

Critical Parameters in the Design of Breathing Apparatus

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Abstract

Breathing apparatuses are essential in hazardous environments, ensuring respiratory protection for workers in industries, such as firefighting, chemical handling, and emergency response. This study examines the critical parameters influencing the design, performance, and safety of breathing apparatus systems. Key parameters include oxygen delivery efficiency, filtration capacity, ergonomic design, and durability under extreme conditions. Oxygen supply mechanisms, including open-circuit and closed-circuit systems, are evaluated for their suitability in various operational contexts. Filtration technologies, particularly in self-contained breathing apparatuses (SCBAs), are analyzed for their effectiveness in removing toxic particulates and gases. Ergonomics and weight distribution are also highlighted, emphasizing their impact on user fatigue and mobility. Furthermore, the durability of materials under high temperatures, mechanical stress, and prolonged use is considered. Innovations in sensor integration and real-time monitoring are explored, enhancing safety through early detection of equipment failure or environmental hazards. Finally, this review underscores the need for compliance with international safety standards and rigorous training to optimize the efficacy of breathing apparatuses in life-critical scenarios.

Keywords: Critical parameters, breathing apparatus, hazardous environments, respiratory protection, firefighting, safety

INTRODUCTION

Breathing apparatus plays a crucial role in ensuring respiratory protection in environments where the air is contaminated, oxygen-deficient, or otherwise hazardous to human health (Figure 1). These devices are used in a variety of critical applications, including firefighting, industrial operations, military engagements, medical emergencies, space exploration, and underwater diving. The design of breathing apparatus requires careful consideration of multiple factors to ensure optimal performance, safety, durability, and user comfort. At its core, a breathing apparatus must provide a reliable and continuous supply of breathable air, whether through compressed oxygen, purified ambient air, or a rebreather system. The efficiency of oxygen delivery and carbon dioxide (CO₂) removal is a fundamental design

parameter that directly impacts the usability and effectiveness of the device. The apparatus must also incorporate effective filtration mechanisms to protect users from harmful airborne contaminants, such as toxic gases, smoke, and pathogens.

Another critical aspect of breathing apparatus design is ergonomics and user comfort. Since these devices are often used in high-stress situations, they must be lightweight, well-balanced, and easy to wear for extended periods. The facepiece or mask must provide a secure and airtight seal without causing discomfort, while the airflow resistance should be minimized to reduce breathing effort and fatigue. Advanced materials, such as high-strength polymers and lightweight composites, are

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increasingly used to enhance durability while keeping the weight manageable. Safety is a paramount concern in breathing apparatus design. Devices must be built to withstand extreme conditions, including high temperatures, impact, and exposure to hazardous chemicals. Features, such as fail-safe mechanisms, pressure regulators, warning alarms, and redundant oxygen supply systems help prevent malfunctions and ensure user protection. Compliance with international safety standards, such as those established by OSHA, NIOSH, and the European EN regulations, is essential for the reliability and certification of these devices. With advancements in technology, modern breathing apparatus is integrating smart sensors, artificial intelligence (AI), and Internet of Things (IoT) capabilities to enhance real-time monitoring and predictive maintenance. These innovations improve user safety by providing alerts for oxygen depletion, equipment malfunctions, and environmental hazards.



Figure 1. Breathing apparatus.

TYPES OF BREATHING APPARATUS

Depending on the application, there are several types of breathing apparatuses (Figure 2), e.g., (i) Self-contained breathing apparatus (SCBA), (ii) Supplied air breathing apparatus (SABA), (iii) Rebreathers and (iv) Emergency escape breathing devices (EEBD).

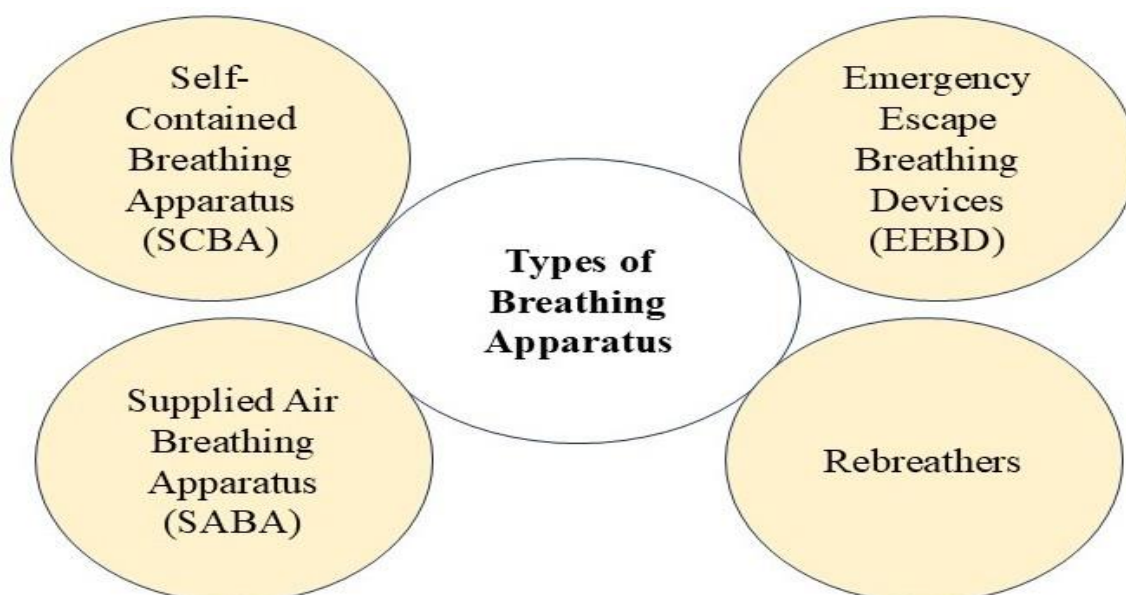


Figure 2. Types of breathing apparatus.

Self-Contained Breathing Apparatus (SCBA)

SCBAs are often used in firefighting and rescue operations, where individuals need to work in environments with zero or highly contaminated oxygen levels [1–3]. These systems consist of an air cylinder, a regulator, and a face mask, allowing the user to carry their own air supply.

Supplied Air Breathing Apparatus (SABA)

On the other hand, SABAs provide air through a hose connected to a stationary source, making them suitable for confined spaces or industrial settings. SCBA is commonly used in firefighting and hazardous environments. It consists of a high-pressure air cylinder, a regulator, and a full-face mask. SCBA provides an independent air supply, ensuring safety in oxygen-deficient or toxic atmospheres. SABAs deliver breathable air from an external source through a hose. These are used in industrial applications where mobility is less of a concern, but a continuous air supply is required.

Rebreathers

Rebreathers recycle exhaled air by removing CO₂ and replenishing oxygen. They are widely used in deep-sea diving and space applications, allowing for extended use with minimal gas consumption.

Emergency Escape Breathing Devices (EEBD)

EEBDs are compact, portable devices designed for emergency evacuations. They provide a short-duration air supply for users escaping hazardous environments like smoke-filled rooms or toxic gas leaks (Figure 3).



Figure 3. Emergency escape breathing devices (EEBD).

Modern breathing apparatuses are designed with a focus on user safety, comfort, and efficiency. They incorporate advanced materials to enhance durability and reduce weight, ergonomic designs to facilitate mobility, and sophisticated mechanisms to regulate air pressure and flow. Some models include integrated communication systems, heads-up displays, and alarm features to warn users of low air levels or hazardous conditions. Additionally, many devices comply with rigorous industry standards, ensuring reliability and performance under extreme conditions. The application of breathing apparatuses extends beyond occupational settings. For instance, they are vital in the medical and healthcare sectors, where ventilators and other respiratory support devices are used to assist patients with breathing difficulties [4]. Similarly, underwater breathing apparatuses, such as scuba gear, enable recreational and professional divers to explore aquatic environments [5]. Training and proper use of breathing

apparatuses are essential to maximize their effectiveness. Improper usage or inadequate maintenance can lead to failures, putting users at significant risk. Regular inspection, cleaning, and adherence to manufacturer guidelines are critical to ensuring the equipment remains in optimal condition. Furthermore, users must undergo comprehensive training to familiarize themselves with operational procedures, emergency protocols, and limitations of the devices.

Thus, the breathing apparatuses are crucial tools that protect individuals in environments where normal respiration is compromised. By providing clean and safe air, they enable workers, rescuers, and adventurers to perform their duties effectively and safely. With ongoing advancements in technology, these devices continue to evolve, offering enhanced features and greater reliability. Their role in safeguarding lives cannot be overstated, making them a cornerstone of occupational safety and emergency response. For any setting involving hazardous air conditions, a well-designed and properly used breathing apparatus is not just a piece of equipment but a lifesaving necessity.

KEY DESIGN CONSIDERATIONS

The design of a breathing apparatus must prioritize several key parameters to ensure safety, comfort, and efficiency in hazardous environments, e.g.,

- (i) Respiratory protection and oxygen supply.
- (ii) Ergonomics and user comfort.
- (iii) Durability and material selection.
- (iv) Weight and portability.
- (v) Breathing resistance and airflow.
- (vi) Filtration efficiency and air purification.
- (vii) Facepiece fit and seal integrity.

One of the most critical aspects is respiratory protection and oxygen supply, which ensures a consistent and adequate flow of breathable air, whether through compressed oxygen, supplied air, or rebreather technology (Figure 4). Filtration efficiency is equally important, as the system must effectively remove harmful contaminants, such as toxic gases, smoke, and particulates. Ergonomics and user comfort are major considerations, especially for professionals, like firefighters and industrial workers, who wear these devices for extended periods. The apparatus should be lightweight, well-balanced, and designed with adjustable straps and a secure facepiece seal to minimize discomfort and fatigue [6]. Breathing resistance and airflow dynamics must also be optimized to reduce strain on the user while ensuring efficient oxygen delivery.

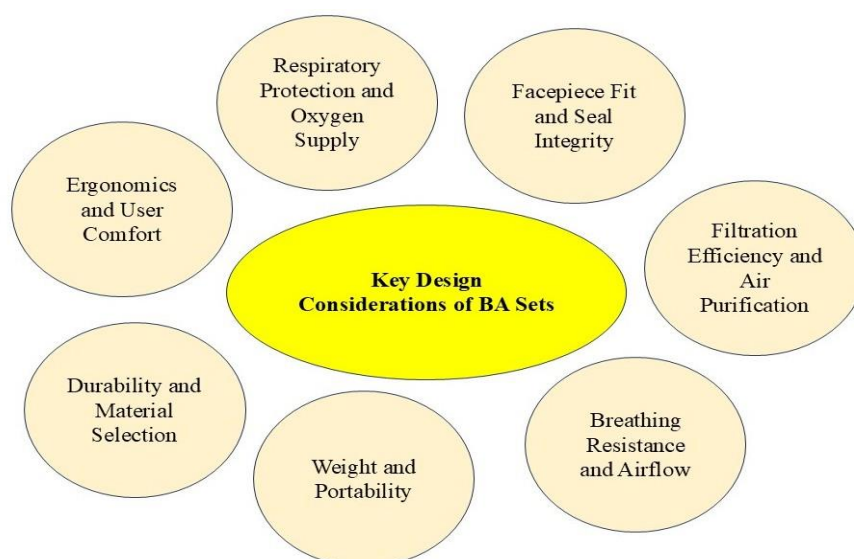


Figure 4. Key design considerations.

PERFORMANCE PARAMETERS

The performance of a breathing apparatus is determined by several key parameters that ensure reliable oxygen delivery, user safety, and operational efficiency, e.g., (i) Oxygen delivery rate and consumption, (ii) Airflow dynamics and resistance, (iii) CO₂ scrubbing efficiency, (iv) Pressure regulation systems, (v) Battery life for powered units. It is depicted in Figure 5.

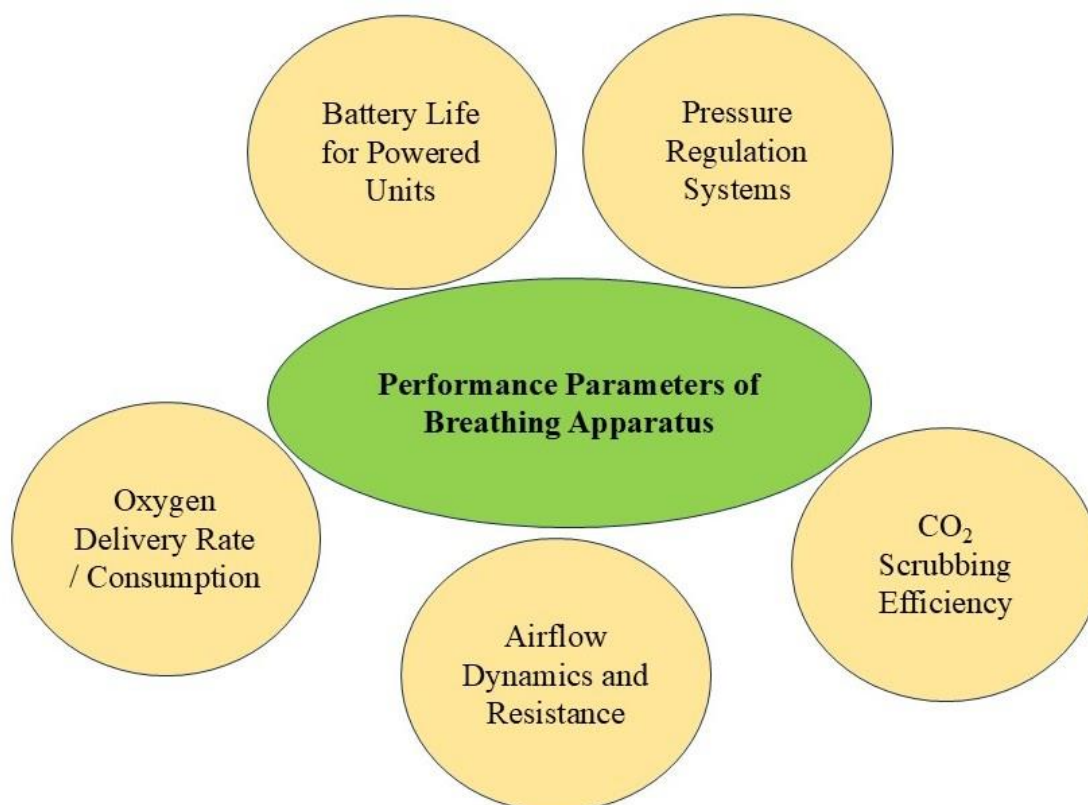


Figure 5. Performance parameters of breathing apparatus.

One of the most critical factors is the oxygen delivery rate, which must be sufficient to meet the metabolic demands of the user under different activity levels. Whether the device operates on compressed air, chemical oxygen generation, or rebreathing systems, it must provide a continuous and adequate supply of breathable air.

Airflow resistance is another important parameter, as excessive resistance can cause breathing difficulty and user fatigue. An optimized airflow system ensures smooth inhalation and exhalation while maintaining pressure regulation to prevent fluctuations. CO₂ scrubbing efficiency is essential in closed-circuit rebreathers, where exhaled carbon dioxide must be effectively removed to prevent hypercapnia [7].

Other performance considerations include pressure regulation, which controls air supply consistency, and filtration efficiency, ensuring the removal of contaminants and toxic gases. For powered breathing systems, battery life is a crucial factor affecting operational duration.

SAFETY FEATURES AND STANDARDS

Safety is a primary consideration in the design of breathing apparatus, as these devices are used in hazardous environments where equipment failure can be fatal. Various safety features are integrated to ensure reliability, durability, and user protection (Figure 6). The main safety features are, (i) Fire and heat resistance, (ii) Explosion-proof design, (iii) Fail-safe mechanisms, (v) Visual and audible alarms, (vi) International safety regulations and certifications, etc.



Figure 6. Safety features and standards of breathing apparatus.

One key safety feature is fail-safe mechanisms, such as automatic pressure regulators and redundant oxygen supply systems, which prevent air supply interruptions. Alarm systems, including audible and visual alerts, warn users of low oxygen levels, high CO₂ buildup, or equipment malfunctions. Fire and heat resistance is crucial for firefighting and industrial applications, requiring the use of flame-resistant materials and heat-shielded components. Explosion-proof designs are necessary for use in volatile environments, preventing the ignition of flammable gases.

Compliance with international safety standards ensures the effectiveness and reliability of breathing apparatus. Organizations, such as OSHA (Occupational Safety and Health Administration), NIOSH (National Institute for Occupational Safety and Health), and EN (European Standards) regulate design, performance, and testing requirements. These standards dictate parameters like filtration efficiency, oxygen delivery rates, facepiece seal integrity, and material durability.

With advancements in technology, smart monitoring systems and AI-driven diagnostics further enhance safety by providing real-time data on equipment performance and environmental hazards.

TECHNOLOGICAL ADVANCEMENTS IN BREATHING APPARATUS

Breathing apparatus technology has evolved significantly, improving safety, comfort, and efficiency in various applications, including firefighting, deep-sea diving, medical care, and industrial work. Modern advancements focus on lightweight materials, enhanced filtration systems, and smart monitoring capabilities.

One major improvement is the development of closed-circuit rebreathers (CCRs), which recycle exhaled air by removing carbon dioxide and replenishing oxygen, extending usage time for divers and rescue workers (Figure 7). In firefighting, self-contained breathing apparatus (SCBA) now feature compressed air cylinders made of carbon fiber, reducing weight while maintaining a high-pressure air supply.



(a) (b)
Figure 7. Development of (a) Closed-circuit rebreathers (CCRs) and (b) Portable oxygen concentrators.

Medical innovations include portable oxygen concentrators (POCs), which extract oxygen from ambient air, offering a more sustainable alternative to oxygen tanks. Wearable smart masks integrated with real-time air quality sensors and biometric tracking are also gaining traction, providing alerts about hazardous gases or inadequate oxygen levels.

For industrial and hazardous environments, powered air-purifying respirators (PAPRs) with advanced HEPA and AI-assisted filtration ensure better protection against toxic particles. Future advancements may include AI-driven adaptive airflow systems and nanotechnology-based filters, further improving respiratory safety across multiple domains. As technology progresses, breathing apparatus will become more efficient, user-friendly, and adaptable to extreme conditions.

CRITICAL PARAMETERS OF BA SET

When evaluating or using a breathing apparatus, whether for firefighting, diving, industrial safety, or medical purposes, several critical parameters must be considered to ensure safety, functionality, and performance (Figure 8).

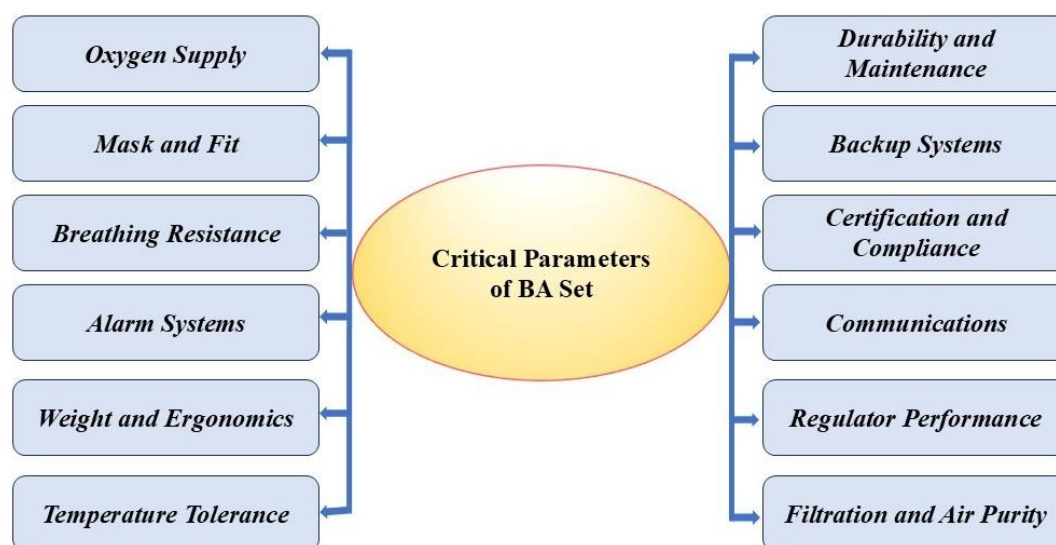


Figure 8. Critical parameters of BA set.

These parameters include:

Oxygen Supply

- *Type of Air Supply*: Compressed air, oxygen-enriched air, or 100% oxygen.
- *Cylinder Pressure*: Typically measured in bar or psi; high-pressure cylinders (e.g., 200-300 bar or 2,900-4,350 psi) provide more breathable air.
- *Duration of Supply*: Determined by the size and pressure of the cylinder and the user's breathing rate.

Mask and Fit

- *Seal Integrity*: Ensures no air leakage and proper face fit.
- *Comfort*: Proper ergonomic fit for extended use.
- *Visibility*: Clear, anti-fog visor for unobstructed vision.
- *Fit Testing*: Regularly conducted to ensure the mask fits securely on the user's face.

Breathing Resistance

- *Inhalation and Exhalation Resistance*: Low resistance is critical for user comfort and reduced fatigue.
- *Valve Performance*: Valves should operate smoothly under various conditions.

Alarm Systems

- *Low Air Supply Alarm*: Alerts the user when the air supply is below a critical level.
- *Pressure Indicator*: Displays the current air pressure in the cylinder.

Weight and Ergonomics

- Lightweight apparatus reduces fatigue.
- Balanced design for mobility and ease of use.

Temperature Tolerance

- *Extreme Conditions*: The apparatus must perform reliably in high-heat environments (e.g., firefighting) or cold underwater conditions (e.g., diving).
- *Material Durability*: Components resistant to temperature-induced degradation.

Filtration and Air Purity

- For supplied air respirators, air purity must meet strict standards to avoid contamination.
- Filters (where applicable) must be appropriate for the environment (e.g., particulate or chemical filtration).

Regulator Performance

- *Constant Flow*: The regulator must deliver a consistent air supply.
- *Pressure Regulation*: Handles high-pressure air from the cylinder and reduces it for breathable delivery.

Communications

- Integrated communication systems may be required for team environments.
- Clear and interference-free audio transmission.

Certification and Compliance

- Meets regulatory standards (e.g., NIOSH, CE, ISO, or local governing bodies).
- Periodic maintenance and testing for compliance.

Backup Systems

- Emergency Supply Systems: Backup air cylinders or escape mechanisms.
- Redundancy in design to ensure fail-safes.

Durability and Maintenance

- Resistance to physical damage, chemical exposure, and environmental factors.
- Ease of disassembly for cleaning and maintenance.

These parameters ensure the breathing apparatus performs effectively in demanding and potentially life-threatening environments [8–11].

Applications of Breathing Apparatus

Breathing apparatus plays a crucial role in ensuring human survival and safety in environments where breathable air is scarce or contaminated. These devices are used across multiple fields, including firefighting, deep-sea diving, medical care, industrial safety, and military operations. Modern advancements have led to more efficient, lightweight, and technologically enhanced breathing systems, making them indispensable in various high-risk professions (Figure 9).

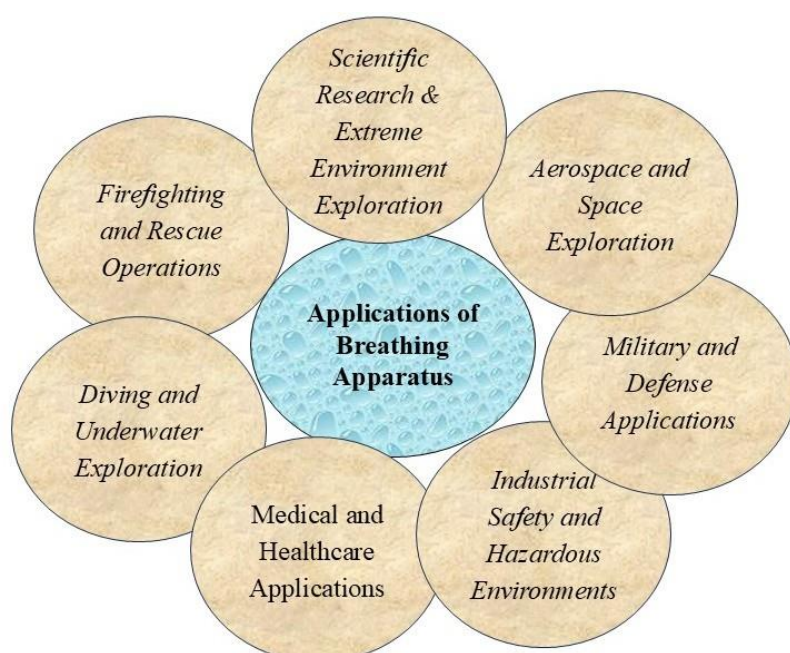


Figure 9. Applications of breathing apparatus.

Firefighting and Rescue Operations

Firefighters often work in smoke-filled environments where inhaling toxic gases, like carbon monoxide and hydrogen cyanide, can be fatal. Self-contained breathing apparatus (SCBA) is essential for firefighters, providing a steady supply of clean air through high-pressure oxygen tanks. Modern SCBAs include pressure monitoring systems, lightweight carbon-fiber tanks, and integrated communication devices, allowing firefighters to operate safely for extended periods. Rescue workers in collapsed buildings or chemical spill sites also rely on breathing apparatus to enter hazardous zones without risk of inhaling dust, toxic fumes, or airborne pathogens [12].

Diving and Underwater Exploration

Scuba diving is one of the most well-known applications of breathing apparatus. Traditional open-circuit scuba systems release exhaled air into the water, whereas modern closed-circuit rebreathers (CCRs) recycle exhaled gases, removing carbon dioxide and replenishing oxygen. This technology allows divers to remain underwater for extended periods while minimizing air wastage and reducing noise, making it ideal for military divers, underwater researchers, and marine biologists. Deep-sea divers working in extreme conditions, such as offshore oil rig maintenance or underwater archaeology, also use mixed-gas diving systems, which regulate oxygen and helium levels to prevent decompression sickness [13].

MEDICAL AND HEALTHCARE APPLICATIONS

Breathing apparatus is essential in hospitals and emergency medical services. Patients suffering from respiratory diseases, such as chronic obstructive pulmonary disease (COPD), asthma, or COVID-19 often require oxygen therapy through ventilators or portable oxygen concentrators (POCs) [14, 15]. In intensive care units (ICUs), mechanical ventilators assist critically ill patients by regulating airflow and oxygen concentration.

Emergency responders use bag-valve masks (BVMs) to provide artificial respiration to individuals experiencing respiratory failure. In neonatal care, specialized oxygen hoods and incubators supply a controlled oxygen environment to premature babies. Portable oxygen systems also allow patients with chronic lung conditions to maintain mobility and an active lifestyle.

INDUSTRIAL SAFETY AND HAZARDOUS ENVIRONMENTS

Workers in hazardous industries, such as chemical plants, mining, and construction, rely on breathing apparatus to protect themselves from toxic gases, dust, and airborne contaminants. Powered air-purifying respirators (PAPRs) use battery-powered fans to filter air, making them suitable for prolonged use in contaminated environments (Figure 10).



Figure 10. (a) Powered air-purifying respirators (PAPRs) and (b) Self-rescue breathing apparatus.

In mining, exposure to harmful gases, like methane and carbon monoxide, can be deadly. Miners use self-rescue breathing devices (SCSRs), which provide an emergency oxygen supply in case of a cave-in or gas leak. Similarly, construction workers dealing with asbestos, silica dust, or paint fumes wear air-purifying respirators equipped with advanced filters to prevent long-term respiratory damage.

MILITARY AND DEFENCE APPLICATIONS

The military uses breathing apparatus in a variety of operations, including chemical, biological, radiological, and nuclear (CBRN) defence. Gas masks and CBRN respirators protect soldiers from inhaling harmful agents during warfare or counter-terrorism missions.

Special forces and navy divers employ rebreathers, which do not release air bubbles, making them ideal for stealth operations. Pilots operating at high altitudes use oxygen masks to prevent hypoxia when flying above breathable atmosphere levels. In submarines, emergency breathing devices are critical for survival in case of a malfunction or fire.

Aerospace and Space Exploration

Astronauts rely on highly advanced breathing apparatus to survive in space, where there is no breathable atmosphere. Spacesuits contain life support systems that regulate oxygen levels, remove carbon dioxide, and control temperature and humidity.

Aircraft pilots, especially those in fighter jets, wear oxygen masks with pressurized breathing systems to compensate for low oxygen levels at high altitudes. Cabin pressurization systems in commercial flights also function as a large-scale breathing apparatus, ensuring safe oxygen levels for passengers and crew.

Scientific Research and Extreme Environment Exploration

Scientists working in extreme environments, such as volcanoes, deep caves, or polar regions use breathing apparatus to endure harsh conditions. Volcanologists wear air-filtering respirators to protect against toxic sulfur gases, while researchers in Antarctica rely on oxygen systems when operating at high altitudes where the air is thin.

Deep cave explorers use specialized breathing equipment to navigate oxygen-deficient underground environments. Similarly, industrial workers dealing with biohazardous materials, such as virologists studying airborne pathogens, utilize advanced filtration masks to prevent contamination.

Maintenance of Breathing Apparatus

A Breathing Apparatus (BA) is a critical piece of equipment used in hazardous environments to ensure the user has a safe supply of breathable air. Proper maintenance is essential to ensure functionality, reliability, and safety. Maintenance involves systematic inspections, cleaning, testing, and storage, ensuring that the equipment performs optimally during emergencies (Figure 11).

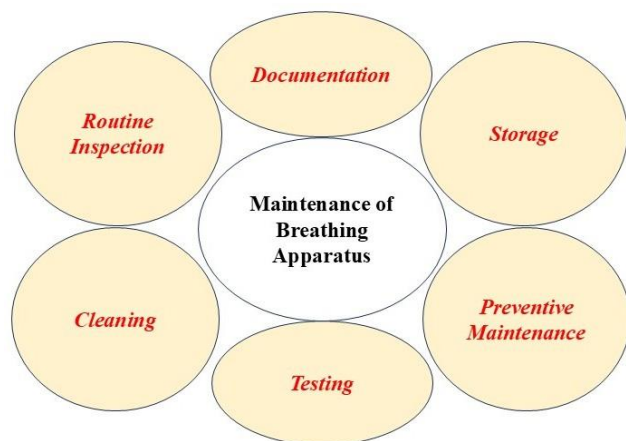


Figure 11. Maintenance of breathing apparatus.

Routine Inspection

Routine inspections should be conducted before and after each use. Pre-use checks include verifying that all components, such as the face mask, straps, hoses, and regulators, are intact and free from visible damage. Additionally, the air cylinder should be inspected for sufficient air pressure and any signs of corrosion or leakage. After use, the equipment should be thoroughly checked for wear or damage caused during operation.

Cleaning

Proper cleaning of the breathing apparatus is vital to prevent contamination, improve hygiene, and maintain the longevity of the equipment. Components, such as the facepiece should be cleaned with warm soapy water or a manufacturer-approved disinfectant solution. The hoses and other accessories

should also be inspected and cleaned to prevent blockages. Ensure all cleaned parts are completely dry before reassembling to avoid moisture damage.

Testing

Functional testing ensures the equipment is operating correctly. Key tests include pressure checks, flowrate testing of the regulator, and leak tests to detect any air loss. Testing the alarm system, which alerts users to low air supply, is also crucial. These tests should follow manufacturer guidelines and be conducted using calibrated tools to ensure accuracy.

PREVENTIVE MAINTENANCE

Preventive maintenance is performed periodically to ensure long-term reliability. This includes servicing the BA as per the manufacturer's schedule, such as replacing worn-out seals, valves, and filters, and checking the integrity of the harness and straps. The cylinder should be periodically hydrostatically tested to ensure it can withstand pressure without failure. Regular lubrication of moving parts helps prevent wear and tear.

Storage

Proper storage is essential to protect the equipment from damage. The BA should be stored in a clean, dry, and ventilated area, away from direct sunlight and extreme temperatures. Cylinders must be stored upright and securely fastened to prevent accidental falls. Ensure that the BA is always kept in a ready-to-use condition.

Documentation

Maintaining accurate records of all inspections, repairs, and testing is crucial. This documentation ensures compliance with regulatory standards and provides a history of the equipment's condition, aiding in effective management and timely replacements.

Future Trends

Future trends in breathing apparatus focus on enhanced safety, comfort, and smart technology integration. Advancements include lightweight, ergonomic designs with improved filtration and extended air supply. Smart sensors will monitor air quality, user health, and real-time oxygen levels, transmitting data to emergency responders. AI-driven systems may predict hazardous conditions and alert users (Figure 12).

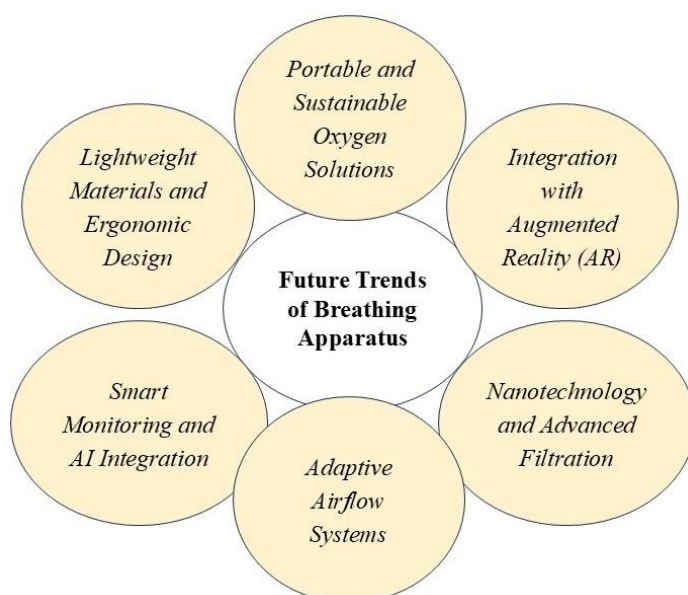


Figure 12. Future trends of breathing apparatus.

Lightweight Materials and Ergonomic Design

Future breathing apparatuses will likely incorporate lighter materials, such as carbon fiber, titanium, and advanced composites. These materials can reduce the weight of breathing apparatuses without compromising their strength or durability. Additionally, ergonomic design will be increasingly prioritized to improve comfort, mobility, and ease of use. The goal is to create systems that are less cumbersome and more intuitive, allowing users to perform their tasks efficiently without feeling weighed down.

Smart Monitoring and AI Integration

Smart technologies are expected to play a significant role in the future of breathing apparatuses. AI-powered sensors integrated into the apparatus could provide real-time monitoring of the user's health metrics, such as heart rate, oxygen saturation, and carbon dioxide levels. These sensors could also detect environmental changes, such as gas leaks or temperature fluctuations, automatically adjusting airflow or filtering mechanisms to protect the user. Furthermore, machine learning algorithms could predict potential equipment failures or malfunctions before they happen, allowing users to take preventive action.

Adaptive Airflow Systems

Future breathing apparatuses may feature adaptive airflow systems that dynamically adjust air supply based on the user's activity level or environmental conditions. For example, if a firefighter is in a high-activity scenario or exposed to increased smoke, the system could automatically increase airflow to accommodate the higher oxygen demand. Similarly, divers or industrial workers could benefit from systems that monitor their breathing patterns and adjust the air supply accordingly to maximize efficiency and minimize fatigue.

Nanotechnology and Advanced Filtration

Nanotechnology holds great promise in the development of more efficient filtration systems. By using nanoscale materials, filters could capture even smaller particles and gases, enhancing the protective capabilities of respirators. Additionally, self-cleaning filters could be developed, reducing the need for regular maintenance. These filters could be designed to remove not only particulate matter but also pathogens and volatile organic compounds, making them suitable for a broader range of environments, including healthcare settings where protection from airborne diseases is critical.

Integration with Augmented Reality (AR)

Another potential trend is the integration of augmented reality (AR) into breathing apparatuses. For example, AR could be used in face masks or helmets to display critical information to users, such as remaining air supply, environmental conditions, or proximity to hazards. This would allow workers, such as firefighters, to make informed decisions in real time, improving both efficiency and safety. Additionally, AR could assist in maintenance procedures by providing visual cues and instructions for troubleshooting or repairs.

Portable and Sustainable Oxygen Solutions

In healthcare and emergency response, portable oxygen concentrators (POCs) have already begun to replace traditional oxygen tanks. The future may see even more compact and efficient versions of these devices, powered by advanced battery technology or renewable energy sources. These portable solutions could also be made more sustainable, with minimal environmental impact, using materials that are biodegradable or recyclable, reducing their overall carbon footprint.

CONCLUSIONS

The design of a breathing apparatus is a complex process that requires careful consideration of multiple critical parameters to ensure safety, reliability, and effectiveness. Key factors, such as ergonomics, material selection, respiratory protection efficiency, weight distribution, and durability play a vital role in the overall performance of the equipment. Additionally, the integration of advanced filtration systems, proper airflow regulation, and user comfort are essential to ensure prolonged usability

in hazardous environments. One of the most important aspects of breathing apparatus design is the choice of filtration and air supply mechanisms, which must provide adequate oxygen while removing harmful contaminants. The use of high-quality materials resistant to extreme conditions, including heat, pressure, and chemical exposure, is equally crucial to maintaining the integrity of the apparatus in demanding applications, such as firefighting, underwater diving, and industrial hazardous environments. Furthermore, the weight and fit of the device should be optimized to prevent user fatigue and allow for extended operational periods.

Modern advancements in technology, such as integrated monitoring systems and automated alerts, enhance the safety and efficiency of breathing apparatuses by providing real-time data on air supply levels, environmental conditions, and user status. Compliance with industry standards and rigorous testing protocols ensures that these devices meet the necessary safety requirements and function effectively in critical situations. So designing an efficient and reliable breathing apparatus requires a balance between functionality, comfort, and safety. By addressing key parameters, such as filtration efficiency, material durability, ergonomic design, and technological enhancements, manufacturers can develop breathing systems that provide optimal protection for users in hazardous environments. Continued research and innovation will further improve the effectiveness of these life-saving devices, ensuring their reliability in emergency and occupational settings.

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