Meeting report of the second research coordination meeting (RCM) of a coordinated research project (CRP) on small reactors without on-site refuelling (CRP i25001)

IAEA, Vienna, 4 – 8 June 2007

Project officer: V. Kuznetsov, v.v.kuznetsov@iaea.org

1. Objectives of the meeting

The second Research Coordination Meeting (RCM) of a Coordinated Research Project (CRP) on Small reactors without on-site refuelling was held on 4-8 June 2007 in Vienna with 16 participants representing 16 research institutes and organizations in Brazil, Croatia, India, Indonesia, Italy, Japan, Lithuania, Morocco, the Russian Federation, and the United States of America, and one observer from non-participating research organization (CRIEPI, Japan), and had the following main objectives:

(1) To review the progress achieved during the period since the previous RCM of 21-25 November 2005 and to present and discuss new results and annual reports on:

- Technical and licensing evaluations required to justify reduced off-site emergency planning for SMRs;
- Economics of reduced off-site emergency planning for SMRs;
- Benchmarking for whole core depletion models of lead-bismuth cooled reactors;
- Benchmarking for cells and fuel assemblies of light water reactors with coated particle based fuel;
- On data and information exchange regarding fuel and coolant properties and progress in design development for the concepts addressed; and
- On inter-regional and intra-regional scenario studies for energy systems with small reactors without on-site refuelling;

(2) To establish collaboration in further activities for the abovementioned and new topics and, specifically, to clarify interest in cooperation with the NEA OECD's Lead-Alloy Cooled Advanced Nuclear Energy Systems (LACANES) that has planned a benchmarking exercise for natural circulation of lead-bismuth coolant based on the tests performed in the HELIOS loop at the Seoul National University (the Republic of Korea).

2. Scope of the meeting

The Agenda of the meeting and the list of participants are enclosed as ANNEX I and ANNEX II respectively.

Previous year reports from participants were presented and discussed; a collection of the presentations and materials submitted to the meeting is available on a CD, upon a request from the project officer, V. Kuznetsov: v.v.kuznetsov@iaea.org. The meeting also included two presentations from the IAEA's INPRO project, on common user criteria for advanced reactors, and on a Collaborative project proposal for non-stationary NPPs.

The CRP has three distinct tasks and groups of participants; therefore, the meeting included both plenary sessions of interest to all participants, and breakout sessions of the three research groups. Major findings, conclusions and recommendations of the meeting are summarized as the following.

3. General observations

(3.1) The participants appreciated the fact that SVBR-75/100, a small reactor of long refuelling interval, has received Russian governmental approval to move forward to final design. As an Alpha class submarine derivative, the SVBR 75/100 reactor was among the very first reactor

concept to be introduced in the small reactor without onsite refuelling class, and is currently the most advanced of the many concepts now existing;

(3.2) The participants learned with appreciation about the scope of the effort ongoing at BARC (India) on design and technology development for a 600 MW(th) lead-bismuth cooled very high temperature reactor and CHTR with thermal/intermediate spectrum of neutrons and long refuelling interval, intended for hydrogen production and other advanced process heat applications;

(3.3) The participants noted a substantial amount of work done by Groups 1, 2 and 3 of the CRP on development of a methodology for re-examining of the emergency planning requirements, on benchmarking for a depletion model of RBEC reactor, on benchmarking for elementary cells of light water reactors with coated particle based fuel, and on conceptual design development for several small reactors without on-site refuelling;

(3.4) A continuing effort of the ANL (USA) in carrying out scenario studies comparing nuclear energy systems with and without small reactors and including material and cash flow analyses was noted.

4. Conclusions and recommendations of Group 1 "Revising the Need for Relocation and Evacuation Measures Unique to NPPs with Innovative SMRs"

Chairperson:

Andrea Maioli (Westinghouse, USA)

Participants:

Davor Grgic (University of Zagreb, Croatia)

Nikola Cavlina (University of Zagreb, Croatia)

Juozas Augutis (Lithuania Energy Institute, Lithuania)

4.1. Scope of Work

The ultimate objective is to establish an approach to licensing of NPPs with a revised (i.e., reduced or eliminated) emergency planning requirements (EPRs). Ideally, the emergency planning zone (EPZ) would coincide with (or be contained within) the site boundary; thus, there would be no need for off-site evacuation planning, and the NPP would become, relative to the general population, the same type of facility as any other industrial enterprise. It will contribute to the overall efforts of this CRP to demonstrate competitiveness of SMRs.

SMRs are ideal candidates for pursuing implementation of reduced EPRs because of, primarily, their inherently enhanced design features. The inherent characteristics of SMRs include a smaller source term (as compared to large NPPs), less frequent refuelling, and inherently better amenability to the use of passive safety systems, increased surface-to-volume ratio which facilitates heat removal in accident situations, inherently lower susceptibility to external events and sabotage (simpler designs relying more on passive safety), and a set of other features. The benefit that could be achieved is potentially larger than for large NPPs, because SMRs are considered for co-generation applications requiring proximity to the ends-user (district heating, desalination, process steam, etc.).

The effort of Group I team members focussed on the following two main aspects:

1. Identification of the technical requirements that would support the redefinition of EPZ for a NPP; this includes a methodology for a risk-informed redefinition of the EPZ and the modelling and licensing considerations required for a sound application of the methodology;

2. Quantification of the potential economic benefit, including co-generation and distributed power generation scenarios that are facilitated by the EPZ redefinition and reduction.

This overall effort is technology-neutral in nature and intent. The IRIS design has been used only as a common test-bed for the various perspectives investigated in this CRP framework.

4.2. Status of Work

Italy/United States

The effort is focussed on identification of a methodology that can re-introduce and support the use of the concept of risk as the basis for the definition of emergency planning zone around a nuclear power plant. This approach aims to take advantage of the increased safety attained by NPPs in the last decades by correspondingly reducing EPRs, while maintaining or even improving the total Defence-In-Depth (DID) and protection of the general public. During the first two years, following a critical review of the past attempts in this field, a methodology was outlined to reproduce the currently accepted risk level around the present NPPs and to determine, on a risk-informed basis, the necessary size of EPZ around new NPPs. This methodology can be used for the identification of risk parameters (i.e., the consequences and the frequency) that represents a starting point for the definition of an EPZ that can assure the same, if not improved, safety level for the population, while decreasing the impact on the plant economics.

A reasonably complete application of the methodology was performed for the IRIS reactor, as an example of advanced SMRs.

Croatia

The performed activity is focussed on a comparative assessment of an existing plant (represented by the NPP Krsko) and a new plant with improved safety characteristics (represented by the IRIS) from the point of view of EPZ size quantification. At previous stages, an overview of the NPP licensing status in Croatia was prepared together with the approach to the EPZ definition. Deterministic criteria were used for both siting and EPZ definition. The US NRC criteria were applied for siting, while the IAEA TECDOC-955 was used to support an EPZ evaluation.

For the NPP Krsko, a sequence with the largest impact on Internal Initiating Events CDF of the plant, namely, the SBO (station blackout) sequence was used as a reference case for the analysis. The NPP responses were calculated using the RELAP5-SCDAP and MAAP codes, and a concept of the risk for population was introduced similar to the NUREG-1493 approach, using the results of the COSYMA code runs for the site specific population and generic meteorological data.

For IRIS, the sequences that are most limiting from a standpoint of the consequences and the initiating frequency were defined and quantified using the RELAP5-SCDAP-GOTHIC coupled codes. Extending the refuelling interval was found to produce a significant reduction in the dose versus probability curve (due to fuel handling accidents). Evaluation has been started for the beyond design basis accidents (BDBA), specifically, including a hypothetical reactor vessel break at low elevation, combined with the postulated failure of the primary safety systems of IRIS. Based on the preliminary results, the design was modified to improve both DBA and BDBA responses of the system.

Lithuania

Economic studies have been performed, which proved a positive economic effect on the nuclear co-generation option with district heating, due to the revised siting requirements with a reduced emergency planning zone, which would allow placement of NPPs closer to the population centres.

Potential economic benefits of a revision of the evacuation requirements enabling a NPP-based district heating have been determined.

For the case of Lithuania and energy markets with similar characteristics, a distributed power generation (i.e., a power generation strategy well suited for SMRs) shows the relevant benefit when compared to a concentrated generation philosophy. This is clearly one of the many aspects to be considered within a broader framework — that with a focus on the security of energy supply. However, it is recognized as one of the key factors to be considered when defining the criteria for comparison between SMRs and larger plants.

4.3. Future Work

In the final years of the project different approaches to the problem, so far investigated on a relatively independent basis, will converge to a more organic framework.

From the point of view of the technical approach to the EPZ redefinition, the following activities are envisioned for the third year of the project:

- With the purpose of underlying the independence of the applied methodology from the selected design, a preliminary application will be performed to an existing NPP;
- The IRIS design will continue to be employed as a common test-bed for quantitative considerations. The evolution of the IRIS design could require a synchronization effort (i.e., in terms of the PRA modelling) and will likely to allow an expansion in some areas so far bounded by the generic assumptions;
- Again, with the aim of re-affirming the technology-neutral nature of the proposed approach (not only in terms of the selected design but also in terms of the tools used), the methodology will be tested on the basis of different codes and boundary conditions: namely, the application to IRIS will be tailored to an existing site, with less generic data on the population density and meteorological conditions. This will involve a transition from a relatively simplified code for dose evaluation, tailored on DBA and requiring a lumped information on the meteorological conditions, to a more refined code that requires more basic data on the specific site (i.e., meteorological conditions, population distribution, etc.) and that, therefore, will allow an easier tailoring of the methodology to different actual sites, with the possibility to provide additional insights on the economic aspects of this study;
- As a result of the iterations and cooperation among the team members, more refined evaluations will be carried out for selected accident sequences, in order to review the extremely conservative assumptions so far used. The Core Damage accident sequences considered as significant for the understanding of the behaviour of the selected SMR (IRIS) will be investigated in more detail. An example of the extreme accident sequence for IRIS is a hypothetical reactor vessel break (which is a lower elevation small-break LOCA that otherwise cannot occur) postulated together with a failure of all main passive and active emergency systems. This is a highly incredible event expected to propagate to a core damage with an extremely low frequency, of the order of 10^{-15}/reactor-year); nevertheless, due to its safety characteristics, IRIS has the potential to deterministically cope with such BDBA events or significantly reduce their consequences. RELAP5/GHOTIC/SCDAP runs will be carried out to evaluate long-term post-accident behaviour of the reactor, in order to produce an additional insight on the DBA and BDBA behaviour of the IRIS and to complete a comparison with the similar analyses performed for the Krsko plant. More realistic considerations for the performance of the containment will also be applied, with the support of the FEM model and analysis that will result in more realistic assumptions on the probability of a loss of the containment structural integrity.

- Additional considerations reflecting the realities of EPZ requirements in the member states of the Group I team are likely to be added and refined in a continuous effort to identify the most commonly accepted approaches and licensing considerations that could facilitate the introduction of the developed methodology (e.g., review the technical basis for licensing regulations in Lithuania, and specifically the emergency response planning for the Ignalina NPP, including an analysis of the changes which would be necessary if the emergency planning for the future power plants in Lithuania is to be eliminated or reduced.)

From the standpoint of economics, the following activities could be performed during the third year of the project:

- An update of the study of the economic impact of revised licensing requirements on district heating is envisioned. Due to the climate, district heating presents a notable fraction of energy consumption in winter time, and infrastructure for its use is already in place in some population centres in Lithuania. This work will continue an overall effort on ultimate determination of the potential economic benefits resulting from a revision of the evacuation requirements and enabling a NPP-based district heating;
- Within the same framework, an update of the meteorological data necessary for dose evaluation for one selected site, based on available databases, is recommended. It is anticipated that detailed hourly data will be used to derive adequate statistical distributions, but an alternative approach may also be applied, if justifiable;
- Uncertainty and sensitivity analyses of the econometric models and results could be carried out.
- An analysis of the impact of reactor size on the security of energy supply seems to be a natural extension of the so-far performed economic studies: in particular, some considerations will be made on the basis of the experience from studies done in the USA, Japan and the European countries on development of the models and a methodology for evaluation and quantification of the security of energy supply. This will result in a collection and analysis of the initial data about the present state and the future development of the energy sector of Lithuania;
- An scenario analysis of energy supply threats (natural disasters, technical failures, economical and political crises) could be performed, thus extending the ongoing studies on reliability analysis of the energy supply networks in Lithuania (electricity, gas, heat distribution networks, fuel transport system, etc.).
- Additional studies could involve economical modelling of the energy sector using the MESSAGE code, economical investigation of different scenarios for the construction of new energy generators (e.g., large power plant versus several small or medium sized reactors), and analysis of the security levels of energy in Lithuania, using the developed mathematical model.

In the third year, participation of an additional team member (Mexico has indicated an intention to join) could broaden the scope of the already identified analysis.

4.4. Planned Deliverables

Each team will commit to the delivery of an end-of-project report dedicated to certain aspects of the analysis that has been performed. A general framework of the introduction/conclusion will be common to all the reports.

5. Conclusions and recommendations of Group 2 “Design And Technology Development For LWR with Coated Particle Based Fuel”

Chairperson: Dr. G. Tsiklauri (PNNL, USA)

Participants:

Prof. F. Sefidvash (UFRGS, Brasil);

Prof. Y. Shimazu (Hokkaido University, Japan);

Dr. E. Grishanin (VNIIAM, Russia);

Prof. A. Chetaine (Mohammed V University, Morocco)

5.1. Scope of Work

Four concepts of LWR with coated particle based fuel were presented. Dr. E.Grishanin presented the results for uranium and gadolinium burn up in a BWR-PB fuel assembly. These results showed an option to organize two sequential operating regimes of the PWR-PB: first 12 years - without moving the micro fuel; and the following 13 years – with continuous refuelling of micro fuel in the core. In the first regime, the reactivity changes due to burn-up are compensated with a Gd_2O_3 absorber. It was shown that burn-up reactivity margin is as small as 2%; Gd-155 and Gd-157 burn-up practically complete; core lifetime for the optimized variant exceeds 4000 effective days; and average fuel burn-up equals 5.4% FIMA. The neutronic analyses were carried out for fuel of the TRISO type.

Prof. F. Sefidvash presented the Fixed Bed Nuclear Reactor (FBNR) concept as an example of a simple and safe design. FBNR uses the spherical TRISO based fuel of 15 mm diameter. The fuel elements form a fixed bed in the reactor core suspended by a flow of water coolant at 160 bar. Under any adverse operation conditions, the main circulation pump is turned off, and the fuel elements fall back into a subcritical fuel chamber, driven by gravity.

Dr. G. Tsiklauri presented the AFPR reactor concept with spherical particles using cermet fuel. The feasibility study performed at PNNL (USA) has shown that TRISO fuel in the LWR conditions possesses some negative qualities, stemming from low operating temperature, such as:

- During irradiation at 300^{o}C, the SiC swells causing a 2% strain;
- The 2% strain would cause unacceptable cracking in the PyC layers.

This feasibility assessment allowed identifying fuel concepts that have a potential for being reliable under LWR conditions. The new cermet fuel was proposed for use in the AFPR, FBNR and other similar LWR concepts. In the case of FBNR, a 15 mm diameter fuel element could be clad by Zr of 300 micron thickness. Prof. F. Sefidvash came up with the following parameters for the fuel element (dimensions are given in microns):

- UO_2 micro- sphere diameter = 500;
- Micro-sphere Zr clad thickness = 25;
- Micro-spheres embedded in Zr with a porosity of 0.40 (60% micro-spheres + 40% Zr matrix, by volume).

Dr. E. Grishanin presented the results of an extensive investigation of the SiC corrosion in the conditions of a PWR primary water and a superheated steam. The experiments were carried out at VNIIAM (the Russian Federation), the duration of the tests was 15 months. All fuel particles have shown a good corrosion resistance and a low loss of weight. Dr. E. Grishanin also delivered a dedicated presentation on the capability of Russian Institutes to carry out out-of-pile and irradiation tests of particle fuel.

After the information exchange and discussions at the meeting, the group noted that there are different opinions on the suitability of SiC fuel particles for the conditions of an LWR: Dr. G. Tsiklauri from PNNL (USA) considers that SiC is not an appropriate material for LWR due to swelling; Dr. E. Grishanin of VNIIAM (the Russian Federation), on the contrary, considers that

SiC is an excellent material for use in LWRs. At the same time, it was noted that all concepts of particle fuel LWRs could benefit from a research on advanced fuel materials, and it may be preferable to have several fuel options in a portfolio to guarantee a success of reactors of such type.

Prof. A. Chetaine presented the PFPWR50 (Japan) assembly and whole core design. The results given by APOLLO and SRAC95 are in good agreement. The validation with MCNP code shows small difference for K_{inf}, we can attribute that to the difference in libraries used and temperature (20^{o}C for MCNP and 295 ^{o}C for APOLLO).

5.2. Status of Work

Benchmark results for various concepts of particle-fuel small reactors without on-site refuelling were presented, as obtained by Prof. Y. Shimazu (Hokkaido University, Japan), Prof. L. Erradi and Prof. A. Chetaine (University Mohammed V Adgal, Morocco), and Dr. E. Grishanin (VNIIAM, the Russian Federation).

The goal of this investigation was to provide verification of the neutronic codes for calculation of physical characteristics in unit cell geometry of LWR concepts with coated particle fuel. The summary of the results is as follows.

(1) The codes used for benchmark calculations were mainly SRAC95 (Japan) and APPOLO (France). Some calculations were done by a Monte Carlo code MCNP, for comparison.

(2) Both basic codes gave fairly good agreements for all of the reactor concepts.

(3) However, the MCNP results are higher than those obtained with the APOLLO, presumably because the MCNP used a different library and a different fuel temperature;

(4) For the BWR-PB, a good agreement was observed with the results of Dr. E. Grishanin in fuel assembly calculations. However, again the MCNP and the APOLLO give different values of K_{inf}, because of a different library and a different fuel temperature being used in calculations;

(5) For PFPWR50, both SRAC95 and APOLLO agreed very well;

(6) For FBNR concept, reactor modelling should be reviewed because a big difference in the core lifetime as evaluated by different codes is observed;

(7) For BWR-PB, an increased fraction of thermal neutrons spectrum is observed in the results of the APOLLO. The result of the APOLLO is, therefore, much higher than that of the SRAC95.

The group decided to recalculate all benchmarks for cells and fuel assemblies, now with the cermet fuel.

5.3. Future Work.

The following activities were recommended for the 3rd year of work:

- To carry out benchmark calculations and analysis for cells and the whole reactor with cermet fuel;
- To continue the study of candidate materials for fuel particles. It is planned to perform verification reactor tests for cermet fuel; It may also be appropriate to carry out irradiation tests to verify the performance of TRISO fuel with outer SiC coatings in LWRs;
- To submit to INPRO a draft CPP proposal titled “Design and technology development for LWR with coated particle fuel”; the objective of this proposal would be to evaluate the four LWRs with coated particle based fuel according to the INPRO methodology (the draft of this proposal is enclosed as Appendix 1).

5.4. Planned Deliverables

Final reports will be prepared in 2008 according to the work plan approved by the 1st RCM.

6. Conclusions and recommendations of Group 3 "Design and Technology Development for Lead, Lead-Bismuth and Molten Salt Cooled Reactors"

Chairperson:
D. Wade, ANL, USA

Participants:
A Nagata, TokyoTech, Japan
G. Toshinsky, IPPE, Russia
P.D. Krishnani, BARC, India
Z. Su'ud, ITB, Indonesia
A. Dudnikov, RRC KI, Russia
S. Nishimura, CRIEPI, Japan (observer)

6.1. Scope and Status of Work

The group has been conducting a neutronics calculation benchmark on an idealized lead-bismuth (Pb-Bi) cooled reactor model (RBEC) including BOL criticality, power distributions, neutron spectra and burn-up predictions. Solutions obtained from the participants displayed discrepancies in the range of 1% Δk at BOL and discrepancies of the burn-up swing of criticality. The inter-comparisons were discussed during the breakout sessions and a path forward was defined involving more detailed edits from the obtained solutions with a target for a final report by December 2007.

Small reactors of long refuelling interval exhibit a different ratio of flux-induced burn-up to natural decay for fission products. Prof. Z. Su'ud has been exploring a fission product modelling procedure which better accounts for the differences between fission products which saturate, those which grow linearly and those which grow non-linearly with burn-up. The results obtained so far were displayed and a plan was identified to use the procedure on the RBEC benchmark. A related report was received on the same subject from "Gidropress" but as it arrived late, the participants had not discussed it.

An opportunity to participate in an NEA/OECD thermal-hydraulic benchmark based on the HELIOS Pb-Bi loop tests at the NUTRECK of the Seoul University (the Republic of Korea) was discussed, and all participants (with RRC KI to confirm) expressed the commitment to participate with a deadline for first results on a forced circulation case due by February 2008.

A goal is to find a way to pursue a neutronics benchmark tied to critical experiments. Participants took action assignments to look into the availability of previously-run experimental programs in Japan and in Russia.

6.2. Future Work and Planned Deliverables

The activities planned for 2007 – 2008 are as follows:

(1) Complete the RBEC neutronics benchmark (see Attachment 2 for required additional edits):
- Data input to Mr. A. Dudnikov due 31 August 2007;
- Prepare final draft report on Benchmark: Mr. A. Dudnikov – December 2007;

(2) Apply Mr. Z. Su'ud's fission product treatment to the RBEC benchmark:
- Prepare final draft report: (Mr. Z. Su'ud) – December 2007;

(3) HELIOS thermal-hydraulics benchmark

- All participants plan to participate (still to be confirmed by RRC KI);
- Forced circulation problem statement to be received from NEA/OECD Committee:- June 2007;
- Submit preliminary results – February 2008 (each participant): include calculated results and description of methodology and listing of input data, of correlations, physical data, etc.
- All participants (still to be confirmed by RRC KI) plan to calculate the NEA/OECD phase 2 benchmark of HELIOS natural circulation test during 2007-2008;
- Participants would encourage NUTRECK (the Republic of Korea) to consider a third phase wherein the natural circulation loop flow path includes the pump – free wheeling in the natural circulation flow and providing an additional flow resistance as might occur in a reactor off-normal event.

(4) During 2007, the participants will consider new directions of work for the next period as follows:

- Mr. Z. Su'ud will look into the potential for specifying a neutronics benchmark based on the JAEA Pb critical experiment;
- Mr. P.D. Krishnani will look into the potential for specifying a thermal/epithermal neutronics benchmark based on the CHTR design;
- Mr. G.I. Toshinsky will look into the possibility of releasing IPPE critical experiment data from previous critical tests of epithermal Pb-Bi cooled reactors.

Attachment 2 provides details for finishing the RBEC benchmark.

7. Scenario studies for systems with and without small reactors

Dr. D. Wade (USA) provided the information on how the DANESS code of material and cash flow analyses developed at ANL could be provided to interested participants. According to the law, the code should pass export control procedures, and there is a successful experience in this with several countries, e.g., the Russian Federation (however, the experience was so far unsuccessful with India). Then, there is a symbolic fee that could be negotiated. The scientific secretary Mr. V. Kuznetsov noted that the IAEA could find a way to support certain interested experts from developing countries participating in the CRP to obtain this or other (IAEA) codes and suggested that, in view of the continued flow of interesting results obtained, each participant of the meeting checks once again with his organization whether there is an interest to obtain the such codes and get involved in scenario studies for energy systems with SMRs of various types, the examples of which were presented by ANL at the meeting. A preliminary positive response from Dr. Z. Su'ud of Indonesia was received. Dr. D. Wade committed to send the information on DANESS code to each interested participant, upon his request.