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Solar Thermosyphon Failure Analysis

B.2. A survey of thermosyphon failure modes, effects, and suggestions

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Solar Thermosyphon Failure Analysis

Deliverable

Subtask B. Thermosyphon Systems

Report B.2. A survey of thermosyphon failure modes, and effects, and suggestions

This is a report from SHC Task 69: Solar Hot Water for 2030 and work performed in Subtask: Thermosyphon hot water systems

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1 Executive Summary

This report addresses critical failure modes in thermosyphon solar water heating systems, providing a comprehensive analysis, and proposing integrated solutions to enhance global industry standards. The investigation identifies four primary failure mechanisms: **incorrect component mounting support**, faulty installation of vacuum breakers, missing or degraded insulation, and corrosion — specifically stress corrosion cracking (SCC) in stainless steel components. Each failure mode is examined through a structured lens of factual evidence, operational effects, and root causes, supported by empirical data and visual documentation. For instance, improper mounting induces dynamic stresses leading to joint fatigue and leakage, while a mispositioned vacuum breaker can disrupt the thermosyphonic action, causing system stagnation (overheating and/or overpressure) or unintended fluid loss. The absence of insulation directly undermines thermal efficiency by parasitic heat dissipation, and chloride-induced SCC compromises tank integrity, resulting in premature failure. These issues are exacerbated by regional variations in water quality, climatic conditions, and installation practices, necessitating tailored technical and strategic interventions. This report underscores that resolving these challenges requires a holistic approach, combining material innovation, intelligent design, rigorous quality assurance, and lifecycle management to ensure systems meet durability expectations across a diverse range of operational environments.

This report examines frequent failures in solar thermal systems, with a focus on thermosyphon systems commonly used in Sub-Saharan Africa. Through a global collection of expert and practitioner experience, it systematically identifies and categorizes key failure factors across three phases: Components, Design & Installation, and Operation. To address these failures, the report presents practical, layered solutions. For structural stability, it recommends using shock-absorbing mounts and flexible supports. For insulation, it stresses the need for complete, gap-free coverage with suitable materials. To fight corrosion, the report suggests using better materials and adding protective anodes. A central proposal is the use of smart controls with IoT sensors. These systems allow for predictive maintenance by monitoring performance. For example, they can use data models to prevent overheating and adjust operations automatically. All recommendations are supported by real-world testing, showing they can significantly improve system life.

Beyond technical fixes, the report advocates for a paradigm shift in system design and quality management. Design optimization employs computational fluid dynamics to balance hydraulic efficiency and thermal performance, while safety architectures incorporate redundant mechanisms—such as dual pressure-relief valves and temperature-activated shunts—to eliminate single points of failure. Maintenance-oriented features, including accessible service ports and self-diagnostic algorithms, transition lifecycle management from reactive repairs to predictive upkeep. Furthermore, installation protocols mandate Building Information Modeling based pre-assembly checks, torque-controlled fastening, and geotagged verification of critical components like vacuum breakers. These protocols are reinforced through standardized documentation and continuous training, ensuring adherence across supply chains. The cumulative impact extends beyond operational reliability: optimized systems demonstrate energy savings of 60–80% in climatic zones like North Africa and Southeast Asia, while robust designs reduce total cost of ownership by minimizing downtime and repair costs.

In conclusion, this report provides a clear path for manufacturers, installers, and policymakers to improve the reliability of thermosyphon systems. Success depends on one critical priority: correct and standardized installation. Proper installation is the essential foundation that ensures design performance, enables effective maintenance, and delivers long-term system reliability.

2 Introduction

Thermosyphon solar thermal systems represent a widely adopted passive technology leveraging natural convection for heat transfer, prominently deployed in residential applications across diverse climates, including the extensive use of evacuated tube systems in markets like China. While valued for their pump-free operation and reduced electrical dependency, these systems exhibit inherent vulnerabilities stemming from interdependent technical compromises. Field evidence indicates that failures frequently originate from material deficiencies, design oversights, installation errors, and operational neglect, collectively undermining performance, safety, and economic viability. The passive nature of thermosyphons fosters a misconception of inherent robustness, obscuring critical dependencies on precision engineering and disciplined maintenance protocols. Without rigorous lifecycle management, systems experience accelerated degradation, falling short of the 15-year service expectancy mandated by international standards such as ISO 9806:2017, while posing risks of scalding, structural damage, and environmental contamination from leaked heat transfer fluids.

Fundamental failures arise from substandard materials and manufacturing defects, particularly prevalent in cost-sensitive markets. Inferior glass quality in evacuated tubes—such as inadequate thermal tempering or reduced wall thickness—succumbs to thermal shock during stagnation events, causing sudden fracture and irreversible refrigerant loss. Parallel material degradation occurs through corrosion, especially in direct systems exposed to aggressive water chemistries characterized by high chloride content (>25 ppm), low pH (<6.5), or elevated hardness (>150 ppm $CaCO_3$). This induces pitting corrosion in copper absorbers and tanks, exacerbated by omitted sacrificial anodes at bimetallic junctions. Such material failures precipitate system depressurization, efficiency losses exceeding 30%, and frequent full-component replacements within 5 years. Secondary consequences include dry stagnation overheating damaging absorber coatings, biological fouling in drained components, and environmental hazards from glycol mixtures contaminating soil or groundwater.

Solar thermal systems play a vital role in the energy transition of Sub-Saharan Africa. However, they often face failures during operation, which harm system stability and shorten service life. This study uses a global information collection method to gather experience from researchers and practitioners. It focuses on practical applications in Sub-Saharan Africa and identifies 16 common technical failures, grouped into three key phases: Components, Design and Installation, and Operation. Typical technical issues include incorrect mounting of components, wrong positioning of pipes or vacuum breakers, missing insulation, lack of safety devices, and improper antifreeze use or maintenance.

These technical failures lead to serious consequences: system inefficiency, fluid leakage, overheating, freezing, and even structural damage. For example, poor component mounting causes roof breakage and leaks, while incorrect pipe positioning stops natural circulation. The research systematically categorizes failure causes—such as unqualified installation, lack of training, and poor material protection—and their impacts. It provides a technical foundation for optimizing system design, standardizing installation processes, and improving operation and maintenance practices. The findings help address root technical problems, enhance system reliability, and support the long-term use of solar thermal systems in challenging environments.

This report aims to systematically identify key failures in thermosyphon systems, analyze their causes and impacts. The goal is to guide better system design, promote standardized installation, and support scientific operation and maintenance. Component selection should use standardized, corrosion-resistant materials. System design must ensure proper pipe slope and correct placement of safety devices. Installation requires precise alignment and pressure testing. Operationally, IoT-enabled monitoring of glycol concentration, pH (7.5–10.5 range), and safety valve actuation cycles enables predictive maintenance, supplemented by biannual infrared inspections and automatic backup heater cutoffs during stagnation. Following these product and maintenance standards can significantly reduce failures and extend system life. This approach helps transform thermosiphon systems into reliable, low-maintenance renewable energy assets. The following sections detail common failure factors and present these integrated solutions.

3 Failure Modes and Effect of Thermosyphon Systems

3.1 Overview

Solar thermal systems hold significant value in the energy supply sector, particularly in driving the energy transition in Sub-Saharan Africa. However, during system operation, failures frequently occur due to various factors, which compromise the system's stability and service life. To comprehensively identify these failure factors, this study adopted a global round-robin approach for information collection. This method extensively aggregates experiential inputs from diverse researchers and practitioners, with a focused emphasis on the practical application scenarios of solar thermal systems in Sub-Saharan Africa. The objective is to systematically categorize failure types, clarify the causes and impacts of failures, and provide a foundation for subsequent optimized system design, standardized installation practices, and scientific operation & maintenance.The table below summarizes 16 common failure factors of solar thermal systems across three key phases: Components, Design and Installation, and Operation.

Table 1: Problems and Case Studies in Thermosyphon Systems.

#	Name	Remarks	
Components			
1	Leakage due to component failures	E.g., direct compact systems with evacuate tubes in China; weak glass used by local manufacturers	Reis Chirinze Karen
Design and installation			
2	Incorrect system dimensioning	Stagnation in summer if over dimensioned, not enough supply if under dimensioned	Karen Surridge
3	Incorrect mounting support for components	System unstable, can lead to leakages, falling apart of components, etc.	Fenni Magano Tweetheni Shidhika
4	Wrong positioning of pipes and components	E.g., defying the thermosyphon principle, laying pipes directly through the roof	Anadola Tsiu
5	Wrong positioning of vacuum breaker	Storage can be completely emptied, leads to stagnation of thermosyphon system, overheating of heating rod, etc.	Sebota Mokeke
6	Leakage due to wrong installation	E.g., incorrect connection of pipes	Tawanda Hove
7	Missing insulation	Leads to higher heat losses	Samson Mhlanga
8	Deterioration of insulation due to missing protection	E.g., missing UV protection	Helvi IILeka
9	Missing safety devices	E.g., missing safety valves, pressure relief valves	Joseph Shigwedha
10	Wrong installed vacuum breaker		Rudi Moschik
Operation			
11	Leakage due to missing or wrong concentration of antifreeze liquid	Leads to freezing, sometimes direct systems are used in regions with temperatures below zero where an indirect system should be deployed	Shaibu Tambula
12	Wrong response pressure for safety valve	E.g., 8 bar pressure for safety valve	Anadola Tsiu
13	Missing inspection of antifreeze liquid	See #10	Reis Chirinze
14	Unsuitable control of back-up heating device	E.g., storage is always kept hot, thermosyphon system in stagnation	Rudi Moschik

15	Corrosion phenomena solar thermal equipment		Guillermo Garrido
16	Poor water quality especially for direct solar water heating systems		Fenni Magano Tweetheni Shidhika Karen

3.2 Failure mode 1: Incorrect mounting support for components

3.2.1 Short introduction

The reliable operation of thermosyphon cooling systems hinges critically on precise component mounting and structural support. Incorrect mounting support represents a significant failure mode with potentially severe consequences for system integrity and performance.

3.2.2 Cause and effect

Cause: Wrong way of installation of solar geyser would lead to roof breaking.

Effect: The roof would break and damage or lead to water leaks in the roof.

Example: Figure shows below the examples of wrongly installed solar collector that has the roof not inspected.

Figure 1: Wrong way of installation of solar geyser would lead to roof breaking.

3.2.3 Possible Causes

When components such as the evaporator, condenser, or connecting piping are inadequately or improperly secured, system instability becomes a primary concern. This instability can manifest as excessive vibration or movement during operation, subjecting joints, welds, and seals to dynamic stresses they were not designed to withstand. Over time, this cyclic stress can directly lead to leakages of the working fluid, compromising the system's thermodynamic function and potentially causing damage to surrounding equipment. Furthermore, insufficient, or misaligned support risks the literal falling apart of components, especially under thermal cycling conditions where materials expand and contract. This detachment not only causes immediate system failure but also poses significant safety hazards. Ensuring rigid, vibration-resistant, and thermally compliant mounting is therefore paramount to prevent these cascading failure effects – instability, leakage, and component separation – which collectively jeopardize the thermosyphon's efficiency, longevity, and safe operation. Proper support mitigates unintended stress, maintains alignment critical for gravity-driven flow, and safeguards against catastrophic structural failures.

3.2.4 Suggested technical solutions.

Implement vibration-damping mounts (e.g., elastomeric pads, spring isolators) at critical connection points (evaporator, condenser, piping junctions) to absorb operational vibrations and prevent stress transfer to joints and welds. Ensure these are rated for the system weight and expected vibration spectra. Anchor the frame securely to the building structure or robust equipment baseplate. Incorporate sliding supports, roller supports, or expansion loops within piping runs to accommodate thermal expansion/contraction without inducing stress on fixed points or components. Ensure supports allow movement only in the intended direction. Use flexible connections (braided metal hoses rated for temperature and fluid compatibility) strategically at interfaces between components and rigid piping to absorb differential thermal movement and minor misalignments.

Ensure precise alignment during installation using laser levels or optical tooling, particularly for the evaporator-to-condenser elevation difference critical for thermosyphon flow. Use adjustable shims or mounts for final leveling. Employ pipe hangers/clamps with adequate load capacity and proper spacing to support piping weight and prevent sagging or point loading on components. Design supports and clamps with smooth, radiused contact surfaces to avoid gouging pipes or components and ensure even load distribution. Perform thorough post-installation inspections to verify correct alignment, secure fastening of all restraints, proper function of expansion provisions, and absence of pre-load stresses. Develop and enforce detailed installation procedures and torque specifications for all critical fasteners in mounting hardware. Document the final as-built support configuration for future maintenance reference.

3.3 Failure mode 2: Wrong positioning of pipes and components

3.3.1 Short introduction

Thermosiphon solar water heaters rely on the natural density difference between hot and cold water for circulation, rather than a pump. Therefore, the installation position of pipes and components is critical; any error will directly result in the system failing to operate or performing extremely inefficiently. Common issues include incorrect relative positioning between the collector and storage tank, improper pipe slope, and exhaust valve position incorrect or missing.

3.3.2 Cause and effect

Cause: The storage tank is installed below or level with the top of the collector. The circulation pipe connecting the collector and the water tank has an “inverted slope” or “air pocket.” Exhaust valve position incorrect or missing. The installation position of the supply water tank is too low.

Effect: Improper installation of pipes or components can result in slow system circulation, reduced efficiency, or even complete system failure. It also poses potential safety hazards.

Example: Figure 2 shows an example of a collector being installed backwards.

Figure 2: Poor positioning of the collector (Source: Rudi Moschik, AEE-Institute for Sustainable Technologies).

3.3.3 Possible causes

- No clear description on the installation inspection manual of the systems in terms of length of draw pipe and length of inlet pipe
- Lack of training, knowledge and understanding of installers and technicians

3.3.4 Suggested technical solutions.

To overcome these faults, the following actions are suggested:

- Provide clear information in installation guidelines and manuals.
- Training and information for installers, plumbers, and technicians
- Improve standards for different regions (no clear standard in many countries)

3.4 Failure mode 3: Wrong positioning / installation of vacuum breaker

3.4.1 Short introduction

The correct positioning and installation of the vacuum breaker are paramount for the safe and efficient operation of closed thermosyphon systems. Wrong positioning or faulty installation of this critical component constitutes a significant failure mode with potentially cascading and severe consequences.

3.4.2 Cause and effect

Cause: Incorrect installation of vacuum breaker. There is no thermosyphon loop in place to prevent back flow out of the tank in case there is not sufficient cold-water supply.

Effect: In case of not having enough water supply, the tank will be drained by leaving the taps open, which were positioned lower as the tank. Having an empty tank, this phenomenon can easily destroy the electrical heating element in the tank.

Example: Figure shows below the examples of wrong positioning or installation of vacuum breaker.

Figure 3: Wrong positioning / installation of vacuum breaker.

3.4.3 Possible Causes

Wrong positioning or faulty installation of this critical component constitutes a significant failure mode with potentially cascading and severe consequences. Primarily, an incorrectly placed or malfunctioning vacuum breaker can allow air ingress into the sealed system, disrupting the delicate internal vacuum pressure essential for controlled boiling and condensation cycles. This breach fundamentally compromises the system's thermosyphonic action, preventing the natural gravity-driven circulation of the working fluid. Consequently, the system experiences stagnation, where heat transfer ceases entirely. The immediate effect is the inability to cool the heat source, typically an evaporator section attached to critical equipment. This leads directly to dangerous overheating of the heating rod or protected component, risking catastrophic thermal damage or failure. Furthermore, in specific failure scenarios (like a stuck-open valve during shutdown or low-pressure events), the vacuum breaker malfunction can paradoxically cause the unintended and complete emptying of the working fluid storage reservoir. This total loss of the heat transfer medium renders the system inoperable and necessitates extensive repairs and recharge. Therefore, ensuring the vacuum breaker is correctly located (typically at the system's high point), properly oriented, and installed according to strict manufacturer specifications is vital to prevent system stagnation, overheating, and unintended fluid loss, safeguarding both operational integrity and equipment longevity.

3.4.4 Suggested technical solutions.

Strictly require installation only at the designated, verified highest point in the thermosyphon loop (typically the condenser outlet or reservoir vent line). Utilize system P&IDs and 3D models for unambiguous location identification during design and construction. Specify and validate the required flow direction/port orientation (e.g., arrow on valve body). Use installation drawings with detailed isometric views showing the exact mounting angle. Define and enforce specific torque values for valve installation (nuts, unions) using calibrated tools to prevent under/over-tightening causing leaks or thread damage. Conduct a thorough system-wide pressure decay test and vacuum hold test after vacuum breaker installation. Position the vacuum breaker where it is readily accessible for inspection and functional testing but protected from accidental impact.

3.5 Failure mode 4: Missing insulation

3.5.1 Short introduction

The absence or degradation of insulation constitutes a significant yet often underestimated failure mode in thermosyphon systems, directly undermining their thermal efficiency and operational stability. Missing or inadequate insulation leads to uncontrolled parasitic heat dissipation along critical components, particularly evaporation and condensation sections, piping, and reservoirs. This heat loss disrupts the delicate thermal equilibrium essential for sustaining the thermosyphon effect, reducing the temperature gradient driving the phase-change cycle. Consequently, condensation efficiency diminishes, impairing the working fluid's ability to complete the gravity-driven return to the evaporator.

3.5.2 Cause and effect

Cause: Insufficient hot water in the morning provision by the system and oversizing systems to compensate for heat loss.

Effect: Oversizing systems and poor performance of the systems.

Example: Examples of uninsulated solar collector outlet pipes.

Figure 4: Missing insulation on the copper hot water pipe.

3.5.3 Possible Causes

The repercussions extend beyond energy waste. Excessive heat loss forces the system to compensate through higher input temperatures or extended operation, accelerating component degradation and increasing energy costs. In cold environments, uninsulated pipes risk subcooling of condensed fluid, increasing viscosity and potentially causing flow stagnation. Conversely, in hot ambient conditions, uninsulated evaporators may absorb external heat, triggering premature fluid boiling and erratic pressure behavior. Critically, localized heat dissipation near sensitive equipment can create thermal hotspots, pose safety hazards or damaging adjacent infrastructure. Moisture ingress into uninsulated cold sections also risks corrosion under insulation (CUI), compromising structural integrity. Thus, comprehensive, and properly maintained insulation is not merely an efficiency measure, it is fundamental to preserving the thermosyphon's thermodynamic function, operational reliability, and long-term viability.

3.5.4 Suggested technical solutions.

Require insulation on all critical components – evaporator, condenser, piping (vapor and liquid lines), reservoirs, and valves – with zero gaps. Explicitly prohibit uninsulated "convenience gaps" at supports or instruments. Calculate and specify insulation thickness using industry standards based on maximum allowable heat flux, operating temperatures, ambient conditions, and economic thickness analysis. Ensure thickness compensates for thermal bridging. Use rigid insulation or install protective sleeves/cladding over softer materials at pipe supports, hangers, and anchor points to maintain thickness and avoid thermal bridging. Establish scheduled visual inspections for cladding integrity, sealant condition, and physical damage. Prioritize areas prone to impact or weather exposure. Implementation of these solutions minimizes parasitic heat loss, maintains the critical temperature gradient for efficient thermosyphon operation, prevents subcooling/stagnation or premature boiling, reduces energy costs, and ensures long-term system reliability and safety.

3.6 Failure mode 5: Deterioration of insulation due to missing protection

3.6.1 Short introduction

Thermosiphon hot water systems, and most of their pipe work are exposed to the environment by nature. Harsh weather conditions pose a threat to the insulation meant to prevent heat loss as well as freezing of water or heat transfer fluid in the pipe network. High irradiance level that can be experienced in region such as Southern Africa, especially Namibia, can damage weak insulation material over a short period of time, say three years, and birds, mice, and other animals also may damage some insulation material. All these are some of the root causes of insulation loss, therefore, protection again insulation loss must always be deployed. However, good insulation comes at a cost, nonetheless, the benefits are justifiable. Preserving good insulation allows for minimal use of electric back-up heating element, which subsequently minimizes the operating expenditure (OPEX) of the thermosiphon systems and allows for a higher solar fraction.

3.6.2 Cause and effect

Cause: Heat losses by the system due to lacking insulation

Effect: Frustration of the client, and water coming out cold of the solar heating system; Outdoor pipes frozen in winter stopping hot water from working and causing leaks; When temperatures drop below zero uninsulated pipes can freeze putting pressure on the pipes causing water not coming out of the taps; Heating system making gurgling sounds when switched on; In winter the pipes can get frozen causing water not to flow out due to freezing pipes because of missing insulation; Long distances uninsulated pipes can lead to wastage of water because the water in the pipe remain cold.

Example: Figure 5 shows the missing insulation protection.

Figure 5: Missing insulation protection (Source: Rudi Moschik, AEE-Institute for Sustainable Technologies).

3.6.3 Possible causes

- No clear description on the installation inspection manual of the systems in terms of length of draw pipe and length of inlet pipe.
- Lack of training, knowledge and understanding of installers, technicians, inspectors, and engineers.
- Unavailability of insulation protection materials.
- No clear guidelines, codes, and standards on the type of insulation, thickness of the insulation and how the insulation should be protected.
- No regulations to enforce the codes, inspection, and commissioning.

3.6.4 Suggested technical solutions.

To overcome these faults, the following actions are suggested:

- Avail various insulation protection materials on the market.
- Adopt standards and develop codes of practice and regulations to enforce regulations.
- Define roles and responsibilities of installers, technicians, and inspectors.

Figure 6 illustrates the correct installation of solar collectors with robust insulation protection using a reflective protective material.

Figure 6: Protection of the insulation material using a weather-proof material that is not susceptible to bird damage.

3.7 Failure mode 6: Missing safety devices

3.7.1 Short introduction

Safety devices form fundamental elements of a thermosiphon hot water heating system. They serve to ensure the safe operation of the system for humans, and against breakdown of the entire system. A well protected system ensures safe operating pressure to ensure the hot water storage tank remains intact. Some of the crucial safety devices of a thermosiphon system are:

- Pressure reducing valve – reduces the cold-water supply pressure to ensure lower working pressure of thermosiphon systems.
- Vacuum breaker – ensures that there is no backflow of water into the supply line; it further ensures there is no vacuum within a hot water storage tank in case there is no cold-water supply.
- Non-return valve – this prevents the back flow of water into an unintended direction. In thermosiphon systems, this prevents hot water in the tank back flowing into the cold-water supply pipe.
- TP valve – this device protects the hot water storage tank against high temperature and against high pressure that can potentially lead to tank or pipe leaks or burst in the worst case.

Safety devices should however be connected in the right position, and their ratings should match to protect the system being protected (i.e., there is no one size that fits all devices). The wrong installation of these devices would equate to it being missing. Therefore, it is crucial to ensure proper installation of the right safety devices.

3.7.2 Cause and effect

Cause: The water is not circulating; danger of explosion of the tank and no client protection; the tank could spring a leak or explode if pressure relief does open or missing when the tank is overheated and if it cannot contain normal water pressure it begins discharging and wasting water

Effect: Frustration of the client, and water not coming out of the solar heating system due to raptured pipes.

Example: Figure 7 shows the missing safety components (air release, PRV, filling and flushing valves)

Figure 7: Missing safety devices. (Source: Rudi Moschik, AEE-Institute for Sustainable Technologies).

3.7.3 Possible causes

- Lack of standardized construction procedures and acceptance processes.
- Construction personnel have not undergone professional training or have failed to perform construction work in accordance with requirements.
- Product design flaws.

3.7.4 Suggested technical solutions.

To overcome these faults, the following actions are suggested:

- Standardized rules and regulations and construction personnel clearly delineate relevant responsibilities.
- Streamline the integrated process of construction, acceptance, and maintenance to ensure product safety.

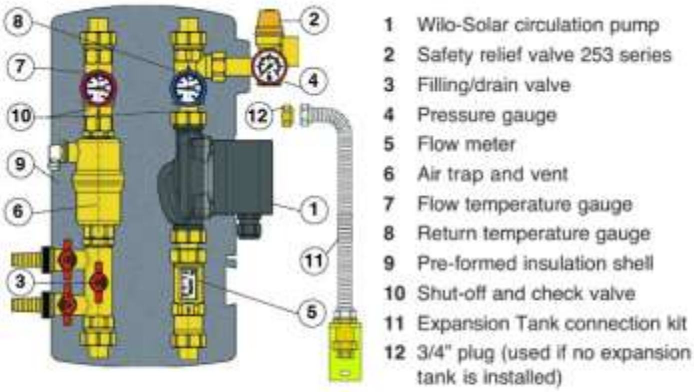

Figure 8. A solar thermal tank schematic with all the safety features included.

3.8 Failure mode 7: Leakage due to missing or wrong concentration of antifreeze liquid.

3.8.1 Short introduction

Antifreeze not only transfers thermal energy but also provides corrosion and scale protection, ensuring the system can operate under certain extreme conditions. It is crucial for guaranteeing the system's long-term durability and stable efficiency. Therefore, antifreeze depletion or incorrect concentration may cause irreversible damage to the system.

3.8.2 Cause and effect

Cause: Weak points such as seals and welds are damaged; Pipes and collectors burst due to expansion from freezing; Chemical corrosion occurs inside the pipes.

Effect: Weak points such as seals and welds are damaged; Pipes and collectors burst due to expansion from freezing; Chemical corrosion occurs inside the pipes.

Example: Figure 8 shows the leakage.

Figure 9: Consequences of the leak (Source: Rudi Moschik, AEE-Institute for Sustainable Technologies).

3.8.3 Possible causes

- Incorrect selection of antifreeze type or concentration during product manufacturing.
- Lack of regular inspection and maintenance, or improper replenishment or replacement of antifreeze.
- Accelerated coolant loss due to extreme conditions or system failure.

3.8.4 Suggested technical solutions.

To overcome these faults, the following actions are suggested:

- Select the appropriate type of antifreeze and have it installed by a qualified technician.
- Establish a comprehensive regular maintenance schedule and replenish antifreeze on time.
- Focus on system operation, maintenance, and status monitoring.

3.9 Failure mode 8: Wrong response pressure for safety valve

3.9.1 Short introduction

In a thermosiphon system, the safety valve serves as a critical triple-function component. When internal system pressure exceeds the preset value, it automatically opens to relieve pressure, preventing system explosion due to excessive pressure. When internal water temperature surpasses the preset value (even if pressure remains low), it automatically opens to relieve pressure, preventing system explosion caused by high-temperature steam pressure buildup. It also prevents backflow of water in the cold-water pipes.

Undoubtedly, the safety valve serves as the lifeline of a thermosiphon solar water heater. Its proper response pressure directly impacts the system's safety and longevity. Should any operational abnormalities be detected, such as failure to release pressure or persistent dripping—immediate action must be taken to address or replace the valve.

3.9.2 Cause and effect

Cause: Under normal operating pressure, the safety valve may open erroneously, discharging small amounts of water and steam. After pressure relief, when the system cools and forms a vacuum, it may draw in air, leading to internal oxidation and corrosion. Antifreeze will continuously leak out.

Effect: System efficiency declines and prolonged exposure may lead to radiator bulging, weld seam cracking, or even physical explosions. Antifreeze is continuously leaking. This will cause the system to lose its freeze protection and corrosion resistance, potentially leading to more severe issues such as freeze cracks or corrosion damage.

3.9.3 Possible causes

- The valve itself is substandard in quality, with poor manufacturing precision or inaccurate pressure settings.
- Valve blockage caused by rust or impurities.

3.9.4 Suggested technical solutions.

To overcome these faults, the following actions are suggested:

- Select the rated pressure of the safety valve based on the design working pressure of the tank and system.
- Use reliable products and replace them regularly to ensure their dependability.

3.10 Failure mode 9: Missing inspection of antifreeze liquid

3.10.1 Short introduction

Failure to inspect antifreeze refers to the neglect of regular checks and maintenance of the antifreeze level, concentration (freezing point), and condition within the system's circulation loop. Such neglect allows minor issues that could have been easily corrected to escalate into severe and costly failures.

3.10.2 Cause and effect

Cause: The system loses its freeze protection and corrosion resistance, resulting in decreased efficiency and inability to function properly.

Effect: Failure to promptly detect issues such as coolant leaks or concentration changes allows system problems to gradually accumulate, ultimately leading to unavoidable damage.

3.10.3 Possible causes

- Lack of a comprehensive inspection system.
- The complexity of the operation makes it difficult to conduct inspections efficiently.
- Lack of awareness of this type of safety hazard.

3.10.4 Suggested technical solutions.

To overcome these faults, the following actions are suggested:

- Establish a comprehensive, efficient, and convenient inspection system.
- Provide relevant information in the operating manual or safety manual.

3.11 Failure mode 10: Unsuitable control of back-up heating device

3.11.1 Short introduction

The core value of back-up heating devices lies in compensating for the inherent unreliability and instability of solar energy, ensuring that hot water supply becomes a stable and dependable household utility—much like municipal electricity and water services. Unsuitable control of back-up heating devices can lead to a series of consequences, including energy waste, reduced comfort levels, and shortened system lifespan.

3.11.2 Cause and effect

Cause: The back-up heating device activated at the wrong time or delivered incorrect water temperature.

Effect: An incorrect start time causes the back-up heating device to prematurely heat the water at the bottom of the tank, reducing the temperature difference between the collector and the tank. This weakens or even halts the thermosiphon effect, preventing the collector from efficiently gathering heat and significantly diminishing the energy-saving benefits of solar energy; Setting the temperature too high wastes energy, meanwhile, setting it too low promotes bacterial growth, posing health risks to users.

3.11.3 Possible causes

- The control logic failed to prioritize "maximizing solar energy utilization," resulting in unnecessary activation or failure to function properly when required.
- Failure to consider the operating environment resulted in incorrect initial parameter settings.
- Changes in the environment or user habits have not been promptly adjusted.

3.11.4 Suggested technical solutions.

To overcome these faults, the following actions are suggested:

- Refine control system manipulation strategies and optimize operational logic.
- Enhance the system's intelligence to enable automatic adjustments based on environmental changes or perform scheduled maintenance.

3.12 Failure mode 11: Corrosion phenomena in solar thermal equipment

3.12.1 Short introduction

Solar thermal energy equipment, with evacuated tube collectors' technology, uses a 0.4 mm thick of 304L austenitic stainless-steel sheet for the internal tank (accumulator or inner tank).

This type of stainless steel has particularly good resistance to generalized corrosion, but can present localized corrosion such as "Pitting," "Crevice," "MIC," "CUI" and "SCC." Frequent deterioration phenomenon that has been detected in equipment that fails prematurely is stress corrosion cracking (SCC), which manifests itself as intergranular and branching cracks.

3.12.2 Cause and effect

Cause: By visual observation inside the accumulators, it can be known (detected) if there are micro cracks due to SCC. Typical cracks are seen on the internal surface of the tank, mainly in the deformed areas and close to the welded joints of the equipment.

Effect: Cracks cause the accumulator to lose its tightness (they become punctured), which first causes a decrease in the thermal insulation capacity and performance (due to wetting of the insulating material); and ultimately puts the equipment out of service prematurely.

Once this pathology has developed in a tank, repair is difficult; since when trying to repair it, secondary cracks are generated and propagate. In this case, there is no alternative but to replace the tank with a new one.

Example: examples of uninsulated solar collector outlet pipes.

Figure 10: Corrosion phenomena solar thermal equipment.

3.12.3 Possible Causes

Austenitic stainless steels are susceptible to the deterioration mechanism called stress corrosion cracking (SCC) when the following factors are combined.

Table 2: Factors Affecting SCC on Austenitic Stainless Steels.

Metal sheet subjected to tensile stresses or residual stresses.	In contact with water		
	with the presence of chlorides	with a slightly acidic pH	with temperature greater than 60 °C
			

The drinking water supplied by the network has natural chlorides forming salts (Cl- ≤250 mg/l) and residual chlorine (≤ 2 mg/l) added for a disinfectant effect. These concentrations are sufficient to develop SCC type corrosion cracks. As the concentration of chlorides increases, the susceptibility for this phenomenon to occur increases.

3.12.4 Suggested technical solutions.

If the inner tank of the geyser is made of stainless steel, a sacrificial anode should be used to protect it. It must be installed in direct contact with the metal structure of the tank. If installing new equipment, it is advisable to choose a tank model that has an auxiliary input to insert the anode. The auxiliary inlet should be located on the covers of the cylindrical body (preferably in the lower part so that there is permanent contact with the water). The lower part of the same cylindrical body is also a technically feasible alternative. Inspection of the sacrificial anodes is necessary. Below are frequencies (how often) and method (how) to carry out the inspection and eventual replacement of the anode. Inspection of the sacrificial anodes is necessary. Below are frequencies (how often) and method (how) to carry out the inspection and eventual replacement of the anode.

Inspection frequency. It depends on the use of the equipment and, fundamentally, on the characteristics of the water (corrosive ions, pH, and hardness). Some installers suggest every year, and most every two years. This last indication is intended to prevent the anode from being completely consumed to replace it. Three reference situations are presented regarding the possible state of the anode at the time of inspection. From the INTI, it is recommended to do first preventive maintenance one year after installing the equipment and then, if there are no difficulties, repeat it every two years.

Table 3: Possible Scenarios During Inspection and Recommended Actions.

TYPE		Situation of the cylinder (anode)	Recommendation
A		Without consuming	The tartar is removed and replaced.
B		Pitting throughout	The tartar can be removed.
C		Completely consumed	Replaced with a new one.

3.13 Failure mode 12: Poor water quality especially for direct solar water heating systems

3.13.1 Short introduction

In an open system, the water flowing through the collector and being heated is the domestic hot water you use directly. This differs entirely from a closed system (which uses a heat exchanger and antifreeze), so water quality issues directly impact the system's core components. For direct-flow thermosiphon solar water heating systems, water quality is the core factor determining their lifespan and performance. In direct-flow systems, issues caused by poor water quality become more immediate and severe.

3.13.2 Cause and effect

Cause: Scale buildup occurs, leading to pipe corrosion or blockage, which reduces thermal efficiency, decreases water flow, and introduces impurities.

Effect: The accumulation of significant scale deposits directly impacts the efficiency and quality of hot water production and may cause corrosion damage to pipes; Impurities in the water can shorten the system's lifespan and promote bacterial growth.

3.13.3 Possible causes

- No pretest of water quality prior to system installation.
- No water softener system installed.

3.13.4 Suggested technical solutions.

To overcome these faults, the following actions are suggested:

- Testing, installation of Water Softeners systems.
- Regular maintenance/ Flushing of the system.

4 Suggestions for Thermosyphon Systems

4.1 Product-Level Enhancements

4.1.1 Components Enhancements

Component failure, especially leakage, is a primary reason why thermosyphon systems break down early. A common issue is the use of weak glass in evacuated tubes by local manufacturers. These cheap materials easily crack under pressure or bad weather, causing immediate system failure. To solve this, industry must set and enforce strict durability standards for all core parts. Both imported and locally made products should pass rigorous quality tests before reaching the market. Manufacturers need to use thicker, high-grade glass for tubes and stronger materials for seals and joints. Independent testing agencies should check these parts to ensure they meet basic international standards. By using stronger materials, we can greatly reduce the number of leaks and broken tubes. This approach not only extends the working life of the solar heating systems but also reduces repair costs for the users. Ultimately, better component quality builds consumer trust and encourages more people to use solar energy.

4.1.2 Improving Anti-Aging and Anti-Corrosion Materials

Solar thermal systems stay outdoors, so they face harsh weather every day. A big problem with many installations is the quick breakdown of insulation materials. Installers often forget to add UV protection. Without this shield, the sun's strong rays quickly destroy the insulation. This leads to massive heat loss, and the system fails to keep water hot. Furthermore, corrosion is a serious threat to metal parts and water tanks. Rust eats away the metal over time, causing fatal leaks. Therefore, it is highly recommended to use materials that resist both aging and rust. All outdoor insulation pipes must have a thick, high-quality UV protective cover. For metal parts, manufacturers should use stainless steel or apply strong anti-corrosion coatings. Regular checks should also be part of the maintenance plan to spot early signs of rust or sun damage. Using sun-resistant and rust-proof materials will keep the heat inside the system and protect the equipment for many years.

4.1.3 Matching System Types with Local Water Quality

Water quality varies greatly across different regions, and it deeply affects solar water heaters. In areas with poor or hard water, directly heating the water causes major problems. When hard water gets hot, it creates scale inside the pipes and the solar collectors. This thick scale blocks the water flow and stops the heat transfer. It also speeds up the rusting process from the inside. Therefore, project planners must test the local water quality before choosing a system. In regions with hard or dirty water, direct heating systems should be completely avoided. Instead, installers must use indirect heating systems. In an indirect system, a special closed-loop fluid collects the heat and safely transfers it to the daily use water through a heat exchanger. This keeps the dirty or hard water out of the sensitive solar collectors. Choosing the right system type based on local water conditions is a simple but highly effective way to prevent blockages and guarantee a long system life.

4.2 Standardization of System Design and Installation

4.2.1 Scientific System Sizing and Capacity Design

Choosing the right size for a solar water heater is very important. Many times, systems are not sized correctly for the people using them. If a system is too large (over-dimensioned), it will produce much more hot water than the users need. In the hot summer months, this unused hot water causes the system to overheat. This dangerous condition is called "stagnation," and it can seriously damage the pipes and solar collectors. On the other hand, if a system is too small (under-dimensioned), it will not supply enough hot water for the family's daily needs. This makes users unhappy and forces them to use electric heaters, which wastes energy and money. To avoid these problems, engineers must carefully calculate the daily hot water demand before designing the system. They need to study the local summer temperatures and the exact water usage habits of the family. A perfectly sized system ensures users always have enough hot water while protecting the equipment from summer heat damage.

4.2.2 Following Physical Principles of Thermosyphon

Overheating protection must be designed through a multi-layered safety system rather than a single point solution. Thermosyphon systems work on a simple natural rule: hot water naturally rises and cold water falls. They do not use water pumps. Therefore, the pipes and parts must be installed correctly. If installers do not understand this physical rule, they might lay pipes too flat or run them directly through the roof incorrectly leading to underperforming or nonperforming systems. Another major mistake is placing the vacuum breaker in the wrong position. If this valve is placed incorrectly, the water storage tank can accidentally empty completely. When the tank is empty, the backup electric heating rod will turn on without any water around it. This "dry heating" quickly burns out the heating rod and can cause severe overheating. To prevent these serious dangers, installers must strictly follow the system design drawings. They must double-check the angles of all pipes and ensure every valve is placed exactly where the manufacturer recommends.

4.2.3 Standardizing Mounting Support and Piping Installation

Solar thermal systems can be very heavy, especially when the tank is full of water. They therefore require strong mounting frames. Sometimes, installers use weak or inappropriate supports or install incorrectly. This makes the whole system unstable. Strong winds can cause the components to fall apart and create massive water leaks. Standardized rules for building strong metal supports are necessary. In addition to the frame, the piping work must also be strictly controlled. Many leaks happen simply because pipes are connected carelessly. Furthermore, installers often forget important final steps. They might leave out the heat insulation on the pipes, which causes the water to lose heat quickly in the cold air. Worse, they might forget to install basic safety devices, like pressure relief valves. Without safety valves, high pressure can build up and burst the pipes. To stop these careless mistakes, companies must provide clear, step-by-step installation guides and check the support frames, pipe joints, and safety valves before leaving the site.

4.3 Establishment of Normative Operation and Maintenance Mechanisms

4.3.1 Strict Management of Antifreeze Fluid

In regions where winter temperatures drop below zero, water inside the pipes can freeze. When water freezes, it expands and breaks the pipes, causing severe leaks. To prevent this, indirect systems using a special antifreeze fluid must be installed. However, just using antifreeze is not enough. The mixture must have the correct concentration. If the antifreeze is too weak, it will not stop freezing. Therefore, installers must carefully measure the antifreeze mixture. Furthermore, antifreeze fluid goes bad over time. Many systems fail because no one inspects the fluid after the first year. A strict maintenance schedule is necessary. Technicians should check the antifreeze levels and quality every year before winter starts. If the fluid is old or the concentration is too low, it must be replaced immediately. This simple routine check will save the system from expensive winter damage.

4.3.2 Calibrating Safety Valve Pressures

Safety valves are critical parts of any solar water heater. They protect the system from dangerous high pressure. As water heats up, pressure naturally builds inside the tank. If the pressure gets too high, the safety valve opens to release a little water and lower the pressure safely. However, a major problem occurs when the valve has the wrong pressure setting. For example, if a system requires an 8-bar safety valve, using a valve set too low will cause it to leak water constantly, wasting heat. On the other hand, if the valve is set too high, the pressure cannot escape. This extreme pressure can burst the water tank or pipes. Therefore, maintenance teams must ensure the safety valve matches the exact pressure limits of the system. During yearly checks, technicians should test the valve to make sure it opens smoothly at the correct pressure point.

4.3.3 Smart Control of Back-up Heating Devices

Most solar water heaters have an electric back-up heating rod inside the tank. This heater is only meant to be used on cloudy days. Unfortunately, many users leave this electric heater turned on all the time. This is a very bad operating habit. If the electric heater always keeps the water hot, the solar system has nowhere to send its new solar heat. When the sun shines brightly, the system overheats because the tank is already full of electrically heated water. This forces the thermosyphon system into a dangerous condition called "stagnation," which damages the equipment. To solve this, the back-up heater must be controlled smartly. It should be connected to a timer or a smart thermostat. The heater should only turn on during specific hours when there is not enough solar energy. Proper control prevents overheating and saves electricity.

5 Appendix

5.1 Abbreviations

SCC	Stress Corrosion Cracking
CFD	Computational Fluid Dynamics
CUI	Corrosion Under Insulation
MIC	Microbiologically Influenced Corrosion
BIM	Building Information Modelling
IoT	Internet of Things
PRV	Pressure Relief Valve

5.2 List of Figures

5.3 List of Tables