TERMS OF REFERENCE
For the INPRO Collaborative Project COOL

Investigation of technological challenges related to the removal of heat by liquid metal and molten salt coolants from reactor cores operating at high temperatures

Brief Summary

Next generation reactors, as needed for hydrogen production and other applications, will need to incorporate innovative approaches to further enhance their reliability and safety as needed for large scale deployment in different regions of the world. An important feature of these reactors will be the use of coolants at temperatures much higher than being used in current generation reactors. This involves addressing a wide range of issues concerning design and safety of these reactors. Joint studies and research, involving several competent research institutes located in different countries, would offer a cost beneficial approach towards addressing these issues. The project covers cooling of reactor cores operating at high temperature up to 1000°C with focus on liquid metals and molten salts for use in high temperature reactors, advanced fast reactors and accelerator driven systems.

Overall Objective

To achieve improved capabilities of reactor core cooling by high temperature coolants particularly liquid metals and molten salts.

Specific Research Objectives

1) **To establish the properties of high temperature coolants (liquid metal, molten salts), establish their thermal hydraulic relationships and investigate issues related to natural circulation of such coolants**. High temperature coolants need to be studied from the point of view of their applications in High Temperature Reactors (HTR) and Very High Temperature Reactors (VHTR), Accelerator Driven Systems (ADS), Molten Salt Reactors (MSR) and advanced fast reactors (FR). It is proposed that a reliable database of such coolants, in the temperature regime of interest, be compiled and established with respect to thermo-physical properties and thermo-hydraulic relationships. Various aspects related to natural circulation for these coolants should be identified. Validation of CFD codes and their internal models and correlations versus experimental data will also be carried out.
2) **Validation of CFD and neutronic codes** and their internal models and correlations versus experimental data will also be carried out.
3) **Addressing various issues related to handling of high temperature coolants:** Issues related to handling of high temperature coolants, such as plugging of leakages, phase change behaviours, handling of active and non-active coolants, etc. will be addressed.
4) **Compatibility of components in intimate contact with high temperature coolants for prolonged service:** Special components that would perform the

functions of valves, heat exchangers, pumps, fuel handling systems, level detectors, flow-meters, etc need to ensure reliable operation while being exposed to high temperature coolants for extended durations. It is proposed to establish guidelines for their design.

5) **High temperature coolant chemistry monitoring and control:** Research on elaboration of methodology for on-line monitoring and control of coolant chemistry under the temperature regime of interest will be carried out.

6) **Transfer of knowledge and promotion of cooperation in the subject area:** Documentation and publication of results, enhancement of databases, dissemination of information and exchange of experience among various institutions and Member States, conducting training and technical courses, etc will be fostered.

7) **Incorporation of new data in the IAEA THERPRO database:** Experimental results and new data will be transferred for compilation in the THERPRO DB.

Background Situation Analysis (Rationale/Problem)

In Table –1 shown below, which is indicative in nature, presents some examples of available experience on liquid metals (LM) and related test facilities and their maximum operating temperatures are presented. Table-2 lists important issues related to LM and molten salt (MS) based coolants, current status of knowledge on these issues and scope of work which needs to carried out for higher temperature application of these coolants.

Table-1: International Heavy Liquid Metal (HLM) test facilities devoted to thermal hydraulic studies [Part of the table taken from Reference 7]

Association/Country	Objectives	Tmax
FZK/D (Germany)	Determination of the local convection heat transfer coefficient and studies on loop control parameters and corrosion- phenomena.	450°C
FZK/D (Germany)	Development and testing of measurement techniques	550°C
ENEA/I (Italy)	Thermal – hydraulics, cooling pin	500°C
ENEA/I (Italy)	Thermal – hydraulics, component development, large-scale exp. and liquid metal chemistry in pool configuration	450°C
CEA/F (France)	Oxygen sensor and Dip sampling system validation, OCS development	550°C
SCK/BE (Belgium)	Gas transport in the beam line, outgas, metal evaporation, simulation of spallation products	500°C
RIT/SE (Sweden)	Thermal hydraulics and heat transfer measurements	550°C
JAERI/JP (Japan)	Flow studies in horizontal LBE target	< 450°C
MES/JP (Japan)	Coolant purification, thermal – hydraulic and corrosion tests	550°C
KAERI/KR (Korea)	OCS, corrosion, Thermal-hydraulics	650°C
LANL/US (USA)	Thermal-hydraulics, corrosion, OCS	650°C
IPPE (Russia)	Lead-based coolants	700°C

Table- 2: Preliminary list of issues related to the removal of heat from reactor cores operating at temperatures up to 1000°C with focus on liquid metals and molten salts [References 1 and 5]

	Scope	Status	Remarks
1	Properties of coolants (liquid m etals and molten salts) at higher temperatures	Data exist up to 650°C for lead based alloys and 700°C for molten salts. For temperature beyond these scattered data for few properties are found (Ref. 3)	Reliable d ata u sing large num ber of data points should be generated for temperatures up to 1000°C.
2	Thermal hydraulic correlations for LM and MS coolants	Correlations for LM and MS have been generated previously, for tubular geometries. Some correlations are available for MS in packed bed geometries (for salts commonly used in non-nuclear industries)	Additional effort is required to generate correlations for non-tubular geometries, e.g. pebble bed geometries at higher temperatures. Additionally effect of dissolved oxides, non-ideal surface conditions, etc need to be assessed. Estimation of pressure drop and buoyancy forces in natural circulation driven systems needs to be carried out.
3	CFD and neutronics studies on LM and MS	Verification of calculation models has been carried out for lower temperatures (~550°C) for LM. These correlations have been assessed for MS commonly used in chemical industry	Verification of calculation models in currently available codes for use in LM and MS systems need to be assessed for higher temperatures. Verification and benchmark of chemical transport codes, such as MASKOR (IPPE, Russia)
4	Freezing/defreezing of LM and MS	Literature on numerical simulation of freezing and defreezing and small experimental results are available.	Extensive studies on melting/freezing in large vessels, long pipes, pebble bed geometry, etc is required.
5	On-line monitoring and	Results of research on	Extensive research for

	Scope	Status	Remarks
	control of coolant chemistry	oxygen control up to 550°C for LM is are available in literature.	use in LM environments at temperatures up to1000°C is required. Similar studies for MS are also called for. Development of technologies for measurement and control of impurities (e.g. oxygen) is needed.
6	Components for service in intimate contact with high temperature coolants, and leakage detection, monitoring ,plugging for LM and MS	No information is available on MS. Limited data on structural materials for LM are known	Development of design guidelines for components operating at higher temperatures while being in contact with LM or MS environments is needed. These guidelines may also include the use of advanced materials and devices (e.g. composites, silicon carbide). Special attention may be paid to issues of joining, ensuring leak proof operation and mechanical design. Additional attention may be paid for development of sensors, detectors and other instruments.

Expected Outputs

1) Report on the results of the study on properties, thermal hydraulic correlations and feasibility of natural circulation in high temperature coolants
2) Enhanced existing databases with therm al hydraulic and thermo-dynam ic properties in the temperature range of interest
3) Guidelines for handling active and non-active high temperature coolants.
4) Guidelines for design of com ponents in intim ate contact w ith high temperature coolants.
5) Methodology for on-line monitoring and control of coolant chemistry

Action Plan; Activities and Schedule

Table-3 gives the detailed list of activities of the collaborative project and aligns them with the three phases of the project listed below. All activities listed are independent and can be started in parallel. Preliminary interest of participants of the CP in the activities is presented in Table-3.

It is planned to study various issues related to higher temperature application of these coolants in phased manner. Implementation plan shall be worked out based on discussions with other interested participants. Draft implementation plan is shown below:

Phase-1 Preparatory phase

May 2008 –September 2009

a) Distribution of ToR and draft implementation plan among all potentially interested participants and discussion of these documents.
b) Survey on the available state of the art knowledge and facilities
c) Based on the results of a) and b) formulation of scope, schedule and responsibilities for the entire project duration
d) Approval at institutional levels
e) Approval of detailed structure of activities and detailed responsibilities through e-correspondence
f) Monthly exchange of newsletters giving information of status
g) E-correspondence and exchange of initial responses

Phase-2

June 2009 – September 2010

a) First technical meeting (exchange views and develop Table of Contents of the final report of COOL CP) (June 2010)
b) Participants to perform agreed-upon activities at their respective workplaces
c) E-correspondence and exchange of results (optionally, periodic telephone and video conferences)

Phase-3

June 2010- December 2011

a) Continuation of activities at participants respective workplaces
b) Compilation of results
c) Preparation of related documents
d) Second technical meeting (to discuss draft final report) – (March 2011)
e) Final printed document (December 2011)

Funding

Each country is expected to meet its own expenses including those on manpower deployed for this purpose. In addition, the flow of information should be done by e-correspondence, hence avoiding the expenses incurred in travel. The meetings will be held at the IAEA HQ in Vienna, or in Mumbai, India, or in the Czech Republic, or hosted by any other participating institution.

Resources

India, Russia and the Czech Republic informed during the Kick-off meeting that they have active high temperature reactor programmes in progress. Extensive analytical and experimental studies have been planned as part of these programmes. Well-equipped laboratories and well-trained manpower are available for carrying out work in these areas. Involvement of capacities of other participating institutions is appreciated

Procedure for Implementation

It is anticipated that Joint Initiative implementation mode (JI) or extra budgetary Coordinated Research Project (CRP) would be appropriate mechanisms of implementation.

Table-3 Detailed list of activities

S. No.	Activity	Participation and contribution	Prio-rity	Schedule
1	**Study on Properties of coolants (LM and MS)**			
1.1	Survey of available data on transport and thermodynamic properties	Czech Rep., India, IAEA		Phase 1
1.2	Experimental works to measure transport and thermodynamic properties of coolants up to 1000^{o}C	Czech Rep., Korea		Phase 2&3
2	**Studies on thermal hydraulic correlations for LM and MS coolants**			
2.1	Experimental and computational studies on correlations for LM for tubular, pebble bed and other geometries	India, Italy		Phase 2&3
2.2	Experimental and computational studies on correlations for MS for tubular, pebble bed and other geometries	Czech Rep., Korea		Phase 2&3
2.3	Experimental study on the effect of dissolved oxygen on	China, Czech Rep.		Phase 2&3

S. No.	Activity	Participation and contribution	Prio-rity	Schedule
	fluid flow and heat transfer			
2.4	Assessment of existing pressure drop and heat transfer correlations for natural circulation flow	China, Czech Rep., India, Italy		Phase 2&3
2.5	Assessment of existing pressure drop and heat transfer correlations for enhanced gas injected circulation	Italy		Phase 2&3
3	**CFD and neutronics studies on LM and MS**			
3.1	Verification of calculation models for lower temperatures for LM and MS. Assessment of correlations for LM and MS commonly used in chemical industry	Brazil(neutronics), Czech Rep., Hungary, India, Italy,		Phase 2
3.2	Verification of calculation models at high temperatures in currently available codes for use in LM and MS systems	Brazil(neutronics), China, Czech Rep., Hungary, India		Phase 2&3
3.3	Preparation of verification report	Brazil(neutronics), China, Czech Rep., Hungary, India, Italy,		Phase 3
4	**Studies on phase change of LM and MS**			
4.1	Numerical simulation of freezing and de-freezing and small experimental results	Czech Rep., India, Italy		Phase 2&3
4.2	Studies on melting/freezing in large vessels, long pipes, pebble bed geometry, etc.	Czech Rep., Italy(TBC)		Phase 2&3
4.3	Preparation of report	Czech Rep., India, Italy(TBC)		Phase 2&3
5	**Development of tool for on- line monitoring and control of coolant chemistry**			
5.1	Research in various loops up to 550°C for LM.	India		Phase 2&3
5.2	Research in various loops up to 700°C for MS	Czech Rep.		Phase 2&3
5.3	Development of technologies and tools (sensors, detectors, instruments and software) for measurement and control of impurities (e.g. oxygen) (for LM)	Germany, India(description of loop), Italy		Phase 2&3
5.4	Development of technologies	Czech Rep.		Phase

S. No.	Activity	Participation and contribution	Prio-rity	Schedule
	and tools (sensors, detectors, instruments and software) for measurement and control of impurities and REDOX control system (for MS)			2&3
5.5	Preparation of documentation for the final report on COOL CP	Czech Rep., Germany, India, Italy		Phase 3
6	**Components for service in intimate contact with high temperature coolants (LM and MS)**			
6.1	Experimental studys on components and various materials that are in contact during operation with LM and MS	Czech Rep., Germany, India, Italy		Phase 2&3
6.2	Preparation of progress report	Czech Rep. Germany, India, Italy		Phase 3

Interface with Other Similar Projects inside or Outside the Agency

To the best of the participants' knowledge, the information provided in Tables 1 and 2 give an overview of the relevant work being done elsewhere. A selected list of documents referred is given in the lists of references below.

The COOL project is seeking synergies with other activities of the IAEA Technical Working Group on Fast Reactors (TWG-FR). All experts in LM/MS participating in TWG-FR are invited to join the COOL project. E.g. the following Member States and organizations: Belgium (SCK·CEN), Brazil (CNEN), Canada, China, Czech Republic (NRI, SKODA), EU (JRC), France (CEA), Germany (FZK, FZJ), India (BARC), Italy (ENEA, Ansaldo, Del Fungo Giera Energie), Japan (JAEA, Tokyo Institute of Technology), Republic of Korea (KAERI, KAIST, KMU), Russia (IPPE, KI, NIIAR), South Africa, Spain (CIEMAT, Universidad del Pais Vasco, Universidad Politécnica de Madrid, Universidad Politécnica de Valencia), Sweden (RIT), Switzerland (PSI), USA (ANL, LANL, UC-Berkley, ORNL, MIT, University of Wisconsin, UNLV, INL) could contribute and benefit from the activities of the COOL CP

COOL also relies on existing TWG-FR implementation mechanisms (e.g. International Database on ADS Related R&D Programs, IAEA/ICTP Schools, etc.)

References

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4. "Theoretical and Experimental Studies of Heavy Liquid Metal Thermal Hydraulics: Proceedings of a Technical Meeting Held in Karlsruhe, Germany, 28-31 October 2003," IAEA-TECDOC-1520, October 2006.
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6. Fast Reactor Database http://www.iaea.org/inisnkm/nkm/aws/frdb/index.html
7. Publication of Data Collection "Thermophysical Properties of Materials for Nuclear Engineering" (IAEA Publication in Press)
8. IAEA/ICTP "School on Physics, Technology and Applications of Accelerator Driven Systems", Trieste, 19 – 30 November 2007, With Special Emphasis on Thermal Hydraulics of Heavy Liquid Metal Targets for ADS
9. "Liquid Metal Cooled Reactors: Experience in Design and Operation," IAEA-TECDOC-1569, December 2007.
10. International Database on ADS Related R&D Programs http://www-adsdb.iaea.org/index.cfm

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