IAEA PROGRAMME TO SUPPORT HWR TECHNOLOGY DEVELOPMENT

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Abstract

The International Atomic Energy Agency (IAEA) works with its Member States and multiple partners worldwide to promote safe, secure and peaceful nuclear technologies. To catalyse innovation in nuclear power technology in Member States, the IAEA coordinates cooperative research, promotes information exchange, and analyses technical data and results, with a focus on reducing capital costs and construction periods while further improving performance, safety and proliferation resistance. This paper summarizes the recent IAEA programme to support technology development for heavy water reactors.

1. Introduction

Heavy Water Reactors (HWRs) are the second most common type of nuclear reactor installations in the world, second only to Light Water Reactors (LWRs). At present 47 HWRs are operating in 7 countries and 3 HWRs are under construction.

The IAEA programme on HWR is planned and implemented with the advice and support from the Technical Working Group on Advanced Technologies for Heavy Water Reactors (TWG-HWR), which is composed of IAEA Member States with operating or planning HWRs.

The mission of the IAEA Division of Nuclear Power is to increase the capability of interested Member States to establish/develop, implement and maintain competitive and sustainable nuclear power programmes and to develop and apply advanced nuclear technologies. The IAEA frames to support the development and the application of HWR technologies includes:

- Coordinated Research Projects (CRP)
- International Collaborative Standard Problems (ICSP)
- Technical Meetings (TM)
- International Collaborative Assessments (ICA)
- Training Courses and Workshops.

This paper summarizes the major recent and ongoing IAEA activities and publications to support HWR technology development.

2. Technical meetings and publications

Many design organizations have been developing advanced water cooled reactors. To provide IAEA Member States with the state-of-the-art information on advanced reactor designs, the IAEA has been periodically issuing status reports based on the technical information collected from the designers [1-4]. These documents present an overview of development trends and goals, as well as detailed descriptions of advanced water cooled reactor designs according to a common outline. The descriptions include summaries of measures taken by the designers to enhance economics and maintainability. Especially TRS-407 [2] is a text book for HWRs including evolution, characteristics, fuel cycles and safety aspects.

Advanced applications of nuclear energy include seawater desalination, district heating, heat for industrial processes, and electricity and heat for hydrogen production. In addition, in the transportation sector, since nuclear electricity is generally produced in a base load mode at stable prices, there is considerable near-term potential for nuclear power to contribute as a carbon-free source of electricity for charging electric and plug-in hybrid vehicles. IAEA-TECDOC-1584 [5] examines the potential of nuclear energy to expand into these markets by presenting an overview of sample applications, their opportunities, challenges and solutions.

The task on "Optimizing Technology, Safety and Economics of Water-Cooled Reactors" was carried out during 1999-2002. Its objective was to emphasize the need, and to identify approaches, for new nuclear plants with water-cooled reactors to achieve economic competitiveness while maintaining high levels of safety. To achieve the largest possible cost reductions, proven means for reducing costs must be fully utilized, and new approaches (such as improved technologies, risk informed methods for evaluating the safety benefit of design features, and international consensus regarding safety requirements so that standardized designs can be built in several countries without major re-design efforts) should be developed and implemented [6].

The pressure tubes of HWRs operate in a high-temperature high-pressure aqueous environment and are subjected to fast neutron irradiation. In order to ensure the PT integrity at all times during their service, they are periodically examined by Non-Destructive Examination (NDE) techniques. The IAEA conducted a CRP on inter-comparison of techniques for HWR pressure tube inspection and diagnostics. The intent was to identify the most effective pressure tube inspection and diagnostic methods, and to identify further development needs. The CRP was conducted in a round-robin manner. The participating laboratories prepared pressure tube samples containing artificial flaws/blisters/hydrogen resembling real defects of concern. The outside surface of sample was covered to facilitate blind testing. The samples, after examination by participating laboratories, were returned to the originating laboratory, which determined 'defect truth' in its sample. The originating laboratory analysed the sample inspection reports from investigating laboratories and compared the defect estimates with their true values. The CRP was conducted in two phases, the first one focused on flaw detection and characterization and the second one dedicated to the ddetermination of hydrogen concentration and blister characterization [7-8].

The value and importance of organizations engaged in the nuclear industry collecting and analysing operating experiences and best practices has been clearly identified in various IAEA documents and exercises. Both facility safety and operational efficiency can benefit from such information sharing. Such sharing also benefits organizations engaged in the development of new nuclear power plants, as it provides information to assist in optimizing designs to deliver improved safety and power-generation performance. In cooperation with Atomic Energy of Canada, Limited, the IAEA organized the Workshop on Best Practices in Heavy Water Reactor

Operation in Toronto, Canada in September 2008, to assist interested Member States in sharing best practices and to provide a forum for the exchange of information among participating nuclear professionals. The papers presented at the workshop were published as an IAEA technical document [9]. Korea Hydro and Nuclear Power Co., Ltd (KHNP) hosted the second workshop on "Good Practices in HWR Operation" in Gyeongju, Rep. of Korea in April 2011.

3. Coordinated research projects

3.1 Benchmarking severe accident computer codes for HWR applications

Currently different countries follow different regulatory requirements for severe accident considerations in HWRs. It is expected that the new reactor projects will explicitly and systematically consider severe accidents during the design phase to minimize the likelihood of severe core damage and large radioactivity releases.

Computer codes used for the analysis of design basis events have been validated against integral and/or separate effects tests, whereas in the case of severe accident computer codes it is rather impossible, or at least quite expensive, to carry out a validation exercise against integrated experiments. Consequently, the code capabilities have to be assessed based on benchmarking against other severe accident computer codes. In view of this, a benchmarking exercise becomes necessary to assess the results from various computer codes to provide an improved understanding of modelling approaches, strengths and limitations. The exercise could also suggest ways to overcome code limitations and thereby increase the confidence in severe accident code predictions. A benchmarking exercise encompassing the various severe accident codes in use within the HWR community is important not only for providing confidence in the overall performance of the codes but also for the reduction of uncertainties in their predictions.

The IAEA started a CRP in 2009 on benchmarking severe accident computer codes for HWR applications to improve the safety for currently operating plants and to facilitate more economic and safe designs for future plants. The expected outcomes from this CRP are:

- improved understanding of the importance of various phenomena contributing to event timing and consequences of a severe accident,
- improvement of emergency operating procedures or severe accident management strategies,
- advanced information on computer code capabilities to enable the analysis of advanced HWR designs.

The CRP scope includes:

- collection and evaluation of existing models, correlations, experiments, and computer codes applicable to HWR severe accident analysis
- determination of reference design and severe accident scenario for benchmarking analysis considering operating HWRs and available computer codes in Member States
- establishment of criteria for fuel failure, fuel channel failure, fuel channel disassembly, core collapse, calandria vessel failure and containment failure, and reactor vault failure

- benchmark analysis for Phase 1 (accident initiation to fuel channel dryout), Phase 2 (fuel channel dryout to core collapse), Phase 3 (core collapse to calandria vessel failure), and Phase 4 (calandria vessel failure to containment failure).

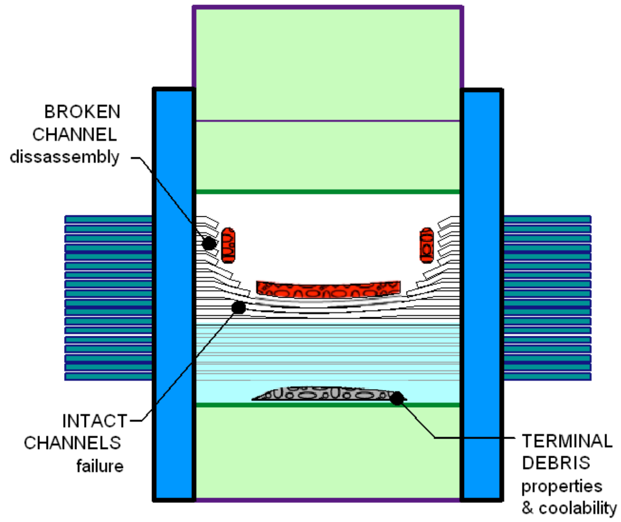

Figure 1 Fuel channel disassembly phenomena (conceptual – not to scale).

3.2 Heat transfer behaviour and thermo-hydraulic code testing for super critical water cooled reactors

There is high interest internationally in both developing and industrialized countries in innovative super-critical water-cooled reactors (SCWRs), primarily because such concepts will achieve high thermal efficiencies (44-45%) and promise improved economic competitiveness utilizing and building on the recent developments for highly efficient super critical fossil power plants.

The higher coolant temperatures proposed for SCWR systems imply fuel cladding temperatures greater than current nuclear reactor operating experience. Because of enhanced heat transfer for supercritical flows and the use of new cladding materials with low corrosion rates, it is necessary to have precise information for establishing both the neutronic and the thermal limits. Consequently, in developing SCWR designs, experimental data for the convective heat transfer from fuel to coolant, covering a range of flow rate, pressure and temperature conditions, are required. Collection, evaluation and assimilation of existing data as well as deployment of new experiments for needed data are necessary to establish accurate techniques for predicting heat transfer in SCWR cores.

Validated thermo-hydraulic codes are required for design and safety analyses of SCWR concepts. Existing codes for water-cooled reactors need to be extended in their application and improved to model phenomena such as pressure drop, critical flow, flow instability behaviour, and transition from super-critical to two-phase conditions.

The IAEA CRP on SCWRs promotes international collaboration among IAEA Member States for the development of SCWRs in the areas of heat transfer behaviour and testing of thermo-hydraulic computer methods. Specific objectives of the CRP are:

- to establish a base of accurate data for heat transfer, pressure drop, blowdown, natural circulation and stability for conditions relevant to super-critical fluids,
- to test analysis methods for SCWR thermo-hydraulic behaviour, and to identify code development needs.

3.3 Natural circulation phenomena, modelling and reliability of passive systems

The use of passive safety systems such as accumulators, condensation and evaporative heat exchangers, and gravity driven safety injection systems eliminate the costs associated with the installation, maintenance and operation of active safety systems that require multiple pumps with independent and redundant electric power supplies. Another motivation for the use of passive safety systems is the potential for enhanced safety through increased safety system reliability. As a result, passive safety systems are being considered for numerous advanced reactor concepts.

The IAEA CRP, entitled “Natural Circulation Phenomena, Modelling and Reliability of Passive Safety Systems that Utilize Natural Circulation”, was conducted during 2004-2009. Specific objectives of the CRP were:

- to establish the status of knowledge: passive system initiation & operation; flow stability, 3-D effects and scaling laws
- to investigate phenomena influencing reliability of passive natural circulation systems
- to review experimental databases for the phenomena
- to examine the ability of computer codes to predict natural circulation and related phenomena
- to apply methodologies for examining the reliability of passive systems.

The IAEA training course on natural circulation phenomena and passive safety systems in advanced water cooled reactors is one of the outcomes from this CRP. This course provides participants with a comprehensive instruction on natural circulation phenomena and modeling in nuclear power plants. The lecture material was published as an IAEA TECDOC [10]. This course has been held at the International Center of Theoretical Physics (Trieste, Italy) and other locations worldwide almost annually since 2004.

As shown in Table 1, four categories in different degrees of passivity are defined and used in IAEA [11]. Passive safety systems in Category D are used in many advanced designs and they can be characterized as having active initiation and passive execution. A second publication from this CRP is a document that examines passive safety systems adopted by 20 reference designs including evolutionary and innovative concepts to identify the thermo-hydraulic phenomena involved in each passive safety system [12].

Table 1 Classification of passivity

	Category A	Category B	Category C	Category D
Signal inputs of intelligence	No	No	No	Yes
External power sources or forces	No	No	No	No
Moving mechanical parts	No	No	Yes	Limited
Moving working fluid	No	Yes	Yes	Limited

The third publication is a TECDOC that includes the improvement in the understanding of each phenomenon, with sample analyses for some integral tests and NPPs, and sample applications of the methodology to examine the passive system reliability [13].

4. International collaborative standard problems

IAEA ICSPs provide a structured approach to advance the understanding of neutronic, thermo-hydraulic, fuel or materials behaviour in advanced nuclear power plants, as well as the performance of nuclear plant systems. ICSPs can be established to

- provide a comparison of best-estimate computer code calculations to experimental data under controlled conditions;
- evaluate the capability of computer codes to adequately predict the occurrence of important phenomena, and the corresponding behaviour of nuclear systems during operating, upset and accident conditions, which are represented in experiments.

4.1 Computer code validation for HWR LBLOCA with RD-14M test

Most internationally recognized codes used for LWR design and safety analysis have been subjected to systematic validation procedures through a number of international programmes. This IAEA ICSP was the first international initiative to compare the performance of codes against experiments for HWR systems.

The reference experiment was performed in the RD-14M test loop located at the AECL Laboratories in Pinawa, Canada. The RD-14M facility is a pressurized water loop with essential features similar to the primary heat transport loop of a typical CANDU 6. A Large Break Loss-of-Coolant Accident (LBLOCA) test, named B9401, was selected as the reference case. This case includes the limited temperature excursion in the core shortly after the LOCA and the demonstration of the performance of the emergency core cooling system. Six different institutes using four different codes and six different idealizations participated in the activity performing the blind and post-test analyses of the B9401 experiment. All codes are two-fluid six-equation codes, except one that is a three-equation code with the drift-flux capability. The strengths and weakness of the codes were identified and the ways to improve the prediction were studied. The participants benefited greatly from the analysis of this experiment due to the exchange of expertise and information that was not available in the open literature [14].

4.2 Computer code validation for HWR SBLOCA with RD-14M test

Building on the successful completion of the ICSP on HWR LBLOCA, a new IAEA ICSP on a HWR Small Break Loss-of-Coolant Accident (SBLOCA) was started in 2007. The objective of this ICSP is to improve the understanding of important phenomena expected to occur in SBLOCA transients, to evaluate code capabilities to predict these important phenomena, their practicality and efficiency, and to suggest necessary code improvements and/or new experiments to reduce uncertainties. Two RD-14M SBLOCA tests were selected for blind calculations. Eight institutes from six HWR countries are currently participating in this ICSP.

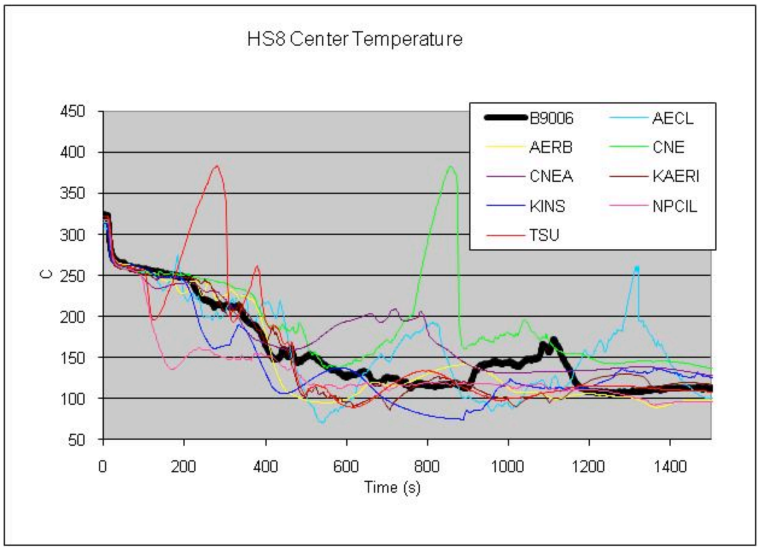

Figure 2 Comparison of fuel element simulator temperature

4.3 Integral PWR design natural circulation flow stability and thermo-hydraulic coupling of containment and primary system during accidents

IAEA ICSP on an integral Pressurized Water Reactor (PWR) design has been prepared as a follow-up to the CRP on natural circulation phenomena, modelling and reliability of passive systems that use natural circulation. Natural circulation flow stability and thermo-hydraulic coupling of primary system and containment during accidents are important phenomena to be examined for integral PWR design. The specific objectives of the ICSP are:

- to compare the best-estimate computer code calculations to the experimental data obtained from the integral test facility representing an integral type reactor
- to improve the understanding of thermal-hydraulic phenomena expected to occur in normal operation and transients in an integral reactor
- to evaluate the capability of computer codes to adequately predict the occurrence of important phenomena, and the corresponding behaviour of nuclear systems during operating, upset and accident conditions, which are represented in experiments.

Oregon State University (OSU) in the USA has offered their experimental facility for this ICSP. The OSU MASLWR test facility models the MASLWR conceptual design including reactor pressure vessel cavity and containment structure. The scope of the ICSP includes two types of experiments: 1) single and two phase natural circulation flow stability tests with stepwise reduction of the primary inventory, and 2) loss of feedwater transient with subsequent ADS (Automatic Depressurization System) blowdown and long term cooling by primary-containment coupling. Participating institutes will perform three phases of simulations (double-blind, blind and open) for the experiments with their own computer codes.

5. Data Bases

5.1 ARIS

IAEA Member States, both those just considering their first nuclear power plant and those with an existing nuclear power program, are interested in having ready access to the most up-to-date information about all available nuclear reactor designs as well as important development trends. To meet this need, the IAEA has developed ARIS (the Advanced Reactors Information System), a web-accessible database that provides Members States with comprehensive and balanced information about all advanced reactor designs and concepts. ARIS includes reactors of all sizes and all reactor lines, from evolutionary water cooled reactor designs for near term deployment, to innovative reactor concepts still under development, such gas cooled and fast reactor or small- and medium-sized reactors. ARIS allows users to sort and filter the information based on a variety of relevant criteria, thus making it easy to capture the general trends and to identify the differences between the diverse designs and concepts.

Figure 3 ARIS data base

The data stored in ARIS is compiled by the IAEA based on the information provided by the developers of each reactor design/concept, and harmonized to result in an unbiased and easy to use source of information. Although the depth of the reactor descriptions may vary depending on the level of development of the various concepts, ARIS includes reports on nuclear steam supply system, safety concept, plant performance, proliferation resistance, spent fuel and waste management, as well as a complete list of technical data. The information is updated whenever there is any significant change on a specific design. The ARIS is accessible from the IAEA public website at http://aris.iaea.org.

5.2 THERPRO

From 1999 to 2005 the IAEA carried out a CRP on establishment of a thermo-physical properties data base of materials for LWR and HWR. The objectives of this CRP were to collect and systematize a thermo-physical properties database for light and heavy water reactor materials under normal operating, transient and accident conditions and to foster the exchange of non-proprietary information on thermo-physical properties of LWR and HWR materials. An internationally available, peer reviewed database of properties at normal and severe accident conditions (THERPRO: http://therpro.hanyang.ac.kr) has been established at Hanyang University (Republic of Korea), and now provides various material properties data and an interactively accessible information resource and communications medium for researchers and engineers. TECDOC-1496 [15] describes the content of THERPRO database. Registering to use freely the THERPRO database is easy by visiting the THERPRO website.

6. Summary and conclusions

HWRs are the second most common type of nuclear reactor installations in the world, second only to LWRs. Therefore, high priority should be given to the development of technology to achieve economic competitiveness with other energy sources and to assure high safety levels for HWRs.

The IAEA mission to foster and facilitate HWR technology development in Member States is successfully carried out through the organization of coordinated research projects, international collaborative standard problems, technical meetings, international collaborative assessments and training courses and workshops.

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