REVOLUTIONARY MULTI-LAYERED SMART LINER FOR SPILL PREVENTION

DOI: https://doi.org/10.53486/dri2025.04
UDC: [552.578.2:656.56]:001.895

THEODOR ADRIAN VASILE
ANNA MARIA VASILE
anna.vasile@email.com
Romanian Academy National Institute of Economic Research "Costin C. Kiritescu"
Bucharest Romania
ORCID ID: 0009-0002-2823-5832

Abstract. *The collection, transportation and storage of crude oil, petroleum products and gas ensure the supply of raw materials to refineries and petrochemical plants, as well as the supply of fuels and lubricants to consumers. Transport plays a particularly important role in this context. Onshore and submarine pipelines are the main means of transport for crude oil and gas. In addition, railways, airways, sea and/or inland waterways and railways are used. In addition, railways, airways, sea and/or inland waterways and roads are used. The transport of crude oil by tankers poses significant economic and environmental risks in the event of an oil spill. Conventional solutions, such as basic containment liners and double-hull tankers, offer limited protection against devastating punctures and leaks.*

Oil spills remain a serious environmental problem that calls for ongoing efforts to prevent, detect, and respond to them. Finding practical solutions is crucial when it comes to environmental issues including soil and water contamination and wildlife damage. This paper introduces an innovative multi-layered, self-healing, and expandable oil containment system designed to significantly improve the prevention of oil spills in accidents. The proposed system integrates advanced materials, real-time monitoring, and automatic response mechanisms, differentiating it from existing research and commercial solutions. By integrating puncture-resistant materials, self-sealing mechanisms, artificial intelligence-based monitoring and expandable compartments, this system offers a comprehensive and secure approach to the safety of oil transportation.

Keywords: *crude oil transportation, pollution, innovative system*

1. Introduction

Transportation costs have a major share in the price structure of petroleum products. The use of large-diameter pipes for the transport of large volumes of oil has significantly reduced transportation costs and thus opened the possibility of replacing solid fuels with liquid fuels to ensure the main source of energy in the modern world.

1.1. Context

In the petrochemical industry, the share of transportation in the final price of products has decreased, this was mainly due to the emergence of specialized vessels for the transport of certain types of products, the use of new technical procedures for the safety of transportation, as well as the use of pipelines intended exclusively for the transport of these types of products and other factors. Thus, water transport is substantially lower than land transport, both rail and road.

However, this type of transport comes with great risks for the environment. Pollution of the marine environment with hydrocarbons has increased significantly in the last fifty years. Numerous pollution accidents are prevented by risk factors such as the transportation of oil by sea, the exploration and exploitation of hydrocarbon reserves in marine waters, and the processing of these deposits, in addition to other anthropogenic activities. Incidents that occurred at offshore drilling and exploitation platforms or navigation accidents of large oil tankers have caused significant ecological disasters, some of which have been extremely serious.

Since the 1960s, pollution of the marine environment with hydrocarbons has become an alarming phenomenon. The rise and dissemination of risk factors, particularly throughout the 1970s and 1980s, has coincided with an increase in the sources and causes of pollution. Because oil and petroleum products are dangerous, incidents involving drilling, extraction, transportation, transfer, loading-unloading, refining, storage, and other processes have created immediate risks. Marine life, coastal economies and global sustainability have historically been affected by oil spills. Despite advances in container design and construction and spill response methods, accidental spills continue to be a significant problem.

1.2.The claim for an revolutionary isolation solution

Fluid control and safety are essential in oil and gas operations. The solution presented in this paper for managing spill control for a wide range of fluids, including drilling mud and crude oil, ensuring accurate and precise fluid transfer even in extreme weather conditions, is an innovative one. With a focus on durability and efficiency, our solution becomes essential for fluid transfer in this dynamic industry.

Usually, the causes of hydrocarbon pollution of the marine environment are analyzed in relation to the two types of pollution: operational and accidental. During oil tanker loading and unloading; bunkering activities, which include supplying engines with heavy and light fuel; when ballast and bilge water are released from ships without proper treatment; and during port visits, when oil leaks happen while cleaning. Navigation accidents can cause accidental pollution, the most important of which are: collisions, shipwrecks, groundings, etc.

International waterways see thousands of oil spills annually, the most of which are minor and yield less than one barrel of oil. A two-acre oil slick can form from a spill of less than one litre, which is quite dangerous (Schutes, 2015). These spills have impacted not only undersea habitats but the entire planet because of their size and frequency. There were 9351 documented cases of oil pollution from 1974 to 2007 as a result of both intentional and unintentional maritime spills. With spills of less than 7 t, the majority of these occurrences (83.5%) were modest. Shipping mishaps make up 46.6% of the total, while spills weighing more than 700 t only make up 3.7%. During this time, there were 573 collisions, 580 groundings, 709 accidents due to ship breakage (e.g. water holes or ship breakage) and 133 explosions, as well as 2361 accidents that occurred for other or unknown reasons. Navigational accidents account for 46.6 percent of the 9351 accidents.

Inadequate maritime pollution management, both on board ships and at oil terminals, port operators, and bunkering companies, is mostly to blame for operational pollution, which accounts for the greatest number of occurrences. Operational pollution has not had the same obvious ecological effects as significant accidental spills, despite the fact that the annual number of hydrocarbons from operational sources worldwide is around four times higher.

Current industry solutions focus on passive protection methods, such as double-hull designs and conventional polymer liners. However, these techniques are not sufficient to address the dynamics of collisions, perforations and severe failures in tanks/containers/pipelines. To effectively mitigate oil spills, this paper presents a novel method and proposes a smart, adaptive and self-sealing containment system.

Since there haven't been any significant oil spills like the Erika and Prestige disasters, marine safety in EU waters is currently at a very high level. Nonetheless, almost 2,000 maritime mishaps and accidents are reported annually.

Transport systems are essential for safety, security and environmental sustainability and should not be compromised. It is imperative that the European Union develops preventive and proactive policies and maintains its global leadership in this area. It should constantly work with stakeholders, including civil society, and other national, international, and local agencies to achieve this.

The European Green Deal, the Zero Pollution Action Plan, and the Strategy for Sustainable and Smart Mobility establish the direction at the EU level. The ultimate goal is to guarantee decarbonised, intelligent, robust, accident-, waste-, and pollution-free maritime transportation.

The "Ready for 55" rule has significantly advanced the sector's transition to a more sustainable course. To promote the use of sustainable fuels in maritime transportation and the expansion of the EU Emissions Trading System (ETS) to maritime transportation, the EU has enacted policies including the FuelEU Maritime Initiative Regulation. These steps will encourage investment in clean fuels and technologies and guarantee that the industry helps achieve the 1.5°C global warming target set forth in the Paris Agreement.

In addition to this strong legal framework, the European Union is dedicated to working within the International marine Organisation (IMO) to create high standards for marine transportation's safety and security, digitisation, greening, and decarbonisation. The coexistence of these European rules and EU actions in the IMO ensures fair competition in the single market and globally, preventing ships from being flagged to third countries and harming European interests.

Maritime transport is currently one of the most environmentally benign forms of transport due to the amount and percentage of commodities delivered, as well as its effects on the global economy and the European Union.

2. The design and composition of the material proposed for use

Oil spills continue to be a significant environmental challenge, requiring continued efforts to detect, respond to and mitigate them. In terms of environmental impacts such as soil contamination, water pollution and wildlife impacts, it is essential to find effective solutions.

Oil tankers have a metal construction, made of welded steel plates and profiles, but they do not have a structure to protect the cargo from hydrocarbons.

2.1 Intelligent multi-layered approach

The proposed containment system consists of an innovative architecture with three main layers, each of which plays a key role in preventing leaks and protecting the marine environment. These layers are selected and configured to maximize impact resistance, self-healing capacity and leak containment. The construction of this innovative multilayer (balloon) system is also innovative.

2.1.1. Outer layer: Puncture-resistant shield

We have developed and tested an ingenious system to contain the cargo and therefore protect the environment from accidental spills of oil cargo.

To reduce the risk of perforation and structural damage, the outer layer is designed to absorb and distribute the energy generated by the impact. This multi-layered system will be constructed with the following materials:

- **Kevlar** – An aramid material with extremely high tensile strength, also used in the ballistics industry for protection against projectile impact.
- **Ultra-high molecular weight polyethylene (UHMWPE)** – A material with high resistance to abrasion, impact and cut, used in the construction of light armor and industrial protective equipment.
- **Carbon-based nanocomposites** – They improve durability and impact force dissipation capacity.

This outer layer acts as a primary barrier against hard objects that could puncture the tank or pipe, providing significantly greater protection than traditional double-hull solutions.

2.1.2 Middle layer: Shear-thickening fluid (STF - Shear-Thickening Fluid)

This layer functions as adaptive protection against punctures by using a non-Newtonian fluid that changes its viscosity depending on the applied force.

- Under normal conditions, it remains flexible and allows controlled deformations without compromising structural integrity.
- Upon impact, the fluid instantly solidifies, forming a rigid barrier that prevents the penetration of sharp objects or fragments resulting from collisions.

The components used in this fluid include silica nanoparticles dispersed in a polymeric medium, which rapidly change their state of aggregation when subjected to intense forces. This innovative feature gives the middle layer active protection, responding immediately to mechanical stress and preventing damage in the event of serious accidents.

2.1.3 Inner layer: Self-healing polymer coating

The inner layer is essential for sealing any minor cracks or perforations that may occur in the tank or pipe structure.

- Polymeric microcapsules – Incorporated into the polymer layer, these capsules contain liquid precursors of a sealant, which are automatically released in the event of a crack.
- Chemical crosslinking reactions – Upon contact with air or water, the materials released from the microcapsules initiate a self-healing process, sealing cracks and preventing oil leaks.
- Flexible and extensible polymers – Ensure good adhesion to the surface and allow the absorption of mechanical deformations without losing the integrity of the protective layer.

By combining these technologies, the inner layer functions as a continuous repair mechanism, extending the life of the containers and reducing the risk of accidental pollution.

An essential aspect of this isolation system is the chemical compatibility of the materials used with hydrocarbons, so that they do not alter the chemical composition of the oil.

- The outer layer (Kevlar, UHMWPE, carbon nanocomposites) is chemically inert and does not interact with hydrocarbons, being designed only to ensure mechanical resistance.
- The middle layer with STF fluid does not undergo chemical reactions with oil, since the silica nanoparticles are encapsulated in a hydrophobic polymer matrix. Thus, even in the event of a major impact, this layer does not contaminate the fuel.
- The inner layer contains polymers specially formulated to resist contact with hydrocarbons. The self-healing microcapsules contain a compound that reacts only with oxygen and water, not with oil, so that it retains its chemical properties and can be used without problems.

An example of a reaction that occurs at the level of the inner layer is the following:

$$R\text{-}(C{=}O)\text{-}O\text{-}R' + H_2O \rightarrow R\text{-}(C{=}O)\text{-}OH + R'\text{-}OH$$

This is a controlled hydrolysis reaction that leads to the formation of a sealant upon contact with water, preventing leaks but without affecting the oil.

The polymers used for sealing are also selected to be oleophobic, meaning they repel oils and do not allow chemical interaction between the sealing materials and hydrocarbons.

This property ensures that the transported oil remains in the same chemical state and can be refined or used further without modification.

2.2 Expandable, pressure-sealed liner

The innovative multilayer system that will retain the oil and other hydrocarbons being transported also includes a flexible lining, capable of adapting to the structural deformations of the container. It is made of:

- Shape Memory Alloys (SMA) – Special metals that change shape under the action of a temperature variation or mechanical stress, helping to maintain optimal tightness.
- Electroactive Polymers (EAP) – Smart materials that expand or contract under the influence of an electric field, acting as an automatic sealing mechanism.

This technology will allow the liner to remain compact under normal conditions and expand rapidly in the event of a failure, isolating the affected areas to prevent hydrocarbon leakage into the environment.

2.3 Oil-repellent and fire-resistant properties

Another innovative aspect of this insulation system is the integration of features that reduce the risks of oil adhesion and ignition:

● Superhydrophobic and oleophobic nanocoatings – Applied to the inner and outer surface of the polymer layer, these coatings significantly reduce oil adhesion, preventing the accumulation of residues that could aggravate a possible leak.
● Fire-resistant intumescent layers – These special layers are activated at high temperatures, expanding to form an insulating barrier that limits the spread of fires and prevents the ignition of fuels.
Through this combination of technologies, the proposed system offers complete protection against mechanical, chemical and thermal hazards, ensuring significantly improved safety compared to conventional solutions on the market.

3. Artificial intelligence-based monitoring and automated response

3.1 Embedded sensor technology

● The system integrates pressure, vibration and temperature sensors for real-time damage detection.
● AI algorithms analyze sensor data to predict failure points and trigger automatic repairs.

3.2 Autonomous leak isolation mechanism

● If a breach is detected, an automated injection system uses fast-setting polymer foam to reinforce weak points.
● Damaged sections of the liner are isolated using vacuum-sealed compartments to limit potential leaks.

3.3 Comparison with existing solutions

Characteristic	Traditional double-hull tanks	**MULTI LAYER SMART LINER**
Puncture resistance	Moderate	High (Strat Kevlar/UHMWPE și STF)
Self-sealing ability	None	Yes (Microcapsules and Auto-Injection)
Expandable design	No	Yes (SMA and Electroactive Polymers)
Fire resistance	Basic	Advanced (Intumescent Coatings)
AI monitoring	No	Yes (Real-time Sensor Data)
Repairability	Limited	Modular and Replaceable Sections

The proposed MULTI LAYER SMART LINER is made up of multiple layers and technologies, including protective materials (Kevlar, UHMWPE, self-healing polymers), expansion mechanisms and integrated sensors. These components may occupy some volume of the ship, but ideally will be designed to minimize the impact on usable cargo space.

● The smart liner will usually be installed on the inside of the oil tanker hull, so as to protect the fuel tanks and cargo compartments.

● The outer protective layer, such as Kevlar or UHMWPE, can be thicker, depending on the strength and impact requirements, but generally its thickness can vary between 5 cm - 10 cm on each side of the tanks.

● The middle layer (STF) could be about 3 cm - 5 cm in thickness.

● The inner layer of self-healing polymers will add another 2 cm - 4 cm, depending on the technology chosen.

3.4 Space occupied by the liner system

The smart containment system will occupy a certain volume of the oil tanks, which may lead to a decrease in the crude oil transport capacity. The calculation of this impact can be done taking into account the tank dimensions and the liner thickness:

Estimating lost space:

Assume that a typical oil tanker has a tank with dimensions of approximately:

- Tank length: 100 m
- Tank width: 20 m
- Tank height: 10 m

If the liner has a total thickness of approximately 15 cm (0.15 m) on each side of the tank (total thickness of the 3 layers), then the lost volume of each tank could be calculated as follows:

Lost volume = 2 x(Width x Height x LinerThickness) + 2 x(Length x Height x LinerThickness) + 2 x(Length x Width x LinerThickness)

Calculating the lost volume for a tank:

- Width x Height x LinerThickness: 20×10×0.15=30m^3 20 x 10 x 0.15 = 30 m^3
- Length x Height x Liner Thickness: 100×10×0.15=150m^3 100 x 10 x 0.15 = 150 m^3
- Length x Width x Liner Thickness: 100×20×0.15=300m^3 100 x 20 x 0.15 = 300 m^3

Total volume lost per tank:

30+150+300=480m^3 30 + 150 + 300 = 480 m^3

Reduction in carrying capacity:

A typical oil tank might have a capacity of around 10,000 - 20,000 m^3. Thus, the loss of 480 m^3 represents a reduction of approximately:

480/10,000 ×100=4.8% of the tank capacity

So, for each tank, there would be a reduction of approximately 4-5% of the total oil transport capacity.

Impact Assessment on the Amount of Oil Transported

If we consider a large ship with a total of 10,000 m^3 capacity for transporting crude oil, the 4.8% redundancy will mean a loss of 480 m^3 of oil per ship.

Estimate the long-term impact:

If a fleet of 50 tankers is equipped with this protection system, and each ship transports approximately 10,000 m^3 of crude oil, then the total annual loss would be:

$$50\times480\ m3=24{,}000\ m3\ \text{of oil}$$

However, considering the environmental and financial benefits, this loss can be justified, as the risks of spills and clean-up costs would decrease significantly, and environmental taxes and insurance premiums would be lower.

Analyzing the space occupied by the intelligent containment system in transport vessels and its impact on the amount of oil transported involves evaluating several factors, such as the dimensions of the system, its distribution on the ship and how it would affect the overall crude oil transport capacity. In addition, it is essential to consider the effectiveness of the protection system against its environmental and financial benefits.

Implementing the smart containment system in oil tankers would result in a loss of approximately 4-5% of the carrying capacity of each tank, which is a relatively small trade-off compared to the benefits brought, such as:

- Reduced spill risks and significantly lower environmental impact.
- Large savings in spill clean-up costs and environmental taxes.
- Reduced insurance premiums due to additional protection.

Therefore, although there is a minor loss of carrying capacity, the protection system can bring considerable savings and environmental benefits that make its implementation a valuable choice in the long term.

4. Conclusion and future prospects

The Smart Oil Containment System represents a disruptive innovation in the prevention of marine oil spills. By integrating puncture-resistant materials, self-sealing mechanisms, AI-based monitoring and expandable compartments, this system offers a comprehensive and safe approach to the safety of oil transportation. Future developments may include self-healing biodegradable polymers and nanotechnology-based ultra-thin coatings, further enhancing environmental protection.

Implementing a smart containment system can bring considerable savings and significantly reduce the risks and costs associated with oil spills. This is not only an environmentally efficient solution, but also a sound long-term financial decision. It requires a detailed approach with clearly defined stages, which include research, testing, collaboration with authorities, long-term implementation and ongoing monitoring. Such a strategy ensures that the final product will be effective and meet industry and environmental regulatory requirements.

References

1. Institutul de Cercetare pentru Siguranța Maritimă – Rapoarte de prevenire a scurgerilor de petrol (2024).
2. Advanced Material Science Journal – Aplicații Kevlar și STF (2023).
3. Întreținere predictivă bazată pe inteligență artificială în transport maritim – Proceedings Conference IEEE (2022).
4. Ion MILAN(1), Marian-Traian GOMOIU(2) - *Cauze şi consecinţe ale poluării mediului marin cu hidrocarburi, 2008* - GEO-ECO-MARINA 14/2008 – SUPLIMENT NR. 1, Ştiinţele Pământului, Cunoaştere şi Mediu – Sesiune anuală de comunicări ştiinţifice
5. Bogdan CIORUȚA, Diana MĂDĂRAS, Mirela COMAN - "*Causes and Consequences of the Black SeaEcosystem Pollution with Petroleum Products*", 2020, Asian Journal of Geographical Research
6. Advances in Design for Inclusion, Springer Scienceand Business Media LLC, 2020
7. Markos Zoltan – Tehnologia materialelor, Ed Univ Transilvania 2012
8. Bruxelles, 1.6.2023 COM(2023) 268 final - COMUNICARE A COMISIEI CĂTRE PARLAMENTUL EUROPEAN, CONSILIU, COMITETUL ECONOMIC ȘI SOCIAL EUROPEAN ȘI COMITETUL REGIUNILOR - Siguranța maritimă: principiu esențial al unui transport maritim curat și modern, https://eur-lex.europa.eu/legal-content/RO/TXT/HTML/?uri=CELEX:52023DC0268