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A Path Toward Environmental Sustainability: Evaluating Alternative Technique for NORM Waste Reduction at the Egyptian Western Desert

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Abstract

The petroleum industry plays a crucial role in supplying transportation fuel, electricity, and petrochemicals, but it also poses significant environmental risks, particularly due to poor waste management practices. During drilling, the extraction process brings up Naturally Occurring Radioactive Material (NORM), a hazardous byproduct that is difficult to manage and poses severe risks to workers and the environment. This study examines conventional NORM decontamination techniques, including High-Pressure Water Jet (HPWJ), and Abrasive Blasting, alongside an alternative technique, and the Bristle Blaster Technique. These techniques were tested on petroleum equipment and confined spaces over a year. Key performance metrics included the main requirements, radiation levels before and after decontamination, and the quantity of waste produced. Results showed the Bristle Blaster Technique as the most efficient method, producing just 2% of the waste generated by all techniques. It reduces the need for waste handling, transportation, and storage. Additionally, it requires less manpower and significantly enhances operational efficiency. By generating less radioactive waste, the Bristle Blaster Technique promotes better environmental sustainability and effective waste management, ensuring the continuity of petroleum industry operations while maintaining environmental sustainability and costs.

Keywords: *NORM Decontamination; Radioactive materials; Environment sustainability; Safety; Waste control.*

1. Introduction

The worldview for radioactive waste changed after the Chernobyl and Fukushima catastrophes. In contrast to the areas of land that were removed from the map because of radioactive pollution, the long-term health impacts of nuclear accidents are insignificant, notwithstanding the press frenzy surrounding them. Unfortunately, the part that fatigue has played in catastrophic events has greatly influenced our understanding of fatigue risk [1]. So, the mere mention of "radioactive contamination or radioactive waste" often evokes negative imagery. And these incidents have contributed to leaving a lingering stigma associated with radiation.

NORM, sometimes referred to as TENORM (Technologically Enhanced Naturally Occurring Radioactive Material) in the scientific world, is terrestrial radiation that is naturally dispersed throughout natural geologic formations [2]. However, the bodies are not impacted by this level of radiation. Instead, they are affected by industrial operations that interact with and produce waste from these operations. In addition to the effects on people, improper management of this waste will cause dust particles to travel and rest on crops and soil, contaminating agricultural regions and livestock. Rivers are among the possible exposure routes, as they can produce radioactive contamination of precipitation when they condense into rain [3]. In the oil industry, TENORM was initially identified as a hazardous waste product in UK oil and gas activities in 1981 after being discovered in scale deposits in the US in the 1930s and 1940s due to interference with well logging data [4]. For thousands of years, NORM has been a part of the earth's crust [5]. and coming to the surface with oil & gas beginning with exploration which uses drilling fluids, sometimes referred to as drilling muds, as an essential component of the rotary drilling method used for both onshore and offshore [6], or production, and refining ending with storage as shown in Figure 1.

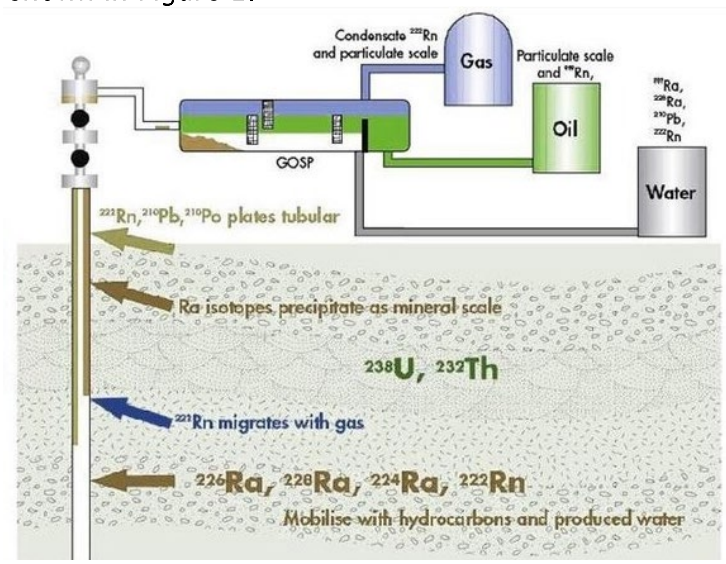

Figure 1. NORM Pathway (modified after [7]).

NORM is found specifically in downhole equipment like Electrical Submersible Pump (ESP), motors, ESP cables, gas separators, production tubing, drilling pipes, and sucker rods. Also, it was found in drilling rigs, subsurface equipment such as drilling mud systems, wellheads, and waste bits, as well as midstream equipment such as flow lines, separators, and storage tanks. Each type has its appropriate method for NORM decontamination based on many factors, for instance, the following:

1) Material properties of the contaminated layer.
2) Radioactive contamination penetration into the material.
3) The mechanical design of the equipment.
4) The radiation level of contaminated areas.
5) Radiation activity concentration per sample.

The expanding oil and gas sector produces a significant number of naturally occurring radioactive elements each year as waste or by products [8]. According to estimates, the petroleum sector produces 2.5x104 tons of contaminated scale and 2.25x105 tons of sludge annually [9].

Despite all TENORM research still having technology gaps and significant information missed in the management of TENORM threats, even after decades of intensive studies that qualitatively address the existence of TENORM and the possible health, safety, and environmental problems in the oil and gas sector [10]. All current NORM management and disposal practices are primarily short-term and only aim to temporarily mitigate direct radiation exposure to workers and the public. Recently, after NORM waste inflation, the oil and gas industry faced the challenge of developing safer and more effective methods to minimize NORM waste with the protection of workers, the public, and the environment.

NORM waste releases three types of radiation: alpha (α), beta (β), and gamma (γ) emissions. Like uranium and its decay products, thorium and decay products, radium and decay products, lead-210, potassium-40, bismuth-210, and polonium-210. These radionuclides can harm a person's health for a long time. As radium-226 decays, it releases radon gas, which is potentially harmful to human health. Although it is more frequently linked to natural gas activities than to oil, radon gas may appear anywhere there has been radium-226. Lead-210 is another radium decay product that is occasionally linked to activities in the oil and gas sector [11].

Bone marrow malignancies can arise from an overabundance of radium, which can replace calcium in the bones. When exposed via inhalation, radium targets the lungs. Similarly, radium that has been consumed may potentially attack the gastrointestinal tract [12].

The key component of effective NORM management is the capability to decontaminate petroleum equipment with the least amount of radioactive waste, which enhances radioactive waste control. So, using better waste management techniques and altering the operational procedure will lessen the possible radioactive effects [13].

The greatest challenge remains to minimize the waste quantity, which reduces the possibility of impending extensive radioactive contamination. And rather search for an effective decontamination technique with the lowest radioactive waste. Consequently, there is less risk for humanity and the environment. That is what will be discussed in the rest of this research.

2. Problem statement

It is known that NORM can build up at several points during the oil and gas production process which poses significant environmental and occupational risks [14]. Around 80% of radiation exposures in humans originate from naturally occurring radioactive sources [15]. Even conventional NORM decontamination techniques often exacerbate the problem by increasing radioactive contamination and the challenges associated with waste management. These issues are brought on by the significant amounts of contaminated material involved, the sizeable land areas required for disposal and storage, structural safety concerns, environmental protection issues like groundwater contamination, and the potential for financial liabilities that are significant enough to jeopardize the sustainability of the relevant industrial activity [16]. This creates a pressing need for a sustainable, efficient, and safer alternative decontamination technique for NORM-contaminated equipment that contains high amounts of radiation that can be sold or reused again [17].

The safe disposal of large amounts of NORM waste, including high-risk materials, has become a larger issue for companies in the last several years following ongoing NORM decontamination procedures. and started holding conferences such as the Conference of Radiation Control Program Directors, which aim to establish a safe framework for handling NORM waste by moving the wastes to a facility licensed by the agency for storage, treatment, or disposal in an injection well [18]. All these precautions had increased the burden on the oil and gas industry, which came out with the wrong selection for proper technique and severe neglect of the quantity of waste resulting therefrom. Accordingly, it is reflected in safety, environment, cost, and definitely on the whole oil industry.

3. Study objectives

Part of a successful NORM waste management strategy is the ability to decontaminate equipment with the minimal amount of NORM waste. Accordingly, it will be reflected in engineering controls and administrative procedures for handling, transportation, storage, and other safety tasks, which will ease restrictions on the petroleum industry. This study summarizes, evaluates, and compares the effectiveness of common NORM decontamination techniques in the oil and gas industry in the Egyptian western desert. Specifically, the study aims to identify alternative cleaning techniques to mitigate environmental harm, reduce radioactive waste, and enhance environmental sustainability in the oil and gas industry.

Alternative cleaning technique has been proven to overcome disadvantages of conventional cleaning techniques. Especially in the amount of waste, whereas the amount of radioactive waste is the primary factor among many others. Proper waste management is essential to a circular economy, which is inextricably linked to sustainability goals [19].

4. Study design

This study was systematically designed to apply and evaluate decontamination techniques for managing NORM contamination in petroleum equipment, with an emphasis on waste management, radiation reduction, environmental sustainability, and guaranteeing adherence to international radiation safety standards.

4.1. Study design framework

4.1.1. Research area profile

The study area lies in the Egyptian western desert. A NORM yard contains a huge volume of contaminated petroleum equipment which accumulated from workover operations over the years.

4.1.2. Duration

The study spans one year to capture comprehensive data, including potential seasonal or operational variations.

4.1.3. Test materials and setup

The case study was for 4 types of petroleum equipment: "ESP pumps, Confined spaces, Sucker rod, ESP cables." A variety of petroleum downhole equipment and confined spaces were selected, with equal proportional testing maintained across techniques to ensure fairness in the evaluation.

4.1.4. NORM survey device

The device that was used in this study is a Ludlum Measurements radiation survey meter. It's a primary instrument to accurately measure radiation exposure and to detect radioactive contamination. It contains a "pancake" Geiger-Mueller detector capable of detecting α, β, γ used to measure the radiation levels. Due to the exposure rate meters' highest reaction to ambient radiation during these hours, the values were obtained between 1110 and 1340 hours [20]. The device is calibrated periodically to maintain its efficiency and ensure that it provides accurate readings throughout the operation period

4.1.5. Radiation level reading

Radiation levels measured before and after decontamination for each technique. The reading levels of contaminated equipment ranges before decontamination were from .7 "Micro-Sievert" µSV to 133 µSV.

4.1.6. Exposure time

The time spent in NORM-contaminated areas is managed by calculating the permissible time in the controlled area. Eating, drinking, and smoking are strictly forbidden in radioactive zones or storage areas. The effective dose rate for workers is measured every three months by thermoluminescent dosimeter (TLD) to ensure their exposure to ionizing radiation remains within safe limits while adhering to the ALARA principle to minimize the likelihood of exposure [21].

4.1.7. Occupational exposure

During the case study, workers over 18 should not be exposed to work in amounts more than the annual effective dose limits of 20 mSv [22]. Also, all workers had good training in job safety analysis and emergency preparedness.

4.1.8. Personal protective equipment (PPE)

PPE prepared to include quarter-face "high-efficiency particulate air [filter]" HEPA disposable respirators or half-face respirators with HEPA cartridges and Tyvek coveralls [23]. In addition to steel-toed boots, gloves, safety goggles, a hydrogen sulfide (H_2S) monitor, and fire-retardant clothes, depending on the specific task requirements [24].

4.1.9. Operational procedures

Standard Operating Procedures (SOPs): Clearly defined SOPs for abrasive blasting, HPWJ and Bristle Blasting at NORM decontamination operations to ensure consistency and safety. Permits and Notifications: Obtaining necessary permits and notifying relevant authorities when required. Training Programs: Comprehensive training for operators on radiation operation, equipment uses, safety practices, and emergency procedures.

4.1.10. Quality assurance and control

Inspection procedures-regular inspections of radiation and quality of blasting to ensure compliance with project specifications. Documentation-keeping detailed records of blasting operations, including materials used, conditions, and radiation before and after results.

4.1.11. Accepted radiation level and regulatory guidelines

According to Egyptian regulations, NORM-contaminated equipment must be managed appropriately, following relevant procedures to protect workers and prevent environmental contamination, ensuring equipment is managed or released with controls. The equipment reaching the accepted radiation level can be reused and disposed of without limitations. The minimum requirements for managing equipment with activity above accepted radiation levels are as follows. (PET 1 and PET 2) [25].

4.1.12. NORM disposal

The NORM waste is gathered and placed into sealed standard barrels [26] made from high-density polyethylene (HDPE) that HDPE is commonly recycled and made into composite wood or plastic lumber.

4.1.13. Analysis and evaluation

Statistical comparison of outcomes from all three techniques. Comparative analysis to identify efficiency and sustainability of each technique. Identification of the most effective technique in minimizing environmental and operational burdens associated with NORM contamination.

4.2. NORM decontamination techniques

The NORM decontamination process has many different techniques, but this study focused on approved techniques in the Egyptian western desert, and they were divided into two sections, conventional techniques, and alternative technique. Conventional techniques: - "Abrasive Blasting and HPWJ" are the traditional techniques in the mentioned geographical and operational area. Alternative technique: Bristle blasting, which was focused on how to overcome conventional decontamination defects.

All the 3 selected techniques reached the acceptable range of radiation level without any impact on personnel & the environment. Abrasive blasting and HPWJ are the traditional techniques in the mentioned geographical and operational area. They were used inside the yard, which were pre-prepared to contain the decontamination process in fixed decontamination units. And outside the yard, to use them at call-out jobs when it will not be easy to move the contaminated facilities to the NORM decontamination yard, like separators, tanks.

4.2.1. Abrasive blasting

An abrasive blasting process can remove the adhesion of existing coatings by blasting various materials. Typically, a granular abrasive medium is propelled using compressed air, liquids, or blasting wheels, with adjustable nozzles to direct the high-energy blast onto the surfaces to propel an abrasive grit at a high speed, which removes oxide layers and other pieces from a material's surface [27]. Abrasive blasting demands regular maintenance, and the abrasive medium must be carefully monitored based on the type and level of contamination, as well as the condition of the granularity.

4.2.1.1. Blasting materials

Selecting the right blasting media depends on the current situation and the intended surface condition. Factors like object material, thickness, and surface roughness should be considered while choosing a blasting medium. On contaminated thin material, “softer” beam techniques are recommended to preclude deformation or other damage to the material. The outcome is largely influenced by the blasting technique and the type of abrasive medium, as shown in Figure 2.

Figure 2 Examples of Different blasting materials.

4.2.1.2. Risks of abrasive blasting

Abrasive blasting in the oil and gas industry carries several risks, both to worker safety and the environment. Here are the key risks:

4.2.1.3. Health Risks to Workers

Respiratory hazards-abrasive blasting generates dust and fine particles that can contain hazardous materials. Inhalation of these particles can cause severe respiratory issues, including silicosis, lung cancer, or other chronic respiratory diseases. Exposure to toxic materials: blasting may disturb toxic materials like asbestos, lead, and even NORM, which could lead to long-term health issues. Hearing loss: the process of abrasive blasting is noisy and can contribute to hearing damage if proper ear protection is not used. Skin and eye injuries: direct contact with abrasive materials can cause cuts, bruises, or eye injuries if protective equipment is not worn properly.

4.2.1.4. Fire and explosion hazards

Sparks from blasting - abrasive blasting can generate sparks, which pose a significant fire or explosion risk, especially in volatile environments where oil, gas, or flammable vapors may be present.

4.2.1.5. Environmental risks

Contamination of surrounding areas - the release of abrasive materials and contaminants (like NORM, hydrocarbons, or chemical residues) into the surrounding environment can lead to soil and water contamination. Airborne contamination: abrasive blasting produces airborne particles that can spread to nearby ecosystems, potentially harming wildlife, or agricultural areas.

4.2.1.6. Damage to equipment

Surface erosion - abrasive blasting, while effective for cleaning and surface preparation, can erode equipment surfaces if not controlled properly, leading to costly repairs or premature wear.

4.2.1.7. Waste management challenges

Disposal of hazardous waste: the process generates large quantities of waste, especially if it contains hazardous materials, which poses a regulatory and logistical challenge.

4.2.2. High pressure water jet (HPWJ)

High-pressure fluid jet cleaning is becoming more and more popular across a variety of industries, particularly in power plants, refineries, and chemical processing industries [28]. Decontaminating petroleum equipment involves the use of HPWJ fitted with specialized nozzles for each contaminated piece of equipment. There are several common types of HPWJ nozzles as shown in Figure 3. They are selected based on some factors: pressure, flow rate, type of material, nature of the surface.

Petroleum deposits can be formed in downhole equipment when mineral-enriched water is affected by temperature and pressure reductions. There are many distinct types of scales, and it is common to find a combination of these scales formed together. These include sulfate scales consisting mainly of barium, strontium, and calcium, which typically form deep downhole, and carbonate scales, such as calcium and magnesium. These downhole deposits usually form in layers, and they are often porous. The deposits range from very soft, such as paraffin, to extremely hard, such as barium. While using the HPWJ technique, all these scales are melting again in water. As a result, all the produced water from the decontamination process becomes contaminated, compounding radioactive scales, which increases waste volume by generating large amounts of water contaminated with (NORM).

Figure 3. Common types of HPWJ nozzles.

The proper micro-management of the recovered water from HPWJ is critical to prevent environmental contamination and infiltration of contaminated liquids into the subsurface, where they may eventually interact with underground water systems or discharge into the sea, posing significant ecological and health risks. The associated radionuclide interacts with sulfates in the river and seawater, where they partially precipitate and are consumed by aquatic animals, hence posing a radiological risk to aquatic life and the final human consumer.

HPWJ is widely used in the oil and gas industry for cleaning and decontaminating equipment, but it also comes with several risks. Here are some of the key risks associated with HPWJ in the industry:

1. Physical injuries to workers
- Slips and falls: wet surfaces created during the HPWJ process can lead to slips, trips, and falls, increasing the risk of accidents on-site.
- Impacted mist: using HPWJ on surfaces of contaminated components generates mist. This issue is particularly concerning in confined spaces, where the mist severely reduces visibility and increases risks to workers.
2. Environmental impact
- Water usage: the process can consume large volumes of water, contributing to environmental concerns in areas where water is scarce.
3. Structural damage
- Equipment damage: using HPWJ with too much pressure can lead to increased corrosion rates.

The alternative technique aims to reduce the overall consumption of raw materials and radioactive waste. Furthermore, it enhances engineering controls and administrative procedures for waste management, which in turn leads to cost, time, and petroleum industry integration.

4.2.3. Bristle blasting

Bristle blasting is a unique scale removal process that is rapidly gaining widespread acceptance among engineers and practitioners in the corrosion/surface preparation community. This process involves the use of a specially designed wire bristle tool that is precisely tuned to the spindle speed of a power tool. The principle of operation is based upon synchronized/repeated impact and rebound of bristle tips with a target surface, leading to a multitude of fractions that remove scales, expose original substrate material, and generate a required anchor profile. Surfaces produced by bristle blasting and grit blasting methods are demonstrated to have comparable morphologies [29].

The hand-held rotary wire brush offers a more efficient alternative to conventional abrasive blasting and HPWJ techniques, replicating an abrasive blast profile in significantly less time. Ideal for removing contaminated scales and radioactive deposits, the tool is particularly suited for a variety of decontamination tasks, both onshore and offshore.

Bristle blaster, which is specifically designed for use in potentially explosive environments. Available in pneumatic, electric, and cordless as shown in Figure 4.

Pneumatic bristle blaster	Electrical bristle blaster	Cordless bristle blaster
		

Figure 4. Bristle blaster types.

It is ideal for surface preparation in decontamination processes, delivering high efficiency and precision while ensuring operator safety due to a variety of features, including:

- Air cooling system and noise reduction.
- Dust extraction attachment for cleaner operation.
- Cordless type with a rechargeable battery, which is used to access areas where it is difficult to extend electrical wires or pass pneumatic hoses through.
- An anti-vibration handle and a robust front head ensure ease of use and safety.
- Swappable handle for ambidextrous use and reduced hand/arm fatigue.
- Adjustable accelerator bars that increase bristle velocity and allow better access to tight spots and difficult angles.
- The tool’s maneuverability and flexibility allow precise positioning of radiation spots during use.

4.2.4. Wire brushes

The wire brush consists of flexible metal bristles mounted in a rotating center. As the center rotates, the ends of the wire repeatedly contact the surface of the work part and generate friction and marks throughout the contact area. This friction is caused by the ends of the bristles, which essentially move across the contact area, thus removing NORM debris and rusty materials. Consequently, the work part surface contains markings that trace the path crossed by individual wire ends during the NORM decontamination process.

There are many types of wire brush materials. But especially copper brushes in the Bristle Blaster Technique maintain effective cleaning and decontamination while minimizing the risk of heat buildup, sparking, and chances of igniting flammable materials or causing burns because the copper is a non-sparking material, which is a significant concern in areas with volatile substances. making it a safer option when working in potentially explosive or flammable environments. Based on the foregoing, copper brushes are an ideal choice for safety in hazardous atmospheres where conventional bristles might pose a fire hazard.

There are many types of copper brushes as shown in Figure 5. Each type of copper brush is specifically designed for a particular purpose, depending on the shape, size, and nature of the radioactive contamination. The varying geometries of the brushes allow for targeted cleaning, ensuring the removal of contamination from even the most intricate surfaces.

Wheel Brush | Cup Brush | Dish Brush | End Brush | Scratch Brush

Figure 5. Example of cobber brushes types.

Safety precautions

Before applying for the bristle blaster decontamination process, some risks are detected. and it was essential to implement strict safety protocols and personal protective measures regarding IAEA & EAEA standards, as the following: -

1. Use non-sparking bristles
- Risk: In environments where NORM is present, sparks from conventional bristles can cause accidents in potentially explosive or flammable atmospheres.
- Prevention: Copper brushes were used, which are non-sparking, to minimize the risk of igniting any gases or flammable materials present during decontamination.
2. Conduct thorough risk assessments
- Risk: Insufficient awareness of contamination levels can lead to ineffective decontamination or exposure to radioactive materials.
- Prevention: a detailed risk assessment was conducted before starting. It included assessing the radiation level and type of contamination.
3. Ensure proper training
- Risk: Improper handling of the Bristle Blaster tools could result in accidents, injuries, or ineffective decontamination.
- Prevention: all operators have undergone comprehensive training on the tool's proper use, specific safety measures for working with NORM, and handling radioactive materials. Only certified personnel were allowed to handle and perform NORM decontamination tasks.
4. Wear adequate PPE
- Risk: Exposure to radioactive particles and debris during the decontamination process can pose serious health hazards.
- Prevention: Full PPE for operators, including:
    - Respirators or masks to protect against the inhalation of radioactive dust.
    - Radiation-protective suits to avoid skin contact with contaminated materials.
    - Gloves that are resistant to abrasion and radioactive contamination.
    - Goggles or face shields to protect the eyes from flying particles and debris.
5. Use dust extraction and ventilation
- Risk: Dust and particles released during the use of bristle blasters can carry radioactive contaminants, leading to airborne exposure.
- Prevention: dust extraction kit and isolated cabinet were used to collect airborne particles during the NORM decontamination process. to maintain a safe working atmosphere. As shown in figure 6.

Figure 6. Isolated cabinet for NORM decontamination.

6. Limit exposure to vibration and noise
- Risk: Extended use of the Bristle Blaster can lead to vibration-related injuries such as hand-arm vibration syndrome (HAVS), and noise exposure can cause hearing damage.
- Prevention:

- By using anti-vibration handles to minimize vibration impact.
- Limit the duration of use by scheduling regular breaks, each 20 minutes.
- By using hearing protection such as earplugs or earmuffs.

7. Safe handling of cordless models

- Risk: Cordless models with rechargeable batteries can pose fire or explosion risks, especially if the battery overheats or is damaged.
- Prevention: the manufacturer's guidelines were followed for charging and storing batteries. Also, avoid exposing the battery to extreme heat, and regularly check for any signs of damage.

8. Emergency procedures

- Risk: In case of an accident or radiation exposure, inadequate response can worsen the situation.
- Prevention: all IAEA emergency protocols were established for NORM-related incidents, including evacuation procedures, radiation exposure response, and first aid for injuries. The workers were thoroughly trained in these procedures as well as in the use of emergency equipment.

5. Methodology

5.1. Targeted contaminated tools

In this study, care has been taken to equally divide contaminated petroleum equipment among the three techniques: abrasive blasting, HPWJ, and bristle blaster, to ensure a fair comparison. The types of equipment tested included ESP pumps, ESP cables, confined spaces, and sucker rods.

Table 1 reflects the tool name, common contaminated part at each type of tool, quantity, and radioactive reading range by μSv. By dividing the tools equally across the techniques, it was confirmed that a balanced assessment of each technique's effectiveness across various petroleum equipment types was achieved.

Table 1. Contaminated tools details.

Tool Name	Specification (contaminated part)	Quantity	Radiation level before (μSv/hr)
ESP cable	Round design (Outer sheath)	9000 ft	2.5-13
Confined space	Storage tank 1000 BBL (Inner lining)	3 Tanks	10-133
ESP pump	Multi-staged centrifugal pump (Stages)	1200 Stages	4-59
Sucker rod	Standard Rods (Outer coating)	210 rods	0.7-25

5.2. Requirements for each technique

It is crucial to define the specific requirements for each decontamination technique, ensuring their environmental suitability and effectiveness in addressing varying contamination scenarios, and to provide a comprehensive understanding of each technique for better comparison.

5.2.1. Abrasive blasting requirement

The implementation of abrasive blasting as a NORM decontamination technique necessitates adherence to specific parameters to ensure safety, efficiency, and environmental compliance. The following sections summarize the requirements and considerations essential for conducting abrasive blasting operations, providing a comprehensive framework for comparison and effective application.

5.2.1.1. Raw material- abrasive materials

- Type of abrasives: selection of suitable abrasives (Garnet, Aluminium Silicate) based on the contaminated surface.

- Quality standards: abrasives must meet industry standards to ensure effectiveness and safety.

5.2.1.2. Manpower

1. Abrasive blasting crew
- Blaster: operates the abrasive blasting machine.
- Assistant blaster: assists the blaster by managing hoses, replenishing abrasive material, and ensuring continuous operation without interruptions.
2. Compressor operator
- Operator: manages and operates the air compressor that supplies the high-pressure air for the abrasive blasting machine.
3. Support and safety personnel
- Radiation safety officer (RSO): Ensures compliance with IAEA safety standards, oversees proper PPE usage, and monitors the health and safety conditions, including reading before & after the decontamination process.
- Fire watcher: ensures immediate emergency assistance, particularly when working in confined spaces or hazardous environments.
4. Maintenance and support
- Technician: responsible for inspecting and maintaining blasting equipment, including the blasting pot, nozzles, and hoses, to prevent breakdowns and ensure smooth operation.
5. Material handling
- Forklift driver: operates the forklift to transport abrasive materials, equipment, and other supplies to and from the worksite, ensuring timely delivery and efficient logistics during the decontamination process.
6. Project supervisor
- Site supervisor: oversees the entire blasting operation, ensuring that it progresses according to schedule, meets quality standards, and adheres to safety and environmental regulations.

5.2.1.3. Equipment

1. Abrasive blasting machine: a suitable machine with a capacity of 200 liters, equipped with blast hoses and nozzles capable of handling various abrasive materials.
2. Compressor system: a high-pressure air compressor (375 CFM, 10 bar) designed to provide the necessary pressure for blasting operations.
3. Forklift (7-ton capacity): used for transporting heavy materials and equipment safely and efficiently.
4. Crane (20-ton capacity): ideal for lifting and moving large or heavy components on-site.
5. Man Lift (3-person load): designed to provide safe and efficient access to elevated areas during work operations.
6. General tools: a variety of general tools for completing tasks required in the project.
7. Standard HDPE Barrels (220 liters): Used for storing contaminated abrasive with scales as part of the operational process.

All parameters are summarized in (Table 2), considering all proper safety and quality standards.

Table 2. Abrasive blasting technique requirements.

Raw Material	Manpower		Equipment	
	Position	No.	Equipment type	Equipment specs
Abrasive material (garnet, aluminum silicate)	Blaster	2	Forklift	7 ton
	Assistant Blaster	2	Man lift	3-person load
	Compressor Operator	1		
	RSO	1	Crane	20 ton
	Fire Watcher	1	Tools	General
	Technician	1	HDBE Barrels	220 Ltr.
	Forklift Driver	1	Abrasive blasting machine	200 Ltr. Capacity
	Site Supervisor	1	High-pressure air compressor	375 CFM 10 Bar

5.2.2. HPWJ requirement

HPWJ for NORM decontamination involves precise adherence to defined parameters to ensure operational safety, efficiency, and regulatory compliance. These parameters encompass the management of essential resources, deployment of qualified personnel, execution of standardized procedures, and strict alignment with safety and environmental regulations. The following sections provide an overview of the requirements, offering a framework for effective implementation and evaluation.

5.2.2.1. Raw material

Freshwater: an adequate water supply system to ensure a continuous water flow during operations.

5.2.2.2. Manpower

1. HPWJ user: HPWJ operator: operates the high-pressure water jetting equipment.
2. Support and safety personnel:
- RSO: ensures compliance with IAEA radiation safety standards, monitors radiation levels during the decontamination process, and oversees proper use of PPE. Reads radiation levels before and after the process to ensure effective decontamination.
- Fire watcher: present to provide immediate assistance in emergencies, especially when working in confined spaces or hazardous environments.
3. Maintenance and support:
- Technician: a specialized technician responsible for maintaining and troubleshooting the water jetting equipment. They perform routine inspections, repairs, and preventive maintenance to ensure the machinery operates effectively and safely.
4. Material handling:
- Forklift driver: handles the transport of materials and equipment around the worksite to maintain workflow efficiency.
5. Project supervisor:
- Site supervisor: oversees the HPWJ operation, ensuring that safety standards and quality control measures are adhered to. and ensure compliance with safety and environmental regulations.

5.2.2.3. Equipment

1. High-pressure water jetting machine (HPWJ machine): a specialized machine capable of delivering pressures up to 250 bar. It includes various nozzles designed for cleaning different contaminated surface types and handling various contamination levels.

2. Forklift (7-ton capacity): for transporting heavy materials and equipment.
3. Crane (20-ton capacity): for lifting and moving large or heavy components.
4. Man Lift (3-person load): designed for safe work access at elevated heights.
5. General tools: various hand and power tools for completing tasks efficiently.
6. Standard HDPE barrels (220 liters): used for storing contaminated liquids and scales.

All parameters are summarized in (Table 3), considering all proper safety and quality standards.

Table 3. HPWJ technique requirement.

Raw material	Manpower		Equipment	
	Position	No. of Person	Equipment type	Equipment Specs
Fresh water	HPWJ operator	2	Forklift	7 ton
	RSO	1	Crane	20 ton
	Fire watcher	1	Man lift	3-person load
	Technician	1	Tools	General
	Forklift driver	1	HDPE barrels	220 Ltr.
	Site supervisor	1	HPWJ machine	250 bar

5.2.4. Bristle blasting requirement

As an alternative technique for NORM decontamination, bristle blasting offers a precise and effective solution, requiring careful consideration of parameters to ensure effective contamination removal, operational efficiency, and strict adherence to safety and environmental standards to ensure its successful application. The following sections outline the main parameters necessary for its implementation and compliance with safety and environmental standards.

5.2.4.1. Raw material

Wire Brushes: Specialized brushes with bristles made from copper materials designed to remove radiation contaminants that are usually mixed with rust and scale.

5.2.4.2. Manpower

1. Bristle blasting crew.
- Bristle blaster: operates the bristle blasting machine, fully knowledgeable about machine settings, the types of abrasive brushes used, and safety protocols. Proper training in the equipment's operation is essential.
2. Support and safety personnel
- RSO: ensures compliance with IAEA safety standards, oversees proper PPE usage, and monitors health and safety conditions, including radiation readings before and after the decontamination process.
- Fire watcher: ensures immediate emergency assistance, particularly when working in confined spaces.
3. Material handling:
- Forklift driver: responsible for transporting materials, equipment, and waste to and from the worksite, ensuring efficient handling and movement during operations.
4. Project supervisor
- Site supervisor: oversees the entire bristle blasting operation, ensuring all work is performed according to safety and quality standards.

5.2.4.3. Equipment

1. Bristle blasting machine: it is a portable machine that consists of a rotating brush head powered by a cordless, electric, or pneumatic motor.
2. Forklift (7-ton capacity): essential for handling heavy loads at the worksite.
3. Crane (20-ton capacity): used for lifting and moving larger equipment or materials.

4. Man lift (3-person load): ensures safe access to elevated areas for work and inspections.
5. Standard HDPE BBLs (220 liters): ideal for handling and storing contaminated scales.
All parameters are summarized in (Table 4), considering all proper safety and quality standards.

Table 4. Bristle blaster technique requirements.

Raw Material	Manpower		Equipment	
	Position	No. of Person	Equipment type	Equipment specs
Cobber wire brushes	Bristle blaster	2	Forklift	7 ton
	RSO	1	Crane	20 ton
	Fire watcher	1	Man lift	3-person load
	Forklift driver	1	Standard HDPE BBLs	220 Ltr.
	Site supervisor	1	Bristle Blasting machine	Cordless and electric motor.

6. Results and discussion

6.1. Results

The results reveal distinct variations in waste generation and manpower requirements across the three NORM decontamination techniques.

6.1.1. Decontamination evaluation for each tested equipment

Data was gathered for the tested petroleum equipment, focusing on waste generation and radiation levels measured before and after applying each decontamination technique.

i. Performance analysis of decontamination techniques for ESP cables

Three decontamination techniques were tested on a total of 9000 feet of ESP cables, equally divided into 3000 feet for each technique. Key parameters, including radiation levels before and after decontamination measured in μSv/hr and waste volume generated measured in BBL, were analyzed as shown in (Table 5). All methods achieved acceptable results with varying waste volumes and radiation level reductions. Bristle blasting produced the least waste at 2 barrels, followed by HPWJ at 33 barrels, while abrasive blasting generated 44 barrels.

Table 5. Evaluation of decontamination techniques for ESP cables.

ESP cables	Unit	Abrasive blasting	HPWJ	Bristle blasting
Quantity	(ft)	3000	3000	3000
Radiation level before	(μSv/hr)	5-11	2.5-7	3-13
Radiation level after	(μSv/hr)	Accepted	Accepted	Accepted
Waste volume	(BBL)	44	33	2

ii. Performance analysis of decontamination techniques for tank

Three decontamination techniques were tested on three tanks, each with a capacity of 1000 barrels. The tanks were equally divided, with one tank assigned to each technique. Key parameters, including radiation levels before and after decontamination measured in μSv/hr and waste volume generated measured in BBL, were analyzed as shown in (Table 6).

The results showed all methods achieved acceptable outcomes, with notable differences in waste volumes. Bristle blasting generated the least waste at 1 barrel, HPWJ produced 19 barrels, and abrasive blasting resulted in 28 barrels.

Table 6. Evaluation of decontamination techniques for tank.

ESP cables	Unit	Abrasive blasting	HPWJ	Bristle blasting
Quantity	(ft)	1	1	1
Radiation level before	(μSv/hr)	12-75	10-51	19-133
Radiation level after	(μSv/hr)	Accepted	Accepted	Accepted
Waste volume	(BBL)	28	19	1

iii. Performance analysis of decontamination techniques for esp pump

Three decontamination techniques were tested on a total of 1200 ESP pump stages, equally divided with 400 stages allocated to each technique. Key parameters, including radiation levels before and after decontamination measured in µSv/hr and waste volume generated measured in BBL, were analyzed as shown in (Table 7).

All methods achieved acceptable results, with differences in waste volumes observed. Bristle blasting generated the least waste at 2 barrels, followed by HPWJ at 15 barrels, while abrasive blasting produced the highest waste volume at 32 barrels.

Table 7. Evaluation of decontamination techniques for ESP pump.

ESP cables	Unit	Abrasive blasting	HPWJ	Bristle blasting
Quantity	(ft)	400	400	400
Radiation level before	(µSv/hr)	17-42	2.5-7	3-13
Radiation level after	(µSv/hr)	Accepted	Accepted	Accepted
Waste volume	(BBL)	32	15	2

iv. Performance analysis of decontamination techniques for sucker rod

Three decontamination techniques were tested on a total of 210 sucker rods, evenly distributed with 70 rods assigned to each technique. Key parameters, including radiation levels before and after decontamination measured in µSv/hr and waste volume generated measured in BBL, were analyzed as shown in (Table 8).

All methods achieved acceptable results with notable variations in waste volumes. Bristle blasting produced the least waste at 1 barrel, followed by HPWJ at 41 barrels, while abrasive blasting generated the highest waste volume at 55 barrels.

Table 8. Evaluation of decontamination techniques for sucker rod.

ESP cables	Unit	Abrasive blasting	HPWJ	Bristle blasting
Quantity	(ft)	70	70	70
Radiation level before	(µSv/hr)	9-25	4-23	1-18
Radiation level after	(µSv/hr)	Accepted	Accepted	Accepted
Waste volume	(BBL)	55	41	1

6.1.2. Waste volume evaluation

The waste generation evaluation revealed distinct differences in waste production as shown in Figure 7. Abrasive blasting produced a large volume of solid waste, including used abrasive media and contaminated debris. HPWJ generated substantial liquid waste, requiring complex treatment and disposal processes. Bristle blaster created the least waste, consisting mainly of small debris.

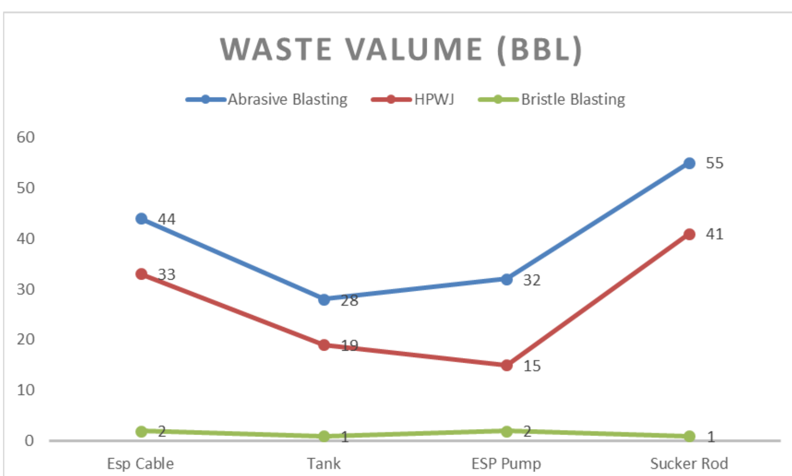

Figure 7. Waste volume evaluation.

The total waste percentage comparison highlights significant disparities between decontamination techniques, with abrasive blasting generating the highest waste at 58%, HPWJ producing a more moderate 40%, and bristle blasting emerging as the most efficient method, with only 2% waste.

6.1.3. Temporary waste disposal

The waste generated from NORM decontamination is temporarily stored in HDPE standard barrels. These barrels are placed on wooden pallets and isolated with "Polyvinyl chloride" PVC sheeting to prevent contamination spread. This method ensures that the waste is securely contained, minimizing environmental risk during transport and storage while awaiting final disposal. Proper labeling and radiation monitoring are essential to ensure safety during storage.

6.1.4. Manpower distribution across NORM decontamination techniques

The manpower varied across the three techniques. Abrasive blasting needed the most personnel, including operators and safety staff, due to the hazardous nature and extensive setup. HPWJ required a moderate-sized team due to complex equipment handling and safety precautions. Bristle blaster required the least manpower, with fewer operators and simpler operation.

6.2. Discussion

The evaluation and analysis of three decontamination techniques over the past year have revealed critical insights into their efficiency, cost-effectiveness, safety, environmental impact, and effects on surface integrity, highlighting the trade-offs between conventional methods and innovative alternative approaches. Conventional techniques is well-established, reliable, but possibly more expensive and have some bad effects on the environment. Alternative technique is Innovative, environmentally friendly, and cost-efficient, but with potential limitations in certain applications. After one year of evaluation and deep analysis of three techniques, it has been found that The alternative technique demonstrated comparable efficiency in removing NORM contamination, particularly on surfaces with light to moderate contamination. The conventional methods proved effective for heavy contamination but often required multiple cleaning cycles.

The alternative technique significantly reduced decontamination time, but conventional techniques require significantly more time due to their complex setup and waste disposal processes. Cost savings were also observed with the alternative method, primarily due to lower material and waste disposal costs. The alternative technique resulted in lower health risks to workers, with no exposure to hazardous extreme airborne particles. Conventional methods posed higher risks and the need for extensive PPE and safety protocols.

The alternative technique was found to be more environmentally friendly, producing less waste and requiring fewer hazardous disposal processes. Conventional methods resulted in higher levels of contaminated waste and posed greater challenges in terms of waste management. The alternative technique maintained the integrity of surfaces better, causing minimal surface damage, whereas conventional abrasive methods caused slight surface erosion in some cases.

6.3. Potential for use bristle blaster in NORM decontamination

While bristle blasters are not specifically designed for decontaminating radioactive materials, they have characteristics that may make them suitable for NORM decontamination, particularly in industrial environments. The bristle blaster's ability to remove surface layers (e.g., rust, paint, coatings) makes it potentially useful for removing the top layers of contamination, which is often where NORM accumulates, especially in equipment and surfaces exposed to the environment over time. The bristle blaster is more portable than larger abrasive blasting systems, which could make it convenient for decontamination in hard-to-reach areas or where space is limited (e.g., tanks and confined spaces). Compared to conventional abrasive blasting, the bristle blaster generates less dust, which could help reduce the spread of radioactive particles. This is especially important in controlled environments where contamination spread must be minimized. It offers a cost-effective and less complex alternative to larger decontamination setups. Its relatively low cost and ease of use could make it an attractive option for smaller-scale decontamination tasks or spot cleaning.

6.4. Recommendation-adoption of the bristle blaster technique

Given its effectiveness in reducing waste and radiation levels, the bristle blaster should be considered the preferred method for NORM decontamination in petroleum operations, especially in confined spaces.

It is essential to ensure that individuals involved in the extraction of contaminated equipment are well-informed about the risks of radiological contamination. Companies must be mandated to conduct regular inspections of equipment extracted from underground sources. Furthermore, it is crucial to assign a radiation specialist to measure the radiological levels of equipment before it reaches workers. Based on these assessments, the equipment can either be directed for normal daily operations or be managed according to recommendations for radiologically contaminated materials.

7. Conclusions

This study highlights the critical challenges and advancements in addressing Naturally Occurring Radioactive Material (NORM) contamination within the petroleum industry. NORM contamination poses significant risks, particularly in environments like petroleum tanks, ESP pumps, ESP cables, and sucker rods, where hazardous concentrations may expose maintenance and operational personnel to radiation-related dangers.

Our research underscores the importance of adopting state-of-the-art decontamination practices that prioritize safety, efficiency, and environmental sustainability. Among the reviewed methods, bristle blasting emerged as the most effective technique for NORM decontamination. It demonstrated superior advantages in waste minimization, workforce optimization, and cost efficiency, effectively reducing the volume of radioactive waste and addressing handling challenges. These benefits position bristle blasting as a sustainable and practical solution for the petroleum industry.

Standardizing decontamination practices, guided by analytics and detailed case studies, is vital to harmonize efforts across the industry. Such standardization ensures compliance with radiation protection protocols and facilitates broader adoption of innovative techniques, thereby enhancing safety and sustainability across operations.

This research contributes to advancing the field of radiation protection in oil and gas industries while fostering a safer working environment. Future studies could expand on these findings by exploring complementary methods or integrating emerging technologies to further optimize decontamination strategies.

Future work

Based on the findings of this study regarding the capability of abrasive blasting to enhance environmental sustainability and safeguard individuals and communities, it would be inspiring to further advance this technique through technology. Developing a fully automated abrasive blasting system with minimal human intervention could help reduce error rates, increase efficiency, and improve safety for all involved.

Abbreviations

Abbreviation	***Description***
ALARA	*As Low As Reasonably Achievable.*
BBL	*A Standard barrel*
CFM	*Cubic Feet Per Minute.*
ESP	*Electrical Submersible Pump*
HAVS	*hand-arm vibration syndrome.*
HDPE	*High Density Polyethylene.*
HEPA	*high efficiency particulate air [filter].*

HPWJ	*High Pressure Water Jet.*
LTR	*A liter.*
μSV	*Micro-Sievert, 1 μSv = 0.000001 Sv.*
NORM	*Naturally Occurring Radioactive Material.*
PPE	*Personal Protective Equipment.*
PVC	*Polyvinyl chloride.*
RSO	*Radiation Safety Officer.*
SOPS	*Standard Operating Procedures.*
TENORM	*Technologically Enhanced Naturally Occurring Radioactive Material.*
TLD	*Thermoluminescent dosimeter*

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