DEVELOPMENT AND ASSESSMENT OF AN INSPECTION TECHNIQUE FOR COATING EVALUATION

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ABSTRACT OF THESIS

DEVELOPMENT AND ASSESSMENT OF AN INSPECTION TECHNIQUE FOR COATING EVALUATION

The US Navy spends around $75 million on maintenance and rework of corroded structures, especially in the ballast tanks of ships. The Navy will profit immensely with better surface coating and ‘quality at source’ with real time inspection system. The approach taken to improve the coating is the use of optically active paint system. This kind of paint will fluoresce with an incident UV light. The fluorescence or glow can be used to detect holidays or defects on the surface.

The inspection prototype developed uses a high end camera and intense UV light source. The paint and additive properties are characterized with the help of ultraviolet-visible spectroscopy (UV – Vis) to study the behavior and to help formulate a theory. The ‘holidays’ or missed spots in the painted surface will appear dark and non-fluorescing which is enhanced with the use of commercial filters.

Key words: spectroscopy • inspection system • optically active paint • fluorescence • holidays •

Mangesh Suresh Kolharkar
Date: 02/10/2004

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DEVELOPMENT AND ASSESSMENT OF AN INSPECTION TECHNIQUE
FOR COATING EVALUATION

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DEVELOPMENT AND ASSESSMENT OF AN INSPECTION TECHNIQUE
FOR COATING EVALUATION

THESIS

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in the
College of Engineering at the
University of Kentucky

By

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Lexington, Kentucky

Director: Dr. Kozo Saito, Professor of Mechanical Engineering
Lexington, Kentucky
2004

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TO MY PARENTS
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I would like to thank Mr. Paul Gossen and Mr. Jay Angal from the National Surface Treatment Center not only for their financial support but also for their valuable guidance.

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Corrosion is one of the most costly and serious problems the metal industry has been facing over the years. The cost of corrosion to the national economy is still a significant concern to the industry. Paints or coatings offer high degree of protection to the metal substrate from corrosion as it shields the exchange of ions between the metal and the environment which is the cause of corrosion. The work done by the paint manufacturers to improve the performance of coating in protecting the metal from corrosion or rusting often faces the following challenges:

a) Operational difficulties
b) Application mistakes
c) Finished coating defects

The operational difficulties can be minimized by following the instructions provided by the paint manufacturer on how to properly mix the paint and use the equipment. Application mistakes occur due to human error and can be kept to minimum. If these two parameters are not controlled then it is expected that defects in the finished coatings would occur. To detect these defects a good inspection system is required to recoat the required areas before the coated surface is set for functional use.

Since the corrosion initiation process occurs when bare metal gets in contact with air or water and ionic exchange process takes place, even the smallest missed spot in the coating can ignite the corrosion process for the substrate very easily. Corrosion can be harmful to the functionality and structural integrity of the coated part and is a major problem for bridges, cars, buildings, ships etc. The presence of saline environment makes the corrosion protection requirements of the marine paints used in ships very demanding. Ballast tanks of the ship are more susceptible to corrosion due to the storage of sea water in it. The anti-corrosion marine coating of these ballast tanks should be of the highest quality to avoid the deterioration of the substrate. This work concentrates on the corrosion of marine ballast tanks of the ship.
1.1 BALLAST TANKS

Ballast tank maybe defined as a water tight container used to carry solid or liquid weight on a ship and facilitates increase of draught, change of trim or improvement of stability [1]. Depending upon the size and design, there can be numerous ballast tanks in one ship. A schematic diagram of the ballast tanks in a ship is shown in Figure 1.1. There are over 2900 ballast tanks in the U.S. Navy inventory and re-preservation of these tanks costs the fleet roughly $75M annually [2].

These ballast tanks come in various sizes from as small as 4’x 4’x 4’ to as large as 40’x 60’x 60’ [4]. There are no standard shapes and sizes for the ballast tanks and so inspection of

Figure 1.1: Typical ballast tanks in a cargo ship [3]
every tank is different. These tanks don’t have any support on the inner walls to climb or hold except for the scaffolding which is temporarily made available during the painting and inspection procedure. The entry into these ballast tanks is typically through a man hole as shown in Figure 1.2. These ballast tanks also have stiffeners, beams and welded areas which are difficult to paint and are often missed by the paint applicator.

![Manhole for ballast tanks](image.png)

Figure 1.2: Manhole for ballast tanks [5]

The ballast tanks once inspected and cleared for usage are commissioned for service. The specifications for current life expectancy of a well coated ballast tank is typically around 10 years as protective coatings when properly formulated and applied, are usually expected to last for ten years with periodic maintenance [6, 7]. During the voyage the ballast tanks are used to maintain the equilibrium of the ships. Whenever the storage from the ship is discharged, the appropriate ballast tanks on the ship are filled to compensate the weight. This loading process of the ballast tank is demonstrated in the Figure 1.3.

The modern ballast tanks of the ships are coated with solvent free epoxy coating. However, poor coating application results in coating voids or ‘holidays’, that reveals the steel substrate to direct contact with sea water and air causing corrosion initiation spots that spread over the tank with time leading to major deterioration of the substrate.
The reason for failure in good quality coatings is mostly stress, which can be produced by the following causes [8]:

a) Mechanical stress
b) Internal stress
c) Chemical attack
d) Weathering stress  
e) Stress due to equilibrium  

These factors are controllable and often taken care by the paint manufacturer through an appropriate formulation and recommendation for optimal application procedure.

Commonly, the onset of corrosion occurs in poor quality coatings, which can be caused due to one or more of the following reasons:

a) Missed areas: Areas without paint (big or small)  
b) Under coated areas (Under mileage): Areas with paint layer thinner the specifications  
c) Entrapment of foreign particles: Presence of external bodies between coatings and substrate  
d) Poorly prepared substrate: Substrate which has already initiated corrosion

This work will concentrate on detecting missed and undercoated areas. To consistently detect these coating defects a good, repetitive and reliable inspection system is required.

1.2 BACKGROUND

As mentioned earlier, ballast tanks come in different shapes and sizes without any standards. The rugged environment, unknown geometry, huge size and hard to reach areas are the major challenges in designing the inspection system. It is hence not surprising that regardless of the technological advances the current process of inspection is still manual and relies heavily on the tank inspector [4]. The inspector enters a tank after the paint is cured with different gauges and randomly inspects some areas in the tank which are sensitive, like edges and corners. According to the input from the visit to a shipyard, the inspector knows that the paint applicators are experienced enough to paint the plain surfaces well so he does not care too much about these areas. If he does not find any defect or under-coated area then he ‘passes’ the tank. The inspector makes a decision of recoating a tank depending on the percentage area of the tank under-coated or missed. The technique fails to document the results and is not 100% accurate as it heavily relies on human discretion and judgment.

The inspectors sometimes also use a technique called ‘wet sponge technique’. This technique is suitable for locating pinholes through a non-conductive coating to a conductive substrate. A sponge, moistened with a wetting agent, is supplied with a low voltage. When the sponge is moved over a pinhole, liquid penetrates to the substrate and completes the electrical
circuit. The resulting current flow generates an audible alarm in the detector [10]. The equipment is shown in Figure 1.5.

![Figure 1.5: Equipment used in wet sponge technique [10]](image)

This technique is more reliable as compared to human inspection and can detect missed spots but is very cumbersome and requires 100% inspection. Hence is less productive. The wet sponge technique also is difficult to use on edges and corners as the wet sponge is difficult to maneuver. Both the inspection techniques rely on contact with the surface and cannot give feed back in real time nor within the recoat interval as the paint is not cured. The cost associated with a delayed feed back is substantial as the paint crew has to again create their setup and redo the job.

To overcome these disadvantages, the US Navy and the marine coatings manufacturer’s developed a new paint system which contains a uniformly dispersed additive known as optically active additive (OAA). This additive will fluoresce in the presence of ultraviolet (UV) light of a specific wavelength. The fluorescence will distinguish between the coated and the un-coated areas and make real time inspection possible for the paint applicator with an additional UV light mounted on his paint gun. The fluorescence will enhance the ability of the paint applicator to identify the un-coated or under coated areas. The idea was to eliminate the inspection stage in the paint coating and make real time paint process monitoring possible.

Though the paint system was developed and has been use for around 2 years, it lacked crucial data and standardization between different paint manufacturers. The effect of percent loading, required lighting conditions, process of interpretation of fluorescence observed etc. were unknown. Hence only limited success was achieved with the optically active paint system as real
time inspection was not feasible at this stage and it could assist only visual inspection which was subjective, non-regulated and non-repetitive.

Though many paint inspection techniques have been developed, till today no particularly relevant work has been done in the field of optically active paint inspection system. One of the additive manufacturing companies has filed a patent in the United Kingdom [11] describing the working of the optically active paint system. The patent also speaks about the inspection of the ballast tanks with digital camera and light meter using this technique, but does not give the specifics of inspection method or the results.

1.3 RESEARCH OBJECTIVE

Within the above frame of ideas, the objective of the research is to understand the fluorescence process and how the additive works in the paint system. This would involve development of a theory to confirm the behavior exhibited by the paint system, analysis of this behavior and to selection of an optimum balance between cost and performance in order to justify the use of the OAA paint system. The outcome of this study will also help in creating a set of specifications and testing the technical feasibility of the system.

Also, an inspection system would be developed to detect and document the defects with high performance. The inspection system is targeted for the tank inspector as it is an easier first step towards the final goal of real time inspection with the help of paint applicator.

The inspection system should satisfy the following conditions:

1. Work effectively with the optically active paint system
2. Provide real time inspection
3. Exhibit better and reliable performance as compared to current systems
4. Provide higher productivity as compared to current systems
5. Should be effective around stiffeners and corners
6. Must be able to document results
7. Must be ergonomic and compact

This system which would be developed in the labs also requires a field trial to test the capabilities in the real world and to get feedback on the challenges it faces.

To analyze the behavior of paints and additives and to compare their performance, a grating spectrometer will be used. In the chemical industry, spectroscopy analysis is a common
tool used to predict or detect the behavior of chemical compounds. This technique is often used for gases and liquids as in the analysis of the chemical derivation of compounds like formaldehyde in its super critical medium by F. Reche at el. [12] or in the measurement of zinc oxide film emission by Rodrigo Ferreira Silva at el. [13]. A few broader applications of spectroscopy in opaque medium or solid substances and the ones in paints are mostly of UV absorbers; in clear coats to study their weathering performance [14] and in automotive paints to study their photo-oxidation resistance by J.L. Gerlock at el. [15] or to study their behavior in detail by C.A. Smith at el. [16]. Analysis of paints and coatings is done by Ulrich Schemau at el. [17] in the analytical laboratories with methods like Infrared (IR) spectroscopy, Nuclear magnetic resonance (NMR) spectroscopy, Ultraviolet - visible (UV-Vis) spectroscopy, gas chromatography, liquid chromatography etc. Hence characterization of the optically active paint system with the use of spectroscopy is pioneer work in this field as no relevant work has been conducted for this particular kind of paint.

UV – Vis spectroscopy is selected for fluorescence emission as most molecules absorb and emit energy in the UV – Vis region. UV – Vis spectroscopy is also know as absorption and emission spectroscopy and can be conducted for atoms, gaseous molecules, liquids and solids [18]. Ultraviolet – Visible (UV – Vis) spectroscopy allows the study of the characteristics for the optically active additive and to find the optimum loading required in the coating material or paint. Different available paints and ambient lights will also be characterized as it form an integral part of the inspection system due to safety regulations which require the ballast tanks to be well lit during the inspections.

For confidentiality purposes the different vendors providing paint for our analysis would be referred to as Vendor A, Vendor B and Vendor C in order to maintain the data integrity. The two types of additives would also be referred to as Additive X and Additive Y.

The characterization of the paint system and the ambient lights will form the base line to design imaging experiments. We will be testing different permutations and combinations in the imaging experiments to find the optimum parameters in order to achieve the best image of the defects. The imaging experiments setup and parameters will be replicated in the prototype for the field trial.

The optical inspection system developed will use non-destructive testing (NDT) techniques to assess the coating quality. It will consist of a high-resolution digital camera
(detector), an intense narrow-band UV light source (stimulator), and a post-processing algorithm. The components of the system are positioned to achieve the optimum detection performance while maintaining single hand operation. This prototype will be commercialized and refined later by professional product developers and launched for the use in ship yards.

1.4 PROJECT BREAKUP AND THESIS STRUCTURE

The project is still in progress and includes deeper analysis and development in the field of spectroscopy, image processing and prototype development.

![Diagram showing project breakup]

Figure 1.6: Project breakup

The thesis consists of two basic sections:

- Paint, additive and auxiliary equipment characterization
- Prototype development and testing

Chapter 2 will include the theory on how the paint system works, design of experiments for spectroscopy and imaging. The results and discussion from spectroscopy analysis are presented in Chapter 3. Chapter 4 will deal with the prototype development and field trial details and results. It will also include the drawbacks of the current prototype developed and probable solutions for the same. The last chapter will include conclusions and future work in the areas of spectroscopy and prototype development.
Figure 1.7: Thesis breakup
CHAPTER 2

THEORY AND EXPERIMENTAL CONSIDERATIONS

2.1 THEORY OF FLUORESCENCE IN THE PAINT SYSTEM

The fluorescence phenomenon is complex and requires additional knowledge of microenvironment of the compound in which it occurs. In this chapter an attempt is made to explain the working of the fluorescence model in the paint system. This chapter also covers the details of the experimental setup and sample preparation.

The basic objective of using fluorescence additives in the paint is to enhance the contrast between a missed spot or “holiday” and coated surface. We expect that with the increase in contrast, the eyes or any other detector can pick the holidays more easily.

Figure 2.1: Sample image in white light (Left) and ultraviolet light (Right)

![Figure 2.1: Sample image in white light (Left) and ultraviolet light (Right)](image)

Figure 2.2: Intensity profile for Defect A in white light (left) and ultraviolet light (right)

![Figure 2.2: Intensity profile for Defect A in white light (left) and ultraviolet light (right)](image)
The intensity profiles obtained using MATLAB, describe the data obtained at defect A in terms of red, green and blue levels (RGB). In figure 2.2 (left), the red level plays the prominent role and the defect is picked with a dip in intensity of around 100 counts in red, 50 counts in green and 30 counts in blue. In figure 2.2 (right), with the help of optically active additive we achieved a better blue shade and the defect here is picked with a dip of 120 counts in blue, 50 counts in green and 10 counts in red. The overall dip in both cases is around 180 counts but with the help of blue we enhance the image characteristics and create a better contrast with the black defects as compared to red.

This contrast is achieved by addition of a uniformly dispersed optically active additive to the paint which absorbs light energy at a specific wavelength (ultraviolet 365nm) and emits the absorbed energy at a visible wavelength (more than 420nm). The phenomena of absorption and emission in a molecule include intricate details which are described below.

2.1.1 UV light travel and absorption

OVERALL BALANCE

Total UV light =
Light scattered in the medium + Light reflected by surface + Light absorbed by molecules

The UV light incident on the surface of the sample is not absorbed totally by the molecules of optically active additives. Some of it is scattered in the medium during its travel to the sample, some is reflected by the surface or internal molecules and the remaining is absorbed by the molecules of the additive.
Figure 2.3: Schematic for the break-up of UV light

X, X₁, X₂, and X₃: Absorbance of molecules which in turn produces fluorescence
The atom absorbs the UV light energy and emits a discreet amount at a particular wavelength range. This is explained by Planck’s theory. Hence every molecule can absorb and emit energy only at selective wavelengths according to the molecular structure.

**Table 2.1: Planck’s theory [19]**

<table>
<thead>
<tr>
<th>Planck’s theory</th>
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<tr>
<td>Atom of a particular wavelength can emit only a discreet amount of energy (expressed in quanta) even though it can absorb larger amounts. The wavelength of light is inversely related to its energy.</td>
</tr>
<tr>
<td>E = hν</td>
</tr>
<tr>
<td>Or E = ch / ?Ô</td>
</tr>
<tr>
<td>where, E: Energy (J)</td>
</tr>
<tr>
<td>?: Wavelength (m)</td>
</tr>
<tr>
<td>c: speed of light in vacuum 2.9979 x 10^8 ms⁻¹</td>
</tr>
<tr>
<td>h: Plank’s constant = 6.6262 x 10⁻³⁴ Js</td>
</tr>
<tr>
<td>v: frequency of atoms (s⁻¹)</td>
</tr>
<tr>
<td>Light of certain wavelengths can be selectively absorbed by a substance according to its molecular structure.</td>
</tr>
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</table>

The energy absorbed by molecules is uniform along the layers of molecules and the actual amount absorbed depends on the percent of light incident on it. This is explained by Beer-Lambert’s law. So the layers which receive the incident energy first will absorb a certain percent out of the incident energy depending upon the properties. The remaining energy is either reflected or transmitted. The transmitted energy will be incident on the second layer and these molecules will absorb the same percent as the first layer of molecules but from lower incident energy. The process will continue in this fashion. This law also shows that energy absorbed by molecules is proportional to the number of molecules. A transparent medium described in the law is a medium which can transmit light.
Table 2.2: Beer Lambert’s law [19]

**Beer Lambert's law**

The fraction of the light absorbed by a transparent medium is independent of the intensity of incident light and each successive layer of the medium absorbs an equal fraction of the light passing through it.

\[
\frac{A}{k} = Stl
\]

\[
\log_{10} \left( \frac{I_0}{I} \right) = kl
\]

Where, 
- \( A \): Absorption of the medium (m)
- \( S \): constant for a given wavelength
- \( I \): light intensity after it passes through the medium
- \( I_0 \): light intensity before it passes through the medium
- \( k \): concentration of solution (M)
- \( l \): path length (m)

Beer’s law claims that the amount of light absorbed is proportional to the number of molecules of the chromophores through which the light passes.

The energy absorption process can be described in details with the energy diagram shown in figure 2.4. Though this figure describes the simplified process of fluorescence, there can be other de-excitation processes for the excited molecule to achieve stable state. This process which also includes a triplet state in the equation of excitation and de-excitation is shown in figure 2.5.

![Energy Diagram](image)

**Figure 2.4: Simplified energy diagram for fluorescence emission**

1: Absorption of UV light, 2: Vibrational relaxation and/or collision, 3: Relaxation to initial stage, \( S_0 \): Ground state, \( S_1 \) & \( S_1' \): Excited state
Absorption (A) of the light quanta by the OAA molecule induces transitions from the singlet ground state ($S_0$) to vibrational levels of the electronically excited singlet states ($S_1$). Molecules in the $S_1$ state are deactivated by several routes. Fluorescence results from radiative transitions to vibrational levels of the ground state (F). Deactivation processes competing with fluorescence are mainly non-radiative transitions to the triplet state (intersystem crossing, ISC).

The amount of energy emitted can be expressed in terms of ratio by quantum yield equation

$\Phi_F = \frac{\text{Number of photons emitted}}{\text{number of photons absorbed}}$

**2.1.2 Fluorescence quantum yield [19]**

$\Phi_F = \frac{\text{Number of photons emitted}}{\text{number of photons absorbed}}$
The absorption of energy not always results in fluorescence emission. There are other ways the molecules can return to the stable state after reaching the excited state. Possible ways of de-excitation of the molecule are shown in figure below [21].

The fluorescence response of a molecule is governed by its microenvironment represented by some physical and chemical parameters like: polarity, ions, electric potential, quenchers, temperature, viscosity, pressure, pH and hydrogen bonds. These factors are controlled by the additive and paint manufacturers.

![Diagram of de-excitation pathways of excited molecules](image)

**Figure 2.6: Possible de-excitation pathways of excited molecules [21]**

To understand this complex process of fluorescence and to be able to develop an inspection technique, following assumptions are made.

### 2.1.3 Assumptions

- Thickness of the film is uniform:
  
  The average value of the five points measured with the dry-film thickness gauge is assumed to be uniform throughout the layer in a given sample
Optically active additives and pigments are uniformly distributed
The pigment molecules and the optically active additives are uniformly dispersed according to the paint manufacturer’s technical data, we maintain the same assumption

Fluorescence is diffused
Fluorescence is diffused and can be measured uniformly from any direction. In the spectroscopy measurements the angle of 30° is used consistently for convenience and assume the readings to be optimum

Spectrum does not change with the experimental time interval
The spectroscopy output is very sensitive and with a little inconsistence in the parameters, the output deviates with an standard deviation measured to be 2.15% and maximum deviation of 5.05%

Substrate does not participate in the process
It is assumed, that the readings obtained are only due to the interaction of UV light within the coating thickness. The substrate cannot be analyzed as the properties and composition is unknown. Hence is removed from the analysis

Only optically active additives are responsive to UV light
It can be easily proved from the 0% additive sample that the pigments in the coatings do not interact with the UV light. It is only the optically active additives.

2.1.4 Interaction with pigments

Figure 2.7: Interaction of pigments with optically active additives

! \begin{align*}
?_1 & : \text{Wavelength of ultraviolet light} < ?_2 : \text{Wavelength of visible range}
\end{align*}
The molecules of the optically active additive (OAA) absorb light at 365 nm ($\lambda_1$) in the ultraviolet range. These molecules get excited and emit energy at a higher wavelength in the visible range ($\lambda_2$) around 420-550 nm depending upon the additive type used. The pigment molecules which are also in the coating layer are assumed to be immune to $\lambda_1$ wavelength as molecules can absorb energy only at a specific wavelength. But these pigment molecules do reflect the light of $\lambda_1$ wavelength which in turn would be absorbed by the OAA molecules.

The energy emitted by the OAA molecules lies within a range and is not specified to the exact value of the wavelength. The study of the behavior shown by two different additives helped create a hypothesis about the problem in one the additives. With the same loading level for both additives and the same paint compositions and thickness, the emission levels are observed to be way too low for Additive Y as compared to Additive X. According to our hypothesis the emission wavelength for these particular OAA molecules is the same at which the pigment molecules absorb and hence the output we receive on the spectrometer is mostly reflection of ultraviolet light.

Our hypothesis cannot be proved with the current limitations of the project and there might be some other problem which we are not able to identify due to the exhaustive list of ingredients in the paint and their chemical interaction, but this hypothesis is worth considering in the detailed study of the OAA molecules and its interaction with the pigment molecules.

2.2 THEORY OF ADDITIVES

Optically active additives (OAA) are similar to fluorescent whitening agents or optical brighteners. These are colorless to weakly colored organic compounds that, in solution or applied to a substrate, absorb ultraviolet light and re-emit most of the absorbed energy as fluorescent light at specific wavelengths [21].

The absorption and the emission curves show similar characteristics as seen in the figure. Absorption by the molecules take place at wavelength within the ultraviolet range and the emission takes place in the visible range.
2.3 SAMPLE CREATION

The samples created with different pigment types, different paint vendors providing different thickness values and different percent loading would be used for spectroscopic analysis as well as imaging experiments to obtain the optimum inspection conditions.

2.3.1 Sample Preparation

In the initial stages of the project, samples were created in-house on a 12” X 12” hot rolled (HR) steel plate with surface roughness in accordance with the SP-10 standard. The paint supplied by the vendor had the optical active additive (OAA) uniformly dispersed in it.

The following procedure was adopted to prepare the samples:

a. Clean the substrate, in this case steel plate to be painted with lurk warm water and dry it completely if required with a blow dryer.

![Figure 2.8: Absorption and emission curves for optically active additives [21]](image-url)
b. Mix the hardener with the base in 1:4 ratios by volume [22] or as specified in the product information sheet.

c. Stir the mixture for about 5 minutes with a rod or electric mixer till the hardener completely disperses in the base and the paint becomes warm.

d. Apply this paint on the steel plate with brush or roller before the end of the paint potlife. The brush can be nylon/polyester or natural bristle whereas the roller should be 3/8” woven with phenolic core [22]. Airless spray gun can also be used for application but in our case we preferred the brush and the rollers due to cost and availability.

e. While coating the steel plate wet film thickness (WFT) readings should be taken with the help of the WFT gauge. In general the WFT should be 2.0 mils more then the dry film thickness (DFT) desired [22].

f. Set the sample to dry for the prescribed curing time after a uniform coat of the desired WFT is applied.

In addition to the above procedure, terms like potlife and curing time should also be taken into consideration [22]

- **Potlife**: The maximum time for which a mixed paint will stay flexible enough to spread and create a good bond is termed as potlife. The potlife for every paint sample is mentioned in the product information sheet and varies with temperature. A typical potlife table is as shown below

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Potlife</th>
</tr>
</thead>
<tbody>
<tr>
<td>68°F (20°C)</td>
<td>60 minutes</td>
</tr>
<tr>
<td>86°F (30°C)</td>
<td>30 minutes</td>
</tr>
</tbody>
</table>

- **Curing time**: The period for which paint must be left to dry for it to reach full strength is called curing time. The curing time for paint is also mentioned in the product information sheet. Adequate ventilation is required for the sample during the curing time. Temperature is inversely proportional to curing time. A typical curing time table gives the following information
2.3.2 Samples Procurement

As the samples prepared in-house were not accurate enough to get reliable results plus as all percent loadings could not be achieved, they were procured from paint companies which manufacture marine coating for the US Navy. Samples with two different additives and different thicknesses and percent loading from 3 different vendors were procured. For an extensive list of the procured samples please refer to APPENDIX 1.

The samples procured from these vendors were of two types

- Sprayed: Coated using airless spray gun
- Drawdown: Coated using drawdown blades

Figure 2.9: Procured sprayed sample
2.4 Film Thickness Measurement

As mentioned in the sample preparation procedure, film thickness is taken when the paint is wet (WFT) or after the paint is cured (DFT). Wet Film Thickness is taken with the help of a WFT gauge which is a calibrated steel chip with different leg dimensions to quantify the thickness when the chip is submerged in the wet paint.

Dry Film Thickness reading is taken with the help of a DFT gauge which operates on ultrasonic technique. It has a digital display which gives the thickness measurement of the coating to the tenth of accuracy.
The variation between wet film thickness reading and dry film thickness reading is measured and represented in terms of percent for certain pilot samples in APPENDIX 2. APPENDIX 3 displays the wet film thickness readings and the dry film thickness readings for the samples used in the experiments.

### 2.5 DESIGN OF EXPERIMENTS FOR SPECTROSCOPY

The results expected from spectroscopy were comparison and study of the emission curves for different samples. The comparison was between:

1. Additive X and Additive Y
2. Vendor X, Vendor Y and Vendor Z
3. Emission levels for different sample thickness
4. Emission for different additive loadings
5. Ambient lights

We also wanted to study:

1. Effect of ambient light
2. Effect of filter on detector
3. Effect of filter on ambient lights
4. Characteristic emission curves for fluorescence output

A group of pilot samples was selected, which would represent the whole array of data to analyze and produce these results. The table of these samples is seen in APPENDIX 3.
2.6 SPECTROSCOPY EXPERIMENTAL SETUP

The spectroscopy setup was finalized after initial trial and error experiments to find the optimum geometry.

2.6.1 Equipment Details

1. **Optical Table**: The holes are tapped to accept screws of ¼”-20 threads. The holes form a line array at spacing of 1”.

2. **Spectrometer**: The spectrometer is with Grating #2 (200-850 nm), SLIT 200 (200 microns wide aperture) and UV2 detector.

3. **UV Light Source**: The UV lamp is highly intense collimated light source.

4. **Holders/ Mounting**: The holders are V-block tube holder for UV light, miniature vice

---

Figure 2.13: Spectroscopy setup for sample analysis
Figure 2.14: Schematic of spectroscopy setup for sample analysis

Figure 2.15: Schematic of spectroscopy setup for ambient light analysis
2.6.2 Variability in spectroscopy setup

Though ultraviolet spectroscopy has been generally available since 1943, there is no compelling evidence that the reproducibility of measurements between laboratories approaches that from within a given laboratory. Reasonable competent operators seem able to achieve acceptable precision but often rather with only poor accuracy [25].

The basic causes of variation are

- Variation in ultraviolet lamp output
- Attenuation of fiber optic sensor at the wavelength of interest [26]
- Stray light effect [25]
- Non-rigid setup

Though similar results were reproduced on an existing setup, with a change in the configuration of the instruments the results vary by ± 10%.

2.6.3 Experimental conditions

The spectrometer reading are taken under three different lighting conditions

1. Only Ultraviolet (UV)
2. Only Ambient (A)
3. Ultraviolet and Ambient (UV + A)

The output spectra of the three conditions are displayed below for a sample with no additive.

![Figure 2.16: Spectrometer output for UV light only](image-url)
The condition in the ballast tank is UV with ambient and that is the one we mostly use for the spectroscopic analysis. But it should be noted that the UV only condition is the best to study
the characteristics of the fluorescent additive as there is no overlap of the ambient light spectrum over the emission spectrum.

2.7 DESIGN OF IMAGING EXPERIMENTS

After the initial spectroscopy analysis, experiments were conducted with the suitable equipment listed below to obtain the best image quality. With the aid of spectroscopy the kind of filters that were the best suited for the experiments were known. The different conditions optimized were:

- Maximum area of coverage from a 2 feet distance
- Minimum size of holiday detected by the camera
- Downloading time of the image to the computer and size of the file stored
- Effect of shutter speed variation on the clarity of image

2.8 IMAGING EXPERIMENTS SETUP

After initial trials with different equipment and parameters the following setup was finalized

2.8.1 Equipment

Most of the equipment was picked up off the shelf and tried and tested before assembling the prototype. The list of the equipment tried is as follows:

- Cameras: High end digital camera, medium resolution digital camera and black and white CCD camera.
- UV light sources: Intense UV light, Industrial UV light and Ring UV light
- Ambient light: Floodlight (25W, 50 W and 75W), Indoor spotlight(25W, 40W and 60W), Industrial halogen lamp, fluorescent lamp
- Photography reflector: Silver coated and gold coated
- Filters for camera: Red, Blue, Green, UV and polarized.
- Gel filter for ambient lights: Orange, Blue and refracting sheet
Figure 2.19: Imaging experiments setup

Figure 2.20: Schematic of imaging experiments
2.8.2 Parameters

The experimental parameters were varied in the following areas

Table 2.5: Array of parameters used in imaging experiments

<table>
<thead>
<tr>
<th>PARAMETER CATEGORY</th>
<th>VARIATIONS/CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image resolution</td>
<td>Small, Small interpolated, Medium, Medium interpolated, Large, Large interpolated</td>
</tr>
<tr>
<td>Samples</td>
<td>Vendor A-Additive X-0.5%-4 mils, Vendor B-Additive X-0.1%-4 mils, Vendor B-Additive X- Commercial- 4 mils</td>
</tr>
<tr>
<td>Lighting condition</td>
<td>Ultraviolet only, Ambient only, Ultraviolet with ambient</td>
</tr>
<tr>
<td>Ambient lights</td>
<td>Spot light, Halogen lamp, Diffused spot light, Diffused halogen lamp</td>
</tr>
<tr>
<td>Light intensity (lux)</td>
<td>50, 100, 200, 400, 800</td>
</tr>
<tr>
<td>Detector filters</td>
<td>No filter, UV filter, Blue filter, polarized filter</td>
</tr>
<tr>
<td>Ambient light filters</td>
<td>No filter, Orange filter</td>
</tr>
</tbody>
</table>

Images were taken with different combinations of parameters from the table above. The optimum parameters out of these were selected for the prototype in the field trial.

2.8.3 Imaging experiments: geometry and specifications

- UV light collimated to 6” diameter and is placed at 27” from the sample
- Detector/ Camera kept at 24” from the sample making an angle of 30° with the light source
- Spot light/ Industrial light set alongside the UV light to give 400 lux on the surface. Both the light sources will be used independently in experiments
- Spot light is bundled with UV light and industrial light will be in the background
- The shutter speed of the camera will be maintained close to 1/45
- Camera and light source are kept at an angle such that it will avoid reflection on the surface of the sample
• Auto focusing is achieved at this stage of the development using sticker technique (explained later)
• UV and ambient light will be incident on the surface without the use of reflectors
• The digital filters will be used from a commercial software
CHAPTER 3
SPECTROSCOPY RESULTS AND ANALYSIS

3.1 INTERPRETATION OF RESULTS

The graph below displays the interpretation of results in a typical spectroscopy output.

- The UV source has the wavelength of 365 nm which represents the first section of the graph.
- The reflection of ambient light is seen in right section of graph, the light source is white light.
- The fluorescence observed is labeled as the emission peak.
- The peak value out of the dual peaks of emission which shows maximum emission is labeled with its corresponding wavelength as \( \lambda_{\text{max}} \).

Figure 3.1: Interpretation of spectroscopy results
3.2 EXPERIMENTS FOR SAMPLES

Numerous experiments were conducted on array of samples to achieve the following:

1. Study the effect of ambient light on the sample
2. Study the difference between the characteristics of the two additives
3. Study the interaction of Additive X with different paint compositions
4. Study the variation in intensity with the change in percent loading
5. Study the variation in intensity with the change in thickness of coating for the sample

These results are displayed in the following graphs:

3.2.1 Study the effect of ambient light on the sample

The presence of white light makes a substantial difference in the spectroscopy output. During the inspection in the ship there will be presence of ambient light due to two reasons; safety of the inspector while moving in the tank and to compensate the high intensity of UV light. The ambient lights used in our experiments were indoor floodlight/spotlight, halogen light and fluorescent light. The required intensity of light inside the tank during inspection should be around 400 lux.

On the other hand experiments with only UV light will exhibit the characteristics of the additives better. The defects in figure 3.2 and figure 3.3 are man made, with the help of a drill machine.
Figure 3.2: Sample with Ultraviolet light

Figure 3.3: Sample with Ultraviolet and ambient light
• SAMPLE: Vendor B, Additive X, 1% and 6 mils
• REPEATIBILITY: Same observation for all samples
• The ambient light used in this case is 40 W indoor spotlight/ floodlight
• As the ambient light curve interferes with the emission curve of the sample, the right end of the dual emission peak has higher intensity then the other curve (UV)

3.2.2 Study the difference between the characteristics of the two additives

The additives used in the study are Additive X and Additive Y. These additives fluoresce at different wavelengths (or in different colors). The intensity of fluorescence of these additives matter a lot as more the intensity more will be the contrast between the “holidays” and the coated surface.
- SAMPLE: All vendors, all additives, 0.5% and 4 mils
- REPEATIBILITY: Same observation for all samples
- **Additive X** exhibits better fluorescence emission as compared to **Additive Y**
- Additive X emits in dual peak around the 435 nm and 470 nm range whereas Additive Y emits around 525 nm range
- The graph is taken on a log scale for Y axis to clearly show the intensity values

### 3.2.3 Study the interaction of Additive X with different paint compositions

This experiment was conducted to see the behavior of Additive X with different paint compositions received from different vendors. There is a high probability that the composition of the paint or pigment color of the paint may be having an effect on emission levels and so different paints will exhibit different emission levels for the same additive.
SAMPLE: All vendors, Additive X, 0.5% loading and 4 mils
REPEATIBILITY: Same observations for all samples
Vendor B exhibits distinctly higher intensity of emission as compared to Vendor A and Vendor C
The UV intensity peak for three different vendors is not inversely proportional to the emission peak, which should be the case. The probable reason is the chemical interaction of paint pigments with the additives which requires further research.

3.2.4 Study the variation in intensity with the change in percent loading

With an increase in the percent loading of the additive, the volume of optically active additive molecules will also increase. Hence the emission will increase. This experiment is carried out to study this behavior in the additive.
Figure 3.7: Effect of percent loading on the emission

- **SAMPLE**: Vendor A, Additive X, all loadings, for 4 and 8 mils at 435 nm
- **REPEATIBILITY**: All loading levels not available for other vendors, so experiment conducted only on Vendor A
- It is clear from the graph that after 0.5% loading there is no significant increase in the intensity and hence no justification to the additional cost
- The optimum loading range is anywhere between 0.1% and 0.5% which is evident with the high slope observed in the graph. Exact percent loading cannot be pinpointed due to the lack of sufficient samples

### 3.2.5 Study the variation in intensity with the change in thickness of coating for the sample

As the thickness of the coating increases the volume of optical active additive molecules will also increase because they are uniformly distributed. Hence with increase in thickness the emission should increase. This experiment is performed to study this behavior in the additive.
• SAMPLE: Vendor B, Additive X, all loadings, all thicknesses at 435 nm
• REPEATIBILITY: The number of samples are insufficient to conduct this experiment for Vendor A and Vendor C
• There is an increase in the intensity or emission with an increase in thickness
• The additive appears to be more sensitive for 0.5% and 1.5% loadings at higher thickness values as compared to the 1% loading
• The intensity of 1.5% loading seems to be less than 1% loading which is probably due to the paint pigment interaction and requires further research

### 3.3 EXPERIMENT FOR AMBIENT LIGHTS AND FILTERS

Experiments were conducted with different lights and filters to

1. Compare different ambient lights
2. Study the effect of filters on ambient light
3. Study the effect of filters on the detector
3.3.1 Comparison of ambient lights

The ambient light used for the prototype should be such that it should not interfere with the emission curve. A few ambient lights to select the one with right intensity and output are compared. Use of certain filter to eliminate the overlap between the emission and ambient light output is also considered.

![Comparison of ambient lights with an emission curve](image)

- Light A is too intense as compared to the emission and may overshadow it
- Light B generates spikes which introduce more noise and hence is undesirable
- Light C (spot light, 40W) seems have ideal intensity as compared to emission
- The sample measurement is taken separately and projected on the graph for comparison

3.3.2 Effect of orange filter on ambient light

The effect of filters on ambient light is studied in this experiment. The orange filter mounted on the ambient light seems to give the best result.
Figure 3.10: Effect of orange filter on ambient lights

- The use of orange filter on ambient lights clearly removes the overlap between the emission curve and ambient light outputs and gives distinct fluorescence signal.
- Hence the use of Light C with orange filter on it will give the maximum contrast in the image.
- Light C (spot light, 40 W) with orange filter seems to be the ideal choice for inspection in the ballast tanks along with the UV light.

### 3.3.3 Effect of blue filter on detector

The effect of different filters on the detector/ camera is studied in this experiment. Blue filter mounted on the camera or the detector gives the best result.
Blue filter cuts the ambient light effect and the UV reflection, leaving only the emission for analysis.

The blue filter is found to reduce the intensity of emission from the sample.

### 3.4 SUMMARY OF RESULTS

Table 3.1: Summary of results from spectroscopy experiments

<table>
<thead>
<tr>
<th>EXPERIMENT</th>
<th>FINDINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of ambient light on sample emission</td>
<td>Interference with emission curve</td>
</tr>
<tr>
<td>Characteristic emission of additives</td>
<td>Additive X emits more than Additive Y</td>
</tr>
<tr>
<td>Additive X with different vendors</td>
<td>Vendor B emits more than other vendors</td>
</tr>
<tr>
<td>Effect of percent loading on emission</td>
<td>Increases, 0.1% to 0.5% optimum loading</td>
</tr>
<tr>
<td>Effect of thickness on emission</td>
<td>Increase in emission with thickness</td>
</tr>
<tr>
<td>Ambient light comparison</td>
<td>Light C exhibits the optimum results</td>
</tr>
<tr>
<td>Filter for ambient light</td>
<td>Orange filter is best suited</td>
</tr>
<tr>
<td>Filter for detector</td>
<td>Blue filter is best suited</td>
</tr>
</tbody>
</table>

Figure 3.11: Effect of blue filter on the detector
CHAPTER 4

PROTOTYPE DEVELOPMENT AND FIELD TRIAL

4.1 IMAGING EXPERIMENTS RESULTS

Images were taken with different combination of parameters from the Table 2.3. The figure below displays images taken for Vendor A-AdditiveX-0.5%- 4 mils sample with large image resolution and 40 W spot light as the ambient light source at 400 lux intensity. Detector filters, ambient light filters and lighting conditions are varied to study the effect on visibility of defects. The defects on the sample are of 5 different sizes with the smallest of 0.25 mm and largest of 2 mm. The most important result from imaging was the geometry and the parameters for the prototype.

![Figure 4.1: Typical images with different parameters](image)

4.2 PROTOTYPE DEVELOPMENT

The prototype developed is a fusion of different equipments: high-end camera, intense UV light source, commercial photography reflector and white light source (40 W spot light) all fabricated with the help of poly-vinyl chloride (PVC) pipes and steel plates. A series of experiments were carried out with this equipment for obtaining the optimum image in terms of quality, area covered, file size and minimal size of defect detected. Various parameters were tested to obtain the best image. According to spectroscopy output and the geometry and
specifications of imaging experiments, the prototype was developed. The prototype was designed as per the availability of the raw material to keep its cost minimum.

Following were the critical parameters of the prototype:

- Distance of detector/camera from sample: **24”**
- Distance of UV light and ambient light from sample: **27”**
- Angle between light assembly and detector/camera: **30°**
- Image size: **24” x 18”**
- Prototype optimized for: **Additive X**
- Prototype optimized for: **0.5% loading or less**
- Ambient light used: **40 W Spot light (Light C in spectroscopy experiments)**
- Preferred filter for ambient light: **Orange**
- Preferred filter for detector/camera: **Blue**

### 4.2.1 Prototype fabrication components

The main components used in the prototype fabrication are listed in the table below:

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot rolled mild steel plate 3.25” x 4.75”</td>
<td>1</td>
</tr>
<tr>
<td>Hot rolled mild steel plate 5” x 6.5”</td>
<td>1</td>
</tr>
<tr>
<td>90° elbow joint for 1” diameter PVC pipe</td>
<td>8</td>
</tr>
<tr>
<td>45° elbow joint for 1” diameter PVC pipe</td>
<td>1</td>
</tr>
<tr>
<td>T-joint for 1” diameter PVC pipe</td>
<td>3</td>
</tr>
<tr>
<td>2” steel pipe holders</td>
<td>3</td>
</tr>
<tr>
<td>1” PVC pipes 4.5” long</td>
<td>4</td>
</tr>
<tr>
<td>1” PVC pipes 2” long</td>
<td>2</td>
</tr>
<tr>
<td>1” PVC pipes 5.5” long</td>
<td>2</td>
</tr>
<tr>
<td>1” PVC pipes 5” long</td>
<td>1</td>
</tr>
<tr>
<td>End cap for 1” PVC pipe</td>
<td>1</td>
</tr>
<tr>
<td>Locking nut for reflector</td>
<td>1</td>
</tr>
</tbody>
</table>
• **Camera mounting plate**

![Camera mounting plate diagram]

Figure 4.2: Camera mounting plate for prototype

• **Lamp mounting plate**

![Lamp mounting plate diagram]

Figure 4.3: Lights mounting plate for prototype

• **Holding rod**: Made from PVC pipe and padded with foam to make it more ergonomic to hold. The length of rod is 5”
Figure 4.4: PVC structure made for the prototype

- **PVC structure**: PVC structure was fabricated using PVC pipes of 1” in diameter, T-joints, elbow joints and locking nut. The pipes were cut to the desired size and glued together with the joints.

- **Pipe holders**: The pipe holders were used on the light mounting plate to hold the ambient light and the UV lamp

All the fabrication of plates which included cutting, drilling and assembly was completed in-house

### 4.2.2 Prototype geometry

The basic aim in the prototype design was to keep the angle between the camera and the reflected UV light 30°. The final design which maintains this angle is represented in the schematic below.
The other dimensions of the PVC pipes and the plates were decided according to the dimensions of the light sources and the digital camera. An effort was made to keep the weight of the prototype minimum and ease of usability maximum within the cost and geometric constraints.

### 4.2.3 Use of commercial reflector

A commercial reflector was included in the prototype to tackle the issue of reflection. After initial experiments with the prototype, it was realized that direct use of ambient and UV light created reflection in some of the images. To avoid this problem during the field trial, the reflector was incorporated in the design.

Figure 4.5: Schematic of prototype design
4.3 FIELD TRIAL

After the prototype fabrication based on spectroscopy and imaging experiments results, it was necessary to test the lab concept in the field and to get a feed back on the real world problems.

4.3.1Overview

Field Trial Date, Length and Location:
6th May 2003, 2 days at a naval shipyard in California

Project Team for field trial:
Mr. Paul Gossen (NST Center)
Mr. Jay Angal (NST Center)
Mr. Mangesh Kolharkar (University of Kentucky)
Equipment:
Prototype developed in the laboratory

Criterion for success:
- Locating holidays of 0.25mm and bigger
- Clearly contrasting the “holidays” with the help of digital filters
- Testing the lab concept in the field

4.3.2 Details
- The tanks

Two tanks were painted by the shipyard painters before the team’s arrival. The dimensions of the tank were 4’ X 4’ X 4’ and included stiffeners and manhole for entry into it. The paint was already cured and ready for defect creation. The tanks were prepared to SP-10 by sandblasting. The average profile on Tank 1 was 4.4 mils and Tank 2 was 4.2 mils. Tank 1 was coated with Vendor A coating with commercial grade loading and tank 2 was coated with Vendor B coating with commercial loading.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Air Temp</th>
<th>Dew Point</th>
<th>Surface Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/30/03</td>
<td>8:00 AM</td>
<td>61</td>
<td>52</td>
<td>58</td>
</tr>
<tr>
<td>Tank 1: Vendor B-Additive X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Time</td>
<td>Air Temp</td>
<td>Dew Point</td>
<td>Surface Temp</td>
</tr>
<tr>
<td>4/30/03</td>
<td>1:00 PM</td>
<td>67</td>
<td>53</td>
<td>66</td>
</tr>
<tr>
<td>Tank 2: Vendor A- Additive X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Creation of defects

The defects were either present in the tank due to the painting process or were created manually by 0.25, 0.5 and 0.75 mm drills. Two arrays of 5 holes of each size were made per tank. One more type of defects used in the tanks were transparencies with the three sized holes created over it with a laser printer. (Figure 4.7)

Figure 4.8: Defects made with a transparency
The image was taken from approximately 2’ distance from the tank surface and would cover an area of 24” X 18”. Approximately 80 images were taken to cover every corner in the tank. The numbers of images were more then what would be estimated for the physical size of the tank because the stiffeners and beams obstructed the continuous imaging of the tank surface. The images were taken with a high end digital camera with a medium resolution to save on disk space. This setting was previously tested in the lab to give successful results.

Sticker technique
Numbered stickers were placed on the tank surface at 12” horizontal and 9” vertical distance (center of every image) to reference the image and also to help the camera auto-focus. This technique was temporarily used till a permanent solution for referencing and auto-focusing was developed. The solution was not feasible in the real field testing where the size of the tanks would be more the 20’. But with this option, some other results and parameters in the developed prototype could be studied. The camera used had only 3 focusing points, the options like laser pointers or camera’s with more focusing points were considered in the final inspection technique. Permanent solution for referencing included in-built chip that stored an algorithm to process the image and give instant feedback on the defects in the surface considered before the camera was moved for capturing the next image.

Image processing
The images taken at the field trial were processed using commercial image processing software’s. The basic actions performed on the image were masking with different RGB levels, threshold adjustment, contrast and brightness adjustments and image inversion. The objective of image processing was to enhance the holidays or defects to be easily visible.
The field trial corroborated the need for improvement in certain parameters which were intended to be complete before-hand. These improvements are tabulated below.

**Table 4.3**: Improvements required as per our experiments

<table>
<thead>
<tr>
<th>Improvement required</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image referencing and focusing in final product</td>
<td>The current sticker technique was good enough for the small tanks but won’t work in the huge tanks where every corner is impossible to reach.</td>
</tr>
<tr>
<td>Reflection problems</td>
<td>Though the reflector helped in solving the problem during the current testing, it is not a permanent solution</td>
</tr>
<tr>
<td>Area covered by the UV and incandescent lamp</td>
<td>The current light source used can throw intense light only on a small area and we need to develop or procure a better light source</td>
</tr>
</tbody>
</table>
After testing the prototype in the field, we had a discussion with the inspectors who got a chance to use the prototype. They mentioned the following improvements in the prototype [14]

<table>
<thead>
<tr>
<th>Improvement suggested</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight and compactness</td>
<td>The inspectors at the shipyard wanted the inspection system to be user friendly and light weight to be widely accepted in the ship yards.</td>
</tr>
<tr>
<td>Zoom function</td>
<td>The inspectors wanted a zoom function in the camera which could take pictures from a distance of around 15 – 20 feet and detect the same kind of defect</td>
</tr>
<tr>
<td>Longer battery life in the final product</td>
<td>During the tank inspection, the inspector typically uses an inspection device for a period of around 8 hours. The inspectors thought that recharging or replacing the batteries would be a hassle and wanted to avoid it.</td>
</tr>
<tr>
<td>Defects need to be quantified as percent area</td>
<td>The US Navy has given guidelines to the inspectors to accept or reject the paint job done in a tank after quantifying the defects as percent area.</td>
</tr>
<tr>
<td>Detection behind edges and stiffeners</td>
<td>This is the most critical area the inspectors want a solution for, because of the high number of defects found here.</td>
</tr>
</tbody>
</table>
CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 WORK SUMMARY

The thesis marks a successful beginning for the systematic development of the inspection method for the optically active paint system. Through this work many drawbacks in the real world application of the prototype are highlighted. Though the drawbacks were known before the field trial through laboratory experiments, the basic aim of detecting 0.5 mm size defects from distance of 2 feet was achieved successfully. There are problems with some basic issues like reflection and image referencing which need to be resolved with refined equipment and other state of art devices.

The most important contribution of this work is the characterization and understanding of the optically active paint system. A theory has been put forward, which explains the working of fluorescence in the paint system and also tries to find out the probable reasons for the failure of one of the additives to perform as per expectations. A lot of information is gathered through the experiments and the results demonstrate an increase in the fluorescence with the increase in thickness of the sample and an increase in fluorescence with increase in percent loading though no correlation can be established for both cases at this stage. A right additive choice is made between the available two and the additive interaction with different paint compositions is also studied. The right kind of ambient light, filters are selected and the effect other commercial filters and ambient lights on the inspection system are studied.

The prototype development was based on the knowledge gathered through the spectroscopy analysis and the fabrication was completed in accordance to the tested geometry used in the imaging experiments. Though the prototype is not very ergonomic, nor a refined version, it helped to prove that the optical paint system can give results to the required performance if other issues involved are taken care off.

5.2 CONCLUSIONS

From the above work summary the following conclusions can be drawn:
1. Spectroscopy analysis is able to show the change in performance of the coating with respect to change in percent loading of additive, thickness of coatings and change in the lighting condition.

2. Spectroscopy analysis has helped to compare the characteristics of the two additives and to select the better additive.

3. According to the spectroscopy analysis, with an increase in the additive percent loading, fluorescence emission increases rapidly till 0.5% loading but almost saturates there onwards.

4. Trends from the spectroscopy analysis also show an increase in the fluorescence emission with the increase in the coating thickness though linear correlation can be established at this stage.

5. A 40 Watt spotlight, orange filter for ambient lights and blue filter for detector, are identified to provide the optimum parameters in our prototype.

6. A prototype UV inspection system has been developed. It features the following characteristics which are important in problem solving,
   - Effective in working with the optically active paint system
   - Provides better and reliable performance when compared to the current systems as it can detect a 0.5 mm defect reliably
   - Exhibits a higher productivity as compared to wet sponge technique which has to cover every square inch in the tank through direct contact
   - Has an ability to document results which the current systems lack

7. There is a strong indication that the paint molecules other than the optically active additives play a role in the fluorescence process and is one of the prime reasons for the unpredictable behavior of the paint system in case of certain samples.

5.3 CHALLENGES AHEAD

The inspection technique is functional but does not perform to the best of abilities. The following set of improvements is desired:

1. Prototype refinement is desired in the following areas
• Real time inspection capabilities with the development of customized algorithms which can be mounted in an in-built chip

• Ability to inspect successfully around stiffeners and corners with machine vision tools or devices like the snake-eye

• Professional product development through commercial companies to make the prototype more compact, ergonomic and cheaper

2. Active participation of the paint manufacturing companies is desired to understand the chemistry of the paints and to be able to analyze the system better

3. More work is required in resolving the issues of light reflection and image referencing in the ballast tank. These problems are because of simple physics and the alternative solutions used the prototype have worked but identification of root cause and elimination would increase the effectiveness of the inspection technique.
## APPENDIX 1

Summary of the paint samples procured

<table>
<thead>
<tr>
<th>Company</th>
<th>Wet thickness (mils)</th>
<th>Loading (%)</th>
<th>Additives</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vendor A</td>
<td>[4,6,10] &amp; {8,12}</td>
<td>0.05,0.1,0.5,1.2</td>
<td>X,Y</td>
<td>DD, Sprayed</td>
</tr>
<tr>
<td>Vendor B</td>
<td>[4,6,8] &amp; {}</td>
<td>0.5,1,1.5</td>
<td>X,Y</td>
<td>DD, Sprayed</td>
</tr>
<tr>
<td>Vendor C</td>
<td>{4-5} &amp; [4-5]</td>
<td>0.5,1,1.5</td>
<td>X,Y</td>
<td>DD, Sprayed</td>
</tr>
</tbody>
</table>

**Legend:**

- **DD:** Drawdown
- **[ ]:** DD
- **{}:** Sprayed
- **--:** Unknown entity
Matrix of variation between given wet film thickness and measured dry film thickness readings for selected samples

### APPENDIX 2

Variation in dry film thickness as compared to given wet film thickness

<table>
<thead>
<tr>
<th>Company/ Application</th>
<th>Given thickness (mils)</th>
<th>Actual thickness with dry film gauge</th>
<th>Percent Variation</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vendor A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drawdown</td>
<td>4</td>
<td>4.704</td>
<td>+ 17.6</td>
<td>+ 0.136, - 0.154</td>
</tr>
<tr>
<td>Drawdown</td>
<td>6</td>
<td>7.62</td>
<td>+ 27.0</td>
<td>+ 0.280, - 0.220</td>
</tr>
<tr>
<td>Sprayed</td>
<td>8</td>
<td>10.88</td>
<td>+ 36.0</td>
<td>+ 1.520, - 1.980</td>
</tr>
<tr>
<td>Drawdown</td>
<td>10</td>
<td>13.34</td>
<td>+ 33.4</td>
<td>+ 0.360, - 0.240</td>
</tr>
<tr>
<td>Sprayed</td>
<td>12</td>
<td>18.58</td>
<td>+ 54.8</td>
<td>+ 2.720, - 1.280</td>
</tr>
<tr>
<td>Vendor B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drawdown</td>
<td>4</td>
<td>5.394</td>
<td>+ 34.9</td>
<td>+ 0.406, - 0.424</td>
</tr>
<tr>
<td>Drawdown</td>
<td>6</td>
<td>4.23</td>
<td>- 29.5</td>
<td>+ 0.450, - 0.580</td>
</tr>
<tr>
<td>Drawdown</td>
<td>8</td>
<td>7.2</td>
<td>- 10.0</td>
<td>+ 0.400, - 0.400</td>
</tr>
<tr>
<td>Sprayed</td>
<td>--</td>
<td>6.12</td>
<td>--</td>
<td>+ 0.180, - 0.220</td>
</tr>
<tr>
<td>Vendor C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprayed</td>
<td>4-5</td>
<td>5.534</td>
<td>+ 10.7</td>
<td>+ 0.666, - 0.664</td>
</tr>
</tbody>
</table>

The dry film thickness is taken with Elcometer dry film measurement gauge. The readings are taken in the area of spectroscopic importance, i.e. in the central part of the sample 5 readings are taken and averaged.
## APPENDIX 3

Matrix of samples used in experiments with WFT and DFT readings

<table>
<thead>
<tr>
<th>COMPANY</th>
<th>ADDITIVE</th>
<th>LOADING</th>
<th>WFT</th>
<th>DFT</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vendor A</td>
<td>X</td>
<td>0.05</td>
<td>4</td>
<td>4.78</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1</td>
<td>4</td>
<td>4.55</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>4</td>
<td>4.44</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>4.5</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>4</td>
<td>4.32</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>6</td>
<td>6.8</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>8</td>
<td>8.56</td>
<td>Sp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>12</td>
<td>14</td>
<td>Sp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.05</td>
<td>8</td>
<td>8.8</td>
<td>Sp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1</td>
<td>8</td>
<td>7.4</td>
<td>Sp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>8</td>
<td>9.9</td>
<td>Sp</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>0.5</td>
<td>4</td>
<td>4.72</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>4.63</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td>Vendor B</td>
<td>X</td>
<td>0.5</td>
<td>4</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>6</td>
<td>4.69</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>8</td>
<td>7.5</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>3.02</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>6</td>
<td>7.4</td>
<td>DD</td>
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<td></td>
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<td>1</td>
<td>8</td>
<td>9.9</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>4</td>
<td>3.89</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>6</td>
<td>7.8</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>8</td>
<td>7</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Y</td>
<td>0.5</td>
<td>4</td>
<td>5.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>5.68</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td>Vendor C</td>
<td>X</td>
<td>0.5</td>
<td>4</td>
<td>2.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>6</td>
<td>3.94</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>2.81</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>5</td>
<td>5.5</td>
<td>DD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>5</td>
<td>5.5</td>
<td>Sp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Y</td>
<td>0.5</td>
<td>4</td>
<td>2.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>2.33</td>
<td>DD</td>
</tr>
</tbody>
</table>

**Abbreviations:**

- **WFT**: Wet film thickness
- **DFT**: Dry film thickness
- **DD**: Drawdown sample
- **Sp**: Sprayed sample
REFERENCES

1. http://www.m-i-link.com/dictionary


4. Input from the field trial at a Naval shipyard

5. www.miseagrant.org/pubs/up/sum02/page7.htm


8. Failure Analysis of paints and coatings by Dwight G. Weldon, 2001


18. Spectroscopy by Oliver Howarth, 1973


20. Product information sheet provided by additive manufacturer’s

21. Molecular fluorescence, principles and applications by Bernard Valeur, 2002

22. Product information sheet for vendors, supplied with the paint samples

23. www.gardco.com/nords1_gage.jpg


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