between them;
- 3) administration of procurement contracts;
- 4) careful and systematic attention to management risks, with a central reserve for those that are at this stage of the project both unknown and unexpected.

The MYRRHA plan is to divide the facility into large blocks that can be procured separately. This is an area that requires special consideration, especially with regard to the proton linear accelerator. The approach was tried for SNS, since Oak Ridge National Laboratory had built and operated several

reactors but had very little accelerator expertise when SNS was started. The initial plan was to have separate laboratory partners deliver large, integrated, operational accelerator sections to the site and supply the expertise needed to install and commission each of them. In practice, the approach was discontinued because it did not cope with the interface problems, escalating installation expense, and its inability to transfer technical knowledge to SNS effectively.

As a result, the SNS central project team took over the management of the procurement and developed in-house expertise that transferred the essential knowledge to the operating staff. One way to accomplish this for MYRRHA would be for SCK•CEN to build a core competency in accelerator technology well before the accelerator is operational, by bringing together at SCK•CEN a partnership of industry, university and other European experts to assist in determining the specifications for the accelerator and to complete some of the necessary R&D.

3.2 Capital and operational costs and project schedule

Presentations to the MIRT gave only high-level cost and schedule information and we did not attempt to perform a detailed audit on either. However, we did attempt to assess the reasonableness of the estimates, based on past experience with similar facilities. Additional design detail will eventually allow a better determination of cost and schedule, especially as MYRRHA's requirements become well-enough specified to allow real quotes for components to be sought. At this point, it is important for the project to include adequate contingency to cover uncertainties in estimated costs and schedules as well as a management reserve to cover any items that may be required but are not known to be needed at this stage.

The estimated capital cost of the accelerator agrees well with that of similar equipment used in the SNS, once that cost has been scaled to the power level of MYRRHA and escalated to 2009 funds. Because the entire front end of the MYRRHA linear accelerator is duplicated to achieve high reliability, there is a very strong incentive not to set over-conservative beam trip requirements with consequent impact on costs.

The investment cost of the MYRRHA subcritical fast reactor is estimated at about EUR 650 M (i.e. total project cost of EUR 960 M less costs directly attributed to the accelerator). For comparison the Jules Horowitz experimental reactor (JHR) now under construction in France, has recently been re-evaluated at EUR 640 M, including provisions for contingencies. The reactor cost comparison is less useful than that for the accelerator because MYRRHA technologies are substantially different and more complex than those in JHR, though MYRRHA is somewhat smaller (57 MW c.f. 100 MW for JHR).

With the above caveats, the overall capital cost estimate appears to be reasonable. The EUR 960 M total cost presented to MIRT for the entire project included a contingency of EUR 193 M, about 25%, which is not impossible for a complex project, but a bit low for an innovative project at this stage, where contingencies are generally in the 30-35% range.

Operating costs of EUR 61 M/year for MYRRHA are based on a detailed estimate of staff, electrical power and equipment for an operating schedule of three cycles of three months with two normal shutdowns and a longer, maintenance shutdown every 14 months. One approach to judging the reasonableness of the MYRRHA estimate is by looking at actual or estimated operating costs for similar facilities. A very general rule for accelerator facilities is that initial operating costs are typically 10% of the capital cost. Applying the same factor to the whole project suggests that EUR 61 M/year is likely to be an underestimate of what is required (see also the comparison with ILL at Grenoble in Section 3.7)

The MYRRHA schedule covered a period of 11 years from initial R&D to the beginning of operation. The details in the Business Plan and in a separate presentation on Project Management differed somewhat in their time frames, but that probably just shows the evolving nature of the planning process. The discussion here is based on the Business Plan, which has the design lasting two years followed by two years of specification development and three years of construction.

The planned method of construction, using large-lot procurement, requires substantial front-end planning and item specification. It therefore seems to MIRT that the two years allowed for that activity is too short to make certain that the equipment requirements are specified well enough and that it begins too soon (only three years) after initiation of the project to be sure that changes coming with further design maturity will not cause substantial cost escalation. In other projects of this nature, detailed engineering design often proceeds concurrently with procurement and construction. For the SNS, design therefore lasted a total of nine years. In the MYRRHA project as currently planned, the detailed design appears to be part of the large-lot procurement process, making development of the requirements and integration of the component designs extremely important to assure a functional, complete system after installation.

Construction and on-site assembly are foreseen by MYRRHA to take four years. This duration can be compared to that of the SNS project which had a construction and equipment installation period of six and a half years. After construction, SNS had a period of three and a half years of commissioning, compared to the two years presented to the MIRT.

In summary, the overall estimated capital and operating costs for MYRRHA, as presented to MIRT, are in reasonable agreement with projects of a similar nature, but there was no material provided on inclusion of a management reserve and the contingency is lower than is typical for a project at this stage of maturity. The schedule to full operation appears to be very optimistic, given the complex management and integration demands of the method of construction and the first-of-a-kind nature of the equipment.

3.3 Procurement and qualification of fuel

For MYRRHA, MOX fuel with 30-35% Pu was originally envisaged. Its procurement is recognised as a critical issue in the risk management of the project.

Among those countries party to the Nuclear Non-Proliferation Treaty (NPT), only Japan has retained the technical capability to manufacture such highly-enriched MOX fuel elements at the scale required for a full core of MYRRHA. However, even the Japan Atomic Energy Agency (JAEA) has a production capacity barely matching the demand from its own fast reactors (MONJU and JOYO). Moreover, since JAEA itself has insufficient plutonium, either plutonium would have to be supplied from Japan Nuclear Fuel Limited, a private company operating the Rokkasho Reprocessing Plant or it must be transported from Europe to Japan for this purpose. Further, current Japanese recycling policy does not allow for providing services or products outside Japan. This implies obtaining the MOX fuel from Japan would require negotiations of a political nature, with uncertainty as regards the outcome.

In France, a prototype sodium-cooled fast reactor of 600-1 500 MWth is being studied. If the project is approved early in the next decade, fuel manufacturing will begin before 2020. It should then be possible for the French project to include the MOX production for MYRRHA. In any case it is advisable to have discussions on this matter with the relevant countries as soon as possible.

An alternative that was presented to MIRT by the MYRRHA team at a very late stage of its review was to use a starter core of LEU (20% ^{235}U) instead of MOX. MIRT did not have time to examine this proposal in detail, but feels that such a significant change of strategy warrants careful examination, in view of the trade-offs between the earlier availability of a ^{235}U core and the limits it would place on the later performance of the MYRRHA.

Discussions about fuel supply should also consider fuel qualification. MYRRHA plans to use 9Cr ferrite-martensitic steel (FMS) for cladding and wrapper tubes, which has not been used in any other reactor. The operating temperature range of the fuel element is also lower than those of other fast-reactor programmes. The 9Cr FMS is preferred for MYRRHA over more traditional fast-reactor fuel-cladding materials because of its better compatibility with the lead-bismuth coolant. On the other hand, 15-15 Ti austenitic steel, which has been developed in the European fast reactor programmes, is also regarded as a candidate for the first core, albeit with a lower target fuel burn-up. However, given the cost and the time to qualify any new clad, the wisdom of retaining two types of cladding materials as candidates for a small reactor like MYRRHA has to be questioned.

It is often necessary to make some long-term commitment in purchasing the precision tubes with special materials specifications of the kind that will be required. Finally, a minimum set of irradiation data of the fuel element is required for licensing. The whole procedure from planning to post-irradiation examination usually takes seven to ten years.

3.4 Licensing issues

Constructing and commissioning a first-of-a-kind lead-bismuth-cooled reactor with unique design features such as accelerator-drive, a spallation module and subcritical reactor core will be a massive task. It will call for early exchanges between the MYRRHA Project Team and the Belgian Federal Agency for Nuclear

Control assisted by the appropriate Scientific Councils of Experts. This is essential for the Federal Agency for Nuclear Control to prescribe safety requirements that will apply to the project and for preventing any delay in the process of obtaining the necessary permits.

On the basis of preparatory work in other countries expecting to file applications for prototypes related to Generation IV systems, the expectations of the Belgium Federal Agency for Nuclear Control may include:

- A clear definition of safety goals, analysis of hazards and of the safety features which mitigate them, in order to conduct the licensing procedure for MYRRHA along similar lines (at least) to those that are in use for Generation III advanced light water reactors. The applicable regulations here are in process of international harmonisation through the Multinational Design Evaluation Programme (the MDEP initiative) launched by the safety authorities of countries involved in the Generation IV Forum and MYRRHA will need to take this into account.
- A survey of past experience of lead-bismuth-cooled reactors and related technologies (liquid metal management, corrosion, instrumentation...).
- Justification for MYRRHA's unique design features (accelerator drive, spallation module, subcritical reactor core...) and extensive references to related systems and technologies.
- The rationale for the R&D programme subsequently considered for MYRRHA.

This information is essential for the Federal Agency for Nuclear Control to set safety goals for MYRRHA and establish a reference framework for analysing the safety features of the project against the goals.

Like prototypes of Generation IV systems, the MYRRHA safety case will have to demonstrate adequate defence-in-depth provisions to prevent, mitigate and manage severe accidents and to protect the plant from external events (airplane crashes,...). Furthermore, it will be necessary to demonstrate (possibly with dedicated experiments) the safe management of specific abnormal situations such as accelerator beam trips or defective operation or failure of the spallation module.

The documentation needed to initiate the licensing applications will have to cover not only detailed design features and planned safety measures of MYRRHA but also studies of risk analysis and environmental impact, so as to provide the Federal Agency with an as accurate as possible information on design features, time line and milestones of the project.

In order to facilitate the MYRRHA licensing process a reasonable cadre of skilled manpower is required, with experience in both critical and subcritical reactor systems and in heavy liquid metal technology. At present, such manpower is not readily available on the market. However, the Belgium Nuclear Higher Education Network (BNEN), which was created in 2001 by five Belgian universities and SCK•CEN, invests a lot of effort in maintaining and developing a high quality programme in nuclear engineering in Belgium. Driven by SCK•CEN, the efforts of BNEN should be further strengthened and directed

towards fast reactors and ADS, so that enough experts leave the education programme and could be hired by the Belgium licensing authority to work on MYRRHA when needed. Given the level of innovation in MYRRHA, one can imagine the licensing process moving in parallel with progress in design, for example starting with outline approval before construction begins.

3.5 Commissioning and performance

During its commissioning period, MYRRHA must be brought to the level of performance needed to support routine operations at high power, especially if SCK•CEN is to obtain the revenue from irradiation services foreseen in its Business Plan. As mentioned earlier, full performance will require substantial effort to achieve reliable high-power operation of the linear accelerator, the LBE spallation source and the subcritical reactor within the two-year period that is now planned. Whereas similar accelerator systems have been successfully commissioned, there is no comparable experience of commissioning an accelerator coupled to a LBE subcritical reactor under the scrutiny of a nuclear safety authority.

Achieving the MYRRHA accelerator beam trip requirement is recognised as one of the most important parts of the project. Incorporation of fault-tolerant design and engineering is evident in the present plan and there have been two independent reliability analyses that predict that the goal can be met with the current design. Nevertheless, it will be only during commissioning that the entire system can be tested. It is therefore possible that achieving the overall reliability aimed for may require some hardware modification, incorporating the lessons learned from any problems encountered during commissioning.

As initially presented to the MIRT, the most demanding reliability requirement was that the number of proton beam trips longer than one second should be limited to a maximum of five in a three-month period. This is to prevent mechanical failure of components from low-cycle fatigue induced by changes in beam power and consequent temperature gradients in the subcritical assembly components. After the first MIRT meeting, where the over-conservative nature of the assumptions was pointed out, the MYRRHA team revisited their lifetime estimates, making more detailed calculations for several representative components. The new results are very encouraging. Even with quite conservative assumptions remaining in the new calculations, the number of allowable trips was shown to be much larger than the initial estimates. The preliminary conclusion from the new study was that up to 800 beam trips of duration less than 5 minutes per 30-day operating cycle, up to a maximum of 2 500 per year, were allowable; and that there could be 8 trips of duration longer than 5 minutes per operating cycle, up to a maximum of 25 per year. These numbers still require very high accelerator reliability, but are much more likely to be achievable during the commissioning period. SNS, a machine not designed for the same level of reliability as MYRRHA, nearly meets those requirements now, and the European Synchrotron Radiation Facility (ESRF) has the equivalent of 20 such beam interruptions per 3-month period. The new results need to be carefully checked, but if further calculations and measurements support the new MYRRHA analysis, there is good likelihood that the facility will meet this

reliability goal. In addition, because all beam trips will reduce component lifetime somewhat, designing vulnerable systems for periodic replacement can further assure that the facility will remain operational for the expected lifetime.

Other aspects of accelerator performance, such as operation at the required beam energy, current and beam loss are not far different from the demonstrated performance at other high-power linear accelerators or on component test stands. Achieving success will depend heavily on many things, but proper management and integration will be essential during equipment installation and commissioning. In particular, the role and impact of the safety authority during commissioning needs to be allowed for if the process is to be completed in the planned time period.

3.6 Hands-on experience and commissioning performance

MYRRHA would be the first large-scale nuclear system cooled by a heavy liquid metal in an OECD member country. In order to reduce the technological risks, a significant increase of SCK•CEN capability via a series of scaled experiments, both single-effect and integral in character, should be envisaged. Such an approach to providing the hands-on experience which is so valuable in this kind of project, and which should cover the capabilities and facilities of international partners, is not well explained in the documents provided to MIRT.

As an example, all the major components of MYRRHA (such as fuel elements, spallation target and liquid-metal loop, pumps, heat exchangers, purification system, remote handling system and decay heat removal system) should be investigated in detail in stand-alone, out-of-pile, well-instrumented simulation experiments. The tests can be on 1:1 scaled components or on properly down-scaled model geometries. This approach has been adopted with great success by the international MEGAPIE consortium.

After the test of each major component by itself, major groups of components and later on all components together should be tested out-of-pile (e.g. electrically heated) in order to investigate their integral steady-state and transient system behaviour. Before going to the full-size demonstration, these integral system tests could be performed on a say 1:8 scale mock-up of MYRRHA.

Mounting a large number of single component and integral tests with a large variation of system parameters may sound excessive and expensive. However, the future MYRRHA operational team needs to be familiar and experienced with heavy liquid metal coolant, its characteristics and every-day handling. This experience with the new coolant and the new machine can best be learnt through hands-on experience on loops and mock-ups operated at SCK•CEN. An alternative possibility is the delegation of staff to other European laboratories, such as ENEA, KIT/FZK, KTH or PSI, where similar experiments are being or have been performed.

3.7 Financial costs and revenues in operation

In the 2009 MYRRHA Business Plan, presented to MIRT by the SCK•CEN team at the outset of our study, SCK•CEN notes that revenue streams amounting to

about EUR 61 M/year would be needed to cover the expected operational costs of MYRRHA. It suggested that these revenues could be obtained from a variety of sources as outlined in the table below.

Table 1: Revenues expected to cover operational costs

| Item | Source of revenue | Amount (EUR M/year) |
|------|---|---------------------|
| 1 | Owners' consortium | 25.3 |
| 2 | From SCK•CEN for R&D services | 2.5 |
| 3 | From other partners for R&D services | 14.6 |
| 4 | For R&D support to international programmes | 10.0 |
| 5 | Manufacture of radioisotopes | 2.2 |
| 6 | Doping of silicon | 4.5 |
| 7 | Other industrial services | 1.0 |
| 8 | Consultancy and training | 1.0 |
| 9 | Total revenues | 61.1 |

The business plan does recognise the need for additional revenues, to repay any loan capital made available to SCK•CEN for the construction of MYRRHA (by the European Investment Bank or others), as well as for paying interest accrued on such loans during the period of construction, commissioning and beyond. However, it gives no details of how such additional funds might be obtained. In this section of its report MIRT therefore simply notes that additional revenues over and above EUR 61 M/year will presumably also have to be found, unless all the capital needed for MYRRHA construction is provided by the governments of Belgium, Flanders and Kempen and via EU grants, without any requirement for payment of interest or repayment of capital.

Another complicating feature in the business plan is that Item 3 in the table is assumed to be financially neutral overall, that is that the R&D services carried out for these partners will actually cost some EUR 14.6 M/year because of the need to strengthen SCK•CEN to do the work. The MYRRHA team assumes that these strengthening costs will not be incurred unless these particular funds are available. MIRT is doubtful about this approach, since it effectively assumes that this additional R&D is charged at marginal costs. Doing this risks undermining the advantages to “owners” of being part of the owners' consortium, because it will be better for most users not to join the owners' consortium but to buy R&D services later at marginal costs. It therefore seems to MIRT to be more sensible at this stage to lump Items 1, 2 and 3 together, as revenue from owners and partners, all of whom contribute to basic operating costs as well as to marginal R&D costs.

MIRT therefore assessed the MYRRHA team's assertion that ongoing operation costs of EUR 61 M/year can be covered by revenues roughly as in the table. Two general comments are perhaps worth making.

The first is that the total budget of EUR 61 M/year, though in the right “ball park”, may be a bit too small. Thus the current actual annual cost of running a simpler reactor facility at the Institute Laue-Langevin (ILL) in Grenoble is

EUR 78.5 M/year. Yet, in comparison with the international funds available for nuclear R&D in Europe, even EUR 61 M/year is quite large. For example it is larger than the total annual spending of the European Commission on indirect action fission R&D (i.e. available to be spent outside the Commission's Joint Research Centre facilities) in the current EURATOM FP7 programme (EUR 287 M over five years). The Commission does also expect to spend some EUR 517 M over five years on work on nuclear fission within its Joint Research Centre, but it is unlikely that this would be made available for MYRRHA since much is concerned with EURATOM safeguards, decommissioning old facilities, maintaining our expertise in transuranics, etc. It therefore seems to MIRT to be unlikely that the EU will be able to make a substantial contribution to total MYRRHA costs unless the EU as a whole is able to expand its EURATOM fission programme substantially. This is difficult, given the requirement for unanimous decisions still in the terms of the EURATOM treaty, because of the unwillingness of some member states to allow the EURATOM work to move into new areas or the funding to grow.

The second general comment is that the contribution from SCK•CEN/Belgium itself seems to be rather small. In their Business Plan, SCK•CEN assumes that they will constitute some 40% of the owners' consortium that they expect to provide EUR 25 M/year (see Item 1 in the table above), i.e. EUR 10 M/year from SCK•CEN. In addition SCK•CEN expects to provide some EUR 2.5 M/year direct research funding (Item 2 in the table). This implies a total SCK•CEN contribution of some 20% of the total operational costs whereas, in many trans-European and international projects/facilities the partners from outside participate only if the host organisation and country pays a bigger host premium than that. For example Europe pays 45% of ITER costs despite having six major international partners (China, India, Japan, Korea, Russia and the USA).

3.7.1 Owners and partners

It is evident from the table that the most important step in providing the required revenues will be setting up an owners' consortium, which SCK•CEN assumes will provide 40% of the operating costs but may have to provide more. Almost equally important is to set up a partners' group, Items 3 and 4 in the table, who are willing to provide another EUR 24.6 M/year for the research they can carry out in the MYRRHA facility. The straightforward commercial services (Items 5, 6 and 7) are less urgent, since any service contracts which may eventually be obtained will almost certainly have to wait until the facility is seen by the commercial customers to be operating successfully and reliably.

The ILL might again be a useful analogue for MYRRHA. ILL provides "neutrons for science" and has both an owners' consortium (which it calls its associates – France, Germany and the United Kingdom) and also a group of "scientific members", roughly equivalent to MYRRHA's partners. For ILL the three associates provide EUR 59.6 M/year of the EUR 78.5 M/year total costs of the facility (i.e. 76%) and the 10 scientific members provide EUR 14.9 M/year (19%). ILL has been operating since the 1960s and it is evident that the scientific communities in both associate and member countries judge that the usefulness of the neutron beams provided by the facility are worth the money they have to

pay for them. But a very wide spectrum of scientists wish to use neutrons to probe the materials they are studying and it seems to us likely that MYRRHA will have to rely on a much narrower range of users.

It is therefore crucial for the MYRRHA team to establish its owners' consortium and its group of partners before the project gets properly underway. SCK•CEN needs to have very good answers to the questions, "Who will be the owners/partners?" (it does list possibilities in its Business Plan), and more importantly, "What benefits will they get for their commitment?", to justify their involvement.

3.7.2 Revenue from users

MIRT envisages there might be five types of MYRRHA users:

- Those interested in exploring and/or developing nuclear waste transmutation (in particular burning minor actinides) using accelerator-driven fast reactors. MIRT believes that, if a group of such countries does come into existence in the EU, the revenues MYRRHA needs will be provided very easily, since it would be uniquely placed to carry out this work. The risk at the current stage of MYRRHA development is that most countries have not yet made up their minds about ADS-driven partitioning and transmutation and it is possible that none will be interested in it when MYRRHA comes on stream. It is therefore crucial to discover in the next year or two whether a group of EU member states can be established which is at least committed to evaluating ADS P&T and to establishing MYRRHA as its lead facility. P&T is already part of the Strategic Research Agenda of the EU's Sustainable Nuclear Energy Technology Platform but SCK•CEN needs to do what it can to make MYRRHA the flagship facility in a serious European P&T programme.
- Those interested in exploring and/or developing lead-cooled fast neutron reactors (LFR). These are currently part of the Generation-IV International Forum programme, alongside two other fast reactors (sodium- and gas-cooled) and three other advanced thermal reactors. It is virtually certain that neither six reactor types, nor three fast reactors, will survive as the programme moves from paper studies to real work. If LFR is retained MYRRHA should be able to win some or all of the initial research work, though this is an area in which Russia may wish to contribute to Generation IV.
- Those organisations who might want to use MYRRHA as a materials irradiation test facility to help develop a new generation of fast neutron fission reactors. In this case it does not matter to MYRRHA which fast reactor type(s) is chosen as long as one or more are – and MIRT believes that the development of one or two fast reactor types will almost certainly be continued. Thus there will definitely be customers for the facility, but they may not be willing to spend many tens of EUR M/year on materials irradiation because they will have other options as well as MYRRHA. They already have much materials data from earlier fast reactors such as Phénix in France, FFTF in the United States and PFR in the United Kingdom. The Japanese reactor MONJU looks likely to return

to operation next year and new development-scale fast reactors of the type(s) chosen in Generation IV will almost certainly have to be built in Europe anyway, for system testing and development. Moreover, our now-much-improved understanding of radiation damage will allow the developers to do much more work with specialised accelerators providing heavy ion bombardment, such as JANNUS at Saclay, than was possible in previous decades.

- Those owners/partners who want to use MYRRHA as a materials irradiation test facility for developing materials for fusion reactors. Again MIRT believes there will be such customers for the facility, but they are unlikely to be willing to spend many tens of EUR M/year on irradiation, though for different reasons. They will also try to do as much work as possible with facilities like JANNUS and they will almost inevitably have to build their own specialised facilities such as the proposed International Fusion Materials Irradiation Facility (IFMIF), because the neutron spectrum in MYRRHA does not mimic perfectly that which will be found in fusion reactors. Other spallation neutron sources such as SINQ in Switzerland and potentially LANSCE in the United States would also be able to compete with MYRRHA for this work; since there is little advantage in having both fission and spallation neutrons in this work.
- Those partners who want to use the neutrons produced in MYRRHA for studies in fundamental nuclear physics. We were told when in Kasterlee about some of the research which might be carried out using MYRRHA but it seemed unlikely that these users would be able to contribute revenues beyond EUR 1 or 2 M/year

In conclusion, the revenue streams anticipated in the Business Plan are not impossible to achieve but MIRT believes they will be achieved relatively easily only if a number of EU countries decide to explore and perhaps develop ADS-driven P&T. Other sources of revenue are most unlikely to allow SCK•CEN to achieve the revenue stream of EUR 60 M/year (or more if capital and interest payments are also required) the organisation says is necessary. Alongside removing uncertainties about the technical design and construction costs, the MYRRHA team therefore needs to devote much effort to setting up the owners'/partners' consortia, to convert assumptions about revenues into commitments, albeit conditional on the project making the planned progress.

3.8 Non-proliferation issues

The non-proliferation characteristics of MYRRHA were emphasised by the Belgian government at a late stage in the review process and the MIRT has therefore made only a limited evaluation of the issue. It notes that this aspect of MYRRHA is best considered in the broader context of Belgian policy for the back-end of the nuclear fuel cycle and not specifically in the context of the MYRRHA review. Thus, there are many possible strategies to optimise the back-end of the fuel cycle while minimising the proliferation risk, but their pros and cons must be analysed holistically. By and large, the choice between critical fast reactors and accelerator-driven hybrid systems in any of these strategies will have little impact on its proliferation resistance.

However, the MIRT recognises that the MYRRHA team has taken very seriously the questions related to safeguards and non-proliferation aspects of the facility itself. The team has defined proliferation threats and barriers according to guidelines proposed by the Pacific Northwest National Laboratory in the USA, and evaluated both MYRRHA as proposed and the existing BR2 reactor against these definitions. This evaluation concludes that MYRRHA is more proliferation resistant than the BR2 in one respect, having less easily divertible mixed plutonium-uranium oxide fuel in MYRRHA. In another respect BR2 is better, having a lower material throughput than MYRRHA. Overall, MYRRHA and BR2 perform equally well on issues of safeguards and physical protection.

Given the impeccable record of SCK•CEN in both safeguards and physical protection, the MIRT considers that there is no reason for a more-than-usual concern about the proliferation aspects of the MYRRHA project.

Reference

Strawbridge, C. (2005), "Project Management in Large Collaborations: SNS Lessons Learned for ITER", 21st IEEE/NPS Symposium on Fusion Engineering, September, p1.

Chapter 4: Conclusions and recommendations

The MIRT has concluded unanimously that MYRRHA is an innovative and exciting project, that the facility would be unique in Europe, indeed in the world, and could play a valuable role both in the management of radioactive wastes and also in the development for the longer term of advanced nuclear reactors, both fission and fusion. It could help the EU achieve the vision set out with the launch of Europe's Sustainable Nuclear Energy Technology Platform.

Thus MIRT agrees that the facility, if built and operated as originally envisaged with a compact, plutonium-fuelled core, could partially demonstrate the principle of nuclear incineration (transmutation) of minor actinides and other long-lived radioactive wastes, using fast neutrons in an accelerator-driven system (ADS). In this role MYRRHA is likely to be unique. However, it is not yet possible to know if partitioning and transmutation can add enough value in the disposal of nuclear wastes to justify the additional costs incurred, nor if an accelerator-driven fast reactor system would be necessary to ensure good control and effectiveness of such a process if ultimately used, or whether other incineration strategies would be preferred. MYRRHA could play a role in making such decisions and would undoubtedly have a major role in developing the technology if P&T with ADS were eventually chosen in Europe.

MYRRHA would (if also operated as a critical reactor facility) allow the EU and the international nuclear-power community to evaluate and develop some aspects of lead-cooled fast reactors (LFR). These are one of the three fast-reactor types being considered as part of the international Generation IV programme for developing advanced reactor systems. Once again, MYRRHA could be unique in such a role but it is possible that EU members will not give LFR a very high priority for fast reactor research within the Generation IV programme.

In addition to these applications, MIRT recognises that MYRRHA could provide:

- Fast-neutron irradiation facilities that would enable materials and component testing for both fast fission reactors and also for DT fusion reactors, where the neutrons will be more energetic and helium production will contribute substantially to the materials degradation. In this role MYRRHA will not be unique and it is not yet clear how much of the research work needed to develop fast fission and fusion reactors will be best done in MYRRHA or in more specialised facilities that will also be constructed.
- Spaces with neutron fluxes which could be used for doping silicon crystals and manufacturing radioactive isotopes for medical and

industrial sources. In these production roles MYRRHA is almost certain to have to compete for the work with other facilities such as the Jules Horowitz Reactor currently under construction in France and the proposed PALLAS reactor in the Netherlands, both inherently better placed to provide less expensive and more reliable (and therefore commercially more attractive) thermal neutron irradiation services. In MIRT's view, MYRRHA would not be well placed to compete for this work at least for some time after it is first commissioned, probably many years.

- Energetic proton beams which would be useful for the Belgian and European nuclear science community and/or for the medical community in proton irradiation therapy, etc. Here the question is just how much of the inevitably-limited funds for fundamental nuclear science and medicine will those communities be willing and able to spend at MYRRHA.

Moreover, MIRT has also concluded that, because the MYRRHA design is so innovative, substantial risks remain. Thus the construction costs may well exceed the current estimates when binding quotations for components are obtained. The time to completion may be longer than envisaged, adding interest during construction to any loan component of finance and possibly financial penalties from contracts with researchers/users, who have provided up-front funds for services that cannot be delivered as contracted. The special plutonium-based fuel, required by MYRRHA as originally envisaged, may be difficult and expensive to obtain and to dispose of after use. At a very late stage of this review, the MYRRHA team proposed an alternative starter core, consisting of LEU (20% ^{235}U) instead of MOX, to reduce the fuel supply risk. MIRT has not reviewed this option but notes that it may well impose constraints on what MYRRHA is then able to accomplish.

In summary, MYRRHA is an exciting project with the possibility of many applications but also with substantial risks:

- in cost, that cost and time to completion will exceed the estimates;
- in performance, that the facility will take longer than planned to achieve the intended performance;
- in financing, that external investment funds will not be available and/or revenue streams from users will prove smaller than planned.

MIRT sees no real alternative to the Belgian government's shouldering most of these risks, and we therefore believe that a prudent course of action for Belgium would be a further stage of risk reduction and allocation before proceeding to construction. In our view, this next stage would consist of:

- Carrying out work to freeze (as far as possible) and detail the design, in close collaboration with potential project managers and component suppliers, so that they will be able to indicate project management and component prices as realistically as possible, giving actual quotations where this is achievable. It should also become much more apparent during this process where individual contract risks would eventually

have to lie. Additional research and development work, in close collaboration with potential international research institutions, may also be necessary to reduce or eliminate uncertainties in the design.

- Making a sustained effort to convert the existing general statements of interest from potential users into harder commitments, either to provide up-front funding for construction, or to purchase neutron irradiation facilities from MYRRHA when it is operating.
- Most important, to try to establish whether the European nuclear power community does wish to explore in depth (and perhaps develop) accelerator-driven fast neutron waste incineration. If so, SCK•CEN should position MYRRHA as the lead European ADS facility, the successor to EUROTRANS, in which a practical evaluation of the costs and effectiveness of waste incineration can be carried out and the technology developed if required.

In an innovative project such as MYRRHA some risks are inevitable and their complete elimination is impossible, but minimisation is prudent. MIRT has not attempted to act as a MYRRHA Project steering committee, that is the role of the SCK•CEN Board and/or the Belgian government, but it does offer the following observation on what it believes might be an alternative, lower-risk strategy.

The SCK•CEN team already envisages making use of the accelerator for the Belgian and EU science community, if and when MYRRHA is converted from an ADS to a critical lead-bismuth-cooled reactor. It might therefore be possible to construct the accelerator at Mol primarily for (and partly funded by) the basic scientific community and in parallel construct a critical lead-bismuth-cooled fast reactor primarily as a European contribution to Generation IV, with the option of connecting the two via the spallation source at a later date to allow MYRRHA to operate as an ADS. By constructing the accelerator and reactor separately, it would be possible to decouple the performance risks of the two major components and achieve reliable operation of each before requiring that they successfully operate together.

In making a specific recommendation, MIRT considered the following three main options from which the Belgian government can choose:

- To give the full go-ahead now, including funding, for construction of the facility. This would remove uncertainties about the future of SCK•CEN and provide maximum encouragement to the MYRRHA project team, but the Belgian government would be shouldering large and uncertain financial commitments for the future.
- To give the go-ahead, including funding, for a further phase of work, comprising:
 - detailed design work, supported by R&D when necessary, in close collaboration with potential project managers and component suppliers;
 - conversion of the existing general statements of interest from potential investors and users into hard commitments;

- clarification of the international interest in accelerator-driven fast neutron waste incineration and position MYRRHA as the leading European accelerator-driven system (ADS) facility.
- To abandon the project now due to costs and risks.

MIRT believes that the costs of investing through the next stage are reasonably well specified and are small compared with the potential benefits to SCK•CEN, Kempen, Belgium, and possibly to the EU and the international nuclear energy community of a successful MYRRHA project. We therefore recommend that the Belgian government take the middle of our three options and fund the next phase, with a major focus on risk reduction for the project, so that full go-ahead could be given in two or three years time.

Appendix 1: Terms of reference

This appendix contains the terms of reference provided by the Belgian government to the Nuclear Energy Agency to perform an independent evaluation of the MYRRHA Project planned by SCK•CEN, the Belgian Nuclear Research Centre at Mol.

1 The nuclear energy context

The present world is characterised by a growing energy demand, which causes an increasing pressure on the use of fossil fuels and on the need of the fight against climate change. Apart from the increased efforts on energy conservation, alternatives will have to be sought for the fossil fuels. It is largely recognised that all energy forms will have a role to play. Next to renewable energies, nuclear energy will also have to contribute to the energy mix.

At present 16% of the electricity produced in the world is done by nuclear energy. In Europe, this percentage rises to 31%. According to several possible scenarios, the nuclear share in the energy mix will grow. This growth can be from rather low to very high, according to the assumptions made (see the *Nuclear Energy Outlook 2008* of the Nuclear Energy Agency).

This growing share of nuclear energy will in the short and medium term be covered by reactors of second and third generation. The present reactors of the second generation present a high level of safety and acceptable technical solutions for the long-term management of the spent fuel and the radioactive waste exist. The reactors of the third generation present an even more improved level of safety. The performance of the second and third generations can be considerably improved in the direction of sustainability (waste minimisation, resource optimisation, etc.).

The second and third generations encounter, however, a number of public acceptance problems, amongst which the long-term management of radioactive waste and spent fuel (time scales to which mankind is not accustomed). In order to overcome these problems and to assure the appropriate role of nuclear energy in the long term, the Generation IV Initiative has been launched. With the nuclear systems of the fourth generation, one envisages to increase considerably the sustainability of nuclear energy. The fourth generation includes a number of improvements, amongst which the minimisation of the waste volumes and the considerable reduction of the lifetime of the waste (to time scales to which mankind is more accustomed), through partitioning and transmutation (P&T). In the Generation IV International Forum (GIF), six

concepts have been selected, amongst which three fast spectrum technologies [the sodium-cooled fast reactor (SFR), the lead-cooled fast reactor (LFR) and the gas-cooled fast reactor (GFR)], which allow to transmute radioactive waste in the frame of the corresponding advanced fuel cycles to be developed and, so, to alleviate the constraints on geological disposal.

Other technologies also form part of the Generation IV initiative. They are the very high temperature reactor (VHTR) for high temperature heat applications (hydrogen production,...), the supercritical water-cooled reactor (SCWR), presenting several economic advantages, and the molten salt reactor (MSR), with some interesting characteristics.

Within the P&T goals, radioactive waste can also be transmuted in so-called accelerator-driven systems (ADS), which will have to work in symbiosis with future LWR and FR and for which the appropriate fuel cycles have to be developed.

All the above-mentioned reactor and system developments require technological, material and fuel research. This research will have to be done, amongst others, in several irradiation facilities with different neutron spectra.

2 The European context of irradiation facilities

In the European Union very important initiatives are taken with respect to the security of the energy supply and the fight against climate change. Two of these initiatives are:

- The Sustainable Nuclear Energy Technology Platform (SNE-TP);
- The Strategic Energy Technology Plan (SET-Plan).

The SNE-TP was launched in September 2007. It then published a vision report, which was endorsed by a large number of stakeholders. In this report, reference is made to the widely shared assessment of the situation of material test reactors in the thematic network FEUNMARR. Following this assessment, a European vision has been defined, building on three major initiatives:

- the Jules Horowitz Reactor (JHR) of the French CEA for material and fuel testing;
- a fast-spectrum experimental system such as proposed by SCK•CEN (the Belgian nuclear research centre), to support the development and demonstration of an alternative technology to sodium;
- a reactor which should replace the high flux reactor (HFR) at Petten (the Netherlands) as the main European provider of radionuclides for medical applications.

In November 2008, the first General Assembly of SNE-TP presented its Strategic Research Agenda (SRA). In the executive summary the same three facilities are mentioned under the heading of the European Research Area. In this summary, continued research on partitioning technologies and fast neutron systems well adapted to transmutation (reactors and accelerator-driven systems) is also mentioned. There is however also stated, regarding transmutation

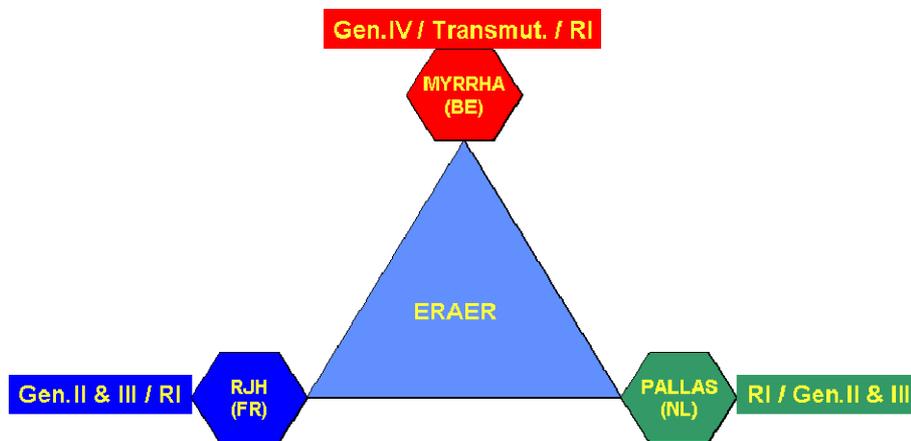
purposes, that the ADS technology must be compared to the FR technology from the point of view of feasibility from the economic point of view, the ADS industrial solution should be assessed in terms of its contribution to the closure of the fuel cycle.

The SRA of the SNE-TP also mentions the HTR/VHTR as an efficient and flexible nuclear system capable of industrial process heat supply and cogeneration. The HTR could therefore extend the contribution of nuclear energy in curbing of CO₂ emissions, reducing energy cost and improving security of energy supply. However, coupling with industrial processes is a major technological, economic and licensing challenge for nuclear energy. Therefore before a heat market breakthrough, an industrial demonstration is necessary. Such a preliminary demonstration is possible by 2020.

One of the objectives of the SET-Plan is to realise European industrial initiatives. One of these initiatives is that for the development of Generation IV technologies (sustainable nuclear fission initiative). In the framework of this initiative the following facilities are foreseen: an SFR prototype; an alternative technology (LFR or GFR demonstrator); fuel cycle facilities; testing facilities; a specific fast neutron irradiation facility (MYRRHA) complementary to the Jules Horowitz Reactor.

One can conclude that MYRRHA has been positioned within the European Research Area of Experimental Reactors (ERAER, see Figure 1). The SNE-TP vision document states that Europe will hold its world-wide leading position in the field of reactor technology and its future development only if this community fosters its efforts towards the realisation of a European research infrastructure. As already said above the research and community service irradiation capacity should be based on three pillars. These are explained in more detail hereafter:

- Jules Horowitz Reactor (JHR) at Cadarache, France, construction of which started in March 2007 as a European collaboration. JHR will be answering the needs for industrial applications for Gen-II and Gen-III in terms of structural and fuel performance improvement as well as some generic Gen-IV research. JHR will also be acting as a back-up irradiation facility for radioisotope production.
- MYRRHA at Mol in Belgium presently serves as a basis of the XT-ADS within the FP6-EUROTRANS project and will be further developed during FP7 as the MYRRHA fast spectrum experimental facility (MYRRHA-FSEF), a first-step experimental device that will serve both as a test-bed for transmutation and as a fast spectrum irradiation facility, operating as a subcritical (accelerator-driven) system in a first stage, and later on as a critical research reactor. MYRRHA will also maintain a back-up position for the production of classical radioisotopes and will focus on those isotopes that request very high flux levels. It can also be used for testing of materials to be used in a fusion reactor.
- PALLAS at Petten in the Netherlands, presently under design for serving the main objective of securing radioisotope production for medical applications in Europe and as a complementary facility in support of the industrial needs for technological development for present and future reactors.

Figure 1: European Research Area for Experimental Reactors (ERAER)

Taking into account these national, European and even world-wide needs in terms of demonstration and irradiation capabilities, SCK•CEN is proposing MYRRHA as a flexible fast spectrum irradiation facility that is able to operate in subcritical and critical modes and that is based on Pb-alloy technology, an alternative coolant technology to sodium.

3 SCK•CEN background

Since its creation in 1952, the Belgian Nuclear Research Centre at Mol (SCK•CEN) has always been heavily involved in the conception, design, realisation and operation of large nuclear infrastructures. The centre has even played a pioneering role in such infrastructures in Europe and world wide. SCK•CEN has always operated these facilities successfully thanks to the high degree of qualification and competence of its personnel and by inserting these facilities in European and international research networks, thus contributing to the development of crucial aspects of nuclear energy at an international level.

One of the flagships of the nuclear infrastructure of SCK•CEN is the BR2 reactor, a flexible irradiation facility known as a multi-purpose materials testing reactor. This reactor has been in operation since 1962 and has proven to be an excellent research tool, which has produced remarkable results for the international nuclear energy community in various fields such as material research for fission and fusion reactors, fuel research, reactor safety, reactor technology and for the production of radioisotopes for medical and industrial applications. BR2 has been refurbished twice (consisting of the replacement of the beryllium matrix and considerable safety improvements), in the beginning of the 80s and in the mid-90s. The BR2 reactor is now licensed for operating until 2016, but around that period it will have to be decided whether another refurbishment around 2020 will have to be done or whether it will have to be replaced by another facility. Therefore, and encouraged by the positive quotations mentioned above and the need of having a fast spectrum irradiation facility, the

Nuclear Research Centre at Mol has been working for several years on the pre- and conceptual design of a multi-purpose flexible irradiation facility that can replace the BR2 material testing reactor and that is innovative to support future-oriented research projects needed to sustain the future of the research centre. Thanks to its BR2 reactor and its other nuclear activities, SCK•CEN has the disposal of the necessary facilities for the preparation of irradiation rigs and for post-irradiation examinations. As such SCK•CEN has at its disposal hot cells and laboratories for the handling of medium and highly active materials.

4 Status of the MYRRHA project

Since 1998, SCK•CEN has been working on the MYRRHA project. In mid-2002 a first pre-design file of MYRRHA with a nominal power of 30 MWth was presented. The design of MYRRHA has further evolved between 2002-2004 and has become a 50 MWth facility.

In the design, as much as possible mature or less demanding technologies in terms of R&D have been favoured. Nevertheless, not all the components of MYRRHA existed. Therefore, a thorough internal and international research and development support programme for the most innovative components began in 1997, was updated since in 2002 and further revised in 2005 for a period of five years.

The pre-design and conceptual activities and the research and development work have already well advanced. In addition to an update of the design, in order to be able to reach all the objectives, the detailed engineering design can start from 2009 on. Parallel to this, the technical specifications will be drafted and the key innovative components for the accelerator and the reactor will be further developed and tested. Once this phase is engaged, a moment of no return has been reached and one should continue with the construction and the operation.

MYRRHA as a flexible fast spectrum irradiation facility being able to operate in subcritical and critical modes, will answer the following application catalogue. MYRRHA will:

- As a first priority, in order to satisfy the global irradiation needs of the nuclear research community:
 - Allow to study efficient transmutation of high level nuclear waste, in particular minor actinides that request high fast flux intensity ($\Phi > 0.75 \text{ MeV} = 10^{15} \text{ n/cm}^2\cdot\text{s}$).
 - Be a fuel research irradiation facility for Gen-IV systems, which need irradiation rigs with adaptable flux spectrum and flux levels ($\Phi_{\text{tot}} = 10^{14}$ to $10^{15} \text{ n/cm}^2\cdot\text{s}$).
 - Be a fast spectrum irradiation facility for material development for Gen-IV systems and for fusion reactors. Both request large irradiation volumes ($3\,000 \text{ cm}^3$) with a high constant fast flux level of $\Phi > 1 \text{ MeV} = 1 \sim 5 \cdot 10^{14} \text{ n/cm}^2\cdot\text{s}$ and for fusion research we typically need a ratio of appm He/dpa(Fe) of 10 ~ 15.

- Allow radioisotope production for medical and industrial applications by:
 - assuring a back-up position for classical medical radioisotopes;
 - focusing on R&D and production of radioisotopes requesting very thermal flux levels ($\Phi_{th} = 2$ to $3 \cdot 10^{15}$ n/cm².s).
 - allow industrial applications, such as Si doping.
- As a second priority, in order to contribute to the clarification of the question about the ADS feasibility needed in the framework of the assessment of the ADS contribution to the closure of the fuel cycle:
 - Be a full ADS concept demonstration coupling the three components (accelerator, spallation target and subcritical reactor) at a reasonable power level to allow operation feedback and reactivity effects mitigation that are scalable to an industrial demonstrator. As such it will allow:
 - beam trip mitigation;
 - subcriticality monitoring and control;
 - restart procedures after short or long stops;
 - feedback to various reactivity injections;
 - spallation products monitoring and control.
- As a third priority, in order to contribute to the LFR:
 - Development and demonstration of specific lead technologies.

MYRRHA as a flexible fast spectrum irradiation facility able to operate in subcritical and critical modes is intended to operate at full power around 2020. A minimum preparatory period of two years is considered for the commissioning of the facility. For a few years, the facility is projected to be initially operated as an ADS in a subcritical mode for completing the full power ADS demonstration and associated transmutation experiments. The facility will then be turned into a critical fast spectrum irradiation facility based on heavy liquid metal coolant technology to support the development of an alternative technology to the sodium fast reactor technology.

In both cases the irradiation experiments foreseen in the first priority will be executed.

The availability of the large and powerful accelerator of MYRRHA is considered from the initial step of the MYRRHA project as an asset allowing to trigger fundamental research with universities in the fields of nuclear physics and neutron science in the areas of complex fluids, crystalline materials, disordered materials, magnetism and supra-conductivity, polymers. Presently a feasibility study in association with KUL (Leuven) on an ISOLDE-like facility called ISOL@MYRRHA is under development.

The total cost of the project (until the start of full power operation, foreseen in 2020) is estimated at about EUR 750 M (2007).

5 Terms of reference for the assessment

The assessment should cover both the following strategic aspects and technical and financial aspects.

Strategic aspects

- Is MYRRHA fit to cover the irradiation needs (or an important part of them) of the Gen-IV reactors and of the fusion reactors and is it sufficiently complementary to other irradiation facilities in operation around 2020?
- Is MYRRHA needed in the future to secure the production of the present medical isotopes in a European context and with regard to the development and production of new medical isotopes (in particular those requiring a double neutron capture), and can MYRRHA do it in the critical and subcritical option?
- Is MYRRHA appropriate for an ADS demonstration or even, as it is cited, for a demonstration of a lead fast reactor (LFR)?
- Is the rationale behind the MYRRHA design objectives and hence characteristics sound? With respect to this question, the panel should examine different angles:
 - The weighing of ADS- and LFR-demonstrations. Are both appropriate?
 - The weighing of the demonstration role and testing and research role. Which aspect should be emphasised?

Technical/financial aspects

- Can MYRRHA be built in the foreseen time schedule, taking into account the presently reached research and development results; what is the impact on the time schedule when limiting MYRRHA to the critical option or subcritical option?
- Is the MYRRHA concept, as it is now conceived, able to fulfil all the functions one wants to attribute to it?
- Are the predicted reliability and availability of MYRRHA in harmony with its objectives and are these reliability and availability predictions realistic?
- Is the cost estimation of the MYRRHA project realistic?
- Are the operational costs of MYRRHA realistic?
- Will the MYRRHA project, as it is now conceived, be able to generate the expected revenues, taking into account the different uses which are foreseen?

6 Documents made available

The assessment has to be based on the following documents:

- MYRRHA project: Business Plan 2007;
- MYRRHA Design 2008, Technical Description;
- MYRRHA R&D Programme 2008.

The assessment team has the right to ask for more information and other documents. If the team wants insight in documents related to the EURATOM framework programmes (i.e. those of the EUROTRANS or PATEROS projects) or strategic European documents (the SNE-TP and SET-Plan documents), they will be made available on request to the extent possible. All documents made available will be in English.

7 Execution of the independent assessment

The independent assessment will be conducted by the Nuclear Energy Agency, which will have the necessary contacts with SCK•CEN for all technical, scientific, financial and economic data needed for the assessment. The SCK•CEN will operate under the supervision of the Belgian authorities who have asked for the assessment.

The contact points for the independent assessment are the following:

- From the Belgian side:
 - The authorities (Energy Administration Division of Nuclear Applications):
Mr. Theo Van Rentergem
Boulevard du Roi Albert II, 16
BE-1000 Bruxelles
Tel.: 32.2.277.64.52/Fax: 32.2.277.52.06
E-mail: theofiel.vanrentergem@economie.fgov.be
 - The research centre (SCK•CEN Institute for Advanced Nuclear Systems):
Mr. Hamid Aït Abderrahim
Boeretang 200
BE-2400 Mol
Tel.: 32.14.33.22.77/Fax: 32.14.32.15.29
E-mail: haitabde@sckcen.be
- From the Nuclear Energy Agency:
Mr. Claes Nordborg
Head of the Nuclear Science Section
12 boulevard des Iles
FR-92130 Issy-les-Moulineaux
Tel. 33.1.45.24.10.90
E-mail: claes.nordborg@oecd.org

8 Timing

The independent assessment should start in January 2009 and the draft report in English is expected to be available within six months. The report should not be translated.

9 Organisation and publication

The first step in the independent assessment should be a kick-off meeting on which the MYRRHA project is presented and the necessary documents are handed over to the members of the assessment team. A visit to the SCK•CEN site can be foreseen at the moment.

Further needs (consultation of documents, questions/answers; further meetings) will be determined by the team itself.

The preliminary findings of the report will be presented to the Belgian authorities and the MYRRHA project team before the publication of the assessment report.

The NEA will publish the assessment report as an agency publication.

10 Elements with regard to expert profiles

Apart from the fact that the assessment team will be assembled independently by the NEA and may include NEA staff, the members of the team should fulfil the following conditions.

The first condition is that they are not or have not been involved directly in the MYRRHA project.

The independent assessment team should have a broad international composition.

The experts should have sufficient competence in experimental reactors, ADS, fast reactors, partitioning and transmutation and economic evaluation of large projects. They should have a rather broad overview in their field of competence, without being too general or too detailed.

Appendix 2: Members of the International Review Team

International members

Frank Carré

Mr. Frank Carré is Scientific Director of the Nuclear Energy Division at the French Energy Commission (CEA).

He graduated in 1974 as Engineer from the École Centrale de Paris, in 1975 as Master of Science in Nuclear Engineering at the Massachusetts Institute of Technology (USA) and in 1976 as pre-Doctoral student in Reactor Physics at the Université Paris XI (Orsay).

Since he joined the CEA in 1976, Frank Carré contributed in successive managerial positions to studies on advanced nuclear systems including light water and fast neutron reactors, advanced fuel cycles, fusion reactor blankets and space power reactors. From 1990 to 1997, he successively managed Services in charge of Innovative Systems for power reactors, and Reactor Fuel Cycle Physics within the Department of Reactor Studies. From 1997 to 2000 he served as Assistant Director of the Strategy and Evaluation Division of CEA in charge of strategic planning of the CEA's civilian activities. From 2001 to 2006 he acted as Programme Director for Future Nuclear Energy Systems within the Nuclear Energy Division. In this responsibility he contributed to shaping and managing national R&D programmes on fast neutron reactors with advanced fuel cycles and high temperature reactors for the cogeneration of process heat and hydrogen. From 2007 to 2009 he acted as Deputy Director for Nuclear Development and Innovation within the Nuclear Energy Division of the CEA. In this position, he co-managed national programmes on future nuclear systems and remained actively involved in collaborative programmes on future nuclear energy systems both in Europe and the Generation IV International Forum.

Frank Carré is also lecturing professor at the École Polytechnique and professor at the National Institute for Nuclear Sciences and Techniques. He was elected a member of the International Nuclear Energy Academy in July 2009.

Jean-Marc Cavedon

Dr. Jean-Marc Cavedon has been Head of the Nuclear Energy and Safety Research Department of the Paul Scherrer Institute and member of its Board of Directors (PSI Switzerland) since 2004.

Dr. Cavedon graduated in 1975 as Engineer from the École Centrale de Paris and in 1980 as Docteur ès-Sciences in Nuclear Physics at the Université de Paris (Orsay).

Dr. Cavedon has occupied various scientific, managerial and strategic positions at the CEA (France) from 1980 to 2004. His scientific and technical interests have covered successively experimental nuclear physics (done with electron accelerators), superconducting accelerator development and isotope separation. His strategic activities have covered high level nuclear waste management and advanced fuel cycles.

Dr. Cavedon heads the Nuclear Energy and Safety Research Department (NES) of PSI, which is structured into five laboratories: Reactor Systems, Thermal-hydraulics, Nuclear Materials, Nuclear Waste Management, Energy Systems Analysis and one division that operates the hot laboratory. NES, with about 180 employees from many different nations and all continents, concentrates almost all types of nuclear research activities of the country. Among these scientists are 25 doctoral students and post-docs.

Dr. Cavedon is also member of the Board of the Competence Centre for Energy and Mobility of the ETH-Domain (CCEM-CH), member of the Swiss Nuclear Safety Committee (KNS), and represents Switzerland in the Policy Group of the Generation IV International Forum. He is also active in various committees at European and international level in the nuclear domain, such as the Board of Directors of the Institut de Sûreté et de Radioprotection Nucléaire (IRSN, France) and has recently been appointed as Bureau Member of the Committee for the Safety of Nuclear Installations of the Nuclear Energy Agency (CSNI, NEA).

Joachim Knebel

Dr. Joachim U. Knebel, born 1962, studied theoretical mechanical engineering at Technical University Karlsruhe. His PhD in 1993 was on “Buoyant Turbulent Jets in Sodium to be Applied in Fast Reactor Technology”. Since then he has been at Forschungszentrum Karlsruhe, which in 2009 merged with the University of Karlsruhe to become the Karlsruhe Institute of Technology (KIT).

He first worked on long-term containment cooling of light water reactors and the European pressurised water reactor (EPR). Since 1996 he has been addressing transmutation of high level nuclear wastes and accelerator-driven systems. In 1997 he was delegated to JAEA Japan.

Within EURATOM he is responsible for the initiation and co-ordination of essential R&D projects on transmutation (*e.g.* EUROTRANS) and nuclear waste management.

Since May 2002 he has been the Head of the Programme Nuclear Safety Research (NUKLEAR) at Forschungszentrum Karlsruhe. He occupied a secondary appointment from October 2007 to May 2009 as acting Head of the Institute of Neutron Physics and Reactor Technology (INR) at Forschungszentrum Karlsruhe, and since July 2009 he has been acting Head of the Institute of Radiation Research (ISF).

In January 2008 Joachim U. Knebel was elected Vice President of the European Nuclear Society (ENS).

Paul Lisowski

Dr. Paul Lisowski is the Deputy Assistant Secretary for Fuel Cycle Management in the Office of Nuclear Energy, presently on assignment as Senior Technical Assistant to the Office of Light Water Reactor Deployment, responsible for developing and implementing a Nuclear Energy Modelling and Simulation “Energy Innovation Hub”. The appointment as Deputy Assistant Secretary includes responsibility for planning and development of fast reactors, nuclear fuel recycling facilities, and advanced fuel cycle research and development, including management of work under international collaboration agreements with France, Japan, Russia and China.

Dr. Lisowski joined the Department of Energy following a career as senior manager and professional scientist at Los Alamos National Laboratory. In his last position at Los Alamos, he was Director of the Los Alamos Neutron Science Center (LANSCE), a multidisciplinary high-power accelerator-based user facility. Dr. Lisowski provided overall direction for the associated accelerator complex, three national user facilities and an isotope production facility. Key areas of science and technology included research in materials science and engineering using neutron scattering, basic and applied nuclear science, proton radiography, and production of research radioisotopes. Dr. Lisowski was the National Director of an Accelerator Production of Tritium Project that designed and successfully tested the key components of a superconducting proton linear accelerator needed for operation at over 100 MW proton power. During his research career, Dr. Lisowski was author or co-author of over one hundred publications, reports and abstracts covering work ranging from investigation of the fundamental physics of weak interactions to precision measurements of fission cross-section data for nuclear energy applications. Prior to his tenure at Los Alamos, he was an Assistant Professor in the Duke University Physics Department.

Dr. Lisowski has a PhD in Physics from Duke University in North Carolina. In addition to past service on advisory committees and on the Editorial Advisory Board of *Progress in Nuclear Energy*, he is a member of the American Physical Society and the American Nuclear Society.

Toru Ogawa

Toru Ogawa is the Director General, Nuclear Science and Engineering Directorate, JAEA (the Japan Atomic Energy Agency).

He received his MS in Nuclear Technology from Tohoku University and joined the Japan Atomic Energy Research Institute (JAERI) in 1975. After half a year of training in decommissioning work in a plutonium facility at the Tokai Research Establishment, he joined the R&D division of HTGR fuel. He was in charge of developing ZrC-coated particle fuel, which is an alternative to the current Triso-coated particle fuel to be used in a Generation IV reactor, VHTR. He received his PhD on the study of the fabrication process and the out-of-pile examination of ZrC-coated particle fuel from Osaka University in 1983. After returning from his stay in 1985-1986 at Chalk River Nuclear Laboratories, Canada, where he studied the fundamental diffusion mechanisms of fission product gases and iodine in oxide fuels, he took a responsibility to examine the feasibility of actinide recycling in dedicated transmutation systems in a special

task team on innovative reactors in JAERI. The study formed a small part of the Japanese OMEGA research programme by the Atomic Energy Commission, which was launched in October 1988. His investigation led to fundamental studies on the high-temperature chemistry of transuranium elements such as the constitution of their alloys and nitrides.

He has edited an OECD/NEA report *Fuels and Materials for Transmutation* (2005), a state-of-the-art report prepared within the activities of the Working Party on Scientific Issues in Partitioning and Transmutation.

Derek Pooley

Since 1998 Dr. Derek Pooley has been an independent consultant in the field of energy and nuclear technology. His projects in this role have included: membership of a Senior Expert Group advising the Director General of the IAEA; due diligence work for Eskom via PriceWaterhouse on Pebble Bed Modular Reactors; due diligence work for Vision Capital via LEK Consultants on purchase of nuclear companies; advising the UK Health and Safety Executive on the Nuclear Installations Inspectorate; advising AWE plc on the UK nuclear weapons facility; European external reviewer for the OECD/NEA's *Nuclear Energy Outlook 2008*; member of the European Commission Expert Group evaluating the current EURATOM Framework Programme 7.

Dr. Pooley first gained a PhD in solid state physics from Birmingham (UK) and carried out research at the California Institute of Technology, USA and then at Harwell, UK. He subsequently became, *inter alia*, the UK Department of Energy's Chief Scientist, the Director of the UK Atomic Energy Authority's Winfrith Nuclear Energy Centre and the Chief Executive of the UK Atomic Energy Authority. In the latter roles he was responsible for operating both thermal and fast reactor power stations; the Steam Generating Heavy Water Reactor – 100 MW and the UK Prototype Fast Reactor – 250 MW. He was also non-executive chairman of WMT Ltd., a radioactive waste management services company. He is a past president of the British Nuclear Energy Society, an Honorary Fellow of the UK Institution of Nuclear Engineers, past chairman of the EURATOM Scientific and Technical Committee, past member of the Corporate Advisory Panel of the UK Atomic Weapons Establishment and of the European Commission's Advisory Group on Energy. In 1995 he was appointed a Commander of the Order of the British Empire by Her Majesty Queen Elizabeth II.

André Versteegh

André Versteegh was Director of the Nuclear Research and Consultancy Group (NRG) in Petten, The Netherlands until 2008. He was one of the founders of this organisation and chairman of the board of directors since the creation of NRG in 1998, at that time a joint venture between the Netherlands Energy Research Foundation (ECN) and KEMA, the research organisation of the utilities. Nowadays NRG delivers and provides sustainable nuclear technology for energy, health and environment and is a full daughter of ECN. He has worked in Petten since 1969 in different positions on nuclear and non-nuclear R&D programmes. At the moment he is Corporate Executive Advisor on Nuclear Technology, Research and International Affairs.

Andre Versteegh obtained a MSc in Nuclear Technology at the Technical University of Delft, the Netherlands in 1969 and joined the Reactor Centre Netherlands (RCN) as Project Manager in Structural Mechanics. He was involved in the construction of the Borssele Nuclear Power Plant, the fabrication of fuel elements for different reactors in Europe, the development and construction of the enrichment facilities of Urenco and the construction of the fast breeder reactor in Kalkar. After starting up a research programme on clean coal technology, he became Head of the Nuclear Division of ECN and was responsible for the operation and research in the High Flux Reactor in Petten. The HFR is currently one of the most important producers of radioisotopes for industrial and medical use. He is now strongly involved in the project to replace the HFR by PALLAS, a modern flexible research reactor for research and isotope production. Andre Versteegh is member of different national and international committees such as the Scientific and Technical Committee for the EURATOM programme, president of NUCNET and president of the Dutch Foundation for Nuclear Infrastructure.

OECD/NEA secretariat

Thierry Dujardin

Thierry Dujardin joined the OECD Nuclear Energy Agency in 2001 as Deputy Director for Science and Development. In this domain, the NEA activities range from the development and dissemination of sound scientific and technical knowledge to the provision of authoritative, reliable information to governments on nuclear technologies, economics, strategies and resources. In the latter context, the contribution of nuclear energy in a sustainable development perspective is a key topic. Thierry Dujardin is also responsible for the Technical Secretariat services that the NEA provides to the Generation IV International Forum (GIF).

Thierry Dujardin obtained a PhD in Chemical Engineering from the Swiss Federal Institute of Technology in Lausanne. He spent most of his career within the French CEA (Atomic Energy Commission) being successively:

- Field engineer, project manager, and head of a research unit mainly in the area of uranium enrichment.
- Executive Deputy-Director for International Relations with a specific responsibility regarding the inter-ministerial co-ordination for the EURATOM Treaty Affairs with a direct link to the Prime Minister's office, and a mission of providing expertise to the government on foreign nuclear policy.
- Director of the Scientific and Technical Information Division in charge of the development of methods and tools in the area of information technology.

Claes Nordborg

Since 1993, Claes Nordborg has been Head of the Nuclear Science Section in the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation

and Development (OECD), a section that assists member countries in developing and disseminating basic scientific knowledge required for the safe and reliable operation of current and next generation nuclear reactors. He also co-ordinates the close collaboration between the Nuclear Science Section and the NEA Data Bank, an international centre of reference with respect to basic nuclear tools, such as computer codes and nuclear and chemical thermodynamic data.

Claes Nordborg obtained a MSc in mathematics and physics at the University of Lund, Sweden in 1969. He then continued with an Engineer exam in physics at the University of Uppsala, Sweden, before starting his PhD studies in neutron physics at the same university, supported by the Swedish National Defence Research Institute. In 1979, he moved to Paris, France, to work for the OECD Nuclear Energy Agency (NEA), at which his initial work was mainly devoted to co-ordinating international efforts in nuclear data measurements and evaluations, before taking up the post as Head of the Nuclear Science Section.