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REVIEW ARTICLE

ECONOMIC AND SCIENTIFIC RELEVANCE OF A BRAZILIAN PRIMARY VACUUM STANDARD

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ABSTRACT

A primary standard is a measurement reference with the lowest possible uncertainty for that quantity. The primary standard tends to be the measurement reference and provides traceability of an entire calibration chain of equipment and measurements, which is why it has a potential impact both in scientific research and in economic and industrial terms. In this article, we carried out an analysis of metrology and vacuum applications exploring the impact of having a Brazilian primary standard on national economic and scientific development in these applications. The results of the analysis showed that the absence of a Brazilian primary standard implies a potential loss of millions of dollars due to the higher costs of standardization abroad and the time required for calibration, which can take longer than 12 months.

KEYWORDS: Primary Standard Vacuum, Metrology, Quality, Economic Impact.

RELEVÂNCIA ECONÔMICA E CIENTÍFICA DE UM PADRÃO PRIMÁRIO DE VÁCUO BRASILEIRO

RESUMO

Um padrão primário é uma referência de medição com a menor incerteza possível para aquela grandeza. O padrão primário tende a ser referência de medida e fornece a rastreabilidade de toda uma cadeia de calibração de equipamentos e medidas. Por isso, ele tem um impacto potencial tanto em pesquisas científicas quanto em termos econômicos e industriais. Neste artigo realizamos uma análise da metrologia e das aplicações de vácuo explorando o impacto de um padrão primário brasileiro no desenvolvimento econômico e científico nacional nessas aplicações. Os resultados da análise mostraram que a ausência do padrão primário brasileiro implica um potencial prejuízo de milhões de dólares por causa dos custos mais elevados da padronização no exterior e do tempo requerido para a calibração, que pode chegar a mais de 12 meses.

PALAVRAS-CHAVE: Vácuo padrão primário, Metrologia, Qualidade, Impacto Econômico.

INTRODUCTION

The act of measurement has been inherent to human activity since the inception of humanity and remains indispensable across all facets of human endeavors. Its significance is so profound that an entire scientific discipline, known as metrology, is dedicated to the study and application of measurement.

In the realm of quality assurance, as per International Organization for Standardization (ISO) 9001[1,2] and ISO 17025 standards, it is imperative to ensure that measurement instruments adhere to calibration practices, favoring traced standards over non-calibrated ones. Traceability, defined as a system's ability to assure measurement quality by associating it with a value of superior accuracy, precision and closer to the true value, is anchored in primary standards or the culmination of primary measurements.

For the determination of pressure quantities below atmospheric levels, specifically in measuring vacuum, the static expansion method serves as a fundamental primary standard[3]. This method involves transferring a known quantity of gas into a chamber with a precisely defined volume and pressure considerably below the intended measurement. Through meticulous control of conditions, highly accurate and low uncertainty measurements of the final pressure (vacuum) can be established.

Vacuum technology holds a pivotal role in cutting-edge industries such as semiconductors and aerospace, as well as in energy and sustainability sectors, including electrical insulation, photovoltaic panel production, and traditional domains like special alloy steelmaking and food packaging.

Despite its widespread impact, Brazil and South America lack a primary vacuum system, compelling users to seek calibration services abroad. This necessity significantly inflates the entire service chain, escalating production costs in Brazil.

This study delved into the economic and scientific ramifications of the absence of a primary vacuum standard in Brazil. It elucidates the economic advantages observed in other nations that have invested in this field, emphasizing the need for strategic advancements to enhance Brazil's competitiveness and reduce production costs.

Metrology, quality systems

Metrology is the science of measurements and of the variables that may affect measurement results, with the objective of obtaining values as close as possible to the true quantity. In other words, the results of measurement shall be accurate with lower uncertainty. If we use the best way to obtain a highest accuracy and lowest uncertainty, we have a primary standard method.

For determination of pressure at low- and medium-vacuum range (over 0.1 to 10^{-6} Pa), once we have vacuum determinations for primary standard, all measurements derived from this system are traceable.

Traceability

The metrological concept of traceability is defined by the International Vocabulary of Basic and General Terms in Metrology (VIM) as the "property of a measurement result whereby the result can be linked to a specified reference through a documented unbroken chain of calibrations, with each step contributing to the overall measurement uncertainty[4]." Traceability pertains to the outcome of a measurement and extends to both the calibration of a process and its specificity. In numerical terms, traceability relates to the uncertainty associated with the result[4].

In a simpler way, traceability involves associating the calibration of equipment or a product with a measurement that has lower uncertainty and higher accuracy, which forms the upper part of the calibration chain. To illustrate, Fig. 1 provides an exemplar of a traceability coil inspired by the work of Thienpont et al.[5] and ISO 17511[6].

In Fig. 1, each calibration step necessitates a preceding stage with greater accuracy and reduced uncertainty. Often, a particular institution assumes responsibility for each specific step. Traditionally, the National Institutes of Metrology (NIMs) oversee primary calibrations. Figure 1 vividly portrays the indispensable role of risk management within NIM laboratories. This underscores the criticality of ensuring quality and traceability in NIMs, which serve as cornerstones for various industrial quality systems and societal sectors. Confidence in the traceability and quality assurance provided by NIM laboratories are paramount.

In practical terms, traceability and primary standardization are essential to ensure measurement quality with the highest accuracy and lowest possible certainty, and these characteristics are essential for vacuum systems.

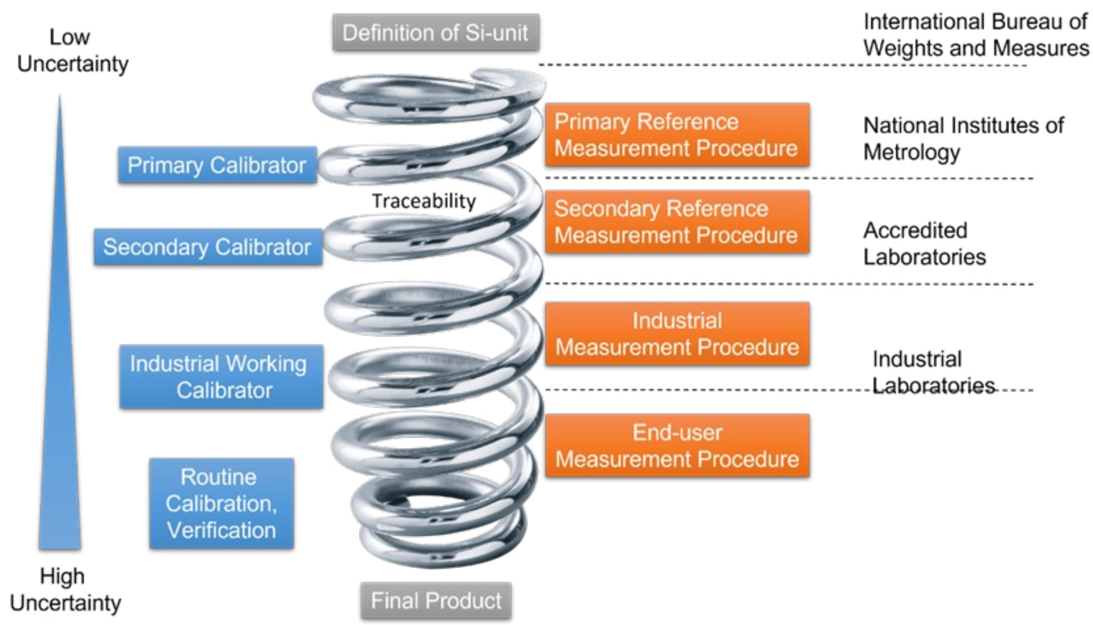

Figure 1: Example of calibration hierarchy[7] as support of traceability chain ("coil").

WHAT IS A PRIMARY STANDARD VACUUM SYSTEM?

A primary standard vacuum system refers to a highly accurate device used to measure vacuum pressure, considered the definitive standard for calibrating other vacuum gauges, and typically developed by national institutes of metrology like National Institute of Metrology, Standardization and Industrial Quality (Inmetro), where the accuracy is based on a fundamental principle of measurement. For the vacuum measurement, methods like static expansion or dynamic expansion are often utilized to precisely control and measure gas flow within a vacuum chamber, allowing for extremely low-pressure measurements with high precision.

The Faculdade de Tecnologia de São Paulo (FATEC) has been developing a primary vacuum system (Fig. 2) with eight chambers with several volumes, from 0.100 to 70 L. The expansion allows the initial pressure to be reduced by more than 99%.

Figure 2: Faculdade de Tecnologia de São Paulo (FATEC) primary vacuum system.

The operation of system is simple, all chambers are submitted to high vacuum after close the valve, and nitrogen (99.9999%) is introduced in one or more of the small chambers until reaches the pressure required (for example, 100 Pa). Thus, the valve to higher volume expansion chamber (70,000 L) is open to transferring the gas for it. Reaching the equilibrium, the measurement or calibration is performed.

The small chambers have just 0.100 L of volume (V1), considering the volume of expansion chamber (70.000 L, V2) and initial pressure (Pi) of 1 mbar. We can calculate the final pressure (Pf) through the Eq. 1:

$$Pix\ V1 = Pf\ x\ Vf \tag{1}$$

The final volume is the sum of volumes of both cameras plus the volume of pipes (Vp) (Eq. 2):

$$Pi\ x\ V1 = Pf\ x\ (V1 + V2 + Vpipes) \tag{2}$$

Thus, there is Eq. 3:

$$Pf = \frac{Pi\ x\ V1}{V1 + V2 + Vpipes} \tag{3}$$

Using the values of initial example and considering de Vpipes 0.001 L, we have Eq. 4:

$$Pf = \frac{100.000\ Pa\ x\ 0.100L}{0.100L+70.000L+0.001L} = 1.400\ Pa \tag{4}$$

This is the great advantage of the use of primary vacuum systems: we can calculate the final value and compare it with the measurement of the sensor. To obtain a reliable result, we need the measurement of volume, initial pressure with excellent accuracy and lowest uncertain.

Once we have a method able to calibrate even the most accurate sensor, we can apply it in several fields of industries and science.

INDUSTRIAL APPLICATION OF VACUUM

Vacuum systems are essential, and often critical, for numerous technologies, including semiconductor manufacturing, nanotechnology, factory automation, satellite industries, and aerospace technologies. They are also crucial in more traditional sectors, such as steel degassing and food packaging. The most widely used vacuum range in the industry is between atmospheric pressure and 10^{-7} Pa[8]. Figure 3 summarizes several processes that require vacuum technology to occur.

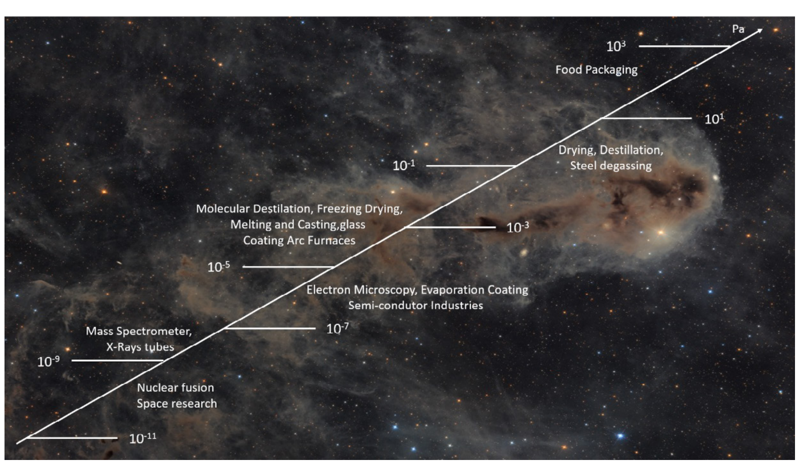

Figure 3: Applications of vacuum by different industries and scientific applications.

Industry automation

Automation and robots would go a long way to alleviate labor shortages, improve work conditions, and lead to increased efficiency, productivity yields, and profitability[9]. If applicated in industrial food industry, they can reduce product contamination and infection spread[10].

One way to grasp and handle objects is through vacuum grippers with a simple vacuum system. Ross et al.[10], modelling the automation of pig-meat industry, used the vacuum grippers for pork bellies transport with lift capacity of 40 kg. Lower vacuum pressure can affect the maximum load capacity resulting in an incorrect downstream or even causing an accident with human risk. Excess of vacuum pressure can cause problems of piece deformation, because pork belly structure includes three layers—skin, fat, and muscle with little or no bone combining. This composition is highly deformable, with a greasy texture making vacuum suction for gripping problematic to achieve.

This is only one example, but similar technical constraints of each industry can be affected by vacuum failure. Therefore, a rigid calibration of vacuum gauge is essential to assure quality in an industrial process.

Steel degassing

Vacuum technology plays a critical role in modern metallurgy, particularly in the secondary refining processes of steel and high-purity metal production[11]. Among these, vacuum degassing is a well-established technique used to remove dissolved gases such as hydrogen, nitrogen, and carbon monoxide from molten steel, thereby enhancing mechanical properties and cleanliness. Reliable vacuum measurement is central to the efficiency, reproducibility, and safety of such operations. Inadequate vacuum control not only reduces product quality but can also result in equipment damage, safety hazards, and economic loss[12,13].

The use of vacuum in the brazing and heat treatment offers several benefits:

- It produces bright parts, often with no subsequent cleaning required;
- It is highly energy efficient, because it eliminates heat loss via conduction or convection;
- It reduces the use of process gas;
- It generates fast, and uniform heating, which reduces distortion in the final component.

Vacuum degassing in steel production

Steel degassing under vacuum is employed to lower the partial pressures of gases dissolved in molten steel. According to Henry's law, the solubility of gases in a liquid decreases as the gas pressure above the liquid is reduced. By applying a vacuum, typically in the range of 0.1 to 5 mbar, hydrogen content can be reduced below 2 ppm, improving ductility and reducing the risk of flaking and embrittlement in high-strength steels. This process is especially important in producing steel for automotive, aerospace, and pipeline applications[12,14].

There are various types of vacuum degassing processes, including: vacuum oxygen decarburization, Rheinstahl-Heraeus (RH) degassing, and vacuum tank degassing. Each of them relies on accurate and stable vacuum environments, which are monitored by vacuum gauges (*e.g.*, Pirani, Penning, capacitance manometers). Deviations in vacuum levels directly influence reaction kinetics and the final composition of the steel[11,13].

Role of vacuum in other metal productions

Beyond steel, vacuum processes are essential in refining titanium, zirconium, tantalum, and other reactive or high-purity metals. For instance, titanium production via the Kroll process involves vacuum distillation to remove magnesium and magnesium chloride[14]. Vacuum arc remelting and electron beam melting are used to produce ultra-pure alloys, in which even trace contamination affects performance[14,15].

Maintaining precise vacuum levels ensures that oxidation and contamination are minimized, and alloying elements are retained within tight tolerances.

Importance of accurate vacuum measurement

In all vacuum metallurgy processes, the quality and accuracy of vacuum measurement determine the process outcomes[16]. Measurement is typically achieved using a combination of:

- Thermal conductivity gauges (e.g., Pirani) for rough vacuum ranges;
- Cold cathode or hot filament ionization gauges for high vacuum regions;
- Capacitance manometers for precise, gas-independent readings.

Vacuum gauges must be resistant to contamination and high temperatures and should provide real-time, stable readings under harsh industrial conditions. Their calibration and maintenance are critical for process repeatability.

There are failures in vacuum measurement or vacuum system integrity with serious impacts:

- Process inefficiency: Incorrect pressure readings may result in incomplete degassing or over-processing, wasting energy and time;
- Contamination: If vacuum levels rise unexpectedly due to leaks or pump failure, atmospheric gases may enter the system, oxidizing molten metal and forming inclusions;
- Product defects: Inconsistent vacuum conditions lead to variability in gas content, which manifests as cracks, porosity, or reduced mechanical strength in the final product;
- Equipment damage: Sudden pressure changes can cause physical stress on vacuum chambers and pumps, leading to costly downtime;
- Safety hazards: In some metal refining setups, vacuum failure during high-temperature operations can cause violent reactions or explosions.

An example of failure impact can be seen in RH-degassing, in which improper vacuum levels delay the decarburization reaction, resulting in steel with excess carbon content—unsuitable for high-specification applications.

Mitigation and monitoring strategies

To avoid such failures, modern vacuum systems shall have:

- Redundant gauge systems for cross-verification;
- Automated leak detection using helium mass spectrometry or pressure decay methods;
- Real-time data logging and alarms for pressure anomalies;
- Regular calibration schedules and contamination checks for sensors.

In advanced plants, vacuum control is integrated with process automation systems, allowing for dynamic adjustments in pump operation, gas flow, and stirring rates based on real-time vacuum readings.

Accurate and reliable vacuum measurement is indispensable for the success of degassing and vacuum metallurgy processes. It ensures consistent product quality, operational safety, and cost efficiency. As steel and high-purity metal demands grow, particularly in critical applications like aerospace and electronics, investment in robust vacuum measurement systems and failure prevention mechanisms becomes increasingly important[12-16].

Future advancements may include self-diagnosing sensors, artificial intelligence-driven vacuum system optimization, and improved resistance to harsh process environments. Regardless of technological evolution, the fundamental role of vacuum measurement as the backbone of metallurgical quality assurance remains unchanged.

Food industries

One major application of vacuum technology in the food industry is beef packaging. Vacuum packaging helps the conservation of food and extend the shelf-life. Form-and-fill packaging systems use one film to construct a pouch with time, pressure, and heat. After forming the pouch, meat products are placed into the pouch, and a second film is overlayed and sealed within the vacuum chamber. Furthermore, vacuum packaging has accounted for 40% of packaging types[17].

While the meat surface color is still regarded as one of the greatest determining factors consumers utilize when purchasing fresh beef in the retail setting, packaging technologies are pivotal in maintaining the surface color of fresh meat.

Benini and Santos[18] verified the reliability-centered maintenance (RMC) used in food vacuum packaging. Their conclusion is the food vacuum packaging without RMC reaches only 57% of the availability rate. After RMC, the availability rate grew to 80%. Benini and Santos[18] just considered the critical mechanical, electrical, and pneumatic failure. If considering that low pressure can be wrong due the absence of calibration and traceability, the failure rate can be higher.

Another application of vacuum technology in food industry is the lyophilization process. Water content significantly impacts the quality of drug products and foods, making effective drying methods essential. Lyophilization (freeze-drying) is widely used in pharmaceuticals and food engineering to extend shelf life and maintain quality[17-19]. However, it is a time- and energy-intensive process that requires optimization to avoid costly failures.

In food industry, lyophilization helps preserve perishable items like fruits, vegetables, and meats, reducing spoilage and storage costs. Additionally, encapsulation techniques using lyophilization enhance stability and shelf life for bioactive compounds but present challenges in scaling up from lab to production[17]. Failures in vacuum, even a slight increase of internal pressure due an error in the calibration of the sensors, can severely increase the cost with loss of products.

Failure in vacuum in lyophilization is so critical that there are some protocols to avoid this. One of this protocol is controlling the leak rates. Leak rates in a system are determined by the rate of pressure increase, which can result from real or virtual leaks[17]. Real leaks occur when external gases intrude due to permeability or defective seals, maintaining a constant rate of rise (ROR) over time. Virtual leaks, caused by outgassing or temperature changes, show a decaying ROR. While virtual leaks originate from chamber contaminants or material desorption, real leaks pose a sterility risk by allowing microorganisms to enter. Since a vacuum freeze dryer can never be entirely leak-free, acceptable leak rate limits must be established to ensure product safety[17-19].

VACUUM ON SCIENCE

The critical role of vacuum technology in aerospace and materials science: implications of system failures

Vacuum technology plays a central role in both aerospace engineering and materials science due to its critical influence on high-precision processes, contamination control, and experimental accuracy. From spacecraft design and testing to advanced materials synthesis and surface analysis, the ability to generate and maintain controlled vacuum environments is essential. However, failures in vacuum systems or inaccuracies in pressure measurement can lead to catastrophic results, particularly in the context of high-stakes applications such as satellite propulsion, semiconductor manufacturing, and thermal testing in simulated space environments.

Importance of vacuum in aerospace applications

In aerospace, vacuum conditions are routinely employed in environmental test chambers to simulate outer space conditions. Satellites, instruments, and components are subjected to ultra-high vacuum conditions (pressures < 10^{-7} mbar) to validate their thermal, mechanical, and electronic behavior prior to launch. These tests ensure the material integrity and operational reliability of spacecraft systems when deployed in orbit or in interplanetary missions. Any leakage or failure in vacuum sealing during these simulations can lead to false qualification of a component, increasing the risk of mission failure once in space[20–24].

Furthermore, electric propulsion systems such as ion thrusters and Hall-effect thrusters rely on vacuum chambers for ground-based testing. These propulsion technologies[20-22] operate efficiently only in vacuum, in which ionized gas particles can be accelerated without atmospheric resistance. Inaccurate pressure readings during these tests can distort thrust data, mask system instabilities, or damage sensitive components due to unexpected plasma interactions[25-26].

Vacuum in materials science and fabrication

Vacuum environments are equally indispensable in materials science, especially in thin film deposition techniques such as physical vapor deposition, chemical vapor deposition, and atomic layer deposition. These processes demand high- or ultra-high vacuum to control film purity, uniformity, and adhesion[27,28]. Small variations in chamber pressure—often arising from leaks, pump failures, or incorrect sensor readings—can result in altered chemical kinetics, non-uniform coatings, or incorporation of impurities, directly compromising the performance of microelectronic devices, optical components, or functional coatings[27,28].

Vacuum-based surface analysis techniques, such as scanning electron microscopy, transmission electron microscopy, and X-ray photoelectron spectroscopy[29–30], also depend on stable low-pressure environments. Pressure fluctuations or undetected vacuum breaches can result in contamination of samples, degraded signal-to-noise ratios, and ultimately unreliable data. For high-resolution characterization at the nanoscale, even minor disturbances in pressure calibration can be detrimental to image clarity and elemental detection[29,30].

Consequences of failure in vacuum or pressure monitoring

The consequences of vacuum failure or inaccurate pressure monitoring range from financial loss to mission-critical failure. For example, in 1999, National Aeronautics and Space Administration (NASA)'s Mars Climate Orbiter[24] was lost due to miscommunication of pressure unit standards between teams, emphasizing the critical need for precision and standardization in measurement. Though not a direct vacuum failure, the event highlights how minute miscalculations in physical parameters can propagate into catastrophic outcomes.

In industrial vacuum processes, undetected leaks or sensor drift can cause batch failures in semiconductor fabrication, leading to millions of dollars in wasted materials and lost productivity. For ultra-sensitive aerospace applications, pressure misreading during thermal vacuum testing could incorrectly certify a non-flightworthy component, putting entire missions at risk. Moreover, in cryogenic systems operating under vacuum (*e.g.*, superconducting magnets or cryopumps)[31,32], pressure rise due to vacuum loss can result in quenching, equipment damage, or safety hazards.

Ensuring reliability: monitoring and redundancy

To mitigate these risks, robust vacuum system design must incorporate redundant sensors, automated leak detection protocols, and frequent calibration of pressure gauges. The use of ionization gauges, Pirani sensors, and capacitance manometers—each with distinct pressure ranges—allows comprehensive and cross-verifiable monitoring across vacuum regimes. Real-time diagnostics and predictive maintenance are increasingly implemented through machine learning algorithms that track vacuum system behavior and flag anomalies before they lead to failure.

IMPACTS ON SCIENCE

The importance of vacuum technology is frequently underestimated in several fields of science. One of the most important instruments in nanotechnology area are the transmission electronic microscopes. Some of this equipment have resolution to experiments with a single or just some atoms groups. But this equipment is severely dependent of ultra-high vacuum to obtain the required performance. Degasperi and Ricotta[33] performed the modeling of field pressure and vacuum behavior into transmission microscope. Therefore, only by increasing the pumping capacity directly in the sample chamber, the amount of gas entering the chamber can be effectively reduced. In addition, the time required for the vacuum system to re-establish a steady pressure field determines how long it takes for the electron microscope to return to normal operation. Furthermore, the degassing rate of the material surfaces depends not only on the type of the material used, but also on the cleanliness and conditioning of the surfaces before exposure to vacuum. Also, we can consider the degassing rate of the material surfaces, in addition to the dependence on the material used, fundamentally on the state of cleanliness and conditioning to which the material surface exposed to the vacuum was subjected.

These results implicate the vacuum was performed in wrong position, or the sample was not clean enough[33]. So, the best results in transmission microscope could not be reached. Vacuum technology is foundational to modern aerospace and materials science applications. Failures in vacuum systems or pressure measurement can have disproportionate and often irreversible consequences. Thus, maintaining vacuum integrity and accurate pressure control is not only a technical necessity but a cornerstone of operational safety, research integrity, and mission success in high-precision scientific and engineering areas.

ECONOMIC IMPACTS FOR THE INDUSTRY 4.0

With the advent of internet of things technologies, the advancement of process digitalization gave rise to industry 4.0, which increasingly requires the development of ever more sophisticated electronic systems. Estimates suggest that by 2025 processes related to industry 4.0 will reduce equipment maintenance costs by 10–40%, energy consumption by up to 20%, and increase work efficiency by 10–25%[34,35].

In 2015, companies associated with the Brazilian Association of the Semiconductor Industry (ABISEMI) had an installed industrial park with 75,000 m^2 of built area containing productive technology, including more than 27,000 m^2 of clean rooms[36].

Semiconductors are the central and essential components for the technology industry involved in the 4.0 revolution, and Brazil is already part of this industry. According to ABISEMI: "Semiconductors are the brain of the electronics industry and the heart of the technological innovations that drive the world. It is at this point that vacuum technologies become essential." Semiconductor manufacturing is critically contamination-sensitive, requiring stringent control.

The manufacture of semiconductors demands a high level of humidity control, sophisticated vacuum equipment such as cryogenic pumps with very precise control systems. The presence of gases and moisture can cause corrosion at circuit points; the photosensitive polymers used to mask circuit lines for the etching process can absorb moisture or form bubbles. These controls must be precise and accurate, requiring high-quality and fast-response vacuum sensors.

The total global economic impact of internet of things technology alone is estimated at between $ 3.9 to $ 11.1 trillion EUR per year by 2025[37]. This is coupled with the trend of geographic decentralization of semiconductor production, initiated after the semiconductor crisis caused by the coronavirus pandemic. Therefore, the semiconductor industry is expected to see significant growth in the coming years.

What products and services can be developed based on the Brazilian primary standard?

A non-exhaustive list includes traceability to the primary standard for accredited laboratories at a lower cost for both the calibration process and freight or visit costs, and calibration of vacuum sensors such as:

- Assisting the industry in developing vacuum, interferometric sensors, and chambers;
- Conducting leakage and micro-leakage tests on equipment;
- Assisting in the development or improvement of vacuum and high vacuum systems by the industry;
- Efficiency tests of vacuum promotion equipment, high vacuum (vacuum pumps);
- Assisting in the development of vacuum sensors by the industry;
- Assisting in equipment functionality tests in a vacuum environment;
- Failure identification services and consulting in industrial vacuum systems;
- Implementing a vacuum quality monitoring service in Inmetro's installations and equipment, with potential expansion to other public institutions.

Economic prospects for Inmetro with the development of a national primary vacuum standard

The economic costs for calibrating vacuum sensors are high for laboratories or industries that need calibrations traceable to the primary standard. The basic calibration cost of an ion vacuum sensor at the Physikalisch Technisch Bundesstaat (PTB), Inmetro's German counterpart, reaches about 1,800 EUR or more than 11,100 BRL. If we consider that any Brazilian client performing this calibration needs to cover transportation and insurance costs, the total costs can exceed 15,000 BRL per item calibrated in basic configurations.

In other words, the existence of a primary standard at Inmetro would reduce calibration costs for all national entities and most likely for all Latin America. Considering that India, an emerging country like Brazil, conducts an average of 125 sensor calibrations involving pressure and vacuum services, and assuming these numbers would be similar to Brazilian ones, with at least 50% being vacuum range calibrations, we would have a potential revenue of nearly 470,000 BRL. This assumes that the analysis, freight, and insurance costs for performing vacuum sensor calibration at Inmetro represent only 50% of the costs involved in calibration at PTB.

The potential revenue for Inmetro is secondary, considering the main gain is reducing calibration costs for the national industry. A direct 50% reduction in calibration costs reduces the entire calibration chain cost and the derived products' costs. This cost reduction can represent an indirect resource saving of two or three times greater than the direct savings.

The primary vacuum system would also allow the implementation of a vacuum quality monitoring plan for Inmetro's equipment. Considering that more than 50 equipment in Inmetro's scientific metrology use vacuum, controlling this equipment would represent maintenance savings, measurement failures, leakage control, and measurement errors caused by vacuum failures.

Following Inmetro's policy of functioning as a toolkit for the national productive sector, the primary standard would open space for a series of important tests for developing products such as more accurate vacuum and pressure sensors or advanced vacuum systems like cryopumps used in the production of superconductors. By using Inmetro's facilities for technological development, industries reduce the financial and technological risks that often cause innovative projects to die in development.

Finally, even in the case of protecting the national market, national vacuum systems would allow, for example, vacuum pump efficiency tests, showing industrial users which equipment is more efficient, faster, or economical for their applications.

This quick summary of potential economic impacts highlights not only Inmetro's revenue potential but mainly the gains for Brazil's technology industry derived from implementing primary vacuum measurement in Inmetro's facilities.

CONCLUSION

The implementation of the primary standardization system is essential both for Brazil's independence in terms of pressure traceability, which guarantees sustainability in terms of internal trade and exports, and to support new areas of knowledge that are emerging in relation to research and innovation. The potential industrial financial and economic gains justify the potential cost and may pay for itself in as little as three years.

CONFLICT OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Arakawa R, Oliveira JS, Degaspari FT, Batista LN; **Methodology:** Arakawa R, Oliveira JS, Degaspari FT; **Resources:** Arakawa R, Oliveira JS; **Project administration:** Degaspari FT, Batista LN; **Formal analysis:** Arakawa R, Oliveira JS, Degaspari FT, Batista LN; **Original – draft writing:** Arakawa R, Oliveira JS, Degaspari FT, Batista LN; **Writing – review and editing:** Degaspari FT, Batista LN; **Final approval:** Batista LN.

DECLARATION OF USE OF INTELLIGENCE ARTIFICIAL TOOLS

Artificial intelligence tools were used to assist in language editing and text refinement. All scientific content, analyses, interpretations, and final decisions were developed and validated by the authors.

AVAILABILITY OF DATA AND MATERIALS

All data sets were generated or analyzed in the current study.

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