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Original Article

Superheated Water-Cooled Small Modular Underwater Reactor Concept

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A B S T R A C T

A novel fully passive small modular superheated water reactor (SWR) for underwater deployment is designed to produce 160 MWe with steam at 500ºC to increase the thermodynamic efficiency compared with standard light water reactors. The SWR design is based on a conceptual 400-MWe integral SWR using the internally and externally cooled annular fuel (IXAF). The coolant boils in the external channels throughout the core to approximately the same quality as a conventional boiling water reactor and then the steam, instead of exiting the reactor pressure vessel, turns around and flows downward in the central channel of some IXAF fuel rods within each assembly and then flows upward through the rest of the IXAF pins in the assembly and exits the reactor pressure vessel as superheated steam. In this study, new cladding material to withstand high temperature steam in addition to the fuel mechanical and safety behavior is investigated. The steam temperature was found to depend on the thermal and mechanical characteristics of the fuel. The SWR showed a very different transient behavior compared with a boiling water reactor. The inter-play between the inner and outer channels of the IXAF was mainly beneficial except in the case of sudden reactivity insertion transients where additional control consideration is required.

1. Introduction

Traditionally, the pursuit of a higher temperature and harder spectrums are the two key paths taken for improving the current light water reactor (LWR) technology. While the latter is focused on improving fuel utilization, the former is focused on improving the economics of the reactor through an increase in power conversion efficiency. With the current vast uranium reserves, improving the economics of a nuclear reactor is of more importance than fuel utilization. In the initial phases of the development of the current LWR technology, the concept of a superheat water reactor (SWR) was explored in the 1950s and 1960s, with only a few years of operational experience accumulated in the US, Sweden, Soviet Union, and Germany. The main motivation behind the SWR concept is to produce superheated steam at approximately 500–600ºC, to increase the thermodynamic efficiency of LWRs that produce steam at approximately 300ºC. A 200ºC

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Nomenclature

AEC	US atomic energy commission
BWR	Boiling water reactor
CRD	Control rod drive
DHR HE	Decay heat removal heat exchanger
EBT	Emergency boron tank
iPWR	Integral pressurized water reactor
ISP	Internal suppression pool
IXAF	Internally and externally cooled annular fuel
LBFR	Lead–bismuth fast reactor
LOCA	Loss of coolant accident
LWR	Light water reactor
MSIV	Main steam isolation valve
PWR	Pressurized water reactor
RIP	Reactor internal pump
RPV	Reactor pressure vessel
SMR	Small modular reactor
SWR	Superheated water reactor

increase in steam temperature results in an approximately 4% increase in efficiency (or 10% relative increase) with an ideal simple steam Rankine cycle [1].

Superheating steam has been used in the power industry for many decades. In addition to an increase in efficiency, the turbine performance is improved by avoiding the presence of droplets in saturated steam. The turbine blades can go through erosion and pitting when exposed to water droplets at high speeds, thus reducing their lifetime. The higher steam temperature will also have broader applications such as industrial process heat and liquid fuel production. The former US Atomic Energy Commission funded many prototype superheat reactors. Other countries also started similar programs. These nuclear systems can be divided into two categories: (1) superheating within the core; and (2) superheating outside of the core. In the latter design, superheating was achieved by use of fossil fuels. The pressurized water reactors (PWRs) or boiling water reactors (BWRs) were coupled to a coal- or oil-fired power plant for increased thermal efficiency. In the former case, the steam from a BWR was used as the input to the reactor core which was cooled by the superheated steam and moderated by light water. The superheat core was either integrated in the same core or a separate reactor. In both categories, the operation reliability (e.g., capacity factor) of both nuclear and fossil power plants was not as high as today [1]. Table 1 lists the various nuclear reactor designs that produced superheated steam as a product. In order to withstand high temperature steam, many of these designs adopted steel alloys which were popular by their construction time instead of zircaloy. However, no significant operational experience was gain and fuels were taken to very low burnups.

Improving the economic performance of small modular reactors (SMRs) is key for allowing their deployment. The Felxblue, a 160-MWe SMR designed by DCNS, is an off-shore underwater reactor using the traditional PWR technology and layout [15]. While Flexblue utilizes technology-ready and proven systems, the design is within a large expensive hull with the LWR pedestrian thermodynamic efficiency of 33%. In order to increase both the compactness and efficiency of the Flexblue design, the integral superheater class of SWRs is considered for this study. Specifically, the use of a SWR conceptual design by Ko and Kazimi in 2010 [1] is investigated. The reason the earlier integral nuclear superheater concepts or other conceptual integral SWR designs discussed in literature were not chosen for such an application is that they all

Table 1 – Design characteristics of the nuclear power plants with superheat [1–14].

Reactor	Designer	Moderator	Coolant	Thermal power (MWt)	Efficiency (%)	Steam exit temp.(°C)	Material	
							Fuel	Clad
A. Nuclear power plant with fossil-fired superheater								
Elk River	AC	H_2O	H_2O	58.2 (N) 14.8(F)	30.8	441	UO_2– ThO_2	SS
Indian Point I	B&W	H_2O	H_2O	585 (N) 215(F)	32.0	538	UO_2– ThO_2	SS
CVTR	West.	D_2O	D_2O	65	29.2	385	UO_2	Zr-4
B. Nonintegral nuclear superheater								
EVESR	GE	H_2O	Steam	17	–	493	UO_2	SS
C. Integral nuclear superheater								
BORAX-V	ANL	H_2O	H_2O & steam	35.7	(T)	454	UO_2 (B) UO_2 SS cermet (S)	304 SS (B) 304 SS (S)
BONUS	GNEC	H_2O	H_2O & steam	50	32.6	482	UO_2 (B) UO_2 (S)	Zr-2 (B) 316 SS (S)
Pathfinder	AC	H_2O	H_2O & steam	203	30.5	441	UO_2 (B) UO_2–SS cermet (S)	Zr-2 (B) 316L SS (S)
APS-1	USSR	Graphite	H_2O & steam	30	(T)	299	U-alloy	SS
Beloyarsk-1	USSR	Graphite	H_2O & steam	285	33	500	U-alloy	SS
Beioyarsk-2	USSR	Graphite	H_2O & steam	457	35	500	U-alloy	SS
Marviken	Sweden	Graphite	D_2O	593	33.7	475	UO_2 (B) UO_2 (S)	Zr-2 (B) Inconel (S)
HDR	Germany	H_2O	H_2O & steam	100	25.0	457	UO_2 (B) UO_2 (S)	SS (B) Inconel (S)

B, boiler; F, fossil fuel power plant; N, nuclear power plant; S, superheater; T, test reactor.

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