E-MOP™ - ELECTROMAGNETIC OIL SPILL REMEDIATION TECHNOLOGY

2019 R&D100 Award Entry

BRIEF DESCRIPTION

Electromagnetic oil spill remediation technology unites electromagnetic forces and innovative engineering to revolutionize the response to the global environmental threats from oil spills. Oil is seeded with magnetite (Fe_3O_4) to create a magnetizable mixture, and then electromagnetic equipment collects the magnetized oil and delivers it to a separator for reuse.

Major Oil Spills Worldwide

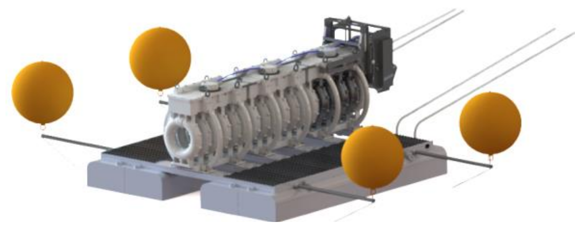
Image of a Large-Scale Spill

SUMMARY

Crude oil spills are one of the most devastating environmental threats to our coasts, waterways and oceans. According to the U.S. Department of Energy, 1.3 million gallons of petroleum spill into U.S. waters alone from vessels and pipelines in a typical year. Major accidents such as 2010's Deepwater Horizon effect catastrophic and lasting impacts on our waterways and oceans, marine life and local economies. Almost a decade and many billions of dollars later, the recovery effort continues.

Electromagnetic remediation tackles these intractable remediation problems through a process that is both efficient and environmentally benign. First, spilled oil is seeded with micron-sized magnetite particles which preferentially target and bond to oil, creating a magnetizable mixture. An innovative electromagnetic boom and magnetic ramp create magnetic fields that direct the mixture along the boom, up the ramp and into a magnetic separator tank. This recovers the particles and oil for reuse and replaces the standard passive boom and skimmer systems. The water serves as the transport medium, but it is left behind at the ramp's interface.

Passive absorbing boom – does not move and separate oil



Active electromagnetic boom – collect, move and separate oil

PRODUCT DESCRIPTION

What does the product do?

Electromagnetic remediation technology provides a system and a method for **remediating oil spills** on water and land. The technology uses electromagnetic pulses and specially timed magnetic fields to produce magnetic forces that move, lift and transport oil. This provides for an effective and non-toxic method for **cleaning "produced" water**, **remediating toxic spills**, **and restoring land and waterways**. The technology utilizes materials that are environmentally safe, reusable and natural.

Oil forms a unique bond with micron-sized magnetite particles. This bond is exploited as the combination of oil and magnetite are rendered magnetic in the presence of magnetic fields. Viscosity effects are enhanced, the ability to **confine, attract and move the spills** is increased, and the **remediation process is controlled** without the use of dispersants and other harmful chemicals and methods. Solenoidal coils and other magnets are used in the process to produce the magnetic field gradients that provide the forces necessary to move the magnetized mixture, collect it, and separate the particles for potential reuse and the oil for possible reclamation.

The solenoids in the system form an active electromagnetic boom (e-boom) which differs fundamentally from the passive booms that are common today. The e-booms collect and transport magnetized mixture within the reach of its fields (on and below the surface) and deliver it to its interface with a magnetic ramp (e-ramp). This includes mixtures that may be several inches below the surface as in the case with **heavy-oil spills**. The ramp in turn collects the mixture and separates the magnetite for reuse while actively rejecting water in the process.

The system also **targets oil at the micron-scale** (the size of the particles used) which is normally either not visible to the naked eye or reveals itself in the form of a sheen. On beaches, rocks, marshlands, roads and other solid surfaces, magneto-rheological effects are exploited to **lift and remove the oil that coagulates** and creates environmental damage to plants and wildlife. In addition, electromagnetic remediation provides a method for **filtering and cleaning water** for reuse in conjunction with magnetizable organic hydrophobic absorbents.

The fundamental principles exploited in the design of the electromagnetic remediation technology system are demonstrated in the videos provided below.

(https://www.naturalscienceusa.com/emop-demos1)

Applications. In addition to large- and small-scale oil spill applications, the technology can be used in industrial applications to filter and remove flocculant from water at treatment plants, process and reclaim "produced" water associated with fracking and oil refinery processes, and clean daily spills in harbors, ports, laboratories and businesses that work with large and small volumes of oil. Water associated with many of these applications is typically contaminated by oil. This water is not potable and does not meet standards for normal disposal.

How does the product operate?

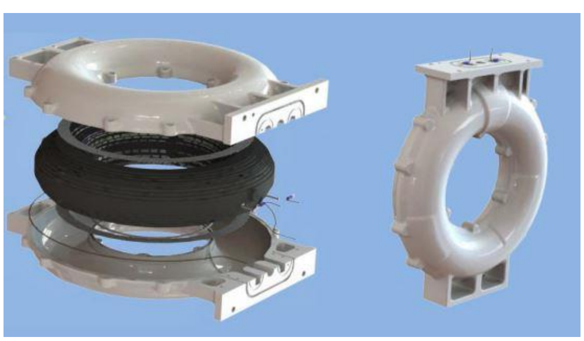
The system works by sequencing several process steps that enable magnetizing of the spilled oil products. The process works both on water, where some of the most difficult and damaging spills occur, and on land, where the effects and the cleanup process present a different set of challenges. Each step and subsystem are described, and the combined system performance and advantages are explained below.

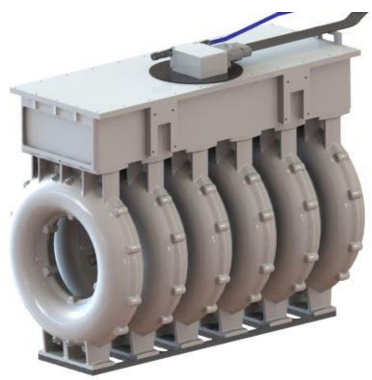
The Seeding Process

Micron-sized magnetite (Fe_3O_4) particles are first dispersed in the oil spill with a pressure-controlled nozzle in what we define as the seeding process. The particles form a very unique and preferential bond with oil due to their size and a combination of forces. The forces that allow the particles to bond with the oil are primarily dominated by the "Van der Waals force." which is the general term used to define the attraction of intermolecular forces between molecules in a liquid. Once seeded, the mixture of oil and magnetite is susceptible to magnetic forces. In the case of a water spill (oceans, lakes, rivers, ponds, etc.), specially designed magnets are then turned on to generate fields that are used to guide the spilled material to a separation container. Here it is collected, and the particles that were injected are magnetically removed for reuse. In the case of a non-water spill, the magnetic forces are used to lift the material and move it to the separator system. In the former case, the water acts as the transport medium, and in the latter case magneto-rheological effects (explained below) provide the mechanism that allows the material to be rigid enough to be lifted and moved in the presence of the magnetic fields.

The E-Boom Magnets

The magnetic system for water applications consists of solenoidal (doughnut shaped) magnets that are coupled together in groups of six to form a module. Several modules are connected together to form an electromagnetic boom (e-boom) structure. The system can be made longer or shorter by adding or removing modules to accommodate the situation. Every magnet in the structure is separated from the next by a fixed distance that optimizes the "gradient" effect of the magnetic fields between them. The force which moves the mixture is directly proportional to the gradient. Each magnet is driven in turn by a time-dependent, electrical-current pulse which generates a magnetic pulse that gradually grows stronger axially as magnets are sequenced on and off. This generates a magnetic "pulsetrain" that attracts and moves the magnetized mixture (oil and magnetite) in the direction of the pulse train. The rate at which the magnetized mixture is transported along the axis is directly proportional to the pulse rate, the magnetic field gradient, the viscosity of the spilled oil and the friction with the surface (water in this example). The last magnet in the e-boom (the last car in the train) is coupled to a magnetic ramp system and transfers the mixture at this interface as it flows in. Videos #6, #7 and #8 in the link demonstartes the concept. https://www.naturalscienceusa.com/emop-demos1

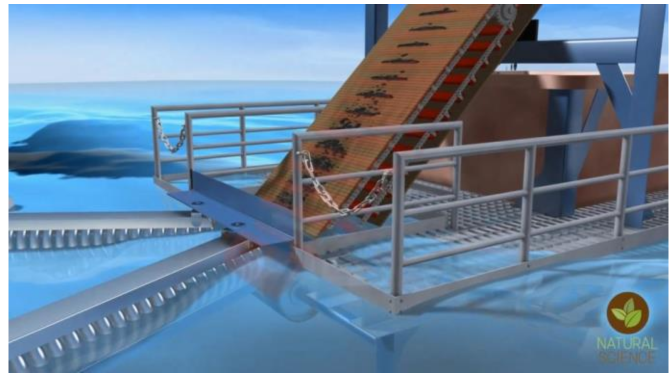




Single solenoid model *Solenoid assembly* *e-boom Module*

The Magnetic Ramp

The fluid that arrives at the output of the e-boom system is collected by the magnetic ramp. The ramp is designed to couple with the last solenoid magnets in the sequence. The ramp has a moving conveyor belt and under its surface there is a moving layer of magnets. These two are independently driven and, therefore, can either move at the same rates or at different rates. The entire ramp is situated at an angle to the e-boom module to lift the magnetized mixture from the water. Due to the angle of inclination of the ramp system, the belt speed, and the magnetic force at the belt, any excess water slides off the belt system while the magnetized oil is delivered to a separation container. View videos #9 and # 10.



Electromagnet ramp and interface with e-boom

https://www.naturalscienceusa.com/emop-demos1

The Separator

Once the mixture of magnetite and oil has been removed from the water by the ramp, the separation system takes over. The magnetite will follow the strongest magnetic force and for this reason the containment vessel is designed with a stronger than average magnetic field at its base that pulls downward on the magnetite particles in the mixture. Unlike the force it experienced when on the water, this force is normal to the surface of the container base. The magnetite naturally goes in the direction of this magnetic force and will stick to the bottom of the container while the oil and any remaining water separate. This allows for the magnetite to be reused and the oil to be recovered.

PRODUCT COMPARISON

How does this product improve upon competitive technologies?

A New Paradigm for Oil Spill Remediation. Standard methods for oil spill remediation and control rely heavily on plastic or fabric **booms** and mechanical **skimmers**. The standard booms used for containment are passive devices and are used in conjunction with the skimmers which only target surface oil. Most skimmers are known to be inefficient and collect a large percentage of oily water during operation. Other primary methods include the use of **chemical dispersants**, **sorbents, in-situ burning** and **bioremediation**. **Manual labor** (shovels and scoops), although not compared here, is surprisingly still widespread and employed even in the United States. These methods are either inefficient or harmful to the environment and the ecosystem.

Electromagnetic remediation allows **e-booms** to actively collect, move, and separate oil, and they are not passive devices. They use materials that are environmentally benign and that are mostly recoverable and reusable. They also recapture the spilled materials and separate them. The method eliminates the harmful long-term and short-term environmental consequences associated with chemical dispersants. It eliminates the waste associated with most sorbent technologies, as well as the harmful toxins associated with burning. Bioremediation takes a long period of time and does nothing to contain spills.

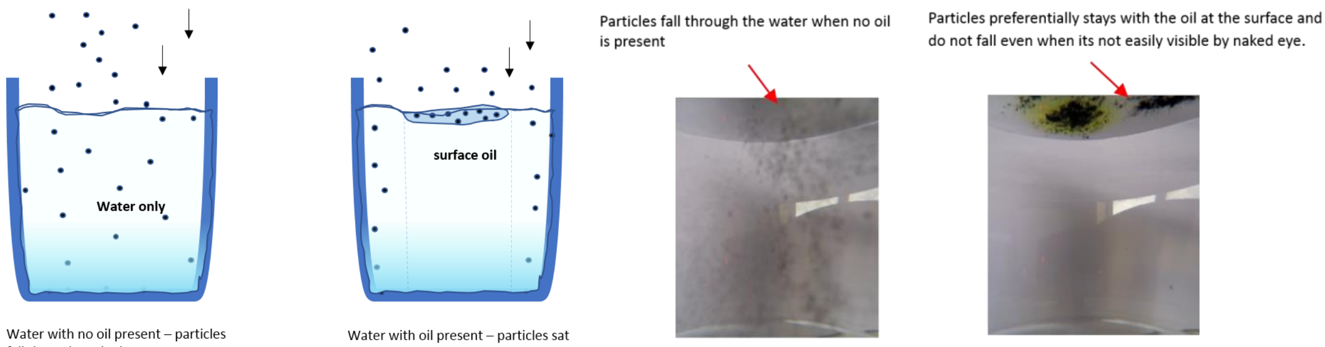
Comparisons

Electromagnetic remediation technology makes it possible to contain and minimize the environmental damage caused by oil spills. Its superiority over existing solutions may be summarized in seven points.

Active technology that uses magnetic fields. Compared with passive booms, these systems actively work to attract and move the oil. Passive booms can still be used to localize and increase the volume of the spill material available for electromagnetic removal, but the electromagnetic fields will continuously feed oil to the ramps for removal.

Surface and subsurface collection. Oil that is below the surface can still be within reach of the e-boom's fields and will be collected and driven toward the magnetic ramp for removal and separation down to the micron scale (the sheen).

A probe for oil. The magnetite particle used during the seeding process preferentially targets the oil and forms a bond with it whether the oil lies on the surface or beneath. It will pass through the water up to the point it encounters oil**.** This provides a novel method that targets and finds oil that is otherwise difficult to locate either because of the size of the droplets or its volatility. See video #11 in the link. https://www.naturalscienceusa.com/emop-demos1



Water with no oil present – particles fall through to the bottom

Water with oil present – particles sat with the oil and can only pass in places where there is no oil.

Water with no oil present

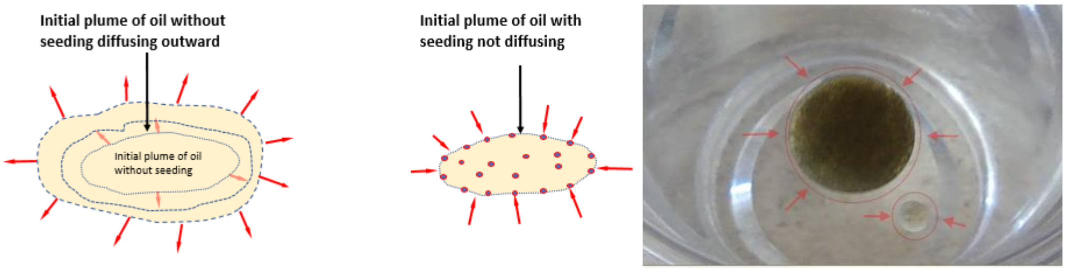
Water with oil present

Environmentally benign. Magnetite is a natural mineral and can be found on most beaches around the world. It is also found in igneous and metamorphic rocks and elsewhere. Our collection and separation process recover close to 98% of the magnetite used. The image sequence below shows, from left to right, snapshots of seeded oil being moved with a magnet to the sides of the containment vessel and 100% of the magnetite particles being extracted. See video #2 which demonstrates this process. This is the same process used at the interface with the magnetic ramp but in that case the surface also moves the oil until separation is required at the containment vessel.

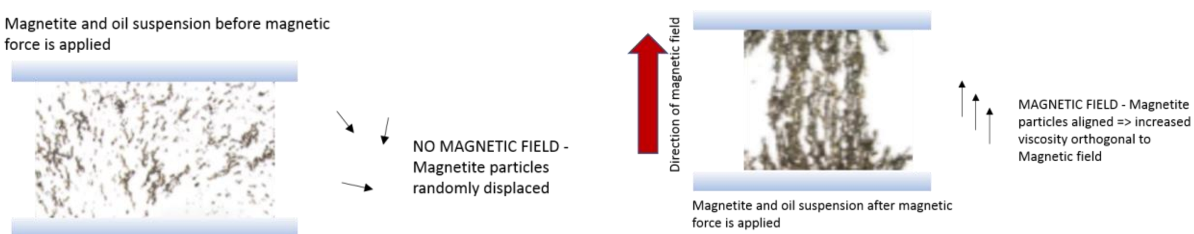
https://www.naturalscienceusa.com/emop-demos1

A magnetic field is used to cleanly separate the magnetite particle from the oil.

Confinement – reduces the spread rate. Oil in water will typically diffuses outward under external forces until it reaches an equilibrium or reaches a boundary. This causes large plumes to form. Once the oil is seeded, the rate of this diffusion is dramatically reduced due to self-interactions of the magnetic particles with the hydrocarbon chains. This leads to a confinement and therefore a reduction in the size of the plume. External forces like waves and the wind have contributing effects; however, when these effects are small the magnetic particles dominate. This is a useful effect in closed systems or in calm waters. With a magnetic boom confinement can be achieved even in the presence of external forces.



Magneto-rheological effects – allows oil to be lifted off surfaces. The particles that are dispersed in oil are randomly distributed. When the magnetic field is turned on, the particles align themselves with the direction of the field. Each becomes a small dipole magnet in the presence of this external field. In addition to aligning with the field, they also attract each other. This directional alignment and attraction add rigidity to the fluid combination (oil + magnetite) which enhances its viscosity effects orthogonal to the direction of the induced field. This induced viscosity ("effective viscosity") produces the rigidity that allows the combination to be lifted from many surfaces including water. (See video #5 at https://www.naturalscienceusa.com/emop-demos1)



Cold water spills. Oil viscosity increases at low temperatures, so recovery, burning and dispersion become more difficult for some oils. In addition, biodegradation of oil occurs at a slower rate compared to temperate conditions. Our electromagnetic oil spill remediation technology is not affected by cold water; in fact, cold water would provide additional cooling for our system making it more thermally efficient.

Unique Features

Electromagnetic remediation technology offers several features that make it unique both in term of its applications as well as its design.

- The particles used are micron sized (~ 10^{-6} m) and provide an efficient bond to oil while abating any environmental hazards associated with smaller scale particles such as nano-particles (~10^{-9} m).
- The magnetite particles are stable and do not break down or form rust in fresh or saltwater applications.
- The design combats wave action by orienting itself in the wave direction. This drives the spill in the same direction as the magnetic force, thereby using an aspect of the problem to enhance the solution.

Product Limitations

The electromagnetic booms (e-booms) can require several kilowatts of power to produce the pulsed magnetic fields for remediation. The power scales with the number of modules employed and with the magnetic fields required to maintain efficiency. This is the most fundamental limitation, which not only drives the cost and scale of the systems but is a practical limitation as well. The coils and modularity of the e-boom systems have been designed and optimized based on these limits.

Electromagnetic remediation provides a novel and disruptive approach to the traditional methods presently used and deployed to combat spills and environmental damage. The support infrastructure that is currently in place around the world has not changed for decades. It was designed and maintained to support standard passive boom and skimmer deployment, the dispersal of chemicals, equipment for burning, and training on these methods. However, because of the flexibility of our system, appropriate training can address and mitigate this limitation.

Advantages/Disadvantages of Various Methodologies

The Deepwater Horizon spill was a huge environmental disaster. And while a multitude of technologies were brought to bear on its clean-up, those efforts continue to this day. In addition, every year there are countless other oil spills here in the U.S. and globally. We still have great need for technological innovations in this area. Natural Science's electromagnetic remediation technologies combine a number of innovations that present unique, efficient and environmentally benign solutions to these and other environmental clean-up situations.

The table below compares in more detail our technologies to existing, traditional clean-up methodologies.

Comparison of Methodologies [2][3]

METHODOLOGY	ADVANTAGES	DISADVANTAGES	COMPETITIVE STRENGTHS OF ELECTROMAGNETIC REMEDIATION
Electromagnetic Remediation Technology System (See above)	• Active - electromagnetic pumping • Remove surface and subsurface spills • Efficient • Controls flow rate without towing • Controls flow direction of spill • Provides containment • Provides separation • Rejects water • Reusable materials • Magnetic effects offer unique properties with oil • Complete system (collect, separate, reuse) • Scalability • Oil reclamation	• Power consumption • Limit of magnetic field range	
Standard Booms A boom is a floating physical barrier used to control the movement of oil. Boom is typically the first mechanical response equipment taken to a spill site. It is used to 1) contain slicks for removal by skimmers or burning, 2) deflect or divert slicks towards a collection area or away from sensitive resources, 3) exclude slicks from selected areas and protect sensitive shorelines and amenities, and 4) ensnare oil by the addition of sorbent material.	• Containment ability • Extensive scalability • Low cost • Extensive availability in a variety of designs, sizes and materials • Towable	• Passive device • Not integrated with skimmers • Spills can go over and under in certain cases • Low tow rates	*Electromagnetic Remediation contains **and collects** oil*

METHODOLOGY	ADVANTAGES	DISADVANTAGES	COMPETITIVE STRENGTHS OF ELECTROMAGNETIC REMEDIATION
Skimmers Skimmers are mechanical devices that physically remove free or contained oil from the surface of water. There are many different types of skimmers but they can be grouped into categories based on oil recovery principles.	• Physically remove oil from the aquatic environment • Available in practically every equipment stockpile • Can be used in any water environment (bays, inlets, etc.) • Their use is widely accepted	• Relatively low encounter and recovery rates especially in thin slicks • Use in high seas and high currents is often not practical • Considerable ancillary and supporting equipment must be planned for • Can be clogged by debris and ice	Skimmers rely on surface tension only and do not control oil dispersal. *Electromagnetic remediation uses electromagnetic forces to control and attract oil flow.*
Sorbents Sorbents are used to recover small amounts of oil through absorption, the penetration of oil into the sorbent material, and/or adsorption, the adherence of oil onto the surface of sorbent material.	Suitable applications of sorbents include: • Final recovery of residual spilled oil in nearshore areas or locations inaccessible to vessels and equipment • Rapid containment of or response to small, inshore spills while slicks are fresh and relatively thick • Cleaning and wiping lightly-oiled surfaces, such as short segments of rocky shoreline • Protecting or cleaning of environmentally sensitive areas, such as turtle egg-laying areas or marshes, where other cleaning methods are restricted because of the damage they could cause	Use of sorbent materials on large spills on water is generally limited by five factors: • Logistics of applying and retrieving sorbents on widespread slicks • Labor-intensive nature of the operation • Relative high cost (versus small skimmers) • Relative low recovery rates • Large amount of solid waste generated In general, use of sorbents is only appropriate during the final stages of a cleanup or to aid in the removal of thin films of oil.	*Electromagnetic remediation has much broader cleanup applications, produces no waste and has no saturation limits.*
Chemical Dispersants Dispersants enhance the natural biodegradation process to speed removal of oil from the water, thereby reducing the potential of oil impacting shorelines, sensitive habitats and wildlife found on or near the sea surface. For maximum effectiveness, dispersants should be applied as close to the source and as soon as possible after a spill. During the early stages of a spill, oil	• Is often the quickest response method • Can be used in strong currents and higher sea states • Inhibits formation of emulsions • Dispersants lower the adhesive properties of oil	• Many governments strictly regulate the use of dispersants • Requires significant logistics planning, including aircraft and/or vessels and refueling capabilities • May adversely affect some marine organisms that would not otherwise be exposed to oil • Not effective on all types of oil under all conditions	*Electromagnetic remediation is environmentally benign and uses materials that are mostly recoverable and reusable.*

METHODOLOGY	ADVANTAGES	DISADVANTAGES	COMPETITIVE STRENGTHS OF ELECTROMAGNETIC REMEDIATION
is un-weathered and less spread out, making it easier to target and disperse.		• If dispersion is not achieved, may decrease the effectiveness of other methods • Adds substances into the marine environment • Limited time window for use	
In-Situ Burning In-situ burning removes oil from a surface by combustion of hydrocarbon vapors and their conversion into predominantly CO_2 and water which are released into the atmosphere. There are often situations where burning may provide the only means of quickly and safely eliminating large amounts of oil.	• Can quickly remove large amounts of oil • Can lessen recovery time and disposal chain for oily wastes • Once ignited, most oils will burn • Can be used in any water environment (marine, estuarine, freshwater) • Can be carried out at night	• Ignition of weathered or emulsified oil can be difficult • Generates smoke and soot • Has inherent but manageable safety risks • Some residues can sink • Fire booms required for burning of freshwater and marine oil spills are large pieces of equipment that are a challenge to rapidly transport	*Electromagnetic remediation does not emit harmful toxins into the environment.*
Bioremediation Bioremediation converts toxigenic compounds in certain oil spills to nontoxic substances through the use of nutrients to enhance the activity of indigenous organisms and/or the addition of naturally occurring non-indigenous microorganisms.	• Low cost solution • Does not require labor intensive equipment • Helps in removing toxic components of oil spill • Environmentally friendly • Minimal physical disruption of site	• Slow process – requires too much time to serve as primary response • Need to specifically tailor to each polluted site • Requires expert evaluation and planning and knowledge of bioremediation • Does not act to contain oil dispersal	*Electromagnetic remediation has much broader cleanup applications and is a much quicker process.*

Product Images

Magnetic Ramp testing

Magnetic Ramp prepared for shipment

Production of Magnetic Ramp

e-Coil Assembly

Price of Product

The electromagnetic remediation systems are designed to be scaled to accommodate the specific spill scenario. The number of modules, the size of the ramp, the separator system, the deployment options, and the power and control systems are all customizable components. The figure of merit that drives the cost of each system is the power and this determines all other system parameters. This cost is $20k/ kW/System.

CONCLUSION

Natural Science believes it has created a significant breakthrough in the cleanup of oil spills and other hazardous materials and hopes the R&D 100 judges agree that we have presented a compelling case not only for an award but also for becoming an important tool for combatting environmental disasters.

References

[1] A. Warner et al., “Development of the Electromagnetic Boom and Mop System (EMOP),” IBIC 2017 http://www.jacow.org/

[2] ExxonMobil Oil Spill Response Field Manual, Revised 2014, Copyright © 2014, ExxonMobil Research and Engineering Company.

[3] Regarding “Advantages” and “Disadvantages” of Dispersants, reference: *IMO/UNEP Guidelines on Oil Spill Dispersant Application*, 1995 edition, IMO, London, 1995.

Patents

[1] A. Warner, Inventor, “Electromagnetic Boom and Environmental Cleanup Application for use in Conjunction with Magnetizable Oil,” US patent 8,795,519 B2.

[2] A. Warner, Inventor, “Electromagnetic Boom and Environmental Cleanup Application for use in Conjunction with Magnetizable Oil,” US patent 9,249,549 B2.

[3] A. Warner, Inventor, “Electromagnetic Boom and Environmental Cleanup Application for use in Conjunction with Magnetizable Oil,” US patent 9,797,538 B2.

Video Presentations

Motherboard – YouTube: “The Magnetic Wand That Cleans Oil Spills – Upgrade”, published December12th, 2014.

TEDx Talk - YouTube: How to clean up and oil spill – magnetize the oil first | TEDx Naperville, Jan 27th ,2016.

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