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Small and Medium sized Reactors (SMR): A review of technology

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ABSTRACT

In this paper the authors review 25 original Small and Medium sized Reactor designs currently under development, licensing procedure or in operation. Technology overview, safety features and ability to mitigate proliferation are considered. In order to show common research trends and highlight the features of particular designs the authors choose to classify the reactors according to used technology and cooling medium. The main requirement for a new reactor design is to secure inherent and passive safety features, thus different ways to achieve it are shown. The Pressurized Water Reactor (PWR) is the most advanced and most commonly used technology. In PWR, passiveness and inherency of safety features are ensured by integrating steam generators inside the Reactor Pressure Vessel (RPV). It eliminates possibility of Loss of Cooling Accident (LOCA); moreover the technology allows swift removal of heat produced during normal or accidental conditions. Heavy Water Reactors (HWRs) are also in operation, however, the design process of improving emergency cooling system is ongoing. The design of Supercritical Water Reactor (SCWR) based on Canadian HWR is reviewed including the ongoing development in novel leakage detection method and material improvement. Liquid Metal Cooled Reactors (LMCR) are in advanced stage of research and development focusing on lead and sodium as the coolants. LMCR are secured from LOCA accidents due to low operating pressure and integration of the most elements in RPV. In case of Advanced Gas-Cooled Reactors (AGCR) the literature indicates several possible system integrations related to high operating temperature under development. AGCRs are able to use fully passive systems during all events due to their low power density. Furthermore, it is noted that the use of innovative reactor designs can mitigate proliferation concerns to an acceptable level. The authors identify the common research trend among all designs as the fuel cycle evaluation and optimization.

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Abbreviations: 4S, Super-Safe, Small and Simple; AECL, Atomic Energy of Canada Limited; AHWR, Advanced Heavy Water Reactor; ALMCR, Advanced Liquid Metal Cooled Reactor; BWR, Boiling Water Reactor; CANDU, CANadian Deuterium Uranium; CAREM, Central Argentina de Elementos Modulares; CBR, Core Breeding Ratios; CEFR, Chinese Experimental Fast Reactor; CERMET, Ceramic-Metallic Fuel; CFD, Computational Fluid Dynamics; CNEA, Comisión Nacional de Energía Atómica; CNP, Chinese Nuclear Power unit; CO_2, Carbon dioxide; DoE, Department of Energy; ECCS, Emergency Core Cooling System; EMP, electromagnetic pump; FBNR, Fixed Bed Nuclear Reactor; FBR, Fast Breed Reactor; FBTR, Fast Breed Test Reactor; FPU, Floating Power Unit; GCFR, Gas Cooled Fast Reactor; GCR, Gas Cooled Reactor; GDWP, Gravity Driven Water Pools; GT-MHR, Gas Turbine – Modular Helium Reactor; HTGR, High Temperature Gas Reactor; HWR, Heavy Water Reactor; IAEA, International Atomic Energy Agency; IXAF, Internally and eXternally cooled Annular Fuel; IHX, Intermediate Heat Exchangers; iPWR, Integrated Pressurized Water Reactor; LANL, Los Alamos National Laboratory; LBE, Lead–Bismuth Eutectic; LBEFR, Lead Bismuth Eutectic Fast Reactor; LEU, Low Enriched Uranium; LFR, Lead Fast Reactor; LMCR, Liquid Metal Cooled Reactors; LOCA, Loss of Coolant Accident; LWR, Light Water Reactor; MOX, Mixed-Oxide Fuel; MSS, Moderator Safety System; NPP, Nuclear Power Plant; OTHCSG, Once-Through Helically Coiled Steam Generators; OTS, Operator Training Simulator; PBMR, Pebble Bed Modular Reactor; PCHE, Printed Circuit Heat Exchanger; PCSS, Primary Coolant Safety System; PFBR, Prototype Fast Breed Reactor; PHWR, Pressurized Heavy Water Reactor; PRISM, Power Reactor Inherently Safe Module; PWR, Pressurized Water Reactor; RFA, Robust Fuel Assemblies; RPV, Reactor Pressure Vessel; SCWR, Supercritical Water Reactor; SFR, Sodium Fast Reactor; SG, Steam Generator; SGL, Steam Generator Liquid Portion; SGV, Steam Generator Vapor Portion; SMART, System-integrated Modular Advanced Reactor; SMR, Small Modular Reactor or Small and Medium sized Reactors; SSR, SuperSafe Reactor; THPS, Thermal-Hydraulic code of PCS; TMI, Three Mile Island; TRISO, Tristructural-Isotropic fuel

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1. Introduction

According to many observations, economic development and growth in population requires secure supply of ever growing need for energy. The most convenient form of which is the electrical energy. One of the most reliable and sustainable power generation technology is nuclear power. This source allows generation of cheap electricity, independent of weather and economic conditions. Majority of commercial Nuclear Power Plants (NPPs) generates high electrical power output ($>1GW_e$); yet, the trend in power generation shifts to smaller units, in order to be able to supply electricity to remote places and to create more distributed energy systems. Recently, we may observe a lot of research efforts with emphasis on creating small nuclear reactors. The Small and Medium sized Reactors (SMRs) pose opportunity to create energy system that is more flexible, thus more suitable for current energy strategy. Constant increase in population and energy consumption per capita requires increase in power production capacities. The humankind is spreading all over the world including remote areas difficult to access such as northern part of Alaska, the United States of America, or Russian Federation, where small and reliable energy source is required to supply electricity or drinkable water [1]. Some countries like China despite investing in large nuclear power plants [2] are also developing smaller units [3]. Many countries are supporting licensing program of small modular reactor designs. The best example is USA where Department of Energy (DoE) anticipates 5-year Licensing Technical Support program worth $452 mln for light water reactor design and another supporting program for generation IV design.

The acronym SMR is used often to describe a small modular reactor [4] because its size should be adequate to be built and assembled in a factory, then shipped to the location. However, according to the International Atomic Energy Agency (IAEA), it now stands for Small and Medium sized Reactor [5–7]. Small reactors are those below 300 MW_e and medium are the ones between 300 and 700 MW_e. Easy to notice that with smaller power output it is more suitable for areas with smaller power grid or remote locations where connection to existing power grid would be economically not justified. In some particular cases i.e. OKBM Afrikantov had designed a reactor that is going to be placed on a boat and become a floating nuclear power plant. Therefore, the position of the power station would be shifted easily in order to supply the energy whenever it is needed.

The SMRs are under development in the following countries: Argentina, Brazil, Canada, China, France, India, Japan, Republic of Korea, Russian Federation, South Africa and the USA. Such high

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