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Design of a Test Bench for Overpressure Valves for Diving Activity Compressors

Diseño de un banco de pruebas para válvulas de sobrepresión para los compresores de actividades de buceo

Daniel Ramírez Ramírez [1]*, Katherine Prada [1] and Edwin Sánchez [1]

[1] Diving School, Escuela Naval de Suboficiales "ARC Barranquilla", Barranquilla, 111071, Colombia; danielramirez2545@gmail.com; kpradasanchezz1017@gmail.com; edward.sanchez@armada.mil.co
* Correspondence: danielramirez2545@gmail.com

Abstract: The objective of this research was to design a test bench for pressure relief valves used in compressors employed in diving operations conducted by the Diving and Salvage Department of the National Navy, based in Cartagena, Colombia. The objective was to optimize operational safety and safeguard both the equipment and the safety of the personnel involved, as there are currently no specific test benches for these valves. This lack of essential tools not only increases operating costs and the risk of damage to vital equipment, but also compromises the safety of underwater operations. The methodology adopted was a mixed approach, which allowed for a thorough analysis of the technical requirements. The results show that the valves tested on the designed test bench met the established pressure parameters, validating the reliability and functionality of the prototype bench. Its modular configuration allowed for its application in various operating scenarios, representing a strategic advantage by generating opportunities for economic and operational improvement in the medium and long term. In conclusion, the project solved the identified problem through the implementation of a versatile test bench, contributing to the strengthening of preventive maintenance, risk mitigation in critical diving and rescue activities, and increased competitiveness in the corresponding industrial sector.

Keywords: Test bench; Compressors; Pressure relief valve; Safety

Resumen: Esta investigación tuvo como objetivo diseñar un banco de pruebas para válvulas de sobrepresión utilizadas en compresores empleados en operaciones de buceo realizadas por el Departamento de Buceo y Salvamento de la Armada Nacional, con sede en la ciudad de Cartagena D.T y C; el propósito era optimizar la seguridad operacional y salvaguardar tanto los equipos como la integridad del personal involucrado, ya que actualmente no se cuenta con bancos de prueba específicos para dichas válvulas. Esta carencia de herramientas esenciales no solo incrementa los costos operativos y el riesgo de daños a equipos vitales, sino que también compromete la seguridad de las operaciones subacuáticas. La metodología adoptada tuvo un enfoque mixto, el cual permitió un análisis exhaustivo de los requerimientos técnicos. Los resultados evidencian que las válvulas sometidas a prueba en el banco diseñado cumplieron con los parámetros de presión establecidos, validando la confiabilidad y funcionalidad del prototipo del banco, cuya configuración modular permitió proyectar su aplicación en diversos escenarios operativos, lo que representa una ventaja estratégica al generar oportunidades de mejora económica y operativa a mediano y largo plazo. En conclusión, el proyecto dio solución al problema identificado, a través de la implementación de un banco de pruebas versátil contribuyendo al fortalecimiento del mantenimiento preventivo, la mitigación de riesgos en actividades críticas de buceo y salvamento, y al incremento de la competitividad en el sector industrial correspondiente.

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Palabras clave: Banco de pruebas; Compresores; Válvulas de sobrepresión; Seguridad

1. Introdution

In the mechanical engineering industry, the safety of compression equipment is of utmost importance to ensure optimal operation and to prevent potential catastrophic failures. Compressors, as fundamental components in a wide range of industrial applications, require control systems to maintain process integrity and to protect both the equipment and the personnel involved in their operation.

In this context, overpressure valves are critical elements for safeguarding the integrity of compression systems, as they release excess pressure in emergency situations and prevent potential damage to the National Navy's Diving and Rescue Department (DEBUS), located at the facilities of the ARC Bolívar Naval Base in the city of Cartagena D.T. y C.

During the development of this research, various aspects related to the design and implementation of the test bench were addressed, including component selection, control system configuration, testing procedures, and evaluation criteria.

2. Contributions

The need to develop a test bench for overpressure valves used in diving operation compressors arises from the urgency to ensure safe and efficient operations, which are essential for the preparation and execution of critical safety and rescue tasks. This project is justified by its ability to introduce a testing method that not only significantly improves the safety of both equipment and personnel, but also contributes to more effective maintenance of compressors, which are essential for diving operability within the National Navy.

The importance of this research lies in its potential to raise safety standards in diving practices by addressing a tangible gap in the current maintenance and verification protocols for compressor overpressure valves within the diving department.

To achieve this, safety conditions are established for both the operator and the equipment. These conditions include the implementation of appropriate protective measures, standardized operation and maintenance procedures, and continuous personnel training. Likewise, the minimum technical specifications required to ensure such safety were reviewed and defined by comparing the current state of the diving department with national and international standards.

3. Related Works

The pressure relief valve, also referred to as a safety or relief valve, is an essential device in air compression systems. Its primary function is to release excess pressure when operating limits are exceeded, preventing structural failures or explosions [16]. It is activated automatically when a critical pressure level is reached and closes once safe conditions are restored [14]. Its reliability is crucial for the operational safety of industrial equipment [8;9].

Operations involving the use of compressors and pressure relief valves (Figure 1) in diving and rescue range from the charging and storage of breathable air for filling SCUBA or semi-autonomous cylinders; the generation of breathing gas mixtures (air, Nitrox, Trimix) for deep or technical diving; respiratory autonomy in underwater rescue during search and recovery operations using SCUBA; the continuous supply of breathable air in surface-supplied diving; and technical testing and calibrations for testing regulators, hoses, or valves, among others. All these activities involve inherent risks due to high pressure; therefore, the validation of these valves in compressors is essential to ensure operational safety.

(a) Air compressor **(b)** Overpressure valve

Figure 1. Compressor of the National Navy Diving Department: (a) air compressor; (b) overpressure valve.

The technologies employed include conventional test benches, online systems, and computational simulations. Smith and Brown [16] highlight that test benches allow valves to be evaluated under controlled conditions, while others emphasize the usefulness of online systems for continuous monitoring and predictive maintenance. Likewise, García and Pérez [4] emphasize the incorporation of advanced sensors and automation to improve test accuracy, while Rodríguez and Martínez [14] illustrate the value of CFD simulation for optimizing design prior to physical testing.

Advances in test bench design are aimed at improving precision, durability, and adaptability. García and Pérez [4] highlight the integration of real-time measurement systems and automated control with optimization algorithms. In addition, computational modeling is being explored to predict structural failures. Rodríguez and Martínez [14] discuss the introduction of wear-resistant materials, such as ceramic coatings and additive manufacturing, which extend the equipment's service life.

Since their origins in the Industrial Revolution, pressure relief valves have evolved into intelligent systems with integrated sensors, automated control, and remote communication. Advances in materials and machine learning algorithms have improved their durability, adaptability, and real-time response capability [4;16]. Case studies in sectors such as oil, chemicals, and power generation have demonstrated the effectiveness of test benches in ensuring valve performance under extreme conditions. Lessons learned in these industries, particularly in risk management and safety regulations, are applicable to contexts such as industrial diving.

The United States, Germany, and Japan lead the development and standardization of technologies for testing pressure relief valves. Standards such as ASME, DIN, and JIS ensure high levels of safety and quality. In contrast, Colombia faces limitations in specific regulations, investment in R&D, and specialized technical training [4;11]. Institutions such as the National University are beginning to engage in the development of technologies associated with compressors and underwater safety [14]. However, testing is still carried out manually and with limited infrastructure, which restricts the country's competitiveness. The adoption of international standards and cooperation could help close these technological gaps [15]. Technology transfer and international collaboration are key to strengthening local capabilities. Participation in networks such as the Ibero-American Network for Education in Industrial Safety can facilitate access to advanced technologies and specialized training [14]. Training technical personnel and importing modern equipment are necessary strategies to strengthen institutional development.

3.1. Regulations and Standards in Colombia

In Colombia, the regulation of air compression systems and the implementation of testing equipment are governed by various industrial safety, energy, and occupational risk prevention standards. Some of the key regulations are those described in Table 1.

Table 1. Regulations and standards applicable in Colombia

Type of Requirement	Description
Resolution 2400 of 1979	This resolution issued by the Colombian Ministry of Labor establishes provisions on occupational health and safety in workplaces. Specifically, it regulates the conditions under which machinery and equipment must operate in working environments, including systems that use compressed air.
Colombian Technical Standard (NTC) 2885	This standard establishes the requirements for the installation, operation, and maintenance of compressed air systems. NTC 2885 defines the technical specifications that compression equipment and overpressure valves must meet, with an emphasis on safety and operational performance.
Resolution 1409 of 2012	Although primarily focused on work at heights, this resolution issued by the Ministry of Labor includes provisions on the use of safety equipment and risk management practices that may also be applied to the operation of test benches involving air compressors and high-pressure valves.
ICONTEC Code of Good Practice	This code, although not mandatory, provides guidelines for the design of industrial equipment, including the implementation of control and safety mechanisms for pressure-related systems such as overpressure valves.

3.2. Applicable International Standards

At the international level, there are widely recognized standards and regulations that define the requirements for the design, testing, and operation of air compression systems and overpressure (safety) valves. These standards are essential to ensure that the test bench meets the highest quality and safety requirements. Some of the most relevant standards are presented in Table 2.

Table 2. Applicable international regulations and standards

Type of Requirement	Description
ASME Boiler and Pressure Vessel Code, Section VIII	This standard is one of the most internationally recognized regulations for the construction and operation of pressure vessels and overpressure valves. It defines the technical requirements for pressure equipment construction and establishes specific methods for testing and calibrating overpressure valves. Section VIII, Division 1, is particularly relevant to ensure that the test bench is designed and built in accordance with the necessary safety standards.
ASME PTC 25-2014	This standard establishes procedures for testing and evaluating the performance of safety and relief valves. The test bench must follow these procedures to ensure that valves operate correctly under test conditions.
European Pressure Equipment Directive (PED) 2014/68/EU	This European Union directive regulates the design and manufacture of pressure equipment, including safety and relief valves. The test bench must comply with the requirements established by the PED to ensure that the valves tested meet European safety standards. In addition, it ensures that equipment is designed to prevent leaks and failures under high-pressure conditions.
International Organization for Standardization (ISO)	ISO 4126: Safety devices for protection against excessive pressure establishes requirements for the design, operation, and testing of safety valves, ensuring that the test bench can accurately measure opening and closing pressures. ISO 8573: Compressed air quality focuses on the purity of compressed air and is relevant because compressors used during testing must comply with these standards to prevent system contamination.
Deutsches Institut für Normung (DIN)	DIN EN 12266-1 establishes requirements for the testing of industrial valves, including safety and overpressure valves. It defines methods for pressure resistance testing, leakage assessment, and performance evaluation under extreme operating conditions, ensuring that the tests conducted on the bench are accurate and reliable.

3.3. Manuals and Procedures

In addition to official standards and regulations, the manuals provided by manufacturers of overpressure valves and compressors are also fundamental to the design and construction process of the test bench. These manuals offer detailed specifications of the components used, as well as recommended procedures for the installation, operation, and maintenance of the equipment.

- Bauer Kompressoren operation manual: provides specific details on the operating conditions of the overpressure valves installed in Bauer Junior 2 and Mariner II compressors. This information includes operating pressures, recommended maintenance, and safety procedures that must be followed during testing.
- Bauer safety valve calibration manual: describes the procedures for calibrating safety valves in air compressors. It is recommended that these procedures be strictly followed on the test bench to ensure that the overpressure valves are properly calibrated before being used in critical operations.
- High-pressure compressor safety manual: provides key information on the safety measures that must be implemented during the operation of high-pressure air compressors, including the use of additional safety devices such as secondary relief valves and real-time pressure monitoring systems.

4. Materials and Methods

The study adopted a mixed-methods methodological approach, combining quantitative and qualitative techniques to comprehensively address the design of a test bench for overpressure valves used in compressors for diving and rescue operations. According to Hernández et al. [6], this research can be classified as applied research, aimed at solving a specific operational safety problem through the implementation of theoretical knowledge in a practical context.

From a quantitative perspective, descriptive and inferential methods were employed to objectively assess the impact of the test bench on improving operational safety [1]. In parallel, as indicated by [2], the qualitative approach enabled an in-depth understanding of the experiences and perceptions of technical personnel through in-depth interviews and focus groups.

The temporal design of the research followed a sequential transformative approach, beginning with an exploratory phase that included a literature review, preliminary interviews, and contextual analysis, followed by a descriptive phase focused on the design of the device, adapting to the complexity of the phenomenon under study [6]. During the conceptual and bibliographic phase, previous studies, standards, and experiences related to test benches and underwater safety were reviewed, allowing for the establishment of a robust theoretical framework for the prototype design. This process included the definition of technical requirements, preparation of technical drawings, component development, and expert validation.

The prototype was manufactured in accordance with technical specifications and evaluated through pressure, strength, and stability tests, as well as surveys and interviews with personnel, which provided information on its usability, effectiveness, and acceptance. Finally, during the results analysis phase, improvements aimed at optimizing the design, ergonomics, and control systems were identified and implemented, ensuring compliance with technical and operational standards.

5. Results

The development of the project began with the determination of the minimum requirements of the test bench based on a technical and functional analysis of the overpressure valves used in high- and low-pressure compressors. This diagnostic process made it possible to identify the operating ranges, materials, and safety parameters required to ensure the accuracy and reliability of the system. Subsequently, the design of the test bench was proposed, integrating specific components (pressure gauges, control valves, pressure lines, and discharge systems) tailored to the conditions inherent to diving and rescue operations, with priority given to stability, safety, and ease of maintenance. Based on these specifications, a functional prototype was developed capable of replicating the real operating conditions of Mariner II compressors, ensuring compatibility with valves covering different pressure ranges.

Finally, the operational verification of the test bench was conducted through controlled testing, commissioning procedures, and review of the operation checklist, which made it possible to confirm the accuracy of the measurements, the proper response of the valves, and the overall efficiency of the system in preventing failures associated with overpressure conditions. The results obtained are described below.

5.1. Minimum Requirements of the Test Bench Based on the Analysis of Technical and Functional Specifications of Overpressure Valves

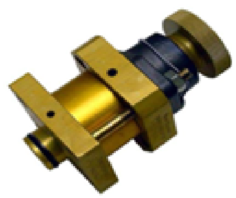
In the design of a test bench for overpressure valves, it is essential to understand the technical and functional characteristics of each valve involved. Table 3 anf Figure 2 presents the overpressure valves used in the Bauer Junior 2 and Mariner II compressors, which are integrated into the test bench.

Table 3. Characteristics of overpressure valves

Valve	Type	Opening Pressure	Stage
Airtek P.T valve	Low-pressure relief valve	120–130 psi	Stage 1
Bauer Safety Valve 072935	Medium-pressure safety valve	860–870 psi	Stage 2
Bauer Safety Valve 059410-330	High-pressure safety valve	3,000–3,010 psi	Final pressure stage
Bauer Valve 0169	Ultra-high-pressure safety valve	5,000 psi	High-pressure stage

(a) Airtek P.T valve

(b) Bauer safety valve 860 psi (072935)



(c) Bauer safety valve 3,000 psi (059410-330)

(d) Bauer valve 0169 (5,000 psi)

Figure 2. Overpressure valves: (a) Airtek P.T valve; (b) Bauer safety valve 860 psi (072935); (c) Bauer safety valve 3,000 psi (059410-330); (d) Bauer valve 0169 (5,000 psi).

Airtek P.T Valve: This valve is ideal for low-pressure compression systems, primarily in the first stage of compressors. It operates by releasing excess pressure when it reaches 120 psi. This type of valve is essential for regulating systems that must maintain pressure within a safe range to prevent damage to internal components. According to Rodriguez and Martinez [14], pressure relief valves protect compression systems from mechanical failures by preventing overpressurization that could compromise system integrity. This valve requires regular inspection of the opening diaphragm and cleaning to remove debris. Calibration is performed by adjusting the spring under controlled pressure conditions.

Bauer Safety Valve 072935: This valve is essential in the second stage of compressors, where pressure is significantly higher than in the first stage. Its function is to release excess pressure to prevent overpressurization damage, thereby protecting both the equipment and the operators. As noted by [5], safety valves in medium-pressure systems ensure uninterrupted operation by releasing accumulated pressure and allowing the compressor to maintain normal functioning. This valve is particularly useful in applications where pressure fluctuations are common. It requires inspection of the spring and high-pressure seals to prevent wear. Calibration is carried out on a specialized test bench to ensure that the valve opens precisely at 860 psi.

Bauer Safety Valve 059410-330: The 3000 psi safety valve is critical in the final compression stage, where pressures are extremely high. This valve ensures that the system does not exceed safe limits by releasing compressed air once the threshold pressure is reached. High-pressure valves are fundamental in preventing catastrophic accidents in industrial systems operating under extreme pressures. Its robust design and high-strength materials ensure reliable performance under demanding conditions. Maintenance involves cleaning the valve body and inspecting the spring and seals. Calibration is performed using a test bench that verifies precise opening at 3000 psi.

Bauer Valve 0169: Designed to operate at ultra-high pressures of up to 5,000 psi, this valve plays a crucial role in ensuring the safety of systems handling extreme compression. These valves are engineered to release accumulated pressure in critical situations, thereby preventing equipment damage and potential explosions. Martínez and Gómez [10] and Fernández and López [3] highlight that ultra-high-pressure valves are indispensable in industrial systems requiring precise control of operating conditions, ensuring operational continuity even under the highest pressure levels. Calibration is carried out using a high-precision pressure gauge. This valve is ideal for applications in ultra-high-pressure compression systems that demand maximum precision and safety.

5.2. Components of the Overpressure Valve Test Bench

For the initial development of the prototype overpressure valve test bench for diving compressors, the process began with the creation of a 3D design. These models enabled precise visualization of the arrangement of each component and the assessment of feasibility prior to fabrication. Through these drawings, potential improvements and adjustments were also identified, thereby optimizing the design to meet the specific pressure and control requirements of the project.

The 3D drawings included detailed representations of the test bench structure, the compressed air supply system, and the control system, which together constitute the main components of the prototype. The digital representation of each component allowed verification of compatibility between parts and the execution of virtual simulations to ensure that the structure could withstand the required pressure conditions. This approach provided a solid foundation for assembly and facilitated the technical documentation necessary for the manufacturing and installation of the prototype. The 3D visualization (Figure 3) made it possible to precisely adjust the system, ensuring stable pressure during testing and preventing potential leaks or structural failures.

The main technical characteristics of the overpressure valve test bench are detailed below:

- Pressure range: 70 MPa (10,000 psi)
- Connection ports: 1/4 NPT female
- Piston seal material: Viton
- Recommended hydraulic fluid: demineralized water or hydraulic oil
- Screw press displacement: 20 cm^3 (1.2 in^3)
- Reservoir volume: 75 cm^3
- Fine adjustment displacement: 0.06 cm^3 (0.004 in^3)

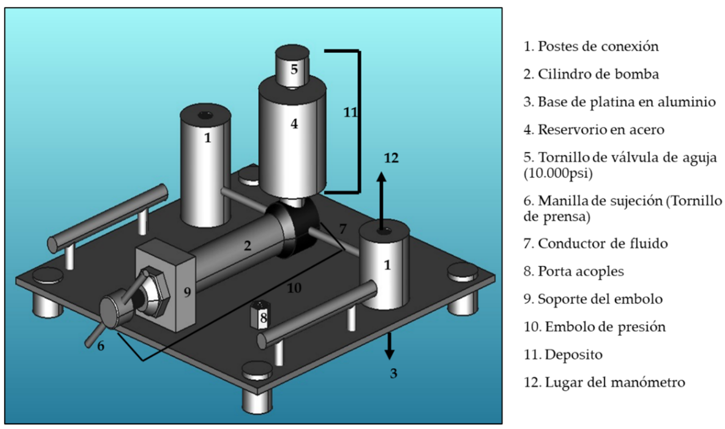


Figure 3. Plan of the test bench prototype.

The pressure generator consists of the following components: connection posts made of AISI 304 stainless steel with 1/4 NPT connection ports; a 1/2 pump cylinder made of AISI 304 stainless steel with a 2 mm schedule; and a copper-free aluminum plate measuring 30 cm × 30 cm × 1/4. The reservoir water valve screw is designed to withstand pressures of up to 10,000 psi. The system also includes a 2 × 4 AISI 304 stainless steel reservoir with Schedule 40 thickness, as well as a clamping handle for the screw press mechanism.

The fluid conduit is an essential component responsible for transporting the working fluid from the pressure source to the different points of the test system. Its cylindrical design ensures a constant and stable flow, allowing the fluid to reach the valves under test under optimal conditions. This flow stability is crucial for maintaining measurement accuracy, particularly in high-pressure systems such as those used in diving and rescue operations.

The fluid conduit withstands the high pressures applied during the testing process without undergoing deformation or premature wear. Its resistance to corrosion and mechanical fatigue ensures durability and operational safety under demanding conditions. In addition, its structure prevents pressure losses and ensures that the flow of distilled water or oil remains within the established parameters for each test. The use of this component optimizes the overall performance of the test bench by enabling accurate and safe evaluation of overpressure valves, maintaining a controlled environment free from pressure flow fluctuations.

The coupling holders represent the test bench couplings and are designed to ensure a firm and secure connection for each type of valve subjected to testing. These couplings feature an internal thread that allows the attachment of valves of different sizes and types, providing versatility to the system by adapting to various overpressure valve specifications. Their robustness and machining precision ensure a tight seal, preventing potential fluid leaks and guaranteeing test stability.

The primary function of the couplings is to facilitate the rapid assembly and disassembly of the valves to be evaluated. By offering a standardized connection, these couplings allow the operator to configure the system according to the characteristics of each valve, optimizing the testing process and reducing setup times. This modular design is a key feature of the test bench, as it enables faster and more precise testing of different valves. The design ensures that the compressed fluid flow is directed in a controlled manner toward the connected valve, preserving test integrity and minimizing the risk of pressure loss or mechanical failure during the evaluation process.

The piston support is a fundamental component within the structure of the test bench, designed to support and align the pistons that regulate fluid flow and pressure within the system. These supports ensure that the pistons remain in a stable and precise position, allowing uniform fluid control during the overpressure valve testing process. Their robust design ensures structural durability, withstanding the forces generated by the system's high-pressure conditions.

This component also plays a critical role in reducing vibrations and unwanted displacements during testing. By fixing the pistons in an exact position, it prevents lateral movement or misalignment that could affect test accuracy and valve performance. The stability provided by the piston support is essential to ensure that each test is conducted under controlled and repeatable conditions, thereby increasing the reliability of the results. Furthermore, this component is designed to withstand wear and the demanding operating conditions of the test bench. Its ability to maintain piston alignment and structural integrity contributes significantly to the overall safety and reliability of the system, minimizing the risk of leaks and ensuring that the valves under test operate optimally under the established conditions.

The final connection for the overpressure valves is the component that ensures the direct coupling between the valves to be tested and the pressure system of the test bench. This connector, designed to withstand high pressures, allows each overpressure valve to be securely and efficiently mounted on the test bench. The final connection maintains a hermetic seal, preventing leaks and ensuring that the fluid flow remains constant and controlled throughout the testing process. Its robust design is essential to prevent deformation or failure under extreme conditions, which is critical for ensuring accuracy in the evaluation of each overpressure valve. In addition, this final connection enables quick and firm installation of the valves, facilitating the assembly and disassembly process for each test. By ensuring proper valve fitting within the system, this connection contributes to the overall operability of the test bench and guarantees that each test is conducted under optimal conditions, ensuring the reliability and safety of the results obtained.

The pressure piston is responsible for generating the pressure required to evaluate the performance of the overpressure valves. This piston operates through a screw-driven mechanism that allows pressure to be increased in a controlled and gradual manner, providing a precise and safe testing environment. The fine adjustment capability of this mechanism ensures that the pressure applied to the valves can be regulated with high accuracy, which is essential for tests requiring specific pressure levels. In addition, the pressure piston is constructed from high-strength materials capable of withstanding mechanical stress and the pressures generated during testing, enabling repeated use without compromising structural integrity and ensuring the durability and reliability of the test bench. The incorporation of the pressure piston allows the test bench to perform accurate and safe evaluations, facilitating the validation of overpressure valves under controlled conditions.

The digital pressure gauge is a key measuring instrument in the test bench, designed to provide precise readings of the pressure generated in the system and, in particular, to measure the opening pressure of the overpressure valves. This device enables real-time monitoring of the pressure at which each valve is activated, which is essential for verifying compliance with safety and performance specifications.

The use of a digital pressure gauge instead of an analog one improves measurement accuracy and facilitates data interpretation by allowing fast and precise readings. Its digital display provides clear visualization and eliminates the human error margin associated with analog scale readings, thereby increasing test reliability. This level of precision is essential for documenting valve performance and for making adjustments when necessary. The threaded connection ensures secure attachment to the system, preventing pressure leaks and maintaining the integrity of the test bench. Beyond continuous monitoring, the digital pressure gauge also contributes to system safety by alerting the operator to any pressure deviations during valve testing.

The reservoir is an essential component responsible for storing the fluid used to pressurize the system during overpressure valve testing. Its inverted conical design facilitates fluid accumulation and controlled release, ensuring that constant pressure is maintained in the system when the testing process is activated. This reservoir allows the test bench to maintain an adequate fluid supply to perform multiple tests without the need for immediate refilling. Its design ensures that the stored fluid remains fully sealed, preventing pressure losses and leaks, critical factors for maintaining the integrity and accuracy of the tests conducted on the bench. Furthermore, the reservoir is integrated in a way that facilitates its connection with the rest of the system, ensuring continuous and controlled flow toward the pressure piston and enabling precise pressure adjustment within the test bench. As such, the reservoir plays a key role in the overall operation of the system by providing the required fluid volume to ensure that each valve test is conducted safely and reliably.

5.3. Prototype of the Overpressure Valve Test Bench for Compressors

The fabrication of the device was carried out entirely using AISI 304 stainless steel, with the exception of the piston and the press screw. The piston was manufactured from phosphor bronze, while the press screw was made of AISI 4140 steel. The base and support structure were constructed from copper-free aluminum, with approximate dimensions of 30 cm × 30 cm and a thickness of 1/4, as shown in Figure 4.

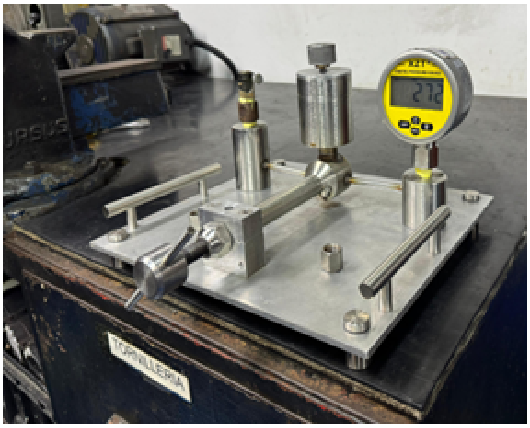


Figure 4. Test bench prototype.

The prototype integrates all the essential components required to perform controlled and safe pressure tests, enabling accurate evaluation of valve performance under simulated operational conditions. Its modular and detailed design ensures an efficient and secure configuration, optimizing fluid flow and pressure regulation at each stage of the testing process.

The system includes a reservoir located at the top, which acts as the pressure fluid container and ensures a constant supply to the system. Through a fine internal thread, the fluid is directed toward the pressure piston located at the center of the system, which generates the pressure required for testing. This piston allows fine pressure adjustment, while the needle screw installed in the reservoir precisely controls the fluid flow toward the piston.

On the upper right side, a digital pressure gauge is installed, enabling real-time pressure monitoring. This gauge is critical for recording the exact pressure at which the valve activates, ensuring measurement accuracy. The final connection ensures a hermetic fit for the overpressure valve, facilitating a controlled testing environment. The arrangement of components on a rigid base provides system stability, enabling efficient operation and minimizing the risk of leaks or failures during testing. This integrated design ensures that the test bench meets the required safety and functional standards.

5.4. Operation of the Test Bench and Operating Checklist

As a result of commissioning the overpressure valve test bench, multiple systematic tests were conducted to verify the performance of each valve under controlled conditions. In all cases, the valves subjected to testing met the expected opening parameters, with consistent pressure values confirmed across five consecutive tests. No significant variations were identified that could compromise performance, demonstrating the accuracy and reliability of the test bench for validating and adjusting the operational settings of the valves.

During the functional evaluation of the safety valve test bench prototype for the Mariner II compressor, accuracy, consistency, and reliability were verified across different pressure stages.

In the first stage, the Airtek P.T 9 bar PN 25 D 6 mm Q2101 valve, classified as a low-pressure relief valve (120 psi), exhibited an exact and repeatable response at the established opening point, confirming its effectiveness in preventing overpressure conditions that could compromise the integrity of the compressor's initial components.

In the second stage, the Bauer Safety Valve 60 BAR 072935, identified as a medium-pressure safety valve (6870 psi), demonstrated precise and stable activation in the five consecutive tests performed, ensuring compliance with operational safety standards and protection of the system's intermediate components.

Regarding the final stage, the Bauer Safety Valve 330 Bars 059410-330, classified as a high-pressure safety valve (4786.25 psi), operated consistently at its nominal opening pressure, preventing exceedances that could lead to structural failures and thereby guaranteeing the overall safety of the compression process.

Finally, the Bauer Valve 0169 (6500 psi), classified as an ultra-high-pressure safety valve, was reliably activated under no-load conditions, preventing unnecessary pressurization of the system. Its stable behavior confirms its critical role in equipment protection and risk prevention during operation.

During the development of the tests using the prototype, several improvement opportunities were identified. These include the implementation of a fixed safety valve for the entire system to ensure that, in the event a valve is not properly calibrated at its designated set point, unreleased pressure does not become a safety hazard. Additionally, the implementation of a protective cover over the valve under test is recommended so that, in the event of abrupt pressure release, the discharge of fluid is safely contained by the enclosure.

In summary, the tests conducted demonstrate that the evaluated valves adequately meet their design parameters, ensuring sequential protection of the compression system across all operational stages.

The following steps describe the procedure required for the proper operation of the prototype overpressure valve test bench used for compressors employed in diving operations carried out by the National Navy Diving and Salvage Department:

Step 1. System purging: Turn the regulating spindle clockwise until it reaches its stop to remove any residual air inside the system. This step is essential to ensure that the system starts under optimal conditions.

Step 2. Connection preparation: Apply Teflon tape to the threads of the valve and the pressure gauge. This ensures a hermetic seal and prevents leaks during testing.

Step 3. Connection tightening: Use an appropriate adjustable wrench to secure the system connections, tightening each component precisely according to the required size.

Step 4. Fluid loading: Fill the reservoir with distilled water.

Step 5. Filling the piston chamber: Turn the spindle counterclockwise to allow the fluid to completely fill the piston chamber, ensuring it is ready for pressure generation.

Step 6. Reservoir sealing: Install the reservoir cap and tighten it firmly to prevent any potential fluid leakage.

Step 7. Leak inspection: Perform a visual inspection of the entire system to confirm that there are no leaks at the connections or at the reservoir before proceeding.

Step 8. Test initiation: Turn the spindle clockwise to gradually increase system pressure. Monitor the digital pressure gauge throughout this process to control the pressure increase.

Step 9. Valve opening verification: Observe the pressure gauge as pressure increases and record the exact moment at which the valve is activated. Visually inspect the valve to confirm proper opening.

6. Discussion

The project demonstrates a significant scope, as it not only enables the calibration of overpressure valves used in industrial compressors, but also allows for the calibration of valves employed in hyperbaric chambers and pressure gauges with set points not exceeding 10,000 psi. This achievement opens opportunities to diversify the applications of the test bench, thereby increasing its usefulness across different industrial environments. However, to fully maximize its potential, further studies are recommended, along with design enhancements and additional testing aimed at expanding its scope and overall impact.

Moreover, this development represents an initial step toward valve certification, enabling the future provision of calibration and certification services using the constructed test bench. For this to become a reality and generate a positive economic impact, continued research is required to support process standardization and compliance with international regulations. This will ensure the commercial viability of the service while strengthening operational safety through the implementation of advanced monitoring technologies and proactive risk management strategies, which allow deviations or anomalies to be detected before they lead to critical failures. In this regard, the studies conducted by Zonta et al. [18] demonstrate that early fault detection through predictive systems based on artificial intelligence and real-time analysis significantly increases the reliability of industrial equipment.

Similarly, a comprehensive safety approach spanning from design to operation has been promoted by model-based engineering methodologies, such as Model-Based Safety Analysis, which integrate risk management throughout the system life cycle. According to Rajabalinejad and Van Dongen [13], the Safety Cube method facilitates the traceability of safety requirements and optimizes the validation of complex systems. In addition, the adoption of international standards, such as ISO 9001 and ISO 45001, strengthens systematic safety and occupational health management. Recent studies show that ISO 45001 certification contributes to improved performance indicators and the development of a preventive safety culture within organizations [12].

Finally, intersectoral collaboration constitutes a key component in the consolidation of sustainable safety practices, particularly in the design and implementation of specialized technical equipment. According to Tancred et al. [17] and the International Journal of Health Policy and Management [7], shared governance approaches promote coordination among technical, industrial, and regulatory sectors, generating synergies that enhance organizational resilience and comprehensive risk management. In this context, the design and implementation of the overpressure valve test bench effectively integrate these sectors, taking into account compliance with both national and international regulations and standards that define safety, quality, and operational requirements. This integration ultimately ensures reliable system performance and the protection of both operators and equipment.

7. Conclusions

The development and commissioning of a test bench for overpressure valves used in compressors proved to be an effective technological solution for ensuring operational safety in diving and rescue activities. Its performance was shown to be reliable, repeatable, and precise, thereby reducing the likelihood of failures during critical operations.

Furthermore, validation through experimental testing confirmed that all evaluated valves met their specified pressure thresholds, demonstrating the test bench's capability to identify deviations in opening pressure and to verify that pressure relief mechanisms are properly configured. Its technical feasibility and potential for industrial certification are further strengthened by the incorporation of advanced control systems and the use of components that comply with international standards.

The modular and adaptable structure of the test bench provides enhanced design versatility, as it can be adjusted to accommodate different valve specifications and operating conditions. This feature, combined with its functional stability, positions the system as a strategic platform for calibration and certification services in the field of underwater and industrial safety.

Finally, this research effectively addressed the identified technical need: the lack of a verification system for overpressure valves in compressors used for diving and rescue operations. The proposed solution improves preventive maintenance procedures, complies with the necessary technical standards, and reinforces operational safety in critical applications. Additionally, it is expected to serve as a foundation for the future integration of emerging technologies, such as real-time data analysis and remote monitoring, which will further enhance innovation capacity and technical competitiveness within the sector.

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Prada, K.: Methodology, Software, Validation, Data curation, Visualization, Writing – original draft, Writing – review & editing.

Sánchez, E.: Investigation, Resources, Validation, Formal analysis, Writing – review & editing, Funding acquisition.

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Authors' Biography

Daniel Ramírez Ramírez Student at the Escuela Naval de Suboficiales "ARC Barranquilla"

Katherine Prada Student at the Escuela Naval de Suboficiales "ARC Barranquilla"

Edwin Sánchez Student at the Escuela Naval de Suboficiales "ARC Barranquilla"