Wireless communication with mobile inspection robots operating while submerged inside oil storage tanks

Richard Anvo[1], **Aman Kaur** [2] and Second **Tariq P. Sattar** [2]

[1,2,3] London South Bank University Innovation Centre, London, UK
anvon2@lsbu.ac.uk

Abstract. Data acquisition during storage tank inspection is one of the most important aspects for petrochemical storage tank owners. Mobile inspection robots designed to enter inside a storage tanks without taking the tank out of service are required to enter through manholes on the roof of the tank with openings as small as 300-millimetre diameter. These robots are controlled via an umbilical cable which supplies power to the robot, sends and receives signals to control robot motion, and transfers inspection data acquired by non-destructive testing (NDT) sensors back to NDT inspectors. It is important to localize a robot inside the tank so that NDT data indicating a defect such as corrosion pitting in tank floors or weld cracks can be mapped for subsequent monitoring and repair. Wireless communication with the robot for NDT data acquisition and localization would enable the minimization of umbilical size and its effective management which is important when a small mobile robot is supplied with a very long umbilical. This paper presents results of a study to develop a wireless communication system that uses radio frequency (RF) signals with low power (< 1W) sent by a transceiver on a robot operating inside an oil storage tank which travel through an oil medium, are transmitted through steel tank walls and are captured by receivers placed in air outside the tank. Simulations using Feko software have been performed to assess the feasibility of using RF for communication in oil storage tanks with laboratory experiments conducted using vegetable oil to validate the simulations. RF signals transmitted by a robot operating inside an oil tank and received by a number of receivers placed in air around the tank has potential application as a robot localization system.
Keywords: Storage tank inspection, EMW, NDT, In-service inspection.

1 Introduction

Several in-service storage tank inspection robots have been developed over the last decade [1], [2] for the purpose of storage tank inspection. During normal inspection operation, these robots gather non-destructive ultrasonic data and are powered via an umbilical cable. However, managing their umbilical cable (>100m) could introduce significant problem because most storage tanks contain some heating coils and roof legs support which make a robot less free to move around to inspect the tank floor corrosion.

Radio Frequency (RF) is a promising technology for many wireless applications due to its large bandwidth, a good ratio of transmission data and low cost. All in-service inspection for petrochemical storage tank robot explored so far have used

Corresponding author: Richard Anvo

cables for robot control and NDT data transmission [3], [4], [5], [6] and [7]. Using very low power with low-frequency RF communication in this environment would be a critical forward step to the widespread uptake of in-service inspection robots because it would eliminate the inspection challenges associated with heating coils and tank roof supports as well as data transmission and for robot localisation. Currently, no work on Radio Frequency communication for in-service inspection robots in petrochemical storage tanks has been published. Associated research on underwater wireless communication is reported in [8], [9] and [10]. Wireless applications for the oil and gas industry past and present methods of communication in oil and gas have included satellite communication (on a limited basis), cellular and specialised mobile radio, fibre-optics, and general offshore telephone service using radio frequencies [11].

So far, all RF devices are designed to work in the air and tested in water environments. However, this paper presents an investigation of radio frequency communication in petroleum media and vegetable oil. Experiment and simulation with commercial electromagnetic software, FEKO and Multiphysics COMSOL 5.4 were used to test and to analyses the attenuation of electromagnetic wave (EMW) propagation in petroleum products and vegetable oil. Section 2 of this paper describes electromagnetic wave absorption with media parameters, section 3 calculation of electromagnetic path loss in petroleum and vegetable oil, section 4 simulation results of the EMW propagation, whilst section 5 describes experimental EMW data transmission in vegetable oil, followed by conclusions and future work in section 6.

2 Electromagnetic wave absorption and dispersion through petroleum products and other medium

The propagation of an electromagnetic wave through matter is governed by three proprieties of the material: conductivity (σ), permeability (μ) and permittivity (ε) or dielectric constant. These parameters' changes with the medium and the electrical conductivity value associated with the medium often vary. Therefore, the wave propagation speed and absorption coefficient, which are directly related to the working frequency, also vary. The electromagnetic wave absorption and dispersion for wave propagation through medium is calculated using equations (1) and (2). Table 1 shows the absorption and dispersion of EM waves with given petroleum medium, air, seawater and vegetable oil.

$$\alpha = \omega \sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right]} \tag{1}$$

$$k_d = \omega\sqrt{\mu\varepsilon_0 k} \tag{2}$$

The dispersion of the Electromagnetic Wave (EMW) varies with the frequency **Table 1**, a higher frequency means strong scattering of the wave and less travel distance. However, the absorption of EMW in Vegetable oil, Gasoline and Kerosene is zero, therefore, there is no resistance to EMW propagation due to their very low electrical properties. The dielectric constant is the most critical factor that affects the propagation of petroleum. Their properties are a function of temperature, so the increase in temperature leads to an increase of attenuation during communication in petroleum. Another factor that could affect the signal depends on water concentration in the petroleum product. The increasing water content will increase power loss. The selection of the optimal RF frequency is an essential factor for realising robot ultrasonic sensor data transfer or robot localisation in a storage tank. Selecting higher frequency than the optimal will increase the attenuation due to wave absorption and limit the distance of propagation.

Table 1. EMW absorption and dispersion in a given medium

Frequency	Medium	Vegetable oil	Gasoline	kerosene
433 MHz	Absorption(N/p)	0	0	0
	Dispersion(rad/s)	15.97	12.83	11.83
300 MHz	Absorption (N/p)	0	0	0
	Dispersion(rad/s)	11.08	8.89	8.20
250 MHz	Absorption (N/p)	0	0	0
	Dispersion(rad/s)	9.22	7.40	6.83
200 MHz	Absorption (N/p)	0	0	0
	Dispersion(rad/s)	7.38	6.63	5.46

3 Calculation of propagation path loss in petroleum and vegetable oil

The path loss is a significant component in analysis and design a telecommunication system. It is the reduction in the power density of the electromagnetic wave as it propagates through the medium. The path loss is calculated using equation (3), the medium is known as a dielectric.

$$\boldsymbol{L_{path\ loss}\,(dB) = L_0(dB) + L_w(dB) + L_{att}(dB)} \qquad (3)$$

Where L_o(dB) path loss in the air, L_w (dB) is path loss due to the medium change and L_{att} (dB) is path loss due to attenuation in the medium. The attenuation constant $\alpha = 0$, therefore, the path loss becomes:

$$L_{path\ loss}\,(dB) = L_0(dB) + L_w(dB) \tag{4}$$

The effect of frequency on the path loss at a distance of 1 m between the transmitter and receiver antenna is illustrated in **Fig. 1**, which shows that as the frequency increases the path loss also increases. Path loss increased in vegetable oil compared to gasoline and kerosene fuel due to its high dielectric constant.

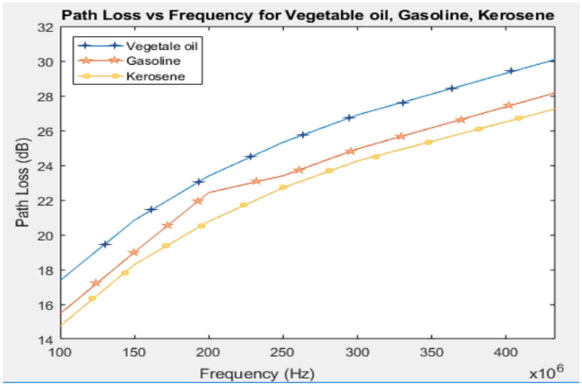


Fig. 1. Path Loss as a function of frequency for Vegetable oil, Gasoline and Kerosene

4 Simulation results of electromagnetic wave propagation in different mediums

4.1 Simulation results 3D radiation pattern

The software used in this design simulation was the popular commercial electromagnetic software FEKO. A dipole antenna was designed with a 433MHz. To simulate electromagnetic propagation in the medium, a box cube with a size of 4 x 4 x 4 meters was used to represent the medium in which the electromagnetic wave will propagate, see **Fig. 2**. The simulation involved four different types of medium based such as diesel fuel, jet fuel, vegetable oil and water. The antenna was placed in the air at 3 meters away from the medium represented by the box cube.

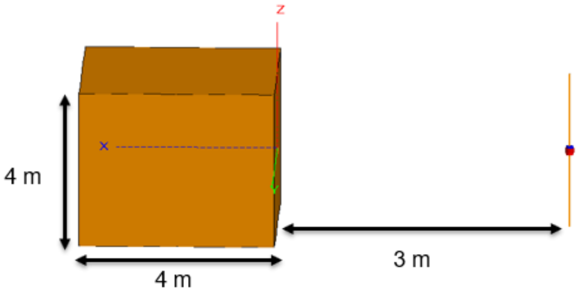


Fig. 2. A 3D view of the dipole with a cube (medium) model.

Fig. 2 shows that the 3D radiation pattern of the dipole is distorted; nevertheless, a strong radiated power is going through the medium (diesel fuel, jet fuel, and vegetable oil) with maximum gain compered to water. Hence, electromagnetic waves propagate easily in a dielectric medium with less distortion than the conductive medium.

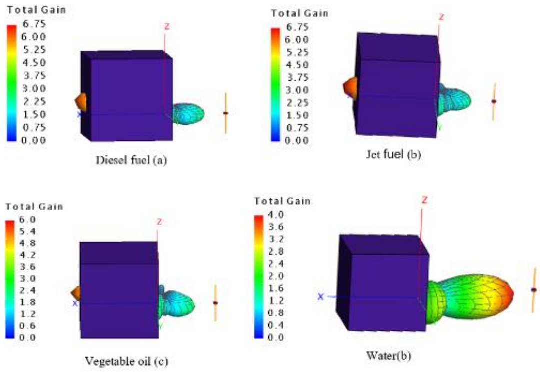


Fig. 2. A full 3D plot of the antenna radiation pattern (gain).

4.2 Simulation results time domain electric field

The time domain simulation using Multiphysics COMSOL 5.4 was setup with LoRa611Pro wireless transceiver data transmission module properties. LoRa611Pro is a commercial radio frequency module for data transmission. The aim was to observe whether attenuation of the electromagnetic wave crossing the steel wall of the storage tank will be detected at the receiver. The electric field, signals were studied with different types of medium such as vegetable oil and petroleum. Real dimension of petrochemical storage tank was setup with an appropriate tank wall thickness in this simulation. **Fig. 3** shows a 2D drawing of the storage tank, two wireless transceivers were used, one of the transceivers located at 25 meters submerged in steel tank with petroleum medium or vegetable oil and the other transceiver located at 3 meters from the tank wall in the air. The thickness of the steel tank wall was setup to be 10.00 mm and the size of the tank was 50 meters in diameter. The tank properties were selected using the American Petroleum Institute standard (API 650 section 5.6.1.1) which specifies the range of petrochemical storage tank sizes and defines the minimum wall thickness required to avoid tank stress.

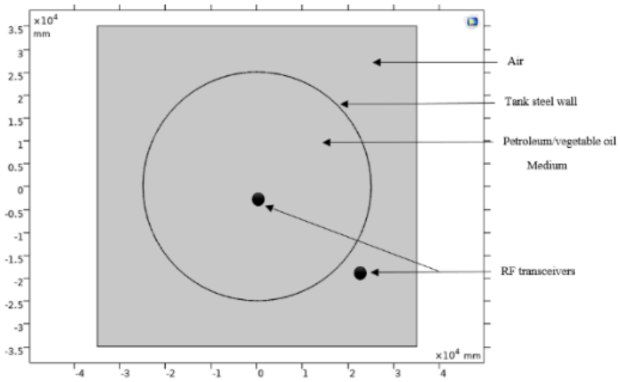
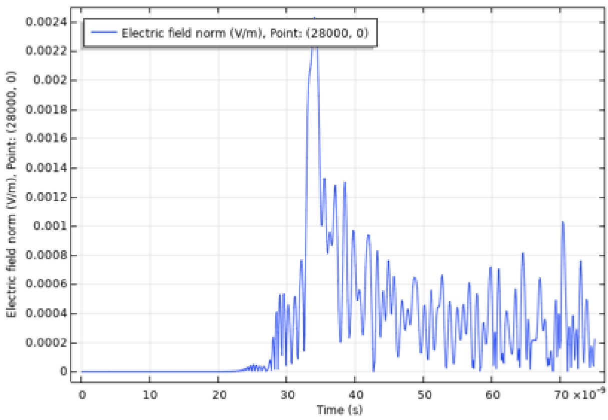
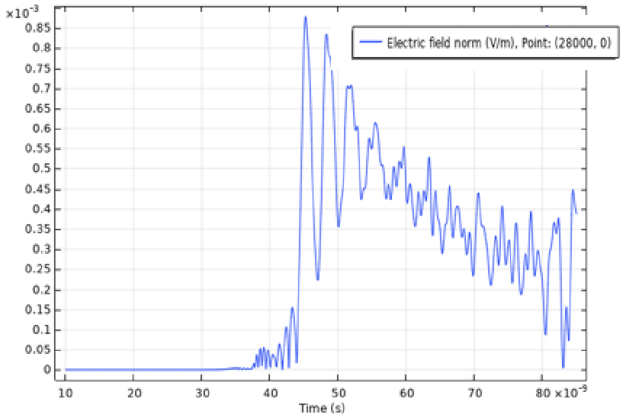


Fig. 3. 2D storage tank setup with two transceivers antenna

Fig. 4 shows two sets of simulation in the air, with the propagation of the electromagnetic wave in the air with no steel wall between both transceivers and another set with steel.



(a)

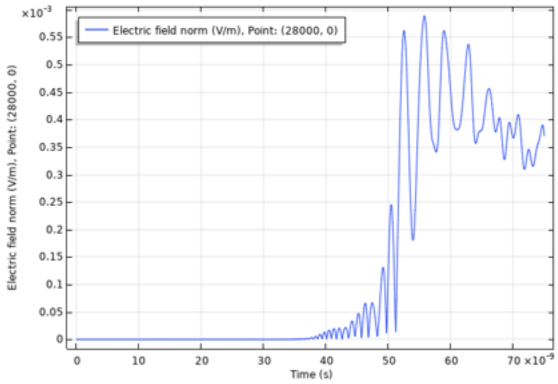


(b)

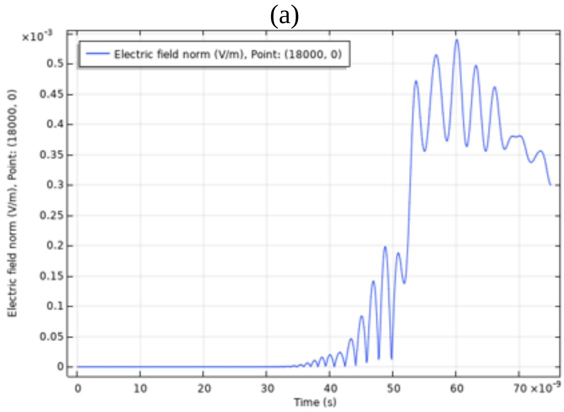
Fig. 4 Electric field propagation between two 433 MHz transceivers antenna beacon in air with (a) steel wall and (b) without steel wall

Propagation in the air with no steel wall shows that the maximum electric field strength is 0.0024 V/m at about 35 seconds compared to propagation in the air with steel wall where the maximum electric field strength was 0.85 $x10^{-3}$ at about 46 seconds. The presence of the steel wall attenuates the electromagnetic wave which is evidenced by the reduction in the electric field strength.

The simulation results for the electric field strength for vegetable oil, diesel fuel and kerosene medium are also presented in this paper. The electric field strength was tested with electromagnetic wave transmission in both directions from air to the medium and medium to air through the steel tank wall. Electromagnetic wave propagation through vegetable oil as medium (**Fig. 5**) has average electric field strength in both direction of 5.1 $x10^{-4}$ V/m compared to electric field strength in the air with steel wall stated in **Fig. 4** which was 0.85 $x10^{-3}$ V/m. Similarly, the average of the electric field strength (**Fig. 6**) of the electromagnetic wave propagation in diesel fuel in both directions is 6.3 $x10^{-4}$ V/m. Compared to the EMW propagation in the air with steel tank wall the electric field strength was 0.85 $x10^{-3}$ V/m. Finally, the average electric field strength (**Fig. 7**) in kerosene fuel medium is 6.95 $x10^{-4}$ V/m compared to 0.85 $x10^{-3}$ V/m for electric field strength in the air with steel tank wall. The electromagnetic wave travels faster in the air than diesel fuel, kerosene fuel and vegetable oil medium.

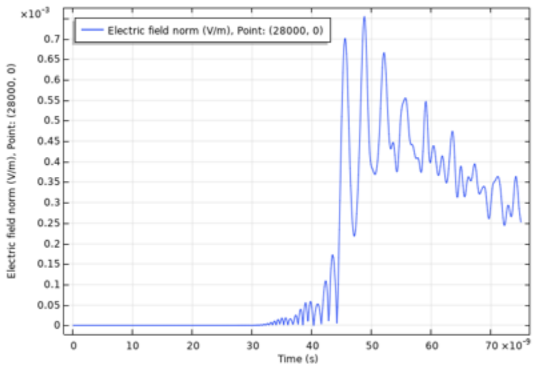


(a)

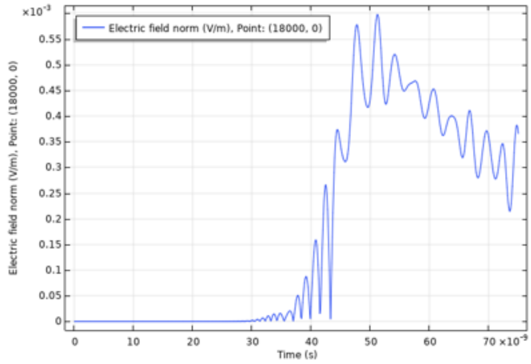


(b)

Fig. 5. Electric field propagation between two 433 MHz transceivers antenna beacon in vegetable oil used as a medium with receiver beacons located (a) inside tank and (b) outside tank

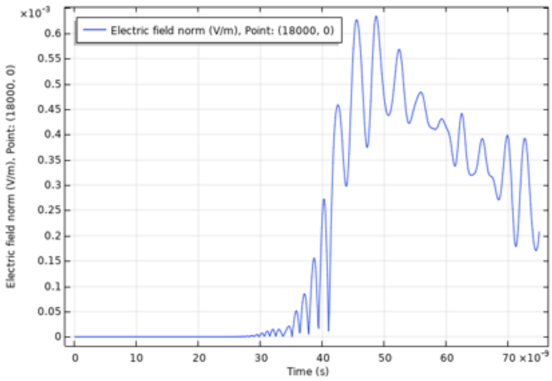


(a)

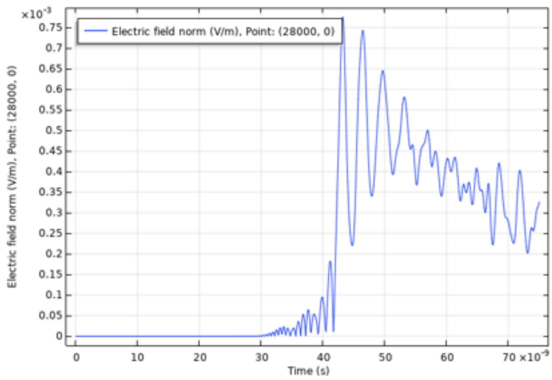


(b)

Fig. 6. Electric field propagation between two 433 MHz transceivers antenna beacon in diesel fuel used as a medium with receiver beacons located a) inside tank and b) outside tank



(a)



(b)

Fig. 7. Electric field propagation between two 433 MHz transceivers antenna beacon in kerosene fuel used as a medium with receiver beacons located a) inside tank and b) outside tank

5 Experimental results

The Radio Frequency device used in this experiment was low power LoRa611Pro wireless transceiver 433 MHz data transmission module. The module implements Lora technology to achieve sufficient sensitivity and excellent anti-interference with 100mW output power. Two transceiver modules are used, and each transceiver was sealed into a waterproof enclosure with end connection adapter RS485 interface for computer usb connection. **Fig. 8** (a) (b) show both antennas in an enclosure.

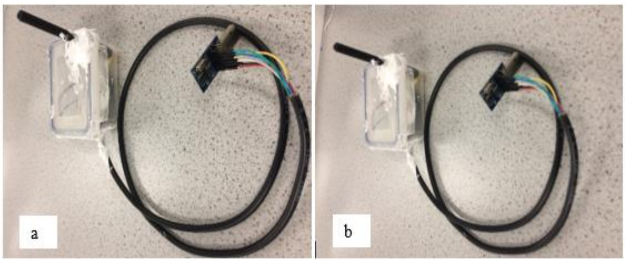


Fig. 8. RF transceivers

both data transceivers were submerged into vegetable oil for data transmission **Fig. 9** (a) and when one data transceiver was submerging and other one left in air **Fig. 9** (b). In this experiment, mixes data were set up and transmitted from one computer to another.

Fig. 9. RF transmission vegetable oil/vegetable oil (a) and air/vegetable oil (b).

A design user interface was used to send data and read data **fig. 10**. The GUI was connected to the RF antenna via a computer communication port. In this investigation, a different type of data was used, such as string data sent through a computer connected to the antenna via communication port 4 (COM4). **Fig. 9** (e) and **Fig. 9** (h) shows the transmitter control user interface and the other computer connected to the receiver antenna via communication port 6 (COM6). The data transmitted was identical to the data received, no loss of information while transmitting through vegetable oil.

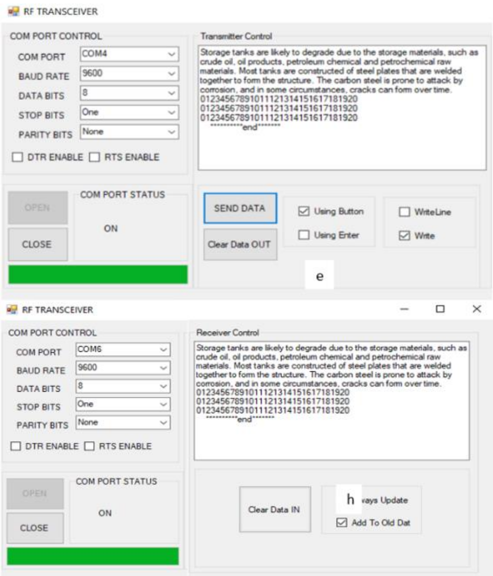


Fig. 10 RF GUI transceiver

6 Conclusion and Future Work

The simulation of electromagnetic wave radiation through petroleum products and vegetable oil has shown some attenuation of an electromagnetic wave through directivity pattern and electric field strength. The time domain simulation has faster propagation in petroleum medium than vegetable oil medium. The experiment for data transmission was investigated with vegetable oil used as a medium. The data were correctly transmitted and received without loss with low power LoRa611Pro wireless transceiver 433 MHz data transmission module. The simulation has shown the electromagnetic wave travel at low speed in vegetable oil compared to petroleum medium. Therefore, radio frequency could propagate better in petroleum products than vegetable oil with less dispersion and path loss. This technology will reduce the problem of heavy umbilical cable for mobile robot and solve the robot localisation problem in the tank.

References

1. J. I. Chang and C. Lin, "A study of storage tank accidents," *Journal of Loss Prevention in the Process Industries*, vol. 19, no. 1, pp. 51–59, Jan. 2006
2. American Petroleum Institute. API Standard 653: Welded steel tanks for oil storage. Washington: American Petroleum Institute, (2014).
3. Maverick Demonstration "Submarine that goes in Gasoline", Solex Robotics, http://www.solexrobotics.com/Solex6.html.
4. H. Schempf, B. Chemel, and N. Everett, "Neptune: above-ground storage tank inspection robot system," *IEEE Robotics & Automation Magazine*, vol. 2, no. 2, pp. 9–15, Jun. 1995.
5. T. P. Sattar, H. E., and J. Shang, "Amphibious NDT Robots," in Climbing and Walking Robots: towards New Applications, no. October, I-Tech Education and Publishing, 2007.
6. Che, X. "A Static Multi-Hop Underwater Wireless Sensor Network Using RF Electromagnetic Communications", Icdcs: 2009 International Conference on Distributed Computing Systems Workshops, pp. 460–463. doi: 10.1109/ICDCSW.2009.36.
7. T. P. Sattar and H. Leon-Rodriguez, "Surface Adaptation Robot for Defect Detection by Performing Continuously an Ultrasound Wheel Probe," in *Nature-Inspired Mobile Robotics*, 2013, pp. 367–374.
8. Rydl, L. and Simpson, C, "Wireless technology uses in the oil and gas industry", V(2), 2004, pp. 666–672.
9. Lloret,J. "Underwater wireless sensor communications in the 2.4 GHz ISM frequency band," Sensors (Basel, Switzerland), 12(4), 2012, pp. 4237–64. doi: 10.3390/s120404237.
10. Centelles, D. "Wireless RF Camera Monitoring for Underwater Cooperative Robotic Archaeological Applications", 2015, pp. 100–102
11. Techcorr.com. 2011, In-Service Tank Inspection, http://www.techcorr.com/in-service-tank-inspections.php