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## नाभिकीय-संयुग्मित हाइड्रोजन उत्पादन हेतु कॉपर-क्लोरीन ऊष्मारासायनिक चक्र का विकास: भा.प.अ. केंद्र में विकास की स्थिति एवं भावी कार्य-योजना

### Development of Copper-Chlorine Thermochemical Cycle for Nuclear Coupled Hydrogen Production: Developmental Status and Roadmap at BARC

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#### सारांश

नाभिकीय-संयुग्मित हाइड्रोजन उत्पादन की दिशा में प्रयास के अंतर्गत, भारत के भाभा परमाणु अनुसंधान (भा.प.अ.) केंद्र में कॉपर-क्लोरीन (Cu-Cl) ऊष्मारासायनिक चक्र का विकास व्यापक अनुसंधान एवं विकास (R&D) तथा समयबद्ध परिनियोजन हेतु अभियांत्रिकी गतिविधियों के माध्यम से सक्रिय रूप से किया जा रहा है। भा.प.अ. केंद्र में विकसित Cu-Cl चक्र की परिकल्पना बड़े पैमाने पर हाइड्रोजन उत्पादन के लिए की गई है। इस प्रौद्योगिकी की प्रमुख विशेषताओं में उच्च तापीय-से-हाइड्रोजन दक्षता, न्यूनतम सहायक चरणों एवं ठोस पदार्थ के प्रबंधन के साथ सघनित एकीकरण योजना तथा लगभग 500°C के मध्यम तापमान की आवश्यकता सम्मिलित है। ये विशेषताएँ इसे मध्यम एवं उच्च तापमान वाले नाभिकीय रिएक्टरों के साथ संयोजन हेतु अत्यंत संभावनाशील बनाती हैं। विकास संबंधी प्रयासों के परिणामस्वरूप, भा.प.अ. केंद्र की Cu-Cl प्रौद्योगिकी ने कई महत्वपूर्ण उपलब्धियाँ प्राप्त की हैं। इस प्रौद्योगिकी का बेंच-स्केल पर 5 NL/h हाइड्रोजन उत्पादन दर पर 170 घंटे की सतत अवधि तक सफल प्रदर्शन किया गया है, जो विश्व स्तर पर किसी भी ऊष्मारासायनिक चक्र के लिए अब तक प्रतिवेदित सर्वाधिक अवधि का संचालन है।

#### ABSTRACT

In a quest for nuclear coupled hydrogen production, the development of Copper-Chlorine (Cu-Cl) thermochemical cycle is being actively pursued at Bhabha Atomic Research Center (BARC), India through extensive R&D and engineering for time bound deployment. The Cu-Cl cycle developed at BARC is envisaged for large scale hydrogen production encompassing several salient features which includes high thermal to hydrogen efficiency, an intensified integration scheme with minimal auxiliary steps and solid handling and moderate temperature requirement of around 500°C, which renders it eminently prospective for coupling with moderate and high temperature nuclear reactors. As an outcome of the developmental endeavors, the Cu-Cl technology of BARC has achieved significant milestones. The technology has been demonstrated at bench-scale at 5 NL/h hydrogen throughput for a sustained duration of 170 hours, making it the highest reported operation for any thermochemical cycle globally. Subsequently, a pilot-scale facility of design capacity 150 NL/h hydrogen throughput has been commissioned and demonstrated for 220 hours. The present article discloses all the developmental milestones and future roadmap pertaining to Cu-Cl thermochemical technology of BARC for expedited deployment of nuclear hydrogen production.

KEYWORDS: *Copper-Chlorine, Cu-Cl, Nuclear, Hydrogen, Thermochemical cycle, Pilot-scale*



एकीकृत क्यू-सी. एल.-एफ. बी. टी. आर. सुविधा

Integrated Cu-Cl-FBTR facility

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## Introduction

The onset of the hydrogen ecosystem in the last decade has propelled innovations and cutting-edge research towards development of state-of-the-art hydrogen production technologies. In particular, nuclear coupled hydrogen production offers distinctive advantages which include large scale production capability, high availability factor, captive and non-captive production philosophy and low levelized cost of hydrogen. In line with the objective of manifesting nuclear hydrogen production, a distinctive class of hydrogen production technology viz. thermochemical cycles are being developed globally. The thermochemical cycles achieve water splitting using a series of chemical reactions carried out in a closed loop, resulting in a net output of hydrogen and oxygen with complete recycle of all intermediate chemicals.

Development of Cu-Cl thermochemical cycle is being actively pursued at BARC in a staged sequential approach comprising of key milestones for time bound deployment of the technology. The initial phase encompassed establishing the feasibility of constituent steps, reaction mechanism and kinetics, modelling of multiphase reactors and development of auxiliary sub-systems for achieving integration of the loop, as reported by Thomas et al. [1-4]. Following this, activities pertaining to demonstration of integrated bench-scale facility were undertaken, encompassing development of a novel integration scheme for closed loop operations, control and instrumentation heuristics, detailed engineering activities and MOC development for key components. As an outcome of the developmental endeavours, a first of its kind bench-scale facility, as illustrated in Fig.1, corresponding to a TRL of 5 was demonstrated at 5 NL/h hydrogen production for a sustained duration of 170 hours, making it the highest recorded duration for any thermochemical cycle globally [5-6]. Subsequently, based on design and operational feedback from the bench-scale facility, a pilot facility (TRL-6) was installed and commissioned with a design capacity of 150 NL/h  $H_2$ , as illustrated in Fig.2. The facility has been demonstrated at 150 NL/h for 220 hours thereby establishing the design basis and integration scheme. The pilot-scale facility encompasses several state-of-the-art systems for multiphase thermal steps, novel separation processes, non-mechanical high temperature solid handling, control and instrumentation. In view of the developments an application has been filed with the Indian Patent Office towards grant of intellectual property (IP) rights.

## Nuclear Hydrogen

As part of the expedited initiative to establish the feasibility of coupling Cu-Cl cycle with nuclear reactors of Department of Atomic Energy, several endeavours have been undertaken. The focus is towards coupling with two high temperature reactors viz. Fast Breeder Reactors, in particular FBTR and secondly the upcoming High Temperature Gas Cooled Reactor (HTGCR). Dedicated activities on multiple fronts have been initiated towards achieving these targets, which involves several first of its kind developments towards establishing the coupling philosophy. This section discusses in detail the pertinent activities.

## Coupling with Fast Breeder Reactors

Chemical Engineering Division (ChED) of BARC in coordination with IGCAR have embarked upon activities to couple the pilot-scale Cu-Cl facility with secondary sodium loop of FBTR, for demonstration of nuclear  $H_2$  production. The main objective of this demonstration is to establish the feasibility of coupling the Cu-Cl process, most primarily the two thermal reactors viz. hydrolysis and thermolysis with sodium systems. The pilot-scale facility has suitably been re-engineered for this purpose. The process and thermal hydraulic design have been carried out for the thermal reactors, with objective to facilitate extraction of heat from secondary sodium loop of FBTR. Further, several key developments, which include safe thermal reactor design, fast acting safety systems, control philosophy and detailed analysis of safety scenarios have been carried out. The Cu-Cl pilot scale facility at BARC was dismantled, transported and re-installed at FBTR, IGCAR. Several new technical systems were also designed and installed to facilitate the coupling interface. At present, the facility has been installed and coupled with secondary sodium loop of FBTR as illustrated in Fig 3.

The coupled pre-commissioning activities and cold-commissioning have been completed. During pre-commissioning, the performance of all the critical engineered systems including the process design of thermal reactor was established as per design intent. Subsequently, the commissioning and demonstration of nuclear hydrogen was carried out as per design capacity on 26th June, 2026. The campaign established operation of the integrated facility and performance of all systems as per design intent. No anomalies in operation and safety were observed during the campaign. This demonstration of Cu-Cl facility coupled with FBTR marks the first instance of hydrogen production using nuclear heat in the world. The facility will act as a test-bench and will be used for generating critical engineering data which will be required for further scale-up and deployment of Copper-Chlorine technology coupled with sodium cooled fast reactors. Additionally, design and associated pre-project activities have been initiated for a future scaled-up Copper-Chlorine facility coupled with upcoming FBTR-II. The design and detailed engineering of the facility pertinent to the hydrogen production process is being carried out by ChED, BARC.



Fig.1: Integrated novel bench-scale facility in metallic systems.



Fig.2: Integrated novel pilot-scale facility in metallic systems.

## Prototype Facility

As a major target of Department of Atomic Energy, the Copper-Chlorine cycle is being designed and scaled-up for coupling with the upcoming gas cooled reactors. The gas coolant from the reactors will be utilized to drive the thermal reaction steps. Since, this being a first of its kind project in the world, there is no precedence and previous engineering data available for such systems. In view of this, a prototype Copper-Chlorine facility with a design capacity of  $10 \text{ Nm}^3/\text{h}$  ( $\sim 1 \text{ kg/h}$ ) is being installed at BARC. The facility will encompass a simulated high temperature gas loop integrated with the Copper-Chlorine process systems. The facility is being designed with an objective to serve as the miniaturized version of the Copper-Chlorine technology which will be deployed. The facility constitutes of novel design of chemical reactors, especially the thermal reactors with extended surfaces, intensified process systems and highly efficient internal heat recovery systems comprising of direct contact heat exchangers and multi-phase heat exchangers having optimized geometry to achieve maximum possible heat recovery, thereby enhancing the overall efficiency of the Copper-Chlorine cycle. The prototype facility will have a technology readiness level (TRL) of 8-9, which will make it ready for deployment. The detailed design of the facility has been completed and the tendering and installation activities are in progress. The facility will provide critical engineering data and will be used for establishing the performance of scaled-up systems and other critical engineering systems of Copper-Chlorine technology.

## Demonstration Facility Coupled with Gas Cooled Reactor

As part of one of the major commitments under the aegis of Nuclear Energy Mission, 2025 by the Government of India, a large-scale demonstration facility is being set-up at BARC, Vishakhapatnam. The upcoming facility will be a large-scale centralized facility dedicated entirely for nuclear hydrogen production. The Copper-Chlorine facility will be coupled with the upcoming 5MWth high temperature gas cooled reactor (HTGCR) as the heat source for the Copper-Chlorine process, a first of its kind dedicated project in the world. The design and engineering of the facility have been completed and the associated pre-project activities are underway. The key highlights of the Copper-Chlorine facility include novel design of thermal reactors with extended surfaces to extract maximum heat utilization from the nuclear coolant, intensified process systems and highly efficient internal heat recovery systems. The major highlight of the upcoming facility is its



Fig.3: Integrated Cu-Cl-FBTR facility.

completely indigenous designed and developed process systems. The upcoming facility at Vizag will offer end-to-end solution for hydrogen and will act as a well to gate technology demonstrator for nuclear hydrogen production.

## Conclusion

BARC has demonstrated the first of its kind Copper-Chlorine (Cu-Cl) thermochemical cycle for production of clean hydrogen through water splitting using a series of closed loop chemical reactions. Further scale-up and deployment activities are being pursued in mission mode and directed towards technology demonstration with prospective high temperature reactors for hydrogen production using nuclear power. By leveraging cleaner nuclear power, the developmental efforts aim to establish a reliable and sustainable method of hydrogen production, leading to self-reliance/Aatmanirbharta in energy security. Also, the project aligns with India's ambitious Net Zero directives set under 'Nuclear Energy Mission'.

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