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RELIABILITY, SAFETY, AND SUSTAINABILITY IN NUCLEAR POWER PLANTS: ADVANCES IN SUPERCRITICAL WATER REACTORS AND CIRCULATION LOOPS

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Abstract

In the last two decades, population and energy requirements have drastically risen. Therefore, it is necessary to provide an adequate amount of energy to the people and industries without affecting global warming and the environment. So, several nuclear power plants are constructed to supply the required demand of the power supply to the household and industries. Nuclear power plants can produce more electricity while maintaining global warming norms. However, during production of higher power from the plants, there are several issues raised, such as the sustainability and safety of the nuclear power plant as well as the reliability of the plants. To resolve these issues to achieve higher plant efficiency, safety of the plant, etc., during operations, several power plants are constructed, such as boiling water reactors and supercritical water reactors to generate power at higher efficiency, while single, two phase and supercritical based natural circulation loops are used to improve the safety of the plant as well as used in operation to improve the power generation from the plant. In past decade, supercritical water reactors and supercritical natural circulation loops have been utilized to increase power generation and enhance the safety of the plant. This review article discusses numerical and experimental investigations of supercritical water reactors and natural circulation loops aimed at enhancing the safety, sustainability, and reliability of various nuclear reactors based on previously published works by several authors, along with identified research gaps and future work scopes.

Keywords: safety, sustainability, instability, natural circulation loop, supercritical water reactor

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I. Introduction

Energy policy decisions are increasingly prioritizing low-carbon sources. In light of the global economic downturn caused by COVID-19 and the discourse on climate change, nations are modifying their energy policies to emphasize net-zero emission solutions that enhance return on investment. Nuclear power reactors exhibit stability, consistency, low carbon emissions, and high energy density. Moreover, the prolonged operational lifespan, low maintenance costs, and load-following capability render nuclear energy a feasible substitute for fossil fuel sources. Also, researchers are trying to remove heat in a compact area of a nuclear reactor, specifically electronic parts using microchannel technology [1-2].These constraints pose a considerable risk to both existing and planned nuclear power reactors. Next-generation reactors are being developed to improve some bottlenecks and improve the safety and economic possibility of nuclear power plants. These reactors demonstrate modularity, improved safety margins, and significantly lower construction and operational expenses, while enabling localized micro-grids and various energy applications. However, the rapid development of next-generation reactors to meet global net zero targets requires significant investment and the application of advanced research approaches and technology. This is evident due to the expensive experimental testing facilities necessary for safety validation. Furthermore, researchers are increasingly reliant on computational approaches that require significantly longer periods to converge [3-5].

The preliminary designs of SCWRs have been formulated in Canada, the European Union, and Japan. The scientific term "supercritical" describes a state of a material when there is no distinct boundary between the liquid and gaseous phases. The SCWR design was one of six Generation IV system designs selected in a fourteen-country initiative, reflecting substantial interest in collaborative Research and Development (R&D) to progress future nuclear energy systems for deployment beyond 2030 [6-7]. Generation IV reactors, such as the Supercritical Water-Cooled Reactor (SCWR), were developed to improve the efficiency and sustainability of nuclear power facilities. Alongside these positive aspects of efficiency and design simplification, SCWRs are designed to function at supercritical pressures and temperatures.Nonetheless, all such developments include particular challenges related to reliability, sustainability, and safety, which must be thoroughly acknowledged and handled. This approach achieves enhanced thermal efficiency, estimated at 44-48%, in contrast to the 34-36% efficiency of current light water reactors. Supercritical water reactors employ water at temperatures exceeding its critical point (374°C, 22.1 MPa) for cooling and moderation functions. The SCWR technology can provide thermal, fast, or mixed neutron spectra, depending on the utilized pressure vessel or pressure tube system. It reduces nuclear waste production and alleviates greenhouse gas emissions. The thermal efficiency of SCWRs is augmented by the removal of fuel rods, hence generating an adequate energy output that reduces the generation of radioactive byproducts and prolongs the fuel cycle's lifespan through optimal fuel usage in nuclear power plants [8-9].

The word dependability of nuclear reactors denotes steady operation over a prolonged duration with minimal significant faults. SCWRs seek to enhance reliability by employing simpler designs, hence decreasing component quantity and minimizing system susceptibility to failure. SCWRs enhance the overall reliability of a nuclear reactor by eliminating pumps, dryers, pressurizers, and steam generators, hence reducing potential points of failure. Nevertheless, operating under supercritical conditions presents drawbacks. Elevated temperatures and pressures amplify the mechanical and thermal strains exerted on materials, necessitating the development of novel materials capable of enduring these conditions. Although SCWRs possess significant potential for reliability, further research in materials and a comprehensive understanding of the related supercritical water chemistry under radiative circumstances are necessary. Sustainability in nuclear power pertains to effective fuel utilization and minimal environmental impact, while also addressing long-term energy requirements. SCWRs promote sustainability through their exceptional thermal efficiency, which optimizes fuel utilization and minimizes waste generation. The efficient design indicates a diminished physical footprint and possibly reduced resource consumption during construction and operation. Moreover, SCWRs can be designed to support various fuel cycles, such as thorium or actinide recycling, enhancing fuel sustainability and reducing the generation of long-lived radioactive waste. Indeed, the diversity of SCWR's design will enable it to achieve numerous sustainability objectives and optimize fuel utilization by reducing waste [10-15].

This paper provides a comprehensive analysis of current SCWRs, elucidating essential elements of safety, sustainability, and reliability in nuclear power facilities. The approaches for creating safety analysis tools for SCWR are outlined to elucidate the primary scientific difficulties and the solutions applied at this stage. The steady-state and transient safety characteristics of contemporary SCWR designs are analyzed comprehensively. The techniques for creating safety analysis tools for SCWR are outlined to elucidate the primary scientific obstacles and the solutions that have been executed thus far. The safety criteria of contemporary SCWR concepts are analyzed. The review and debates accurately delineate the research status of SCWR concepts, the development of safety analysis methods, and their safety attributes.

II. Literature Review

I. Safety and Reliability of the Supercritical Water Reactors (SCWRs)

Nuclear power plants (NPPs) are developed to generate higher energy to fulfill the demand and supply of energy for households and industries. In order to provide the demand required by various industries, NPPs are trying to produce the optimum quantity of energy. However, to produce an adequate amount of energy, NPPs produce maximum quantity of heat generations, which increases the core temperatures as well as drastic changes of density near the pseudo-critical point that makes plants unstable. These phenomena affect the performance of the NPPs. Therefore, it is necessary to investigates the fluctuation of the temperature and density with time and without time for accurate prediction of the thermal hydraulic behavior of the supercritical water reactor and supercritical natural circulation loops (SCNCLs) using various methods such as numerical and experimental. These methods are capable of identifying the various factors that influence the safety and reliability of the NPPs, SCWRs [16-18], and SCNCLs [19].

II. Safety Identification of the Safety Mechanism and Criteria for Nuclear Power Plants

The fundamental principle of examining the safety of nuclear reactor plants involves combining all components of the plant during operations, effectively managing and segregating all heat generation components, and minimizing hazards to ensure the plant functions safely. The process includes systematically varying the pressure at different mass flow rates during steady state, as well as adjusting the mass flow rate, velocity, and temperature over time at various power levels to determine the threshold criteria and mechanisms for identifying safe operational conditions. To assess the safety or instability of supercritical water reactor-based plants, several authors investigated transient instability using density wave oscillation, while for steady-state conditions, they analysed the variation of pressure at different power levels relative to mass flow rate and noted a negative pressure drop, indicating static instability that can be very harmful during the startup of the nuclear plant. Furthermore, for full safety of the plants, researchers must examine various components of the reactors, such as fuel assembly and cooling systems, both steady-state and transient processes, as well as the dryout condition of the plant during accidents like loss of coolant accidents. In the NPP, two primary types of reactors operate based on the neutron spectrum. Fast reactors, like the supercritical pressure water-cooled rapid reactor (SWFR) developed by Japan, operate at high temperatures. The fuel blanket serves as a moderator to absorb neutrons during the fission process, generating high energy without impacting void reactivity or the core design. Supercritical pressure and temperature-based reactors are working on high temperatures, such as CANDU SCWR and U.S. SCWRs. Nonetheless, their coolant flow rate and the utilization of control rods as a moderator ensure the safety of the core. In this reactor, two cooling system passes are employed; the first generates power, while the second serves as a passive system to regulate the reactor's temperature and maintain the operational conditions of the SCWRs. In both cases, instability is likely, which is very harmful to the reactor. It can be seen that the amplitude of the mass flow rate is increasing with time and becomes unstable, while the mass flow rate with respect to time decreases and becomes stale. However, we refer to the mass flow rate as neutral when it remains constant over time. These mechanisms are used to determine the safety of the nuclear plants in terms of instability. Additionally, another approach for determining the safety mechanisms of the nuclear reactor is to accurately estimate the melting temperature of the core from a material perspective, which aids in preventing reactor accidents caused by excessive heat generation within the core. This phenomenon strengthens the safety and reliability of nuclear power plants, mitigates global warming, and improves the economy of the nation. This method compares the wall temperature and the threshold limiting temperature of the core wall during steady and transient states to ascertain the deterioration of heat transfer, which indicates the safety criteria of the supercritical reactor and natural circulation loop. Figures 1 and figure 2 illustrate the schematic diagram of the nuclear reactor.

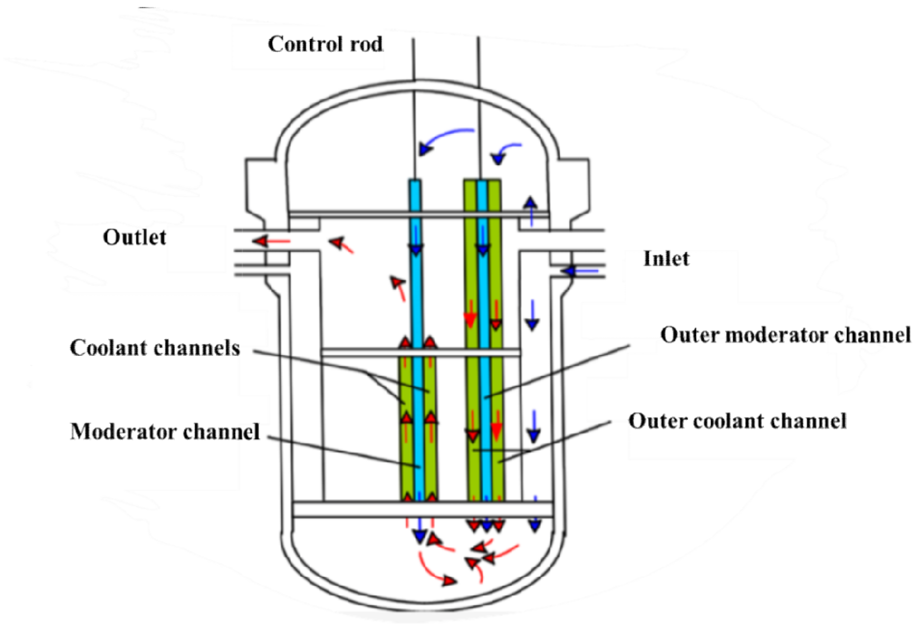

Figure 1: *Schematic diagram of US SCWR [18]*

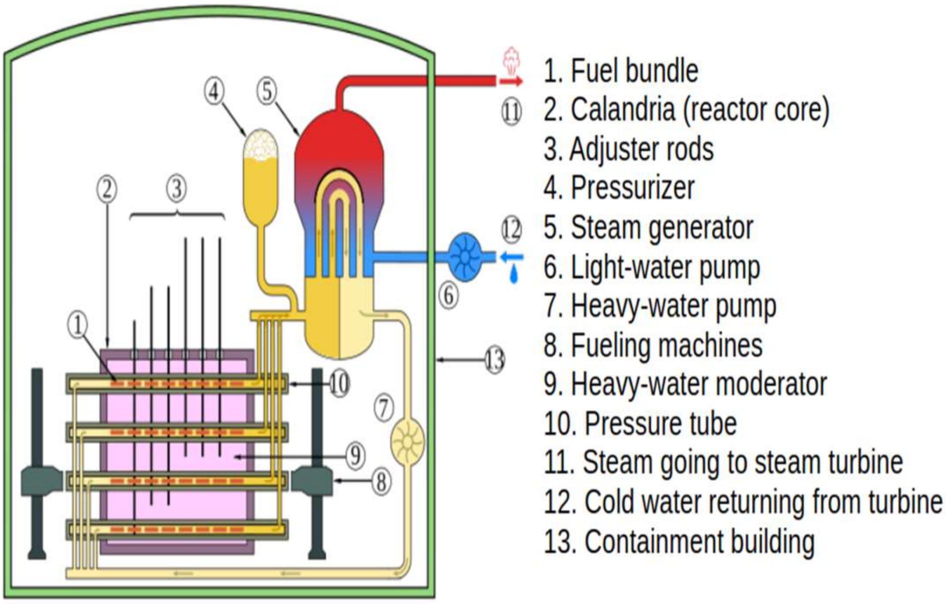

Figure 2: *Schematic diagram of CANDU SCWR [17]*

Figure 3 and figure 4 illustrate the mechanics of nuclear reactor to assess the safety standards. It can be seen from figure 3 that the wall temperature of the reactor exceeded the threshold limiting value, which is 850°C which showed the DHT in the reactor.

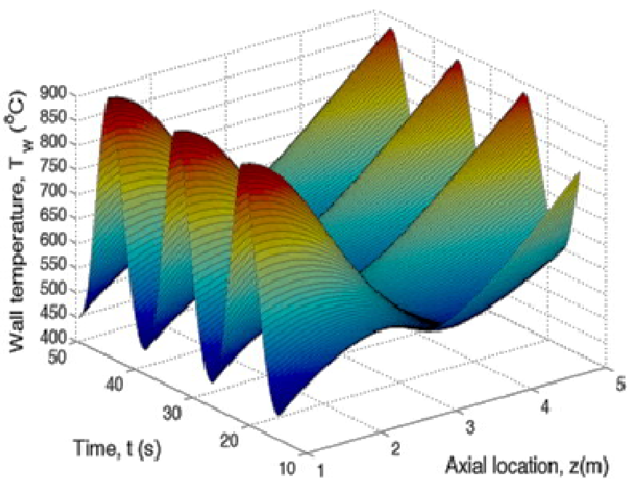

Figure 3: *Mechanism of the DHT in the reactor to predict the safety of the reactor [16]*

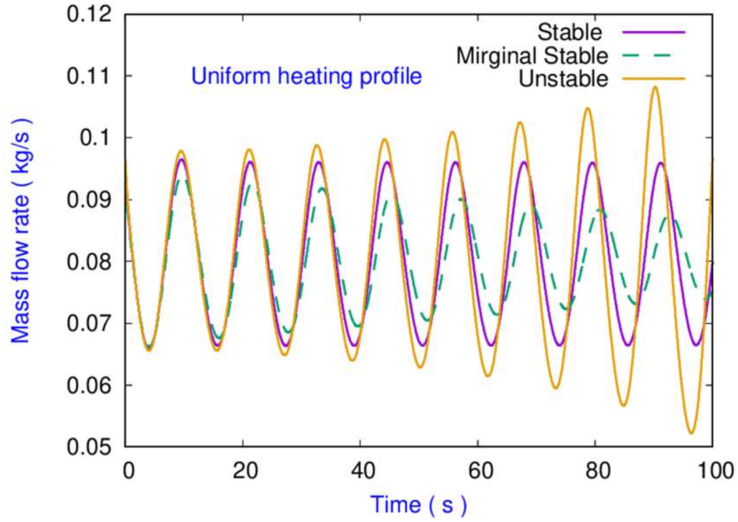

Figure 4: *Mechanism of the instability to predict the safety of the reactor [20]*

III. Safety, Reliability and Sustainability of the Supercritical Water Reactor and Supercritical Natural Circulation Loop Based Nuclear Power Plants

The demand for energy is increasing rapidly each day, necessitating fulfilment. In this context, our main goal is to construct several nuclear power plants (NPPs) that can generate substantial energy while also providing green energy, ensuring the safety and reliability of the NPPs and the environment. SCWRs and SCNCLs are designed to provide high energy while maintaining the safety and reliability of nuclear power plants. Nonetheless, both operate at high pressure and temperature, improving the thermal efficiency of the nuclear power plant (NPP). However, due to the significant change of the thermal physical properties of supercritical fluids (SCFs) near the pseudo-critical point, supercritical water reactors (SCWRs) suffer instability, which presents safety problems for the NPP.

This section discusses the safety, reliability, and sustainability of SCWR-NPP.There are various numerical and experimental studies performed by numerous researchers to achieve higher efficiency for the NPPs using water in different phases, such as single, two-phase, and supercritical. Hennig [21] in 1999, reported the stability characteristic of the boiling water reactor (BWR) and suggested that for achieving the higher efficiency, BWR-based NPPS experience instability, which is harmful for the NPPs. Similarly, Stosic et al. [22] developed SWR-1000 BWR to achieve higher thermal hydraulic performance as well as produce higher energy with a promising innovative safety concept for NPPs. Also, Theriault [23] suspected the design of the BWR for improving the safety of the NPPs by bifurcating the BWR into two important factors, like the reactor system and containment design, which separately control the safety features of the NPPs. Further, Su et al. [24] performed the comparative investigation of BWRs and SCWRs and reported that SCWRs gave higher thermal efficiency as compared to BWRs. By using the water in a supercritical state, the thermal efficiency of the plant is increased by 28.57% as compared to BWR as well as providing higher safety by eliminating the dryer and separator from the SCWRs. Further, by increasing the efficiency of the NPPs by utilizing the supercritical water, Cervi and Cammi [25] investigated the instability, safety, reliability, and sustainability of the SCWR, and its outcomes revealed that SCWRs provide higher stability at higher power ranges. Also, Wu et al. [26] suggested that SCWRs provide higher safety due to their compact size and low fuel consumption. They also proposed that due to the compact size of the SCWRs and safety features, they can be used in various applications for generating high power density.

Based on the several reports of found higher thermal efficiency using SCWR in the NPPs, Zhao et al. [17] investigated instability characteristics and their consequences at operating parameters like pressure drop in the channel. In this research, they utilized three fluid mixing simulation techniques to evaluate the flow instability of the SCWR. The results demonstrate increased marginal stability of the SCWR at an inlet loss coefficient of 20, which acts as a safety factor for NPPs. A non-dimensional stability map was developed to ascertain the usual operational boundaries for the reliability and safety of nuclear power stations (NPPs). In their subsequent study, Zhao et al. [27] conducted a follow-up study on SCWR, examining flow instability in relation to design parameters and pressure loss coefficients. Their findings indicate that the stability zones of SCWR have expanded relative to BWR due to the use of a low loss coefficient for the exit valve in the flow pipe beneath the core. Further, Chen et al. [28] developed a computation code to predict flow instability in both single and parallel channels of the SCWR. The code effectively predicts both static and dynamic instability, as well as the impact of numerous characteristics, such as geometry and operating circumstances, on flow instability. Examinations indicated that single-channel systems encounter more significant pressure drops, which is harmful for the NPPs, as well as that single-channel systems do not provide significant safety for the NPPs. Additionally, they proposed a safer and more reliable limit for SCWRs. Zhao [29] studied the flow problems and safety of the single-channel U.S. SCWR using a matrix method. They found that the decay ratio does not impact flow instability. However, the inlet orifice coefficient of the channel makes it more stable and safer in comparison to the smooth inlet channel. Also suggested is the manufacturing of the channels, which have different inlet orifice coefficient values for SCWR, to provide safety during operations. Also, Shitsi et al. [30] examined dynamic wave instability (DWI) across multiple channels with commercial 3D STAR-CCM+ software, demonstrating that SCWR undergoes DWI and produced a stability map for SCWR to ensure the nuclear power plant operates within stable and safe parameters.

Jyotish et al. [31] indicated that instrumentation and control systems are crucial for the safe operation of nuclear power stations (NPPs). Also, Gabriel [32] has demonstrated a reliability measurement precision of 99.9905% for safety-critical systems. Choi et al. [33] proposed that supercritical water reactors (SCWRs) implement a sustainability program aimed at enhancing reliability while reducing expenses through the optimization of safety margins. Utilizing decision-making tools to identify hazards enables the execution of operations that are both secure and economically efficient. Furthermore, innovations utilizing nuclear energy, such as helium-cooled compact modular reactors, exhibit potential for enhanced sustainability due to their reduced dependence on active safety protocols. Obaidurrahman et al. [34] conducted a study highlighting the significance of reliability and sustainability via a comprehensive safety framework that integrates essential safety principles, deterministic and probabilistic safety assessments, and uncertainty evaluations of NPPs. These regulations ensure safety at every stage of the process, from planning to finalization. The insights gained from previous nuclear incidents have resulted in more stringent safety regulations and an enhanced emphasis on reducing the unpredictability of safety assessments. Advancements in nuclear technology offer significant advantages; nonetheless, concerns persist over public perception and the potential for catastrophic incidents. For nuclear energy to have a future, these concerns must be addressed via transparent dialogue and continuous efforts to enhance safety protocols. NPPs are reliable and durable, as demonstrated by Kroger et al. [35], indicating they are a clean energy source. Nonetheless, previous accidents and errors by individuals continue to evoke concerns around safety. The innovative design of supercritical water reactors (SCWRs), akin to small modular reactors, aims to enhance safety and public acceptance. Kumar et al. [36-39] conducted a study examining the reliability and availability across several power plants by analyzing different systems.

Further, some active CANDU and USA SCWR and passive (SCNCL) systems are used to provide the safety of the core as well as to be used as an operating system to produce energy. Rai et al. [40-41] discussed the significance of Ledinegg instability and DWI, particularly within a single-channel loop, to ensure the safety of nuclear power plants. Furthermore, they investigated the impact of various operational and geometric parameters of the single-channel loop, which can help improve the safety, reliability, and sustainability of NPPs at elevated power levels and during accidents. In their subsequent study, Rai et al. [42-43] discussed improvements in SCWRs within nuclear technology, addressed issues about the validation of safety analysis techniques and the necessity for thorough accident assessments, which remain essential for the secure implementation of nuclear power plants, and determined the stable and safe limits in both points of view, like DWI stable and the material point of view, to protect the melting of the core by excess heating of the core wall. Similarly, Swapneel et al. reported steady-state instability for SCNCL, which is used as a passive system to protect the NPPs during operation and accidental conditions. Further, Upadhyay and Dutta [44] established a stable and secure limit for the U.S. SCWR. Figure 2 illustrates that the reactor is thermally stable; nonetheless, it poses a safety risk regarding materials, as the wall temperature surpasses acceptable limits at a specific power level. According to the stable and safe criteria of U.S. SCWR, a stable and safe operational limit has been established for the NPP at specific power ranges, ensuring safety for the facility. Dutta et al. [45] developed a code, THRUST, that can forecast the steady state and DWI of the CANDU SCWR, and the influence of various parameters on this instability has been analyzed. They identified DWI in the SCWR and illustrated both the reactor's marginal stability boundary and the stable and safe limits for the SCWRs. Dutta et al. [46-47] examined the performance of the SCWR in both steady and transient states utilizing two distinct computational approaches, THRUST and commercial software ANSYS, to determine the DHT in the SCWR, which poses significant risks to the reactor.

It can be seen from figure 5 and figure 6 that the marginal stability of DWI and the marginal safety limit of the SCNCL and SCWRs of CANDU and USA reactors are drawn. The reactor's thermal hydraulic conditions are stable; nonetheless, the material temperature surpasses the maximum allowable temperature of the reactor wall. Consequently, the reactor is deemed unsafe. The reactor's established, stable, and secure limit has resulted in the formulation of a combined stable and secure limit. SCWRs show a higher stable and safe zone as compared to SCNCL.

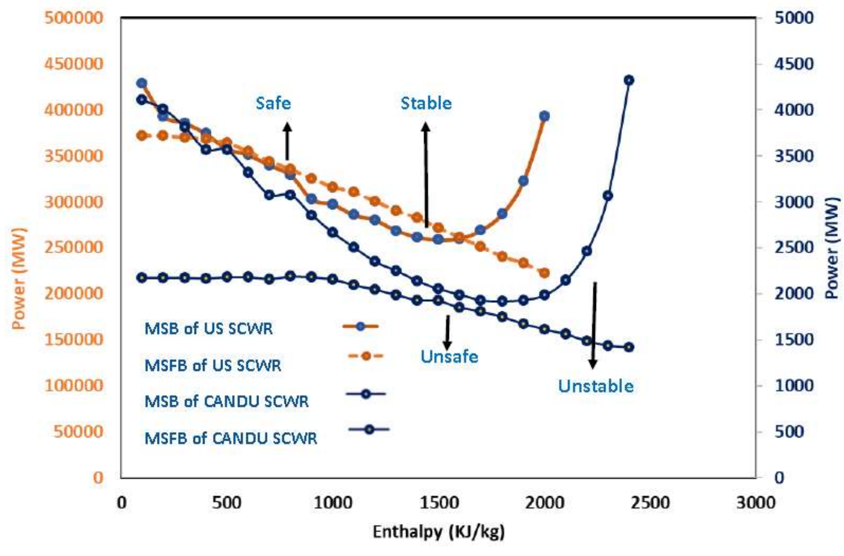

Figure 5: *Stable and safe limits of SCWRs [45-47]*

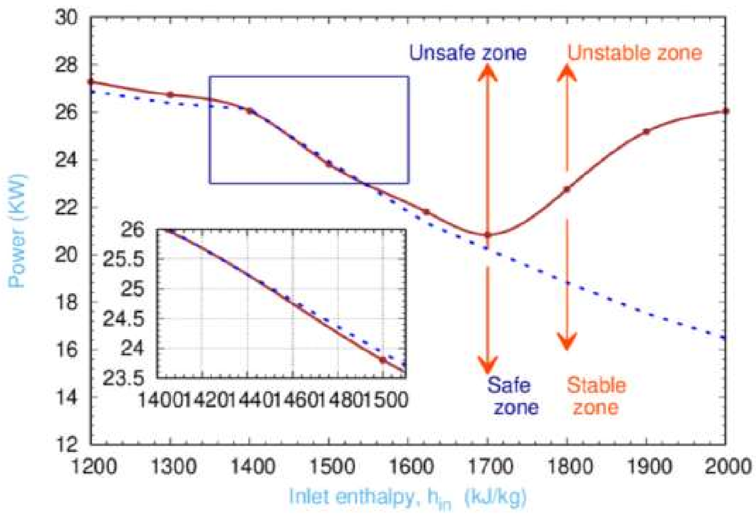

Figure 6: *Stable and safe limits of SCNCL [20]*

IV. Conclusions

In this present work, a thorough literature review of existing SCWR concepts and numerical and experimental investigations has been carried out to discuss the safety, reliability, and sustainability of high-pressure and temperature-based NPPs and determine their safety characteristics. Based on the literature review, the following important findings are found, which are discussed below.

The design of a multi-flow pass in the SCWR core is the primary approach to eliminate the transient flow instability, which provides the safety of the SCWRs. Supercritical fluid based NPPs are more efficient than two-phase and single phase based NPPs as well as supercritical water reactor plants are safer and more stable at high power as compared to boiling water reactors plant due to absence of the separator and dryer from the plants.The mass flow rate relative to thermal power is a distinguishing characteristic of SCWR, in contrast to PWR and BWR, which could potentially lead to compromised safety performance. SCNCLs are one of the best solutions to provide the higher safety of the NPPs during accidents as well as at normal operating conditions.The CANDU SCWR and U.S. SCWR were examined to ensure that the wall temperature of the core remains within safety limits during normal operation. Also, various computational methods are used to determine the safe and stable zone based on the transient analysis of the SCWRs and it is found that SCWRs are stable in point of TH, while in material point of view, it is not safe.

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