Degradation of Fluorophores in Hydraulic Fluids: Impacts on Fluorescence Intensity and Color Contrast for Underwater Leak Detection

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Camera and lighting systems are widely used in underwater environments for research and inspection purposes. Many submerged machines use hydraulic fluids that contain luminescent markers. This characteristic can assist in visual detection through imaging systems. However, due to environmental conditions, these fluorophores undergo degradation, which affects fluorescence intensity. To study the effect of fluorophore degradation on color contrast in hydraulic fluids, color contrast and spectroscopy tests were conducted. This study is relevant for the development of image-based leak detection systems for fluids containing fluorescent markers.

Keywords: Fluorescence. Contrast. Spectroscopy. Degradation.

Abbreviations: WCAG, Web Content Accessibility Guidelines. RGB, Red Green Blue. SDK, Software Development Kit. LED, Light Emitting Diode.

Imaging and illumination systems designed for underwater environments have been the focus of intensive research since the early 20th century in order to improve visual performance under challenging optical conditions [1]. These technologies have found widespread application in marine life, and, more recently, in detection and monitoring of subsea fluid leakages [2,3].

Some of these fluids contain luminescent fluorophores, meaning that when they interact with photons of a specific energy level, they become excited and emit light, fluorescence, with photons of lower energy than those used for excitation. As a result, the fluo-rescence spectrum generally occurs at longer wavelengths than the absorption spectrum, following the Jablonski diagram and the Stokes shift for fluorescence (Figure 1) [4].

Previous studies on fluorescent hydraulic fluids have reported emission spectra ranging from 540 nm to 640 nm, with an emission peak centered around 580 nm. The emission intensity is proportional to the concentration of the fluorophore solution, providing a quantifiable optical signature [5]. This phenomenon can generate chromatic contrast between the leaking fluid and its surrounding environment, which can be quantified using color contrast calculation methods [6]. Such spectral distinction enhances the detectability of leaks, when captured by imaging systems equipped with color-sensitive sensors [7]. However, the optical behavior of these fluorophores is susceptible to degradation over time, which significantly affects both fluorescence intensity and spectral characteristics. This degradation arises from physicochemical processes such as fluorescence quenching, triggered by environmental parameters including temperature, pH and exposure to reactive species [2]. These alterations can be tracked through spectral analysis, which reveals both the reduction in emission intensity and potential bathochromic shifts of the fluorescence peak as the compound,like hydraulic oil, undergoes chemical aging [2,8]. This work investigates the degradation of the fluorophore within a hydraulic fluid sample over seven days and assesses its impact on the resulting color contrast between the fluid and a controlled background.

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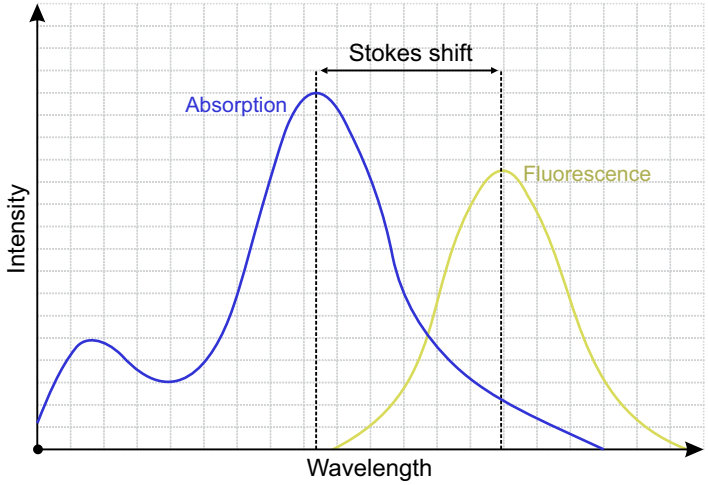
Figure 1. Stokes shift graph example.



Materials and Methods

To assess the effect of a seven-day degradation period on the chromatic contrast generated by the fluorophore, two complementary experiments were performed. The first evaluates the color contrast between the hydraulic fluid and a background, using the contrast ratio metrics defined by the Web Content Accessibility Guidelines (WCAG) [6]. The second experiment employed spectroscopic analysis to characterize the extent of fluorophore degradation in the fluid sample.

To evaluate the change in color contrast due to fluid degradation under controlled lighting conditions, an experiment setup was assembled inside a compact photographic lightbox (Figure 2) that provided uniform illumination and eliminated the ambient light interference, which was composed by white light sources. The experiment occurred within a room with the air conditioner turned on and offering the temperature of 20°C. A glass tank, measuring 24.5 cm × 10 cm × 8 cm, was filled with approximately 1.7 L of water. A custom-built support structure was installed inside the tank to securely position the cuvette. A black background plate was placed directly behind the sample holder to simulate the low light conditions typical of deep-sea environments. The illumination source, a Thorlabs LED module, emitting in the blue spectral region, to provide uniform illumination across the entire cuvette volume.

Image acquisition was carried out using a camera connected to a computer via a GigE interface. The camera was externally mounted on the front facing side of the tank, with a lens attached to the camera and with careful precision to achieve the ideal focus on the cuvette through the water-filled aquarium precisely focused on the cuvette to ensure high-resolution imaging.

All of the equipment was fixed in the correct positions with the aid of small metal pipes, with the intuition of keeping everything held in place and still to avoid unwanted modifications in the optical alignment and images-gathering. The sample under investigation comprised a 3.5 mL solution containing 70% water and 30% hydraulic fluid, with a pH of 9.1 known to exhibit green fluorescence when exposed to radiation in the blue range.

The experimental procedure involved introducing the sample into the cuvette, activating the LED module, and maintaining a fixed optical power by limiting the supply current to 1 ampere (A). Image capture was then initiated through a custom code which allowed real-time control over individual RGB color gains, adjustment of exposure duration, image acquisition, and

execution of contrast analysis using WCAG and the camera manufacturer's Software Development Kit (SDK). Contrast evaluations were performed by systematically varying the Blue (B) and Green (G) gains parameters within the RGB model and setting the Red (R) gain and exposure time at 5000 ms.

In parallel with the color contrast test, a spectroscopy analysis was conducted to monitor the degradation of the same prepared sample. As shown in Figure 3, the optical setup incorporated two solarized optical fibers, Ocean Optics model QP600-2-SR, with a diameter of 600 micrometers. One end of each fiber was connected to an Ocean Optics CUV-FL-DA cuvette holder. Emitted fluorescence was collected orthogonally to the excitation beam and directed to a spectrometer for spectral analysis. This orthogonal geometry minimized the detection of scattered excitation light and enhanced the signal-to-noise ratio of the fluorescence measurements. Similar to the other experimental setup, this second experiment was built within the same room and with the same temperature (20°C), and the cuvette was closed with a lid, with the goal of minimizing evaporation from the water contained within the cuvette.

Results and Discussion

Figures 4 to 7 present the contrast level obtained in the first test conducted. The X and Y axes correspond, respectively, to the gain values to the blue and green channels, assigned by the RGB gain control algorithm implemented in the imaging system. The Z axis represents the computed contrast

Figure 2. Laboratory setup for contrast tests.

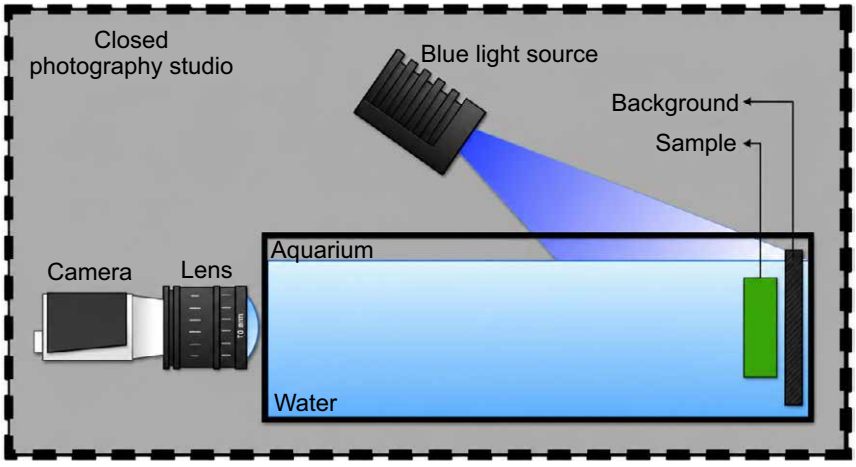
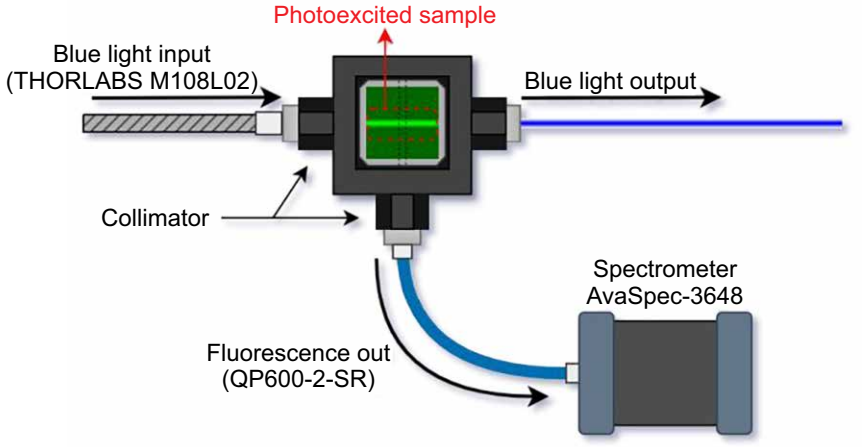


Figure 3. Laboratory setup for fluorescence tests.



intensity for each configuration, quantifying the visual distinction between the hydraulic fluid and the background based on colorimetric analysis.

Specifically, Figure 4 shows the contrast distribution for a freshly prepared sample. Figures 2 to 4 illustrate the progressive contrast variations observed after 2, 4, and 7 days of sample aging, respectively.

The superficies profiles depicted in the graphs exhibit consistent topological patterns over time. However, a progressive decline in overall contrast intensity was observed upon examination of the data point distribution. As summarized in Table 1 the maximum contrast value decreased systematically with sample aging, culminating in an approximately 45% reduction after seven days.

Figure 8 displays the fluorescence spectrum acquired from the sample over seven days, beginning on the first day of degradation. A progressive decline in fluorescence intensity was observed throughout the week, with the emission signal gradually diminishing and ultimately reaching a minimum by the final day.

Figure 4. Contrast results from the first day.

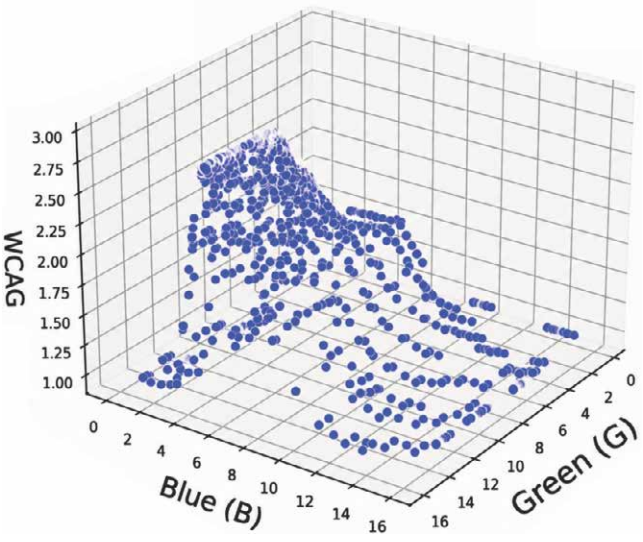


Figure 5. Contrast results from the second day.

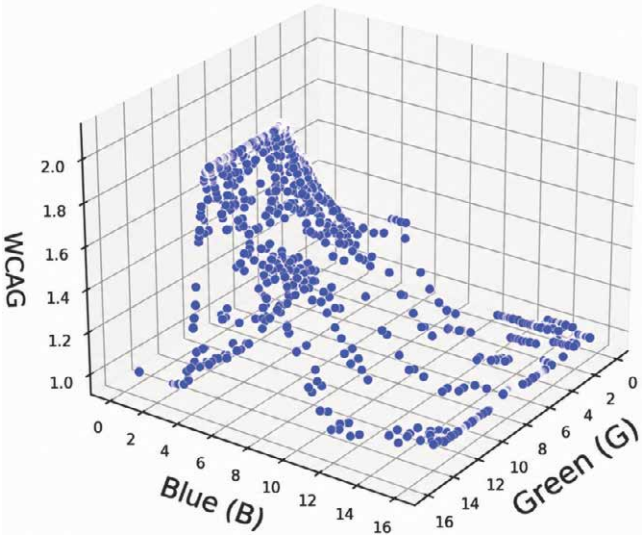


Figure 6. Contrast results from the fourth day.

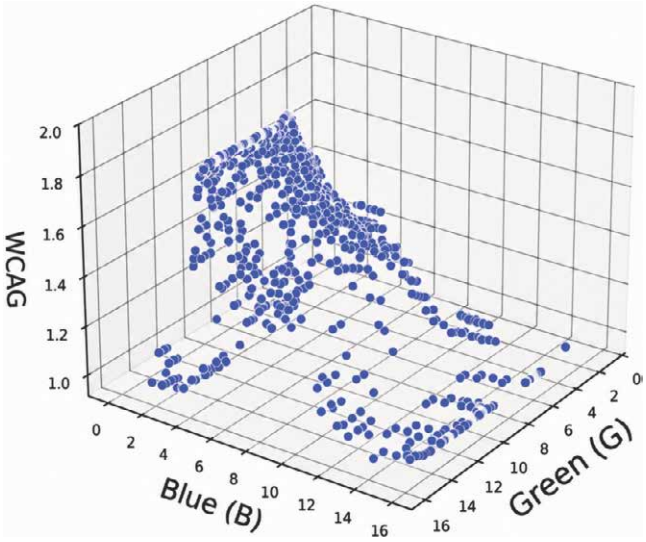


Figure 7. Contrast results from the seventh day.

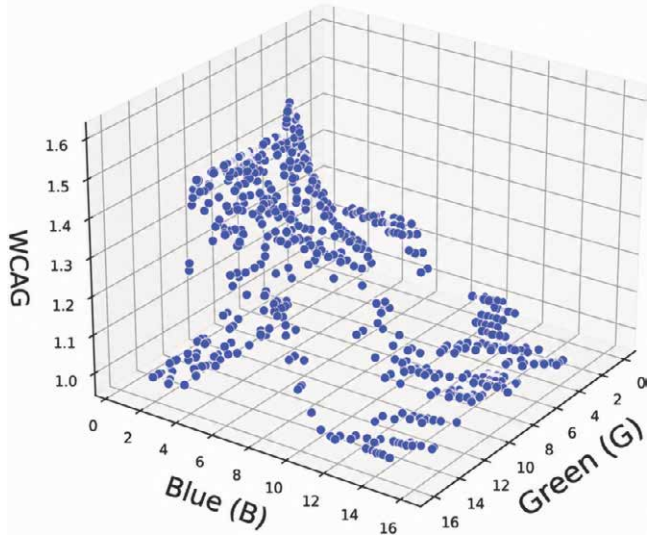


Table 1. Maximum WCAG values from each graph in the fluorescence test.

Day	WCAG Value
Day 1	2.91015625
Day 2	2.076171875
Day 4	1.931640625
Day 7	1.594726563

Table 2. Peak values from the fluorescence test on the vertical axis.

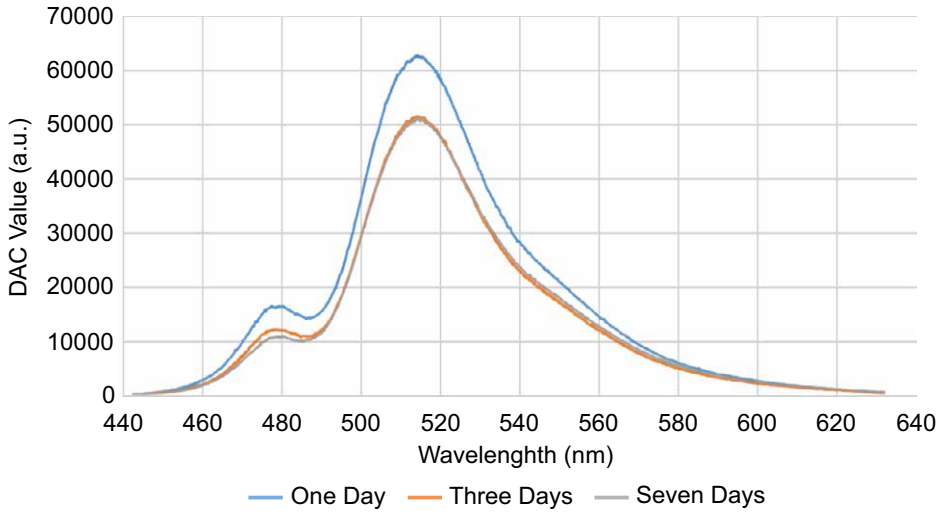
Day	Maximum ADC Value (a.u.)
One Day	62737
Three Days	51978
Seven Days	51863

Table 2 presents the maximum intensity values recorded. A pronounced decrease in intensity was observed between the first and third days. Beyond this point, the fluorescence amplitude stabilized.

The findings from both the contrast and spectroscopic analyses confirm that the temporal degradation of the sample adversely affects its fluorescence emission. In the first test, there was a total loss of 45.2% for the WCAG value over 7 days, while in the second test, there was a total loss of 17.3% for the maximum ADC value over 7 days. As the fluorophore deteriorates, the emitted intensity under constant excitation power diminishes, leading to a corresponding reduction in the color contrast between the sample and the background. In the contrast evaluation tests, the fluorescence phenomenon is responsible for generating a vivid green hue in the fluid, which, when placed against a black background is designed to maximize visual contrast. As fluorescence weakens over time, the loss of this characteristic green emission results in a measurable decline in contrast, impairing the visual differentiation between the fluid and its surroundings.

These conclusions are relevant to practical applications involving subsea inspections of oil and gas equipment. On the seafloor, light penetration is severely limited [9], which hinders the visual identification of fluids handled by these systems. Under such conditions, excitation at specific wavelengths permits the detection and distinction of those substances via their characteristic fluorescent emissions [10]; however, because emitted fluorescence light declines as fluorophores degrade over time, and even under constant excitation power, awareness of this temporal reduction, also known as photobleaching, is essential to avoid loss of fluid recognition during inspections [11].

Figure 8. Spectrometer results for the fluorescence test in graph format.



Conclusion

In the context of leak detection techniques for substances containing fluorophores, exploiting luminescence properties is an alternative approach to enhance visual contrast and facilitate identification. This study showed that the progressive degradation of the fluorophore present in a specific hydraulic fluid resulted in a reduction of fluorescence intensity, directly impacting the fluid's visibility against a black background. This decline in luminescent response over time constitutes a limitation for the reliability of fluorescence-based detection systems.

The observed decrease in emission intensity increases the likelihood of undetected leaks, environmental contamination and unplanned maintenance interventions. These challenges carry direct economic impacts: more frequent inspections may become necessary, and investments in advanced real-time monitoring and diagnostic systems may be required to maintain sensitivity and reduce detection latency. Without such measures, regulatory scrutiny and liability exposure are likely to increase. [12].

As a potential focus for future research and to mitigate these limitations future implementations could benefit from strategies such as, increasing the illumination intensity and positioning the light source closer to the fluorophores constitute viable measures to partially counteract the observed fluorescence decay. Moreover, while the experiments reported herein were limited to a seven-day observation window due to temporal restrictions during the study, extending the experimental period of analysis in future investigations would provide a more rigorous evaluation of long-term marker stability and operational viability. This methodology may be extended to other fluorescent fluids, such as Rhodamine WT [13], which emerges as a relevant candidate, since it exhibits a maximum fluorescence decay of 5% over 327 hours. This slower degradation rate and higher resilience to photobleaching directly contribute to maintaining fluorescence intensity over longer operational periods, thereby supporting more reliable visualization and contrast under field conditions.

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