Call for Research Proposals for Participation in the New Coordinated Research Project (CRP) Sponsored by the International Atomic Energy Agency (IAEA)

Advancing Thermal-Hydraulic Models and Predictive Tools for Design and Operation of SCWR Prototypes

<<CRP I31034>>

Summary of the CRP

There is a strong interest in Super-Critical Water cooled Reactor (SCWR) designs among the Member States beyond the current fleet of water cooled reactors for electricity production and non-electric applications and to contribute to climate change mitigation. Several conceptual designs of SCWR have been developed to generate greater than 1000 MWe in Canada, China, European Union, Japan and the Russian Federation. In addition, the development has been expanded to include the designing of super-critical small modular reactors (SCSMR) for generating capacity of up to 350 MWe, which can also be adopted as prototypes for the reference SCWR design. The design process requires advances in key technology areas such as neutronics, fuel, materials, chemistry, thermal-hydraulics, control and safety. Thermal-hydraulics is one of the remaining critical areas important for maintaining coolability of the fuel and hence safe operation of the reference and prototype SCWRs. A significant amount of thermal-hydraulics studies was performed to support design, licensing and operation of the current fleet of nuclear reactors operating at subcritical pressures. However, information and experimental data remain scarce on thermal-hydraulics behaviours for fluids at supercritical pressures. The objective of this CRP is to therefore, establish a coherent body of knowledge about fluids at supercritical pressures and/or temperatures needed to prototype the SCWR designs. This is an ambitious goal, which can be achieved only with a renewed effort in research and development (R&D) that identifies and closes current gaps in technology areas as well as enhances knowledge and technological bases relevant to design options. Achieving this goal would also enhance the knowledge basis in similarity to the level of availability in water cooled reactor technologies at subcritical pressures. The scope of the CRP is the advancement of predictive tools (such as correlations, system and sub-channel codes) and models supported by computational fluid dynamics (CFD) tools, based on improved knowledge and understanding of thermal-hydraulics phenomena, for the design and operation of SCWR prototypes.

This CRP will bring together experts from Member States with water cooled reactor technologies to utilize, test and further improve modelling tools. Predictive capability of these tools will be assessed against experimental data or benchmarked against other tools. The associated research activities will foster national excellence and international cooperation, promote sharing of newly developed knowledge, and contribute to capacity building in developing countries.

Completing activities covered in this CRP would provide improved predictive tools to Member States for design and operation of SCWRs and prototypes. These tools could also be applied for licensing and operation of the current fleet of nuclear reactors. Participating in this CRP would enhance the R&D capability and infrastructure (such as system and subchannel codes), as well as facilitate training of highly qualified personnel for the nuclear industry in both developed and developing Member States. In addition, the newly developed knowledge to be shared with Member States through various activities, will be as well aimed at supporting the graduate students and broaden the representation of female graduates in the field.

Duration

- 3 years
- Expected starting date: January 2022

Background Situation Analysis

The supercritical water cooled reactor (SCWR) is an advanced nuclear reactor concept that operates at light water conditions beyond the critical point (i.e., 22.1 MPa and 374°C). It has enhanced characteristics of higher efficiencies, better fuel utilization, lower cost and improved safety than common light water reactors (LWRs). Additionally, licensing and operation of SCWRs mimics closely those of LWRs. However, design and operation challenges are envisioned from sharp variations in water properties at operating pressures and temperatures for current SCWR designs as compared to LWRs. On the other hand, the SCWR poses much less challenges and concerns regarding corrosion, erosion, and chemical reactivity than other advanced reactor concepts (such as sodium cooled reactors, lead cooled reactors or molten salt reactors).

The design approach to SCWRs toward their deployment requires advances in key technology areas such as neutronics, fuel, materials, chemistry, thermal-hydraulics, control, and safety. Thermal-hydraulics is one of the remaining key critical areas to close the existing gaps important for assuring the coolability of the fuel and hence safe operation of the SCWR prototypes. A significant volume of thermal-hydraulics studies was performed in the last six decades to support design, licensing, and operation of the current fleet of nuclear reactors operating at subcritical pressures. However, information and experimental data remain scarce on thermal-hydraulics behaviours for fluids at supercritical pressures when applied to nuclear installations. Heat transfer and thermal-hydraulic behaviour of fluids at supercritical pressures have been studied for decades and ultimately found use in fossil fuelled power plants. While contributions to the literature from these past studies along with the operations of the fossil plants is of significant value, it must be improved to allow design and operation of a nuclear reactor. Nuclear power plants require rather complete understanding of phenomena and systems to meet the strict requirements in terms of safety and reliability of operation. Therefore, since the proposal of SCWR concepts, the attention of the scientific community has been deepened and focused on completer understanding of the mechanisms that give rise to phenomena like heat transfer enhancement and deterioration, flow stability, chocked flow and trans-critical fluid behaviour during postulated reactor accidents and thermal-hydraulic effects due to cladding surface characteristics. Presently existing gaps in knowledge required for the development of conceptual designs to prototypes SCWR are but not limited to:

- *Prediction of maximum cladding temperatures*: is an important requirement for SCWR design. A method to identify heat transfer regimes (i.e., normal, enhanced or deteriorated heat transfer) and reliable prediction tools are required.
- *Cladding surface conditions*: corrosion is one of the main issues affecting the performance of nuclear reactor operation. It is particularly crucial for SCWRs due to high temperature and high pressure operating environment that leads to high fuel cladding temperature. Development of models of corrosion effect on heat transfer

requires high quality data obtained experimentally and high fidelity simulations using CFD models with detailed surface roughness characterisations.

- *Hydraulic resistance*: is an important factor in controlling the mass flow distribution within fuel assemblies. It couples strongly with heat transfer and depends on geometric factors. In addition, the effect of boundary layer laminarization on hydraulic resistance has not been fully characterised in a supercritical pressure environment. This has an impact on other key phenomena, such as flow instability and critical/choked flow.
- *Critical heat flux (CHF) in the near critical pressure region*: fluids do not exhibit the phase change phenomena at supercritical pressures. Therefore, CHF phenomena are no longer being considered as a safety factor for normal operation of SCWRs. It remains to be of interest when establishing the start-up and shut-down strategies as well as analysing postulated large-break loss-of-coolant accidents. Large amount of CHF data has been obtained at subcritical pressures in support of the design and licensing of current fleet of nuclear reactors. However, limited CHF data are available at pressures near the critical point. Despite of a few CHF experiments being conducted recently at near-critical pressures, additional information is needed to improve modelling capabilities in support of the SCWR design.
- *Effect of non-uniform axial power distribution on heat transfer*: fuel assemblies exhibit non-uniform axial power distribution in the SCWR core. However, most heat transfer experiments were conducted with test sections (i.e., tubes, annuli and bundle subassemblies) having a uniform axial power distribution. Heat transfer data remain scarce for test sections with non-uniform axial-power distribution. Additional information is needed to quantify the effect of non-uniform axial power distribution on heat transfer in fuel assemblies.
- *Flow instability and natural circulation*: currently, only a limited amount of data is available for verification and validation of computational tools and models in predicting flow instability and natural circulation. Additional experimental data are needed to confirm the validity of the models and prediction tools.
- *Depressurization and choked flow*: in the very unlikely event of a pipe or tube rupture or a controlled blowdown procedure during normal operation, it is necessary to be able to predict flow rates and depressurization rates. Critical (or choked) flow from a supercritical state is a complex phenomenon that is not well understood. The sharp variation of properties as the fluid approaches and passes through the vapour dome can drastically change the flow rate.
- *Computational analysis tools*: sub-channel and CFD based codes need to have the ability to predict the non-uniform distribution of the circumferential cladding temperature around the fuel rod, accounting for the subchannel turbulent mixing in supercritical fluids and the influence of wire wraps. The ability to calculate and analyse the entire fuel assembly is the additional necessary development. The development of system analysis code needs experimental data from integral experiments for validation and verification.
- *Exploiting digital technologies and code coupling*: this could truly modernise the thermal hydraulics methodology with the aid of modern computers (high power computing, HPC) and numerical method developments, supported by experimentation and a comprehensive database. The platform would include a novel coupling methodology (between CFD and system codes, for example), new ‘full life cycle design’ platform, uncertainty quantification, machine learning, high performance computing simulations (numerical experiments), big databases through experimentation, to mention just few. Like other innovative reactor designs, SCWR

development poses challenges but also offers unique opportunities to use new advances in computer technology to modernise the design stages.

The two successfully completed CRPs generated new knowledge and advanced the understanding of thermal-hydraulics behaviour and phenomena of fluids at supercritical pressures relevant to the SCWRs:

1. Heat Transfer Behaviour and Thermo-hydraulics Code Testing for Super-critical Water Cooled Reactors (SCWRs) (September 2007 – January 2013);
2. Understanding and Prediction of Thermal Hydraulics Phenomena Relevant to Supercritical Water Cooled Reactors (June 2014 – June 2019).

The first CRP established emerging reactor design needs, provided new experimental data, which were collected and used for the assessment of available and new models suitable to predict phenomena relevant to reactor design, such as but not limited to heat transfer, hydraulic resistance, natural circulation, stability, chocked flow. The CRP findings pointed to the need to continue with the new effort with the goal to expand knowledge in relation to heat transfer and friction in fuel bundle conditions. Therefore, a second CRP was conducted with the focus of collecting new experimental and theoretical data. The corresponding TECDOC-1900 was published in 2020. This is the third CRP that is solely aimed at closing the remaining gaps in thermal-hydraulic models and predictive tools needed for current conceptual SCWR designs to translate onto SCWR prototype facility to be built in near future.

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Scope of the CRP

The primary scope of the CRP is the advancement of design tools and models (system and sub-channel codes) supported by CFD for the design and operation of SCWR prototypes based on improved knowledge and understanding of thermal-hydraulics related phenomena such as but not limited to heat transfer, hydraulic resistance, instabilities, and corrosion effects. Achieving this scope will include development of new predication models and performing benchmark on the specific phenomena.

In addition, this CRP is focused at the development of R&D capabilities and infrastructure as well as training of highly qualified personnel on thermal-hydraulics to support the nuclear industries at Member States.

Participants in the CRP are expected to have active programmes relevant to the CRP objectives and experience and basic knowledge in the field of supercritical fluid thermal-hydraulics phenomena, simulation tools and benchmark capabilities. As part of the research proposal, the attached questionnaire must be completed and attached to the research proposal.

This IAEA CRP is coordinated with other parallel international activities to avoid duplication and provide synergies to advance the state-of-the art and closing the currently existing gaps in thermal-hydraulics designs of SCWR for their prototyping.

CRP Specific Research Objectives

1. Review and improve correlations for prediction of relevant thermal-hydraulics phenomena such as but not limited to heat transfer, critical heat flux, hydraulic resistance, choked flow and natural circulation in support of SCWR prototype development to establish suitable fluid-to-fluid similarity theories;

2. Acquire the data and develop/improve engineering correlations and modelling tools applicable to supercritical pressure conditions for advancing conceptual designs into prototype SCWR facilities;

3. Exploring the use of advanced computing technologies to work towards establishing an integral digital design platform;

4. Report all analysis steps (assumptions, evaluation boundary definitions, design parameters, experimental data) and the results achieved;

5. Develop education / training programmes for early-career engineers and scientists, and establish opportunities for MS and PhD dissertations to strengthen promotion of research in advancing SCWR thermal-hydraulic design towards their prototyping; especially encourage female students to participate in graduate studies in the CRP framework R&D areas.

Activities

A. Submission of research proposals for evaluation — 1 October 2021

B. Participation in 1st Research Coordination Meeting (RCM): — February 2022

   Participants should be prepared to present on the background experience relevant to CRP scope and objectives, and propose contribution inclusive of their expertise and experience in the areas relevant to CRP of interest to advancing the SCWR designs towards prototyping.

C. Develop to start implementing the CRP *umbrella* in supporting graduate programmes across the CRP members and the CRP *scheme* in supporting young and female professionals and graduate students — February 2022

D. Participation in 2nd RCM — February 2023

E. Participation in 3rd RCM — February 2024

F. Develop and conduct training workshops, develop eLearning modules — 2022,2023

G. Written submissions to Final Report (e.g., TECDOC, NES) — 2024

H. Technical review of Final Report (e.g., TECDOC, NES) — 2024-2025

CRP Outputs

1. Final CRP report (TECDOC) and other relevant IAEA publications;

2. Relevant training workshops, courses and supporting lecture materials, and learning tools to be developed;

3. Publications in conference proceedings and peer reviewed journals; and

4. MS & PhD training programmes within the CRP to strengthen promotion of research in developing Member States and support advancing the SCWR thermal-hydraulic designs through pair building between agreement holders and contract holders institutes.

CRP Outcomes

1. Advance thermal-hydraulics designs of SCWR conceptual designs toward their near-term prototyping;
2. Enhance the capabilities and expertise in Member States to analyse/predict fluids thermal-hydraulic behaviour at supercritical pressures in advancing SCWR designs towards their prototypes; and
3. Enable Member States to establish best practices in the design of thermal-hydraulic systems at supercritical pressures.

Funding

The IAEA will contribute €1,500 per year towards each contract and support financially the attendance of CRP participants that have made substantial contributions (through contract or agreement) in the three research coordination meetings (RCM) planned to be held during the CRP lifetime.

Application Procedures

Interested scientists should submit their research contract or research agreement proposal that cover part(s) or all of the scope of the CRP, along with the completed questionnaire attached (the scope of the coverage of a proposal is to be determined by the Project Officer after evaluating the proposal and the capacity of the scientist(s) involved and the capability of the institute). The standard research contract/agreement proposal form is available at http://cra.iaea.org/cra/forms.html.

Research proposals should be submitted by email to Official.Mail@iaea.org by 1 October 2021.

Any administrative question should be addressed to the Research Contracts Administration Section (NACA) via research.contracts@iaea.org .

Technical enquiries should be addressed to the project officer for this CRP, Ms Tatjana Jevremovic (T.Jevremovic@iaea.org).

Further general information relating to the participation in CRPs and the Coordinated Research Activities in general is available on http://cra.iaea.org.