Meeting Report
of IAEA Technical Meeting “Review of Enabling Technologies for SMRs”

16 – 20 October 2006, VIC, Vienna

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1. Objectives

The IAEA technical meeting to review enabling technologies for SMRs was held on 16 – 20 October 2006 in Vienna. The objectives of this meeting were as follows:

(1) To provide a forum for the discussion of national experience and new initiatives for SMRs with a link to the possible role of the IAEA;

(2) To elaborate on a newly proposed IAEA activity on Review of Strategies to Overcome Loss of Economies of Scale for SMRs; through a series of comparative assessment studies, this activity is to identify competitive strategies for NPP design and deployment, define investor requirements and re-examine market needs for SMRs;

(3) To review the progress in preparation of a new report “Options to break the economies of scale for SMRs”, a starter for the above mentioned bigger activity, and to produce suggestions for its furthering; and

(4) To review the submissions for a new report “Passive safety design options for SMRs” and to work out a plan and recommendations for its finalization.

2. Scope of the meeting

Eighteen experts nominated by the governments of Argentina, China, Croatia, Japan, India, Lithuania, the Republic of Korea, the United States of America, and the NEA OECD participated in the meeting and delivered presentations on its topics. Twenty original papers on topics of the meeting were submitted. The scope of the presentations and discussions convened is outlined in the Agenda, enclosed as Annex 1.

A collection of the presentations and papers submitted to the meeting is available upon request from V. Kuznetsov, e-mail: v.v.kuznetsov@iaea.org .

3. Major observations

Indian observations

(3.1) The Indian experience with SMRs has been very positive. Starting for cooperation with AECL, India has now reached maturity in all aspects of nuclear power in a self reliant manner.

The plant load factors, safety performance, construction technology have all been benchmarked to the respective world-class operations. The technological benefits to the industry have been enormous and India is today one of the few countries of the world where the technology is current. The Indian experience has also demonstrated that participation of the local industry decreases the cost of construction. Many countries have adopted this route of technology cooperation and today new nuclear suppliers like the Republic of Korea or Argentina are emerging. India also has a potential to export standardized 220 MW(e) PHWRs and their costs, relative to other countries that offer larger reactors, are an advantage. The fuel cycle and associated activities including tie up for full supplies need to be linked up with other States. Similarly, the renovation and modernization works including the coolant channel replacement jobs has been undertaken successfully for three PHWRs (RAPS-2, MAPS-1&2), making India a potential supplier of nuclear services as well as making the Indian industry a global player for supply of equipment, etc.

India has plans to set up 700 MW(e) PHWRs and imported light water reactors in the near future. The nuclear power has great potential in increasing the per capita energy consumption. Many in-land locations away from coalmines are competitive sites for SMRs in view of non-availability of large quantities of cooling water and in-land infrastructure for transportation of heavy equipment. SMRs of 300 – 600 MW(e) are most suitable for such sites.

While the capital cost of 200 MW(e) SMRs is higher by about 15% as compared to 700 MW(e) PHWRs, this is actually offset due to the ability of SMRs be set up close to a load centre avoiding the introduction of new transmission grids. Further cost reduction is possible by standardized design and simultaneous setting up of a large number of such SMRs.

While there is a considerable variation amongst different countries in overnight cost of construction, it was recognized that gestation period and ability to complete the project in line with the schedule is of great importance for SMRs.

During the discussions it also emerged that natural uranium reactors (PHWRs) in once-through mode (open cycle) have large inventory of spent fuel and SMRs with LEU have an advantage of producing much less waste.

India’s PHWR programme is to be seen as part of long-term three stage programme for utilization of thorium through sequential execution of the three stages, which have fuel cycle linkages.

Also from the Indian perspective, in case of coal power stations it has been observed that construction cost for KW(e) is lower for lower unit size. Thus, the cost per kW(e) in case of 210 MW units is significantly lower than for 500 MW units. That is to say that economies of scale are in favour of smaller unit size for coal-fired plants. One of the reasons is that large number of standardized units has been built and the design costs have been fully recovered.

However, in respect of nuclear reactors, it is found that economies of scale are in favour of large units. During discussions it was observed that SMRs need to be conceptualized or scaled down from large reactors. Many new features/upgrades, current safety standards, first of its kind design costs seem to be pushing the capital cost resulting in widening the gap to beat economies of scale.

To break the economies of scale, therefore, new innovative designs with features like very long fuelling cycles (10-20) years may not lead to positive results in the near term.

Considering that a significant role of SMRs in the near future will be for electricity production in developing/underdeveloped countries, a unit size 300-600 MW(e) is considered appropriate over less than 300 MW.

The potential, therefore, is to adopt conventional designs with proven record in 300 – 600 MW(e) range or to realize the designs by scaling down 1000 MW LWRs which contribute to largest share of nuclear power.

Large variation in overnight cost ranging from $ 1000 – 2500/kW(e) have been observed amongst various countries. There can also be a possibility of variations in constituents of overnight cost. Some consensus need to be developed on uniform methodology for establishing the overnight costs and levelized cost of generation.

The exchange rate adopted for conversion is another important variable. In case of developing countries, there is a large variation between the market rate and purchasing power parity (PPP) rates. While some expenses could be at PPP, others are at market rate. The rate to be adopted for arriving at comparable overnight cost has to be somewhere in-between PPP and market rate.

The expenditure can be classified in three categories as international/local/combination of international and local. The land cost, civil works, infrastructure work, cost of regulatory clearances are local expenditures. The expenditure on erection/commissioning with participation of local industry will vary from country to country depending on the extent of local participation and available infrastructure in the country.

The above mentioned analysis is needed to bring the overnight cost to a comparable level applicable for all situations.

US observations

(3.2) The participants from the USA described the global nuclear energy partnership (GNEP) programme**.** Key elements of the GNEP are:

- Expand nuclear power (NP2010);
- Manage & minimize spent fuel (Yucca Mountain);
- Demonstrate advanced recycle technology (No separated Pu);
- Demonstrate Advanced Burner Reactors (Sodium FR);
- Establish reliable fuel services (Leasing, Backup);
- Demonstrate small, exportable reactors (Robust, Secure);
- Enhance nuclear safeguards technology (Design Norms).

Many of the world's developing countries and many smaller developed and emerging countries cannot accommodate current large Generation III+ designs, because they are too large, too expensive, and too complex. For GNEP to fully achieve its strategic vision of a large-scale increase in worldwide use of nuclear energy it needs reactors that are better suited to these countries. In the U.S. view, such reactors should be:

- Economically competitive;
- Proliferation resistant;
- Passively safe;
- Minimal infrastructure requirements (grid, personnel, government)
- Simple to operate;
- Easy and effective to safeguard;
- Robust against terrorism and sabotage.

Such reactors might have the following characteristics:

- Multiple types/sizes to serve various markets and needs;
- User needs defined through international effort;
- NRC design approval for US designs;
- GNEP compatibility (fuel and reactor);
- Work as much as possible within existing R&D frameworks (e.g., Gen-IV, INPRO);
- Partner with industry;
- More affordable;
- Have lower overall capital cost, which means smaller cash outlay even for equivalent generating capacity;
- More flexible;
- Allow incremental entry into nuclear energy;
- Better suited to small or weakly linked grids;
- Attractive for district heat and desalination;
- Easier to operate and maintain;
- More robust and secure.

It was recognized that no one existing reactor has all these attributes and that, in fact, in some senses these are conflicting requirements.

GNEP Is Pursuing A Two-Track Approach For SMR Development. In the near-term, goals are:

- To minimize up-front technology development needs;
- To emphasize deployment to developed economies.

In the longer-term:

- To address technology developments needed to fully meet GNEP objectives;
- To emphasize deployment to developing economies.

Participants in the meeting observed that SMRs that might be available in the near term would meet many of the goals that GNEP has identified.

U.S. participants took note of the recent IAEA General Conference resolution encouraging the development of SMRs, stressing the need to establish common user criteria and recommending that INPRO refine such common user criteria in a timely manner.

U.S. participants also took note of IAEA General Conference resolutions calling on the Secretariat to examine innovative/unconventional means of financing the construction of nuclear power plants, particularly for developing countries. Participants suggested ideas that could be investigated: world bank financing, financing by national foreign assistance programmes, financing by regional development banks, changes to rules for clean development mechanisms and different ownership options such as: “build, own and operate” and “build, operate and transfer”.

RoK and Argentine observations

(3.3) Regarding GNEP requirements to innovative SMRs, experts from Argentina and the Republic of Korea expressed their concerns about how these requirements would affect national programmes of SMR development with potential for exporting as carried out in these countries. The U.S. participants provided the explanation that GNEP is an offer of partnership, not a binding initiative, and that misunderstandings could be resolved through further discussions.

Croatian observations

(3.4) According to the expert from Croatia, SMRs may not be competitive within large grids, but would be especially effective in smaller grids and in special cases (small and non-interconnected grids, lack of cooling water, desalination, heat generation).

Owner risk in building innovative SMR is considerably less if there is a reference plant. The condition for acceptance is licensing in the country of origin and availability of well-documented licensing criteria. Only an experienced licensing organization can judge whether the plant systems and components development is sufficient for licensing.

A partnership between vendor and user is needed in the area of licensing, training and long-term material procurement.

US observations

(3.5) According to the U.S. experts, SMR competitiveness with larger reactors still needs to be demonstrated. However, deploying a FOAK plant in a user country without having the same plant operated in the country of origin could be supported, apart from the partnership, by adequate planning to reduce potential concerns. This could be the case for water cooled reactors based on proven technology but is unlikely to apply to non-water cooled innovative SMR concepts, for which a prototype plant is generally required, and typically would be built in a vendor country.

(3.6) Also according to the U.S. experts, SMRs’ primary objective is not to compete with larger plants in large grids but to target other markets. Grid stability and return period may be factors affecting the decision on SMRs more than cost disadvantages within a certain range.

Canadian observations

(3.7) The expert from Canada, who noted that CANDUs can be competitive with larger plants, supported this viewpoint making a note that markets are different for smaller-sized CANDU version (the Enhanced CANDU 6 is up to 750 MW(e)).

The Canadian expert also noted that some clustered CANDU plants have a single control room with individual control panel for each of the reactors. The high degree of computerization in the CANDU reactors and its extension in the EC6 can help reduce operating costs.

The expert also demonstrated the importance of learning from previous experience by detailing the safety and economic improvements to the CANDU line of reactors. The Canadian expert noted that clusters of 700 MW(e) and larger reactors are situated close to load centres, which is different from the Indian experience. He also showed the waste impact of a PHWR vs. a LWR and their similarity in space requirements for interim storage and their similar costs.

Canadian and Indian observations

(3.8) Experts from both Canada and India mentioned that there are multiple examples of PHWRs being built ahead of schedule and within the budget.

RoK observations

(3.9) The expert from the Republic of Korea described changes in the programme and a new schedule for the SMART project. According to the decision taken in June 2006, the prototype 1/5th scale SMART-P plant will not be constructed; instead a full-size SMART leading plant (perhaps, with unit power up-rated from the current 300 MW(th)) will be constructed on a coastal site, with SMART commercialization now targeted for ~2014.

The reasons for changing the SMART Development Programme were mentioned as follows: public resistance because of plant location at the in-land site, requests for safety enhancement, such as double containment and back up systems, non-commercial operation due to being categorized as a research reactor; and requests from the utility company to increase plant power. All this facilitated a decision to go to coastal sites where there are already NPPs and to increase unit power.

US observations

(3.10) The IRIS project developed by International Consortium led by Westinghouse (USA) is targeting deployment in the 2015-2017 time frame, with a commercial FOAK plant.

Chinese observation

(3.11) According to the expert from China, public acceptance has not been an issue for nuclear power so far, but may be an issue in case cogeneration plants are suggested to be located near the cities, replacing coal-fired plants. Plant size is currently not a driver for nuclear power development in China; huge current demand is a driver. Brayton turbo-machinery programme for HTR-10 high temperature pebble bed test reactor is still under implementation in OKBM of the Russian Federation.

Argentine observations

(3.12) Regarding the CAREM project in Argentine, information was provided about an Argentine Government Resolution 1107/2006 of 24 August 2006 stating that it is in the Argentine national interest to construct and start operation of the CAREM prototype of about 30 MW(e). The CAREM prototype cost is estimated at US$ 100M.

CAREM prototype will be built as a power reactor, i.e., licensed as a NPP, not as a research reactor. Local and private investors and suppliers have already expressed their interest. Site preparation activities are starting at the Atucha site.

Argentina has exported many research reactors. A US$ 200 M exportation project has been successfully performed.

According to the expert from Argentine, nuclear power could be a driver for national economies in many countries, including those countries that will never build a NPP on their own but would prefer to have the capacity to support and maintain the imported plant domestically during its whole lifetime. Developing countries have lower labour costs; therefore, cost distribution is different.

Japanese observations

(3.13) According to the expert from Japan, the 4S reactor pre-application review by NRC is to be started by March 2007. The 4S realistic electricity cost is under 10 US$ cents/kW-h, the targeted lifetime is 10 – 30 years. In the discussion it was noted that current NRC regulations on security guards could make their requested number unrealistic for a population centre the size of Galena (population approximately 1 000) – a targeted site for the 4S.

(3.14) When the cost is discussed for small reactors, one should consider the total electricity cost, including generation cost, transportation cost, distribution cost, etc. In the case of a small reactor, the transportation cost can be small. And the initial investment cost is smaller than for a large reactor. Those countries that are interested in small reactors can not construct a large reactor because they do not have a large power plant as well. Then, the discussion should be based on comparison with fossil-fuelled small power plants.

NEA OECD observations

(3.14) An expert from NEA OECD informed the group that NEA would perform studies on a transition to a sustainable fuel cycle – in collaboration with IAEA.

General observations

(3.15) Several participants presented the technical aspects of inherent safety design and passive design systems which can prove the use to other members. More specific was the presentation from India, and the one from Canada showing the improvements introduced into the CANDU6.

4. Conclusions and Recommendations of the Meeting

(4.1). The history of LWR deployment has almost exclusively been for electricity production in markets of high electric demand at low/moderate cost. Cost in \$/kW(e), therefore, has been a central metric that rolls together with levelized cost of generation, operational availability, utilization of fuel, etc. SMRs are not primarily intended for, and have little prospect of, competing in such markets (except being possibly ganged together as modular units). The performance and economics of modern large LWRs is such that there would be needed a new justification for moving to a new reactor technology, especially one that would require development of a new support infrastructure. Any decision to adopt an SMR will be supported by its ability to fill a niche in which it addresses a different market or market situation, e.g., more distributed electrical supply, matching the energy demand growth rate, siting flexibility, hydrogen generation, other process heat applications, etc. By definition, an SMR will not benefit from “economy of scale,” and use of the phrase misdirects the consideration. Instead, as for the importance of avoiding overly prescriptive licensing requirements, the framework for discussing and evaluating SMRs should be the one that encourages innovation to meet new situations and applications. SMRs, however, have a role in many countries that have a small nuclear power programme, relatively small electricity grids, or are interested in nuclear power with minimum investments.

(4.2). SMRs almost assuredly will not simply be miniaturized LWRs. They will have new solutions to issues of safety, heat removal, fuelling, etc. Originality in developing and adopting such solutions should be strongly encouraged. The IAEA could use its influence with local regulators to move to risk-informed or issue-based licensing, rather that the prescriptive nature that has grown up around the LWR technology.

(4.3). IAEA’s role in SMR development and distribution could be to facilitate the communication between those countries interested in acquiring SMRs and potential developers/vendors. This is particularly important in an area in which the customers will have unique requirements and the SMR vendors will (likely) be offering technologies with new features/characteristics not available in large LWRs. Initially, this communication could entail creating a set of requirements/criteria for selection that would both guide the vendor as to potential SMR customer’s needs and aid customers in SMR selection. Prioritizing within this list would be helpful, but should not be too detailed. A grouped form of priorities – e.g., Class A: essential; Class B: strongly desired; Class C: desirable, but not essential, etc. – would seem sufficient. Also very helpful would be for each potential customer not simply to list desired features but to provide explanations that include potential trade-offs. As an example, if cost, extended fuelling cycle and low water usage were Class A priorities, explanations might read as follows:

- *Cost:* The country is almost wholly dependent upon imported fossil energy sources. Therefore, costs are important both in minimizing foreign exchange and cost of energy (COE) to the consumer and in assuring stability of both of these. Cost evaluation will be based on a weighted consideration of all three factors.
- *Extended fuel cycle:* The country lacks the technical infrastructure to undertaking a commitment for periodic reactor refuelling. Therefore, an acquired SMR must either have a lifetime (or extended) fuel load; or the vendor must provide or assure a fuel replacement service, with sufficient guarantees.
- *Low water usage:* The region of installation of the SMR is lacking in plentiful water, either for reactor cooling or for public/agricultural usage. High selection priority will be given either to SMR capability for air-cooling or to the use of waste heat for water desalination, or preferably both.

These examples illustrate the importance of communicating the concern or problem to be solved, not in prescribing a feature or requirement. Given in this way, the vendor can work with the potential customer to address the concern within the capability of a technology whose flexibility may enable new optimizations.

5. Comments on the work done

(5.1). Regarding new IAEA activity “Review of Strategies to Overcome Loss of Economies of Scale for SMRs”, a new title “Strategies to Demonstrate Competitiveness of SMRs in World Markets” was suggested, reflecting the fact that alternative markets could drive SMR development and deployment rather than competition with larger plants.

(5.2). In that same activity, the highest priority was assigned to task 5 “Definition of a set of parameters and development of a country-independent methodology to re-examine and quantify the need for SMRs in world markets”. A brainstorming session was conducted, which produced a preliminary set of such parameters enclosed as ANNEX 2.

(5.3) Task 2 “Analysis of plant design strategies” coupled with task 4 “Analysis of plant deployment strategies and associated issues” was defined as the next priority; both of these tasks could be effectively addressed using the new methodology of Modularity Impact on SMR & Large Plant Comparative Costs developed by C. Mycoff of Westinghouse (USA) and the G4-ECONS methodology developed by the GIF Economic Modelling Group and presented at this meeting by K. Williams.

(5.4) Regarding the new report on “Passive Safety Design Options for SMRs”, which is at an advanced stage (structure PSDO descriptions were finalized by the designers of 9 out of 10 targeted innovative SMRs); certain clarifications were provided by the designers present at the meeting. A.K. Nayak took an obligation to draft the remaining crosscutting chapters throughout November 2006.

(5.5) A chapter on general incentive for incorporation of passive safety design options to SMRs was reviewed, and the comments were as follows:

(a) “Decreasing the reactor size also facilitates…” should be changed to “Decreasing the reactor power density also facilitates…”
(b) “Increased robustness of barriers for sabotage protection” should be changed to “Reduced vulnerability to sabotage”
(c) Relationship of PSDO to proliferation resistance features should be clarified with Mr. Sienicki of ANL (USA); if a convincing example is not provided, it should be deleted.
(d) Examples should be given for each bullet under “Areas other than economy”

(5.6) A new paragraph should be added after the above mentioned bullets:
"However, there are potential concerns related to passive safety systems, derived from smaller experience database of reactor design with such systems:

- Reliability of passive safety systems may not be as well understood as that of active safety systems. This issue is partly addressed within a parallel Agency's activity on Review of experience and options relevant for validation, testing and demonstration of passive safety systems
- There may be potential for undesired interaction of active and passive safety systems.
- Implications for incorporation of inherent and passive safety features into SMRs to achieve the safety goals need to be proven and the requirements by the regulatory bodies for these need to be worked out.
- It may be more difficult to "turn off" an activated passive safety system, if so desired, after it has been automatically started."

(5.7) It will likely be necessary to confirm that over the plant lifetime passive systems retain capability to perform its safety function as designed. New approaches may be needed to perform this confirmation, different than with active systems. One approach to deal with this issue is outlined in a short paper contributed by D. Wade, enclosed as ANNEX 3.

6. Further work

(6.1) Mr. Mycoff will perform generic study with his approach including sensitivity analyses covering SMR design and deployment strategies. D. Wade, Y. Sun, D. Delmastro, and A.K. Nayak will consider collaboration in such a study by providing certain data relevant to the conditions and experience in their member states. Mr. Mycoff could later on distribute his methodology, shaped up as an Excel-sheet code, to the participants.

(6.2) Mr. Williams will, possibly, distribute G4-ECONS methodology, shaped up as an Excel-sheet code, along with the manual, to all interested participants under a promise of providing the feedback. Y. Sun, S. Thakur, A. Minato, and P. Girouard expressed their preliminary interest to participate. An option to address the designers of 56 SMRs with an offer of participation will be considered by the scientific secretary through further communications with Mr. Williams.

(6.3) Regarding the methodologies for analysis of competitive total investments risks based on stochastic methods, Mr. Feretic will distribute the description of a set of data needed to perform such a study to be considered by all participants of this activity. Mr. Wade has expressed interest to compare a 1000 MW coal plant with 3 SMRs of the equivalent cumulative power.

(6.4) Regarding the methodology of reduced design complexity assessment by P. Florido, which arrived just before the meting, Mr. Wade has expressed his interest to use it in SMR studies. This methodology will be reviewed by PESS and discussed with other participants at the following meetings.

(6.5) Mr. Wade will continue scenario studies for systems with small reactors without on-site refuelling within a CRP "Small Reactors without On-site Refuelling".

(6.6) A proposal for consolidated methodology to help investors in interested countries assess the overall benefits of SMRs, developed by M. Ricotti, arrived on the final day of the meeting and needs to be discussed at further meetings.

(6.7) Regarding a new report "Options to break the economies of scale for SMRs", a change of title to, tentatively, "Approaches to assess competitiveness of SMRs" was recommended.

(6.8) As K. Miller will not be able to participate further, new contributors to this report were defined. Mr. Mycoff and Mr. Williams will contribute papers on their methodologies and examples for a chapter "Advanced methodologies for capital expenditure profiles, learning from construction and optimum plant size models, inclusion of "Capital at Risk' as a key parameter in defining competitiveness of SMRs – GEN-IV and IRIS approaches", first drafts by 30 January 2007 and final drafts by 28 February 2007. An updated work plan for this report is enclosed as ANNEX IV.

(6.9) Mr. Petrovic will prepare an introduction, possibly with modified scope, within the same timeframe.

(6.10) Mr. Carelli may consider elaborating his short contribution to "Investor requirements for SMRs".

(6.11) Mr. Delmastro will prepare a paper on Argentinean experience and perspectives with SMRs, the timeframe to be defined later.

(6.12) Mr. Toth of IAEA will provide a summary of IAEA tools with an outline of option to be applied for SMR analyses; after all other contributions are collected.

(6.13) Mr. Girouard will consider contributing on mechanisms in the company to benefit from serial production, for chapter 5 "Common approaches and enabling technologies that could help ensure competitiveness of SMRs".

(6.14) Mr. Wade will team up with J. Phillips of IAEA to prepare a chapter "Enabling institutional developments".

(6.15) An ad hoc working group headed by P. Girouard and involving A.K. Nayak, B. Petrovic and D. Wade will finalize the questionnaire ANNEX 2. A. Burkart will review requirements on international conventions. This set would be used by research teams at NPCIL and at OKBM and RRC KI (Russian Federation) to develop and probate, based on national experience, a country-independent methodology. It was also suggested that another smaller developing country be identified for this dry-run. Independently of this, this questionnaire will be handed over to the organizers of IAEA Workshop of 5-6 December 2006, for possible use.