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Water Desalination for Underground Shelters: A Comprehensive Literature Review

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Abstract: This paper tackles the coupled challenges of water availability and energy resources as key factors for the sustainability of autonomy of underground shelters, specifically emphasizing remote and post-disaster areas where infrastructure cannot be easily accessed. The paper offers an organized compilation of the most current developments from the literature regarding desalination processes, specifically energy-based desalination systems suitable for underground environments. The compilation of the current developments covered studies conducted mainly from 2019 to 2024 and included various desalination processes such as thermal, membrane, and hybrid, as well as newer processes using waste heat and/or Small Modular Reactors (SMRs). The review examines the operational profiles, energy requirements, and sustainability aspects of such technologies in an underground environment characterized by limited space, poor ventilation, issues related to brine disposal, and the need for a stable and efficient energy delivery system. Particular attention has been given to nuclear-assisted hybrid system designs that could use electrical power and waste heat together in such a manner that the aggregate energy efficiency of the system could be improved. Instead of proposing a new concept, the present review article aims at compiling existing knowledge that could explain how optimal energy use & waste heat recovery might be utilized in an underground shelter for the generation of freshwater. The paper ends with an analysis related to the most pertinent technical issues and research gaps with regard to energy efficiency, the integration of waste heat, and the issue of energy autonomy that must be dealt with to make sustainably implemented SMR-powered underground desalination plants possible.

Keywords: Water desalination; Underground shelter; Energy sustainability; Small Modular Reactor; Waste heat recovery; Energy autonomy; Hybrid desalination system; Confined environment

1 Introduction

The rising requirement for freshwater, which has been increased by the growing number of people, expanding industrial sectors, and rising climatic changes, contradicts the ability to sustain and guarantee energy [1, 2]. For the tightly constrained and highly demanding environment of underground safe shelters, utilized either for emergency protection or military and long-term autonomous functionality, the availability of water and the provision of energy become an integral and inseparable part of the latter [3, 4]. The systems have to operate within a closed and autonomous mechanism, which can supply freshwater even within the most constrained space and operational requirements [5].

Desalination technologies, particularly Reverse Osmosis (RO) and Multi-Effect Distillation (MED), have been widely developed and implemented at surface plants worldwide [6, 7]. On the other hand, nuclear power, especially Small Modular Reactors (SMRs), is being increasingly recognized as a stable and clean resource that can offer both electricity and low-temperature heating necessary for desalination [8–10]. However, most of the research carried out till now has been on the larger above-ground plants, where the geometric constraints, cooling, rejection of both heat and the resulting liquid, and accessibility, are all very different from what happens underground [3, 11].

1.1 State of the Art

There has been extensive research carried out on the performance and energy efficiency of desalination processes such as RO, MED, Multi-Stage Flash (MSF), Humidification–Dehumidification (HDH), Membrane Distillation (MD), and their hybrids [12, 13]. The research has focused on the most widely used parameters, including specific energy consumption, gain output ratio, the potential for waste heat recovery, integration with renewable and nuclear power sources, and nuclear-assisted desalination plant safety and the environment [8, 14–16]. On the other hand, research has also focused on underground infrastructure and control of the environment, especially with respect to tunnels and protected areas [11].

Despite the wide scope of research, the existing literature mostly covers desalination and energy systems in surface-level perspectives, and the existing literature on underground conditions seldom studies desalination in the context of the integrated subsystem of the energy-water system. Thus, the relationship between desalination systems, the use of energy, and the distinctive conditions of underground systems still warrants further integration in the existing literature.

1.2 Research Gap and Purpose of the Review

The lack of a specific and focused synthesis that tackles desalination while dealing with underground constraints can be considered a substantial research gap. Nothing has been done before to assess systematically how underground spatial constraints, limited ventilation, vibrational sensitivity, closed-loop brine system approaches, thermal accumulation, accessibility, and emergency independence can impact desalination apparatuses together in terms of their efficiency.

This review seeks to fill this knowledge gap by critically reviewing the literature, mainly from 2019 to 2024 for an understanding of how existing desalination processes and their nuclear-powered variants may be used in an underground setting. This research will neither focus on a novel design concept nor a model applicable for subterranean applications but will take an energy systems approach that could enhance an understanding of how both electrical and heating energy, especially from SMRs or waste-to-heat power, might need to be harnessed effectively for enabling a reliable and sustainably produced water source by focusing on (i) theoretical foundations of popular desalination processes, (ii) comparisons of how these might operate within subterranean energy/conditions, (iii) schemes for incorporating SMRs/heating subsystems, and (iv) filling knowledge gaps in energy-efficient subterranean desalination processes.

1.3 Literature Collection and Review Methodology

Within this review, the literature review process follows a structured and replicable procedure. Primary literature is searched using prominent literature databases such as Scopus, Web of Science, IEEE Xplore, Science Direct, Springer Link, and the International Nuclear Information System (INIS). Grey literature is searched using Google Scholar to focus on literature involving nuclear energy, desalination, the utilization of waste heat, energy efficiency, and environments below ground or other constrained sites.

A corpus of literature discovered among studies published between the years of 2019 and 2024 represents the principal consideration, supplemented where necessary by earlier seminal works. A principal criterion for inclusion in this literature survey was the desirability of studies revealing clear methodologies, performance data, and/or system perspectives that specifically relate to desalination, energy integration, and closed/isolated systems. A critical consideration was given to the level of the discussions pertinent to the use of energy, waste heat recovery, and comprehensive system sustainability in the longer term.

2 Results and Thematic Review

2.1 Principles and Comparative Analysis of Desalination Technologies for Underground Shelters

The major desalination technologies considered for underground shelters operate on fundamentally different scientific principles, which directly influence their energy demand, operational stability, and suitability within confined environments. RO relies on applying hydraulic pressure exceeding the natural osmotic pressure of seawater to force freshwater through a semi-permeable membrane while rejecting dissolved ions. This electrically driven, non–phase-change process offers relatively high energy efficiency; however, it depends on extensive pre-treatment to mitigate fouling and scaling [6, 16]. In underground installations, the use of high-pressure pumps introduces vibration loads that must be carefully managed to avoid long-term structural fatigue.

As shown in Figure 1, the RO system operates by pressurizing feedwater and forcing it through membrane modules to separate freshwater from dissolved salts. This reliance on high-pressure pumping explains the vibration and mechanical stresses associated with RO units, which become more critical in underground shelters where confined geometry can amplify structural and acoustic effects. Consequently, mechanical isolation and vibration damping are essential design requirements for underground RO deployment.

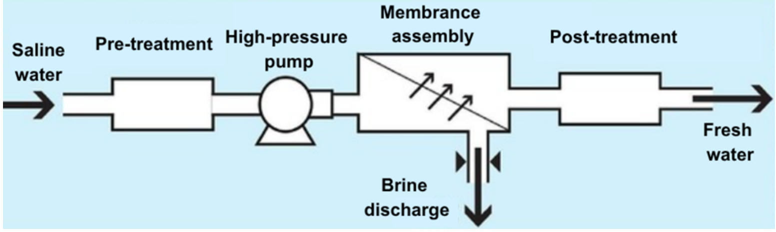

Figure 1. Reverse Osmosis (RO) system

Source: Adapted from the study [8].

In contrast, MED is a thermal desalination process based on sequential evaporation and condensation across multiple effects operating at progressively lower pressures, with each stage reusing the latent heat from the previous one [12]. This staged heat recovery makes MED highly compatible with low-grade thermal energy sources, particularly SMR waste heat, while reducing sensitivity to feedwater quality variations [8, 14]. As illustrated in Figure 2, the MED process relies on cascading heat reuse, which lowers thermal losses and reduces maintenance demands compared to membrane-based systems. These characteristics make MED especially attractive for underground environments where long-term operational stability and reduced intervention are critical.

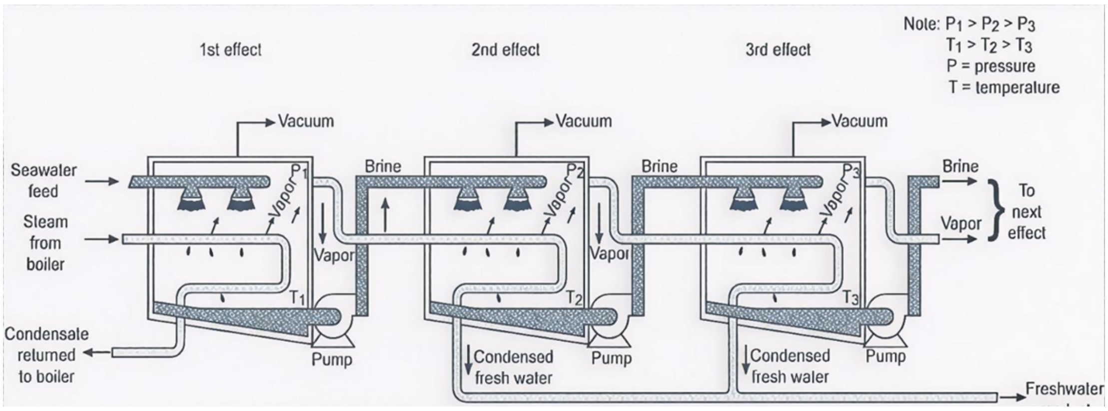

Figure 2. Multi-Effect Distillation (MED) system configuration

Source: Adapted from the study [1].

MSF, another thermal desalination method, produces freshwater by flashing near-boiling seawater into vapor across a series of chambers at decreasing pressures. Although MSF is mechanically robust and widely deployed in large coastal facilities, its requirement for high-temperature steam, large equipment volume, and substantial heat-rejection capacity renders it unsuitable for underground settings [16]. As shown in Figure 3, MSF systems rely on extensive flashing stages and condensers, which demand significant spatial allowance and cooling infrastructure—constraints that cannot be easily accommodated underground.

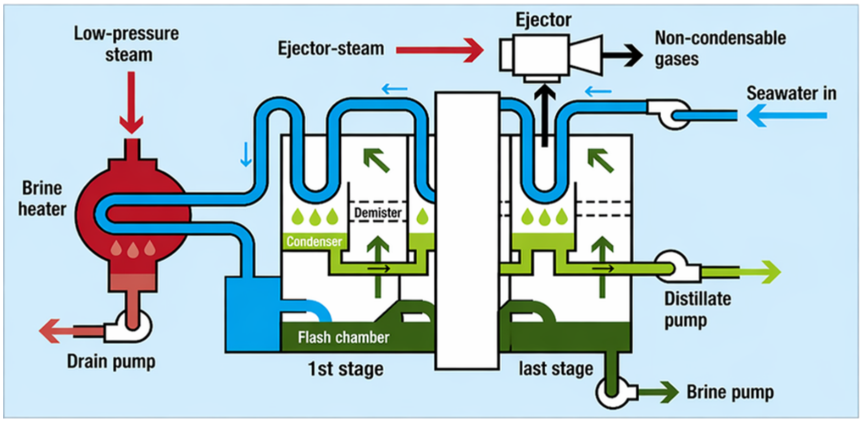

Figure 3. Multi-Stage Flash (MSF) system layout

Source: Based on the study [8].

Low-temperature desalination processes, including MD, HDH, and Adsorption Desalination (AD), operate using vapor pressure gradients, air–water vapor equilibrium, or adsorption–desorption cycles. These technologies can utilize low-grade waste heat and offer mechanical simplicity; however, their limited production capacities, sensitivity to temperature gradients, and installation constraints restrict their feasibility as primary freshwater sources in underground shelters. Together, these theoretical distinctions establish the foundation for evaluating each technology's practical viability under subterranean conditions.

The comparative cost and energy performance of MSF, MED, RO, and hybrid configurations are summarized in Figure 4, highlighting the relative advantages of MED-based and hybrid MED–RO systems when assessed against underground constraints such as space limitation, energy efficiency, and operational resilience.

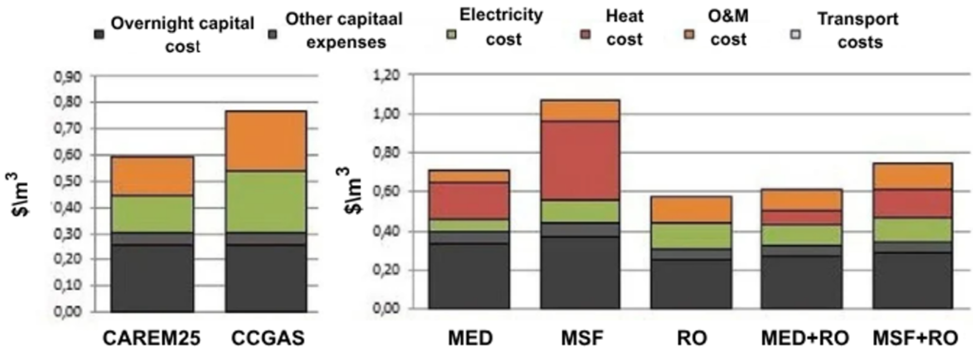

Figure 4. Comparative cost and energy performance of desalination technologies

Note: MED = Multi-Effect Distillation; MSF = Multi-Stage Flash; RO = Reverse Osmosis.

Source: Based on the study [12].

2.2 Comparative Evaluation within Underground Shelter Constraints

Designing desalination systems for underground shelters requires a fundamentally different framework compared to surface-level plants [3]. Structural confinement, restricted ventilation, limited maintenance accessibility, and the inability to discharge brine externally significantly influence system feasibility and long-term performance. Under such conditions, desalination technologies often exhibit operational behaviors that differ markedly from their aboveground counterparts.

RO systems are initially attractive due to their compact footprint, modularity, and relatively low specific energy consumption. However, their sensitivity to fouling and scaling presents serious challenges in underground environments, where elevated humidity and microbial accumulation can accelerate membrane degradation [7]. The high-pressure pumps required for RO also introduce vibration loads that may interact with structural elements if not adequately dampened. In addition, RO generates highly concentrated brine streams that necessitate integrated zero-liquid-discharge (ZLD) or crystallization solutions in the absence of external disposal options.

MED represents a more robust alternative for long-term underground autonomy. Although MED units typically occupy a larger footprint than RO systems, they exhibit lower maintenance requirements, greater tolerance to feedwater variability, and intrinsic compatibility with SMR waste heat [9, 15]. Their mechanical simplicity reduces vibration risks, while phase-change separation ensures stable operation over extended periods. The primary challenges associated with MED deployment underground relate to spatial integration and the management of residual heat within confined environments.

MSF, while extremely reliable in large coastal installations, is fundamentally mismatched with underground constraints. Its high operating temperatures, large physical size, and substantial heat-rejection demands make it impractical for confined facilities with limited cooling capacity [16].

As shown in Table 1, the operational requirements of MSF, MED, Seawater Reverse Osmosis (SWRO), and Electrodialysis (ED) differ substantially in terms of operating temperature, electrical demand, and thermal energy consumption. These distinctions clarify why certain technologies are more compatible with underground deployment. Overall, Table 1 provides a quantitative basis supporting MED and hybrid MED–RO configurations as the most energy-efficient and structurally compatible options for underground desalination.

Low-temperature technologies such as MD, HDH, and AD offer niche advantages in underground applications. MD is compact and thermally efficient but sensitive to temperature polarization. HDH is mechanically simple and can assist with humidity control, although its freshwater output is limited. AD offers favorable energy performance but requires large adsorbent beds that are difficult to accommodate underground. Consequently, these technologies are better suited as supplementary components rather than primary freshwater production systems.

Table 1. Energy data for desalination technologies

	MSF	MED	SWRO	ED
Operation temperature (°C)	90–110	70	Ambient	Ambient
Electricity demand (KWh/m^3)	2.5–3.5	1.5–2.5	3.5–5.0	1.5–4.0 feed water 1500–3500 ppm solids
Thermal energy demand (KWh/m^3)	80.6 ($\approx$290 kJ/kg)	80.6 ($\approx$290 kJ/kg)	0	0

Note: MSF = Multi-Stage Flash; MED = Multi-Effect Distillation; SWRO = Seawater Reverse Osmosis; ED = Electrodialysis.

2.3 Mechanical and Computational Fluid Dynamics-Based Design Optimization

Design optimization plays a critical role in improving the efficiency, reliability, and long-term viability of hybrid nuclear-powered desalination systems, particularly when deployed in underground environments. These systems involve tightly coupled physical processes, including heat transfer, phase change, and high-pressure fluid flow, all of which are highly sensitive to geometric configuration and operational parameters [17]. As a result, recent research increasingly emphasizes the combined use of Computational Fluid Dynamics (CFD) and optimization algorithms to enhance system performance without relying on extensive experimental modification.

CFD enables detailed analysis of flow behavior, temperature distribution, and heat-transfer efficiency within key desalination components such as pressure vessels, evaporators, condensers, and heat-exchange surfaces.

Kariman et al. [7] demonstrated the effectiveness of such coupled CFD–Genetic Algorithm approaches in improving flow distribution uniformity within membrane modules. Their study showed that non-uniform flow significantly accelerates membrane fouling and reduces permeate flux. By optimizing internal flow geometry, they achieved approximately a 12% improvement in membrane performance through enhanced flow uniformity. These findings are particularly relevant for underground desalination systems, where reduced maintenance frequency and extended membrane lifespan directly support long-term operational autonomy.

Beyond flow optimization, advances in materials science have also contributed to mechanical and thermal performance improvements. The study [13] reviewed the application of corrosion-resistant and high-conductivity materials in desalination equipment, noting that conventional metallic alloys used in evaporation and condensation units often degrade under prolonged exposure to saline environments and elevated temperatures. The incorporation of titanium-based alloys, nanocomposite coatings, and graphene-functionalized surfaces has been shown to enhance both corrosion resistance and thermal conductivity. When such material advancements are combined with CFD-optimized geometries, overall efficiency improvements in the range of 10–15% have been reported.

Optimization efforts extend beyond physical design to encompass operational control. Transient CFD simulations provide insight into system behavior during startup, shutdown, and part-load operation—scenarios that are particularly relevant for nuclear-coupled systems operating under load-following conditions [10].

2.4 Integrated Assessment

The integrated assessment of desalination technologies under underground shelter constraints reveals a fundamentally different hierarchy of technical suitability compared to conventional above-ground installations.

Among the reviewed technologies, MED consistently emerges as the most reliable and operationally stable option for long-duration underground application. Its ability to operate using low-grade thermal energy aligns naturally with shelters powered by SMRs, which provide a continuous and predictable source of waste heat [8, 14].

RO presents a more nuanced performance profile under underground conditions. Its high electrical energy efficiency, compact footprint, and modular architecture remain valuable advantages, especially in space-limited installations [2]. These limitations indicate that RO is best deployed as part of a hybrid system rather than as a primary standalone solution in underground shelters.

MSF, despite its long-established robustness in large-scale coastal installations, is fundamentally incompatible with underground environments [16].

Low-temperature desalination technologies, including MD, HDH, and AD, offer valuable supplementary capabilities but lack the production capacity and operational stability required for primary freshwater supply.

Overall, the hybrid RO–MED configuration provides the most balanced architecture across all evaluated dimensions, including energy integration, maintenance demand, structural compatibility, brine management feasibility, and long-term autonomy [6, 12]. RO contributes compactness and high-efficiency freshwater production using electrical energy, while MED delivers thermal stability, reduced fouling sensitivity, and strong synergy with SMR waste heat.

As illustrated in Figure 5 adapted from the study [6], this hybrid arrangement combines the strengths of both systems, enabling continuous freshwater production even if one subsystem experiences reduced performance. Such redundancy and energy flexibility align closely with the operational and environmental demands of underground shelters. By distributing energy demand across electrical and thermal domains, the hybrid configuration reduces peak electrical loads, enhances operational resilience, and facilitates more manageable brine treatment when coupled with ZLD or crystallization units. Overall, this integrated assessment confirms the growing consensus in the literature that hybrid desalination architectures represent the most reliable and energy-sustainable pathway for long-term freshwater production in confined and autonomous underground environments. The conceptual schematic illustrated in Figure 6 demonstrates the engineering integration between a SMR and a hybrid RO-MED desalination system specifically designed for underground shelters. The diagram highlights how the reactor's outputs are intelligently partitioned: electrical energy is directed to power the high-pressure pumps of the RO units, while the low-grade waste heat is recovered to drive the MED processes. This configuration ensures maximum utilization of the generated energy while mitigating heat accumulation within the confined space. Additionally, the schematic incorporates brine treatment systems and geothermal heat rejection pathways, reflecting the closed-loop approach required to prevent environmental contamination and protect the shelter's structural stability.

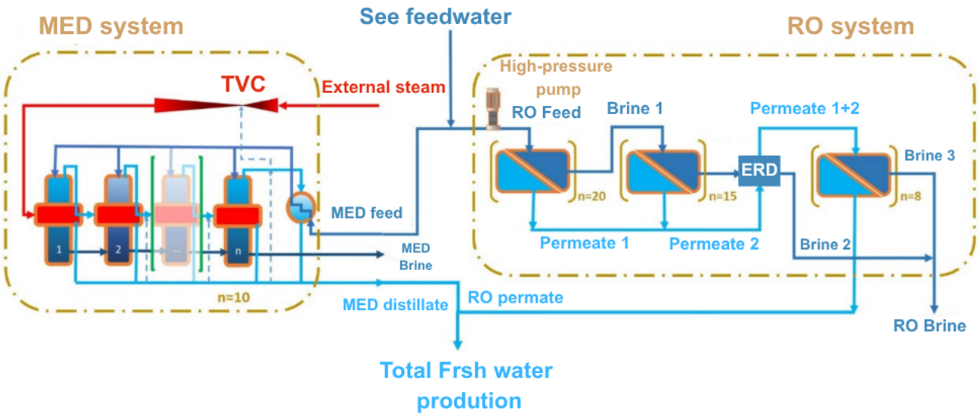

Figure 5. Reverse Osmosis–Multi-Effect Distillation (MED) hybrid system

Note: ERD = Energy Recovery Device; MED = Multi-Effect Distillation; RO = Reverse Osmosis; TVC = Thermal Vapor Compression.

Source: Adapted from the study [6].

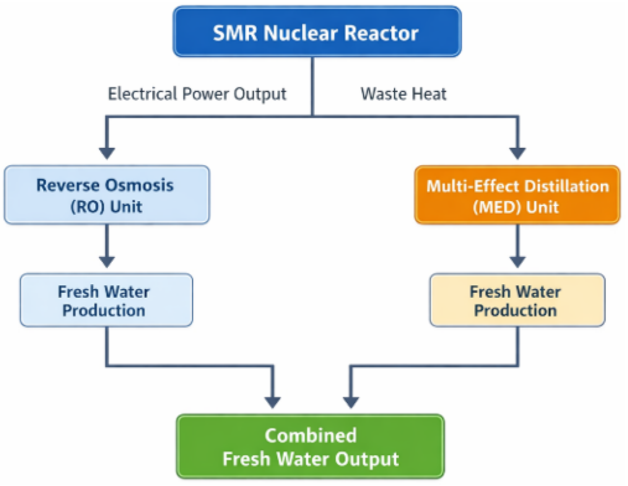

Figure 6. Schematic small modular reactor hybrid desalination system (reverse osmosis + multi-effect distillation)

This conceptual schematic in Figure 6 illustrates the integration of SMRs with hybrid RO–MED desalination systems in underground shelters [9, 10]. Electrical energy is primarily utilized for RO, while low-grade waste heat is recovered to drive thermal processes such as MED and auxiliary low-temperature desalination units.

3 Discussion

3.1 Operational Constraints and Environmental Interactions in Shelters

Underground shelters constitute one of the most technically demanding and environmentally restrictive contexts for the deployment of desalination systems [3, 4]. Unlike surface-level desalination plants, which benefit from open atmospheric conditions, natural airflow, flexible land availability, and external waste-disposal pathways, underground facilities operate as sealed, highly insulated, humidity-sensitive, and spatially constrained environments. These constraints are not marginal; they fundamentally reshape all engineering decisions related to desalination technology selection, thermal management strategies, brine treatment, system layout, maintenance planning, and long-term operational resilience. In this setting, desalination evolves from a relatively standardized water-treatment process into a complex interdisciplinary challenge that integrates thermodynamics, structural engineering, nuclear coupling, HVAC control, and closed-loop environmental management.

Among the most critical challenges in underground desalination is heat accumulation. Thermal desalination technologies—particularly MSF and high-temperature MED—generate significant quantities of waste heat as an inherent consequence of their phase-change processes [15, 16]. In surface plants, this heat is readily dissipated through seawater discharge, cooling towers, or open-air convection. Underground shelters, by contrast, lack natural convection pathways and function as thermally insulated volumes in which heat dissipation is slow and accumulation can rapidly reach unsafe levels if not actively managed. Even membrane-based systems such as RO, which do not rely on phase change, generate frictional heat through high-pressure pumping and require continuous thermal regulation to maintain membrane performance.

As underground structures cannot depend on passive cooling, they must incorporate forced heat-rejection mechanisms, including chilled-water loops, embedded rock heat exchangers, geothermal sinks, or controlled thermal coupling with the secondary loops of SMRs [8, 10]. In nuclear-coupled shelters, thermal integration becomes particularly sensitive: heat rejected from desalination processes must neither compromise reactor cooling margins nor accumulate within surrounding geological formations, where it could induce thermal expansion, elevated humidity, or structural degradation. MSF systems are especially disadvantaged in this respect due to their extreme cooling requirements. Even MED units, despite their superior thermal efficiency, may require active heat-removal strategies that exceed the natural thermal conductivity of the host rock, making thermal control a decisive factor in technology selection.

Closely linked to thermal management is the challenge of humidity control. Underground shelters are typically designed to operate within narrow humidity ranges—commonly between 45% and 60%—to ensure human comfort, protect electronic equipment, minimize corrosion, and prevent microbial growth. Desalination systems interact directly with moisture dynamics: MED, HDH, and MD all involve vapor–condensation cycles that introduce moisture into the surrounding environment [11]. In sealed underground settings, even modest humidity increases can trigger condensation on structural and electrical components, accelerate corrosion, increase latent HVAC loads, and promote biological fouling. Consequently, humidity regulation becomes a core operational parameter rather than a secondary environmental concern.

Effective underground desalination therefore requires tight integration with the shelter's HVAC systems. Vapor-generating subsystems must be isolated within sealed mechanical zones equipped with dedicated dehumidification, while airflow routing must prevent moisture migration into living or control spaces. Unlike surface plants, where humid air can be vented externally, underground shelters rely on recirculated air loops, amplifying the consequences of poor moisture management. Elevated ambient humidity also impacts desalination performance itself: RO membranes are vulnerable to accelerated biofouling under humid conditions, while MD systems suffer efficiency losses when condensation occurs within membrane pores [7]. In this context, moisture control becomes as critical to desalination performance as salinity removal.

Maintenance accessibility represents another persistent constraint. RO systems, while compact and efficient, require frequent membrane replacement, chemical dosing, backwashing, and pretreatment maintenance [6]. These tasks are straightforward in surface facilities but considerably more complex underground, where access corridors are narrow, equipment density is high, and chemical storage and ventilation are restricted. Handling large volumes of treatment chemicals introduces additional safety concerns in confined spaces. MED systems, in contrast, impose a lower maintenance burden due to their reliance on phase-change separation rather than filtration. Although scaling still occurs on heat-transfer surfaces, cleaning cycles are less frequent, more easily automated, and require fewer consumables—an advantage for shelters expected to remain isolated for extended periods [12].

Brine management constitutes one of the most formidable challenges in underground desalination. While surface plants commonly discharge brine into oceans or large water bodies, underground shelters cannot release concentrated saline effluent without risking groundwater contamination, corrosion of infrastructure, or long-term environmental damage. RO is particularly problematic, as it produces highly concentrated brine streams that cannot be sustainably stored without treatment. MD systems similarly concentrate brine at high recovery ratios. MED, however, generates lower-salinity brine, placing a reduced burden on downstream treatment systems. Thermal crystallization powered by SMR waste heat offers a viable closed-loop solution, enabling brine concentration, freshwater recovery, and conversion of residual salts into solid forms suitable for storage or reuse [2]. Advanced sensing systems are required to monitor brine salinity, temperature, pressure, and volume to ensure environmental safety in sealed underground ecosystems.

Taken together, these constraints lead to a critical conclusion: the most suitable desalination technologies for underground shelters are not necessarily those optimized for maximum energy efficiency in surface plants, but rather those that best align with the realities of confinement [14, 15]. Stable thermal behavior, low maintenance demand, manageable brine output, vibration compatibility, and seamless integration with HVAC and nuclear systems emerge as dominant selection criteria. MED consistently performs well across these dimensions, while RO remains indispensable for compact, high-recovery operation when integrated within hybrid architectures. MSF is largely excluded due to its thermal and spatial demands, and low-temperature systems such as MD and HDH serve primarily as auxiliary technologies supporting humidity control, redundancy, and thermal management.

3.2 Integrating Passive and Hybrid Systems for Enhanced Stability and Resilience

Passive and hybrid desalination systems offer some of the most effective strategies for addressing the tightly coupled operational challenges of underground shelters [12]. Unlike surface desalination plants, which function as isolated utilities with access to expansive cooling sinks and external support infrastructure, underground shelters operate as closed systems where thermal accumulation, humidity regulation, energy allocation, and maintenance logistics interact continuously. Under such conditions, desalination technologies must be evaluated not only for efficiency, but for their ability to integrate harmoniously with nuclear power systems, environmental control infrastructure, and long-term autonomy requirements.

Central to this integration is the optimized utilization of low-grade waste heat generated by SMRs. SMRs provide two valuable energy outputs: stable electrical power and continuous thermal energy from secondary loops [9, 14]. In surface installations, much of this thermal energy is discarded; in underground shelters, however, heat rejection is both difficult and undesirable. Passive desalination technologies such as MED, HDH, and certain MD configurations align naturally with this constraint, as they operate efficiently at relatively low temperatures and can directly convert waste heat into freshwater production. This process not only mitigates thermal accumulation but also transforms an operational liability into a productive resource, creating a thermodynamic synergy between nuclear generation and desalination.

Hybrid configurations extend this synergy by combining membrane-based and thermal processes to balance strengths and mitigate weaknesses. The integration of RO and MED is consistently identified in the literature as the most effective hybrid architecture [6, 15, 18]. RO excels in converting electrical energy into freshwater with high efficiency, but suffers from fouling sensitivity, chemical dependency, and high-concentration brine generation. MED, conversely, leverages thermal energy, tolerates feedwater variability, and produces less concentrated brine. In underground shelters, this complementarity is magnified. RO can operate during periods of high electrical availability, while MED can run continuously on waste heat, preserving electrical capacity for life support and critical systems.

Redundancy is particularly vital in underground environments, where system failure carries disproportionate consequences [17]. Hybrid RO–MED systems provide dual-mode operational resilience: if RO performance degrades due to fouling, membrane failure, or pump malfunction, MED can sustain water production independently using waste heat. Conversely, during reactor maintenance or thermal transients, RO can continue operating on stored electrical energy. This mutual backup capability significantly enhances system robustness and ensures continuity of water supply under a wide range of operating scenarios.

Beyond redundancy, passive and hybrid systems contribute directly to environmental stabilization. HDH and MD modules, when integrated into HVAC networks, perform the dual functions of freshwater production and humidity control. Excess humidity poses a major risk in underground shelters, promoting corrosion, electrical failure, and microbial growth. HDH systems inherently absorb and condense moisture, while MD exploits temperature gradients to extract water vapor from humid air. This dual functionality transforms passive desalination modules into essential components of the shelter's environmental control system rather than optional add-ons.

Passive systems also improve structural and acoustic stability. Unlike RO, which generates mechanical vibrations due to high-pressure pumping, MD, HDH, and AD operate with minimal mechanical motion [7]. Reduced vibration lowers the risk of microfracturing in concrete structures, minimizes resonance with nuclear installations, and improves occupant comfort and equipment reliability. Furthermore, passive and hybrid architectures naturally support ZLD strategies. RO brine can be routed through MED- or MD-driven concentrators powered by waste heat, enabling staged evaporation, additional freshwater recovery, and near-complete elimination of liquid waste—an essential requirement in sealed underground ecosystems [2].

From a logistical perspective, hybrid and passive systems reduce reliance on consumables. RO-intensive operations require frequent membrane replacement and chemical supplies, whereas MED, HDH, and MD systems demand fewer consumables and exhibit longer component lifespans [13, 18]. This reduction in logistical burden is critical for shelters designed to remain isolated for extended durations. When viewed holistically, passive and hybrid desalination configurations represent not merely an increase in water-production capacity, but a fundamental redesign of the shelter's thermodynamic and environmental architecture. Their synergistic integration enables heat redistribution, humidity control, vibration damping, energy efficiency, and operational resilience, positioning hybrid RO–MED systems—supplemented by MD and HDH modules—as the most viable long-term solution for underground freshwater autonomy.

3.3 Safety, Reliability, and Long-Term Autonomy in Nuclear-Assisted Underground Desalination

Safety and reliability become defining requirements for underground desalination systems, particularly when integrated with nuclear power sources such as SMRs [8, 10]. Underground shelters differ fundamentally from surface-level facilities because they may be required to sustain prolonged isolation periods during which external intervention, technical support, or rapid equipment replacement is not feasible. Under such conditions, desalination is not merely an auxiliary utility but a life-sustaining subsystem. A failure event not only threatens potable water availability; it can cascade into HVAC imbalance, heat accumulation, structural stress, brine storage hazards, and compromised nuclear safety margins. Accordingly, underground desalination must be governed by an engineering philosophy centered on high mechanical reliability, conservative safety margins, and system-level autonomy that remains functional despite external constraints.

When desalination is coupled to nuclear energy—especially SMRs—distinct safety requirements become critical. The foremost requirement is strict separation between the nuclear primary circuit and the potable-water production loop [8, 16]. Because primary reactor coolant may contain activated radionuclides, any leakage into the desalinated water stream would render the water unsuitable for consumption and could contaminate the shelter's internal ecosystem. To mitigate this risk, nuclear desalination designs typically employ intermediate heat exchangers with dual or triple containment barriers, engineered pressure differentials that bias leakage toward contaminating the reactor-side loop rather than the potable-water loop, and redundant isolation valves. Multilayer mechanical barriers, corrosion-resistant alloys, high-integrity welds, and continuous monitoring systems—covering temperature, pressure, radiation, and flow anomalies—are essential at the coupling interface. These measures are even more critical underground, where detection and repair of breaches may be delayed by restricted access and operational urgency.

Reliability considerations extend beyond nuclear–thermal interfaces to include mechanical and structural interactions. A critical issue in underground installations is vibration behavior. High-pressure RO pumps generate cyclical vibration loads that can propagate through rigid concrete or rock structures, potentially interacting with natural resonant frequencies and inducing micro-cracking and fatigue over long time horizons [7]. Unlike surface plants—where vibration energy can be partially dissipated through flexible structures and open environments—underground walls are rigid, acoustically reflective, and strongly coupled to machinery foundations, increasing the likelihood of stress accumulation. Mitigation therefore requires structural decoupling of pump rooms, vibration-dampening mounts, anti-resonance plates, floating slabs, and shock-absorbing frames. Acoustic damping liners may also be needed to reduce resonance buildup in enclosed cavities. In parallel, periodic structural integrity assessments—using methods such as ultrasonic scanning, strain gauges, fiber-optic sensing, or acoustic emission analysis—provide early detection of degradation mechanisms.

Thermal desalination systems such as MED carry substantially lower vibration risk due to their reliance on phase-change cycles rather than high-pressure pumping. However, they introduce another reliability dimension: heat rejection and thermal stability. In underground shelters, where natural convection pathways are limited and thermal insulation is high, unmitigated heat can accumulate in geological surroundings and compromise shelter habitability, accelerate corrosion, disrupt HVAC performance, and potentially interfere with reactor heat-dissipation patterns. Therefore, MED integration must be designed around controlled heat sinks, including engineered geothermal rejection pathways, SMR secondary-loop coupling, or dedicated cooling circuits [14, 17]. Long-term thermal drift must be avoided through thermal mapping and monitoring of underground chambers, supported by heat-transfer modeling and conservative design margins.

Another major determinant of long-term autonomy is dependence on consumables and spare parts. RO systems, while efficient, are consumable-intensive: membranes, cartridge filters, anti-scalants, biocides, pH modifiers, and chemical cleaning agents are required to maintain stable operation [4]. In surface installations, consumables are replenished continuously; in underground shelters, resupply may be impossible, requiring large inventories to be stored for months or years. This imposes storage burdens and introduces safety risks related to shelf-life limits, chemical degradation, and handling constraints in confined spaces. Moreover, RO membrane failure is particularly consequential because it can allow saline breakthrough and contaminate freshwater reservoirs. For these reasons, RO is difficult to justify as a fully self-sustaining standalone solution unless supported by redundancy, hybrid operation, or robust long-term consumable logistics.

MED systems, by contrast, typically require fewer consumables. Their long-term performance is mainly governed by gradual surface scaling and corrosion, which can be monitored and managed through predictable maintenance cycles. Cleaning is often achieved via periodic chemical washing rather than membrane replacement, and scaling risk can be reduced through appropriate temperature control and materials selection [13]. These characteristics make MED a stronger foundation for extended autonomous operation in underground shelters, reducing dependence on vulnerable supply chains and enabling longer isolation endurance.

Brine management further differentiates reliability outcomes. RO brine is highly concentrated and chemically aggressive, and long-term underground storage carries risks of corrosion, leakage, and potential contamination of groundwater layers if containment fails. MED brine is generally less concentrated, reducing the burden on downstream crystallizers and ZLD units. When coupled with low-temperature evaporation or crystallization processes powered by SMR waste heat, MED can support internal brine volume reduction and conversion into solid residues suitable for safer storage. This strengthens autonomy by lowering storage requirements and reducing the likelihood of brine overflow scenarios.

Reliability is also reinforced by the inherent stability of SMRs. Compared to large conventional reactors, SMRs typically incorporate passive safety mechanisms such as natural-circulation cooling, gravity-driven shutdown systems, and sealed containment, reducing reliance on external power and active intervention [8, 19]. These features align well with underground operation. Predictable thermal output stabilizes MED performance and supports efficient heat recovery under steady-state and partial-load conditions. In addition, SMR designs often emphasize modularity and long fuel cycles, minimizing refueling frequency—an important advantage in isolated shelter contexts.

Finally, human reliability is an essential layer of long-term autonomy. Operators in underground nuclear-assisted desalination facilities require training not only in desalination processes but also in radiation protection, chemical handling, confinement protocols, emergency cooling procedures, and environmental monitoring [8]. Regular drills, simulation exercises, and digital twin platforms can improve preparedness for events such as pressure surges, membrane rupture, heat exchanger leakage, radiation alarms, or HVAC failure. The psychological and ergonomic challenges of confined operation further justify intuitive interfaces and fault-tolerant control architecture.

Collectively, these considerations demonstrate that safety, reliability, and long-term autonomy in underground nuclear-assisted desalination require more than robust equipment; they require integrated systems engineering that anticipates subterranean failure modes, embeds redundancy across mechanical and energy subsystems, emphasizes low-maintenance pathways such as MED, and exploits the stable operating characteristics of SMRs [9, 16]. When these elements are combined, underground desalination can achieve sustained operation, high water quality, and environmental safety under the extreme constraints of long-duration isolation.

3.4 Future Trends

Future developments in underground desalination systems—particularly those integrated with nuclear energy—are expected to concentrate on modularity, energy coupling, brine management, automation, and digital resilience. As underground shelters evolve toward increasingly autonomous infrastructures capable of extended isolation, desalination systems must transition from conventional mechanically operated units toward tightly integrated, self-optimizing water-production ecosystems. Several technological and systems-level trends are likely to shape the next generation of underground desalination architectures.

A key trend involves deeper integration of multi-energy coupling across SMRs, renewable sources, and advanced thermal storage. Emerging work increasingly emphasizes modular thermal storage concepts such as molten-salt tanks, multi-modular water-phase change material tanks, and compact steam accumulators to stabilize thermal availability for MED and MD subsystems [2, 14]. This energy buffering is particularly important under operational scenarios where the SMR performs load-following, undergoes planned maintenance, or experiences transient operating modes. Future hybrid architectures are therefore expected to combine nuclear baseload supply with photovoltaic or other secondary sources and long-duration storage, forming layered energy systems designed to reduce downtime and preserve critical loads [9]. In underground shelters, where energy shortages can directly threaten safety and habitability, such multi-path energy resilience is central to sustainability.

Brine management is also expected to shift from waste containment toward resource-oriented valorization. Advances in electrocrystallization, high-efficiency vacuum crystallization, and ion-selective recovery methods aim to convert concentrated brine into recoverable salts, strategically useful minerals, or materials relevant to storage and thermal management. This approach reduces dependency on large brine storage volumes and supports closed-loop water cycles. When powered by low-grade SMR waste heat, improved low-temperature crystallizers and surface-enhanced evaporation systems can lower the energy footprint of ZLD operations, making fully closed brine handling more practical in confined underground settings [15].

Automation and autonomous maintenance represent another major trend. Next-generation desalination systems are increasingly designed around predictive control frameworks in which digital twins simulate system behavior continuously, detect anomalies early, and optimize operating parameters in real time [10]. AI-assisted diagnostics—including sensor fusion for conductivity, temperature, pressure, and vibration—can reduce the need for manual inspection. Robotic handling concepts for cartridge replacement, automated flushing, and self-cleaning membranes are expected to reduce labor requirements and improve reliability under isolation conditions. For underground shelters, where human intervention may be limited by safety protocols and accessibility constraints, automation directly contributes to operational sustainability.

Parallel to these developments, future desalination units are expected to emphasize ultra-compact modularity tailored specifically to underground geometry [7]. Design directions include plug-in membrane cartridges, vertically stacked MED modules, vibration-isolated nuclear–thermal exchangers, and scalable "add-on" capacity units that can be deployed within narrow corridors or dedicated technical decks. This modular approach supports repairability, redundancy, and staged expansion of capacity without major structural modification. Additionally, there is increasing interest in integrating desalination subsystems with shelter-wide environmental control networks. In particular, HDH and MD modules may be designed not only for water production but also to support humidity control and thermal redistribution, strengthening overall shelter stability [3, 11].

In summary, future underground nuclear-assisted desalination systems are likely to be defined by modular and layered energy coupling, advanced brine valorization and closure, autonomous monitoring and maintenance, and tight integration with nuclear and environmental-control architectures [16]. These trends collectively point toward resilient, closed-loop, long-duration water–energy ecosystems capable of sustaining next-generation underground shelters under severe isolation constraints.

4 Conclusions

This review has examined desalination technologies within the specific context of underground shelters powered by nuclear energy, emphasizing how energy availability, confined geometry, limited ventilation, closed-loop brine management, and long-term operational autonomy fundamentally alter the conventional performance hierarchy of desalination systems. While RO remains the most compact and electrically efficient option in surface-level installations, its dependence on intensive pre-treatment, maintenance-intensive membrane operation, and production of highly concentrated brine introduce significant challenges in underground environments. In contrast, MED demonstrates strong compatibility with low-grade thermal energy from SMRs, reduced sensitivity to feedwater variability, and lower maintenance demands, making it a particularly robust option for long-duration, isolated operation where reliability and energy stability are critical.

The comparative assessment indicates that single-technology solutions are unlikely to satisfy the full spectrum of technical, energy, and operational requirements imposed by underground shelters. Hybrid desalination architectures—particularly RO–MED configurations—emerge as the most balanced approach by distributing energy demand between electrical and thermal domains, enabling effective utilization of SMR waste heat, and introducing functional redundancy in the event of partial subsystem degradation. From an energy systems perspective, such hybridization enhances overall energy efficiency, reduces reliance on peak electrical loads, and improves resilience under variable operating conditions. When combined with ZLD or crystallization subsystems, hybrid configurations also mitigate the sustainability challenges associated with brine accumulation in sealed environments.

Passive and low-temperature desalination technologies, including HDH and MD, further contribute to system-level sustainability by supporting waste heat recovery, humidity regulation, and thermal load balancing. Although their freshwater production capacity is insufficient for primary supply, their integration as auxiliary subsystems enhances environmental stability and supports more efficient energy utilization within the shelter. These technologies exemplify how desalination in underground environments must be evaluated not solely as a water-treatment process, but as a multifunctional component of the broader energy and environmental control architecture.

Overall, the sustainability of underground desalination systems, as defined in this study, encompasses energy efficiency, effective waste heat utilization, operational reliability, and the ability to sustain autonomous operation over extended periods with minimal external support. The novelty of this review lies in its energy systems-oriented synthesis of desalination technologies under extreme confinement, highlighting how energy–water coupling strategies can enable resilient freshwater production in underground shelters powered by nuclear energy. By identifying key constraints, evaluating technology trade-offs, and outlining research gaps related to energy integration and long-term autonomy, this work provides a foundation for future research and design efforts aimed at developing sustainable, nuclear-assisted desalination systems tailored to the unique demands of subterranean environments.

Author Contributions

Conceptualization, I.A.I. and S.A.S.; methodology, I.A.I. and S.A.S.; validation, M.H.H. and E.M.A.; formal analysis, I.A.I. and S.A.S.; investigation, I.A.I. and S.A.S.; resources, A.A.K. and A.A.A.; data curation, I.A.I. and S.A.S.; writing and original draft preparation, I.A.I. and S.A.S.; writing—review and editing, M.S.A.; visualization, I.A.I. and S.A.S.; supervision, M.S.A.; project administration, A.H.N. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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