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Life Cycle Management of Structural Components of Indian Nuclear Reactors and Reprocessing Plants

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Abstract

The increasing demands on reliability, safety and economics of nuclear systems translate to challenges in realization of high-performance components for operation at steady state, transient and severe accident conditions. The authors, based on their four decades of research, development and deployment experiences, present a review of findings relating to life cycle management of critical structural components in Indian thermal, fast reactors and reprocessing facilities. The challenges relating to specific structural components are described with highlights of materials to improve life for prolonged service with safety and economics.

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1. Introduction

The life cycle management of key structural components in any nuclear system assumes significant importance and requires a high degree of systematic, professional and specialized expertise to provide, reliability, safety and economics for operation at steady state, transient and severe accident conditions [1-3]. In order to maximize the efficiency of new systems and enhance the performance of ageing components, it is essential to understand degradation in a qualitative and quantitative manner. Also to achieve high level of reliability and excellent performance, several issues related to design, materials selection, fabrication, quality control, transport, storage, condition monitoring, failure analysis, etc. have to be adequately addressed and implemented, for structural components used in nuclear systems [1-6]. In addition to meeting the demands of extended service life, with cost competitiveness along with enhanced safety requirements; it is essential to demonstrate materials integrity and reliability so as to enable nuclear power plants to operate, beyond their initial design life. At the forefront of any energy challenge in the life cycle management of structural components, it is a necessity that plants operate for as long as possible in a safe, reliable and cost-effective manner.

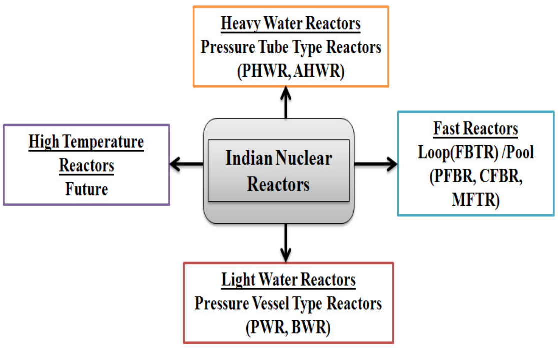

Fig 1. Indian nuclear power reactor portfolio [9, 10].

Comprehensive approaches desire trans-disciplinary teams capable of testing, evaluation, analysis and implementation towards achieving the robust design, materials, manufacturing, modeling, simulation, monitoring and

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effective management. It has been demonstrated that with holistic approaches, the life cycle can be managed with safety and cost-effectiveness. The authors explain their approaches with a few substantial examples including aging and degradation of zircaloy-2 pressure tubes of Pressurised Heavy Water Reactor (PHWR) that has been extensively investigated and understood to decide en-mass replacement of coolant channels in earlier PHWRs of Rajasthan atomic power station and Madras atomic power station [7, 8]. During service, pressure tubes are susceptible to hydrogen pick up, delayed hydrogen cracking, creep, and formation of blisters. The life of pressure tubes could be prolonged by replacing zircaloy-2 with Zr-2.5Nb material. Similarly, the Monel-400 alloy tubes used in steam generator of PHWRs where tube leaking due to under deposit attack and pitting corrosion was encountered have been replaced with Inconel 600 alloy tubes [7, 8]. In Sodium Cooled Fast Reactor (SFR) with closed fuel cycle programme of India, comprehensive studies to understand behaviour of materials in liquid sodium by exposing the representative samples and components in liquid sodium loops operating at reactor conditions for long durations and evaluating their performances with extensive validated modelling have enabled right choices of materials, monitoring llingstrategies and manufacturing [1-4]. Steam generators for SFRs are key to realize safe operation with high availability of the nuclear system.

The paper addresses life cycle management of this important component as an illustrative example of our comprehensive approach. In the spent nuclear fuel reprocessing and waste management systems, a systematic approach has been pursued to study degradation causes and mechanisms during service with life cycle analysis approach, by taking into consideration the material, fabrication, comprehensive quality management, service, operating conditions etc. The study has identified susceptible locations, where high degradation due to corrosion is expected in nitric acid medium leading to adaptation of methodologies to eliminate such occurrences during service. In this paper, the authors describe experiences of life cycle management of critical structural components in Indian nuclear systems, based on their four decades of research, development and deployment experiences.

2. Materials and challenges in safe and reliable operation of the nuclear components

Design, materials, manufacturing health monitoring techniques and methodologies enable component to perform the intended function with higher, efficiency, improved availability, increased safety and lower maintenance. Even though the design life of a nuclear power plant (NPP) is typically 30 or 40 years, NPP including reprocessing plant materials do suffer various failures during the design life, which are expensive and involve repair, inspection and replacements [1, 5, 7, 8]. In addition to satisfying the materials design criteria based on tensile properties, thermal creep, cyclic fatigue, creep-fatigue, fracture toughness**,** etc. structural materials for current and proposed future nuclear energy systems must provide adequate resistance to environmental degradation phenomena and radiation damage, chemical compatibility and damage tolerance to fracture [2, 9]. Hence, materials aging degradation are significant concern and thus pursuit for nuclear and reprocessing plants materials. The different Indian nuclear power reactor configurations are shown in Fig 1 [9, 10].

The global installed nuclear power capacity has remained nearly dormant for the past few decades and the world wide developments scenario has changed after the Fukushima nuclear accidents in some countries. The present nuclear power share in India is about 3.5 %. In order to improve the average world per capita consumption of energy, India has envisaged a “Three Stage Nuclear Power Programme” for achieving energy independency by effective utilization of its limited natural uranium reserves and exploitation of its large thorium deposits. India has high emphasis on sodium cooled fast breeder reactor with closed fuel cycle. This approach is central to nuclear energy sustainability of India.

Indian reactor power plants have witnessed over 300 reactors year of accident-free safe operation with high overall capacity factor of 80% and availability factor of 90% during the last operation [1, 7]. This could only be possible due to sound design of components and systems, appropriate material selection, maintaining quality assurance at all stages and strict chemistry control supported by extensive in-service examinations using the state of art and chemistry based technologies. The sound design of equipment has played physics a vital role in corrosion control, and reliability materials performance [7, 8]. A variety of materials are required for the construction of BWR and PHWR. For example, materials like Ni alloys, are used for steam generator (SG) tubes (Monel-400, Inconel 600, 690, Incoloy 800, etc.). The majority of the components holding radioactive water or gas are made of 300 series of SS. Zr 2.5Nb and zircaloy-4 are used as cladding and pressure tube. Admiralty brass, aluminium brass, cupronickel, titanium, etc. are mainly used in condenser tubes and balance of plant heat exchangers [6, 7]. Most of these materials and component and system technology have been fully developed indigenously and the technology has been translated into production plants, which are successfully operating as various units of Department of Atomic Energy (DAE), India [7, 8]. Modeling of hydrogen pick up in pressure tube and cladding tube in PHWR, experimental back up, prediction models of life estimation, in-service inspection technologies and replacements of these components are some of the key achievements leading to success of PHWRs life cycle management.

3. Structural components management in sodium cooled fast reactor

In SFR with closed fuel cycle programme of India, comprehensive studies to understand the behaviour of materials in liquid sodium by exposing the representative samples and components in liquid sodium loops operating at reactor conditions for long durations and evaluating their performances has enabled right choices of materials, monitoring strategies and manufacturing. Developments of