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# FMECA and FTA analysis applied to the manufacturing process of pulsating heat pipes

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**Abstract**
Pulsating heat pipes (PHPs) offer significant advantages for the thermal control of electronic components due to their simple manufacturing and high heat transfer rates. The reliability of PHPs has traditionally been assessed through long-life testing, but detailed reliability analyses from an equipment perspective are limited. The study of PHP reliability is essential due to its application and operational conditions. For instance, in aerospace applications these devices operate under severe conditions, and maintenance or replacement is impossible during operation, making them critical components in system functionality. The reliability analysis of PHPs focuses on the manufacturing process, considering future operating conditions. Although preliminary PHP testing will be conducted on Earth, laboratory conditions are less stringent due to the difficulty of replicating launch acceleration and space conditions for long-term testing under microgravity. This study presents an FMECA (Failure Modes, Effects, and Criticality Analysis) of the pulsating heat pipe manufacturing process, breaking down the production of each component. The results indicate that the most critical point is concentrated in the assembly of these components, leading to a higher incidence of welding failures. It recommends further work to improve welding and analyze mechanical stresses within the heat pipe.



*Keywords*: FMECA, FTA, Pulsating heat pipes, Manufacturing

## 1. Introduction

A pulsating heat pipe (PHP) is a type of passive heat exchanger that takes advantage of phase change for the transport of energy from a hot region to a cooler one. To perform its function, it needs to operate under vacuum conditions, and it must be partially filled with a working fluid (see Figure 1). The idea behind having a working fluid under vacuum conditions is to achieve a balance between a vapor phase and a liquid phase under lower saturation conditions compared to atmospheric pressure. These devices offer a significant advantage due to their straightforward manufacturing process and their ability to transfer high heat fluxes [1]. The primary role of a PHP is to transfer high heat fluxes to maintain the operating temperature within a specific range, which depends on the internal pressure of the tube. Figure 2 provides a concise functional analysis of the PHP, which is defined by the transfer of energy from a heat source located in the evaporator to a sink in the condensation region.

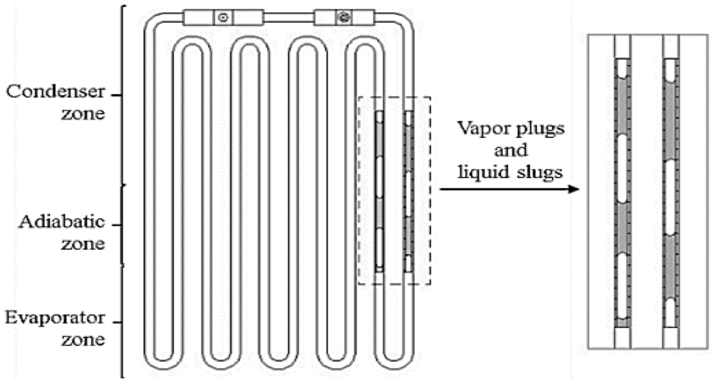


Figure 1. Diagram representation of a pulsating heat pipe [2]

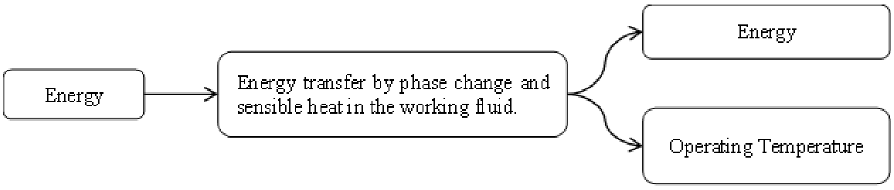


Figure 2. Pulsating heat pipe functional analysis

According to ref. [3], [4], [5] PHPs are simple, reliable, and noiseless, with low manufacturing cost, low weight, and high heat transfer efficiency, which makes them an excellent alternative as a heat transfer device. However, there are some manufacturing processes that need more attention to guarantee the device's reliability. For instance, the presence of Non-Condensable Gases (NCGs), caused generally due to an incorrect filling procedure, can affect the PHP thermal performance by a rise in the operating temperature and pressure [6] and consequently on thermal resistance; the incorrect welding of the elements can leave some pores and leakages, which will affect the quality of the vacuum, crucial for the proper performance of the device. The engineering industry is exposed to numerous risks and failures that can vary in degree and criticality [7] including in the manufacturing process. Analyzing the manufacturing process quantitatively enables proposed process improvements, thereby preventing the need for intricate and costly correction procedures [8].

Various risk analysis techniques, including Failure Mode and Effect Analysis (FMEA) and Failure Modes, Effects, and Criticality Analysis (FMECA), are indispensable components of risk management strategies for engineering systems, processes, and operations. They help prevent accidents, and the need for redesign, and ensure the development of reliable designs and processes [9]. According to [10] FMEA identifies failure modes and risks for a product, while FMECA further ranks these risks by criticality, guiding actions for product development, reliability, and cost reduction.

The work of [8] presents a fuzzy risk priority number evaluation for manufacturing failures in solar gel batteries using a combination of FMEA and fuzzy logic techniques. Additionally, it includes a classification of critical causes through a Pareto chart, leading to the identification of five critical failure causes for which corrective actions are proposed. The authors clarify that the improvement is not limited just to the manufacturing process and intend to expand the analysis to operation mode. Considering the high failure rate in plastic production, applied the FMEA with fuzzy Bayesian Network (FBN) and fuzzy best-worst method (FBWM) to identify these failures [11]. The results were enhanced by the insights from experts regarding the significance of failure modes for both the product and the entire system. The comparison was made between two methods (classical FMEA and the proposed one), and in both, the same failure was identified as the most critical: FM2 - “The raw material in the extruder cannot be adjusted to the appropriate melting temperature”. FMEA and FMECA methodologies are employed to analyze an integrated photovoltaic-thermal-fuel cell (IPVTFC) system [10]. The authors investigated how component failure modes may influence system reliability and provide insights for improved design and maintenance of photovoltaic-based energy systems. Concluding that results prevent the interruption of the energy supply and enhance competitiveness for IPVTFC systems. A data-driven framework to analyze production failures using Failure Mode, Effect, and Criticality Analysis (FMECA) is introduced in [12]. Machine Learning techniques, including Association Rule Mining and Social Network Analysis, were used to understand cause-effect relationships and identify critical patterns. The approach was applied to an offshore and onshore platform to bridge theoretical analysis with practical implementation, revealing unknown relations and cause-effect relationships among variables.

The tool has also been used for assessing sustainable aspects of manufacturing processes. A novel approach to assess the environmental, social, and economic impacts of failure modes in industrial equipment is introduced in [13]. The authors use a hybrid method for risk ranking and demonstrate its effectiveness through a case study, highlighting stability and robustness. The integration of FMECA with multi-criteria decision-making (MCDM) in the manufacturing industry is discussed [7]. Electronics manufacturing is the dominant application, and the Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) is the most applied MCDM approach. The research identifies FMECA limitations and provides recommendations. This paper is Part I of a two-part review; Part II covers other major industries.

With the aim of assessing the reliability of the Residual Heat Removal System (RHRS) for Hualong Pressurized Reactor 1000 (HPR1000) is applied directly to heat exchange devices [14]. They used a novel approach that combines FMEA, fault tree analysis (FTA), and fuzzy Bayesian network (FBN) methods to establish an FBN model for residual heat removal system (RHRS) reliability assessment. The approach's applicability was validated in East China.

Therefore, the aim of this study is to implement FMECA and FTA tools in the manufacturing process of pulsating heat pipes to identify failures and their criticality, enabling the implementation of corrective actions to minimize failures and enhance the reliability of such devices.

## 2. Research method

This research is divided into two parts. The first one includes the analysis of the heat pipe manufacturing process, while the second part focuses on FMECA and FTA analyses.

### 2.1. Pulsating heat pipe manufacturing process

There are two main variations of a pulsating heat pipe. The first one is called a meandered pulsating heat pipe, and the second one is called a flat plate pulsating heat pipe, which consists of at least two flat plates with machined channels that are joined by several manufacturing processes (e.g. vacuum brazing and diffusion bonding). This work evaluated the meandered one, whose manufacturing cost is lower as it consists of a coiled serpentine within a matrix, which is welded to a larger tube referred to as the junction. In addition to connecting the ends of the serpentine, the junction adds another component called the umbilical, which is used for vacuuming and filling the working fluid, as shown in Figure *3* (a). These elements are joined through soldering, or a Phos-Copper brazing process carried out using oxyacetylene equipment. Figure *3* (b) presents a prototype of a pulsating heat pipe fabricated by coiled serpentine. In the engineering industry failure may happen in all processes from the design to the manufacturing and maintenance.


(a) (b)

Figure 3. (a) PHP components (b) PHP prototype fabricated by a meandered serpentine [2]

The present study is conducted to gain a better understanding of the manufacturing process of the heat pipe through an FMECA analysis, which will enable the improvement of the PHP reliability to fulfill its function of transferring a specified power at a temperature determined by the process conditions. To achieve this, it is important to have a comprehensive understanding of the device's manufacturing process.

#### 2.1.1. Serpentine modelling

The first step in the pulsating heat pipe manufacturing involves bending a copper tube around a template. This template is designed with minimal clearance to ensure parallel alignment of each straight section. Bending the curves must be done with great care to avoid any constriction of the tube's inner diameter due to material deformation. Recognizing this ovality defect resulting from the tube bundle manufacturing process, different techniques have been attempted to mitigate it, such as water filling and end sealing, copper heating during the molding process, and redesigning the template to increase the bending radius.

#### 2.1.2. Polishing the serpentine terminals

It is necessary to perform polishing of the tube ends before soldering the junction and the umbilical, as burrs are left at the ends because of the tube-cutting process. If this procedure is not carried out, the tube may experience greater pressure drop or partial or complete blockage. To finish the edges, polishing is done using abrasives of different grits.

#### 2.1.3. Welding parts

Before welding the joint to the serpentine, the umbilical is joined (soldered or brazed) to the joint to check for a potential blockage following the soldering of the smaller channel in the heat pipe, which is the inner diameter of the umbilical that connects to the joint (see Figure 4).

Figure 4. Welding region between the umbilical and the joint with the serpentine [15].

After welding the joining must be reviewed to ensure it is not blocked, and the predetermined clearance in the design and the concentricity of the through-hole made to join the serpentine terminals must be measured. Furthermore, the welding of the junction to the umbilical should allow an unobstructed connection of the internal passages of these two components to allow the vacuum and load of the working fluid. Finally, the joint and serpentine are welded.

#### 2.1.4. Vacuum test

Vacuum test is performed with a leakage detector (Figure *5*), which can detect leaks as small as a helium atom, making welding a highly demanding process.

Figure 5. Helium applied to a PHP [15]

### 2.1.5. High vacuum

High vacuum is achieved with different vacuum pumps, which reach an absolute pressure of the order of magnitude of $10^{-6}$ mbar, considered high vacuum, for which a prior leak analysis is necessary to ensure stagnation.

### 2.1.6. Working fluid load

The loading of the fluid is a step carried out after a high vacuum, in which the fluid is added, with the use of a bypass system and a valve to control the amount of fluid added. In the case of the analyzed PHP meandered type of this study, the amount of fluid is about 30-50% of the total internal volume.

### 2.1.7. Sealing and welding of the umbilical

After loading the tube bundle with the working fluid, it is necessary to seal the umbilical to retain the fluid under the vacuum conditions achieved. This is done using a closure by mechanical deformation, performed with a special tool that allows the creation of a restriction in the umbilical's diameter and maintains the fluid in a vacuum ( Figure *6*). The calibration of the pliers is extremely important to apply the necessary pressure to seal the tube without cutting it.

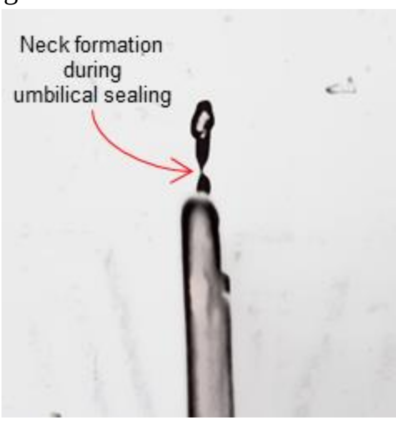


Figure 6. Sealing by deformation and welding of the umbilical

After sealing, the umbilical end welding is carried out, adding Phos-Copper filling material inside through brazing as shown in Figure *6*. The welding of the umbilical is the final step in the manufacturing of the PHP.

## 2.2. FMECA analysis

To accomplish the aim of the FMEA and FMECA analysis in Pulsating Heat Pipe Manufacturing it is necessary to identify and evaluate potential failure modes, their effects, and their criticality in the pulsating heat pipe manufacturing process, like the following:

- Formation of analysis team to ensure a comprehensive assessment: Two professionals in thermal sciences engineering with deep knowledge in manufacturing engineering.
- Identification of process steps: List and provide detailed descriptions of the manufacturing process steps, including serpentine bending, polishing, welding, leak testing, vacuum, fluid charging, sealing, and umbilical welding.
- Identification of Failure Modes: For each process step, identify all possible failure modes that may occur.
- Analysis of Failure Mode Effects: Determine the effects resulting from each identified failure mode.
- Severity Assignment [S]: Rate the severity of failure effects on a scale from 1 to 10, where 1 indicates a minor effect, and 10 indicates a catastrophic effect.
- Occurrence [O]: Rate the occurrence of a failure mode on a scale from 1 to 10, where 1 indicates a minor occurrence and 10 indicates a high occurrence.
- Cause Identification and Failure Detection [D]: Identify potential causes for each failure mode and assign a failure detection rating on a scale from 1 to 10, where 1 indicates high detection probability and 10 indicates low detection probability.
- Potential Risk Calculation: Calculate the Potential Risk Number (NPR) by multiplying severity, occurrence, and detection for each failure mode.
- Failure Mode Prioritization: Rank failure modes based on the calculated NPR, prioritizing those with higher NPR.
- Development of Corrective Actions: Identify corrective and preventive measures for the prioritized failure modes, including process improvements and quality controls.
- Monitoring and Verification: Implement corrective actions and monitor progress to ensure a reduction in potential risk.

# 3. Results and discussions

The r/esults consist of a risk analysis of each item, containing, also, the modes and the potential risk scores (RPN). This information allows us to see the critical areas that require immediate attention. The critical Failure model is indicated. Each item is classified according to its main function and the possible functional failures. Each functional failure depends on one or more failure modes, and, by the way, each failure has a failure mode effect. So, each failure mode is classified by the severity (s), causes and their occurrence (O), and the current controls defined by the detection level (D). By multiplying these indicators (S-O-D) the RPN of each assessed item is obtained. After this first RPN calculation, the professional experts recommend actions to mitigate the RPN number and the manager can decide to adopt complete or partially the recommendations. After that, a new RPN is calculated.

The results are summarized in Table 1 and the Failure Tree Analysis is presented in Figure 7. Based on that, it should be noted that the failure modes with the highest Risk Priority Number (RPN) in descending order increase in thermal resistance caused by corrosion rupture of the corrosive environment (RPN=448), surface encrustation (RPN=392), failure to connect the ends of the serpentine and/or the umbilical caused by welding with pores or unwelded regions and leakage of the working fluid (RPN=320). It is possible to note that there are four main causes for this: environment, working fluid, cleaning, and welding process. If the recommended actions are implemented, it is possible to see that the increase in thermal resistance caused by corrosion rupture due to contaminated medium lows from RPN=448 to RPN=280, surface encrustation from RPN=392 to RPN=294, failure to connect the ends of the serpentine and/or the umbilical caused by welding with pores or unwelded regions and leakage of the working fluid again changes from RPN=320 to RPN=160.

Table 1. FMECA analysis by a component of the PHP manufacturing process; adapted from [16]

| Item | Function | Functional failure | Failure mode | Failure mode effect | Severity (S) | Causes | Occurrences (O) | Current controls | Detection (D) | RPN (S·O·R) | Recommended actions | Responsible and scheduled end date | Actions Taken | Severity (S) | Occurrences (O) | Detection (D) | RPN (S·O·R) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Serpentine | Contains the working fluid | Does not contain the working fluid | Mechanical rupture | Leakage of the working fluid; Greater thermal gradient | 8 | Mechanical stresses beyond capacity | 9 | None | 10 | 720 | Computational simulation of stresses | Professional 1 | All | 8 | 4 | 3 | 96 |
| | | | Melting rupture | | | High power supplied | 2 | Electronic control | 3 | 48 | Fuses | Professional 1 | All | 8 | 1 | 2 | 16 |
| | | | Corrosion rupture | | | Contaminated medium | 7 | Elimination of contaminants | 8 | 448 | Elimination or control of contaminant sources, deionization of water | Professional 2 | All | 8 | 5 | 7 | 280 |
| | | | Blockage due to: - Deformation (ovalizing) - Corrosion material | Decrease in thermal exchange efficiency; Greater thermal gradient | 8 | Pipe shaping error | 8 | Ovality measurement | 1 | 64 | Mold redesign and training personnel for serpentine forming | Professional 2 | All | 8 | 5 | 1 | 40 |
| | Allows the heat exchange | Does not allow the heat exchange | Increase in thermal resistance | Greater thermal gradient | 7 | Surface encrustation | 8 | Cleaning | 7 | 392 | Evaluate other materials, chemical cleaning | Professional 2 | None | 7 | 6 | 7 | 294 |
| | Mechanical contact | Does not allow the | Misalignment; Loosening of fastening; | Greater thermal gradient | 7 | Punctual or generalized | 4 | Dimension measurement | 1 | 28 | Measurement of overall dimensions and | Professional 2 | All | 3 | 3 | 1 | 9 |

| Item | Function | Functional failure | Failure mode | Failure mode effect | Severity (S) | Causes | Occurrences (O) | Current controls | Detection (D) | RPN (S·O·R) | Recommended actions | Responsible and scheduled end date | Actions Taken | Severity (S) | Occurrences (O) | Detection (D) | RPN (S·O·R) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mechanical contact | Mechanical deformation | | | deformation in the tube | | | | | each straight section of the tube | | | | | | |
| Joint | Connecting the ends of the serpentine and the umbilical to the serpentine | Does not make the connection of the ends of the serpentine or the umbilical to the serpentine correctly | Do not connect the terminals | Improper coil positioning | 3 | Encrustation inside the joint | 6 | Cleaning inside the joint | 1 | 18 | Measurement and review of dimensions and possible blockages | Professional 2 | All | 3 | 3 | 1 | 9 |
| | | | Misalignment of the coil ends, general geometric misalignment | Improper coil positioning | 2 | Inner diameter eccentric joint | 2 | Milling with a drill longer than the total length of the joint | 3 | 12 | Verification of misalignment and dimensions | Professional 2 | All | 2 | 2 | 2 | 8 |
| | | | Impossibility of achieving vacuum and loading the working fluid | Improper umbilical positioning | 8 | Misalignment in the hole for umbilical connection | 2 | Clogging test using a thin-diameter wire to verify unblocking | 2 | 32 | Manual inspection of dimensions and blockage | Professional 2 | All | 8 | 2 | 1 | 16 |
| | | | Fluid leakage | Greater thermal gradient | 8 | Excessive clearance between the joint and the coil | 2 | Measurement of dimensions | 6 | 96 | Manual inspection of dimensions and blockage | Professional 2 | All | 8 | 2 | 4 | 64 |
| Umbilical | Allows the loading of the working fluid | Does not allow the loading of the working fluid | No loading of the working fluid | Greater thermal resistance | 8 | Blocked inner diameter | 3 | Clogging test with a thin-diameter wire to check for unblocking | 3 | 72 | Visual inspection and obstruction check in the smallest diameter with a thin wire | Professional 2 | All | 8 | 2 | 2 | 32 |
| | Allows the vacuum | Does not allow a vacuum | Non-achievement | Greater thermal resistance | 8 | Blocked inner diameter | 3 | Digital control of pressure in | 3 | 72 | Visual inspection and obstruction check in the | Professional 2 | All | 8 | 2 | 2 | 32 |

| Item | Function | Functional failure | Failure mode | Failure mode effect | Severity (S) | Causes | Occurrences (O) | Current controls | Detection (D) | RPN (S·O·R) | Recommended actions | Responsible and scheduled end date | Actions Taken | Severity (S) | Occurrences (O) | Detection (D) | RPN (S·O·R) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | process in the system | process in the system | of vacuum within the coil | | | | | the vacuum pump system | | | smallest diameter with a thin wire | | | | | | |
| Welding | Joins and seals the ends of the serpentine and the umbilical to the joint | Does not join and seal the ends of the serpentine and the umbilical to the joint | Failure to connect the ends of the serpentine and/or the umbilical | Working fluid leakage, vacuum loss, greater thermal resistance | 8 | Welding with pores or unwelded regions | 8 | Helium detection system leakage test | 5 | 320 | Leakage detector Edwards 5000 | Professional 2 | All | 8 | 5 | 4 | 160 |
| Working fluid | Heat exchange | Does not exchange heat | Do not operate as a pulsating heat pipe | Greater thermal resistance | 8 | Insufficient quantity of fluid | 2 | Manual measurement of quantity | 3 | 48 | More precise measurement | Professional 2 | All | 8 | 2 | 2 | 32 |
| | Recirculate within the serpentine | Does not recirculate within the serpentine | Do not operate as a pulsating heat pipe | Greater thermal resistance | 8 | Internal ducts blockage | 2 | Manual review of obstructions | 2 | 32 | Ultrasonic inspection | Professional 2 | None | 8 | 2 | 2 | 32 |
| Mechanical | Seal the system at the umbilical area | Failure to seal the system at the umbilical area | Heat pipe leakage, increase in internal heat pipe pressure | Greater thermal resistance | 8 | Working fluid loss | 2 | Measurement at strategic deformation points | 2 | 32 | Analyze the measurement points and redistribute them | Professional 2 | All | 8 | 2 | 2 | 32 |

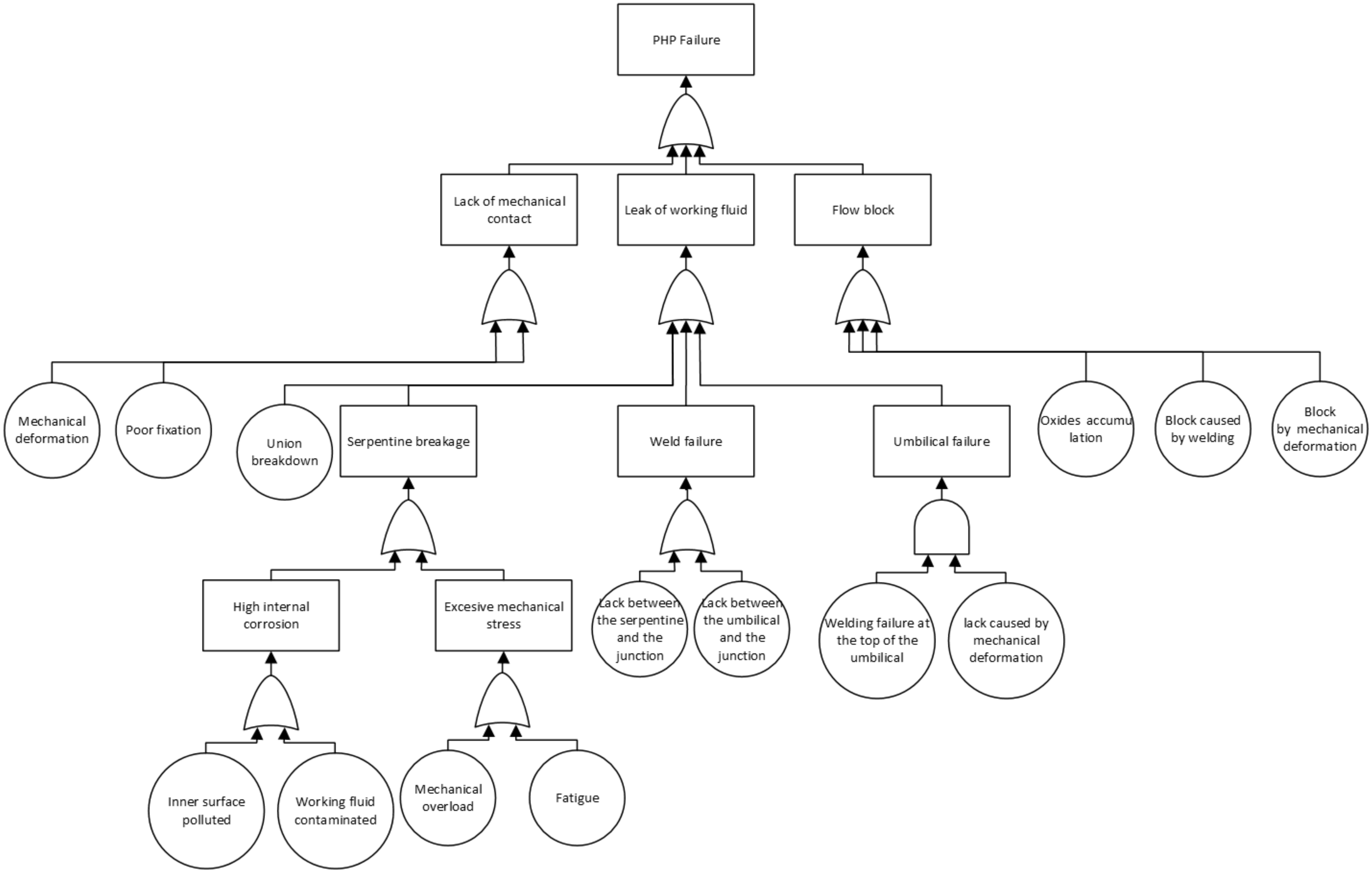


Figure 7. Failure tree analysis - FTA

## 4. Conclusions

This study implemented FMECA and FTA tools in the manufacturing process of pulsating heat pipes, which allowed for the identification of failures and their criticality, enhancing defect detection. From this work, it is possible to conclude that:

- The main failure identified through FMECA analysis is related to the loss of specific operating conditions in a pulsating heat pipe, specifically vacuum levels and working fluid content. The most frequent causes are found in the junctions of the serpentine components, with welding defects being the most recurring and challenging to detect. Specialized equipment is required to identify these small holes, prevent these failures, and maintain a high vacuum environment. The main effect of this kind of failure increases the thermal resistance and, subsequently, impacts the thermal control.
- The primary contributing factor to these failures is the unsuitable brazing process used to join the device components, and the inherent difficulty in detecting such defects. Rigorous control of the welding process and a thorough post-weld inspection of the internal channels can substantially reduce the overall occurrence of such failures. This, in turn, enhances the reliability of the heat pipe, ensuring its optimal performance and functionality.
- Other failures that can result in fluid and vacuum loss are easily detectable during the manufacturing process. By following recommended actions, their occurrence can be significantly reduced.
- FTA analysis enabled the tracing of root causes in manufacturing and operation that can lead to equipment failure. This is of utmost importance in identifying precursors that could potentially trigger catastrophic equipment failures.

### Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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### Author contribution

The contribution to the paper is as follows: Pamela Hulse, Luis Betancur-Arboleda, A. D. Rincon-Quintero: study conception and design; J. G. Ascanio-Villabona, B. E. Tarazona-Romero: data collection; Pamela Hulse, Luis Betancur-Arboleda, A. D. Rincon-Quintero: analysis and interpretation of results; Pamela Hulse, Luis Betancur-Arboleda, A. D. Rincon-Quintero: draft preparation. All authors approved the final version of the manuscript.

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