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Thermographic Detection of Near and Far-Side Corrosion

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ABSTRACT

Active thermography has been demonstrated to be an effective tool for detection of near-surface corrosion hidden under paint, as well as hidden material loss due to corrosion. Compared to established point inspection techniques (e.g. ultrasound, eddy current), thermography offers fast, wide-area inspection of flat or curved surfaces that does not require direct contact or coupling. In its simplest form, it can be used to perform qualitative inspection using a heat gun or lamp and an uncooled IR camera. Recent developments in thermographic signal processing, coupled with improved IR camera and thermal excitation technology have resulted in significant advances in resolution, sensitivity and probability of detection of near and far-surface corrosion, and the ability to perform quantitative characterization of corrosion.

INTRODUCTION

Thermography has become a widely used method for Nondestructive Inspection (NDI) in the aerospace, power generation and automotive industries. Unlike conventional thermography, where a single infrared (IR) surface temperature image may provide sufficient information for the required diagnosis, NDI requires active thermography, in which the component is thermally excited (e.g. using light, hot/cold air or direct contact) and observed with an IR camera as it responds to the stimulus. While conventional thermography measures the instantaneous or average surface temperature of the part, active thermography uses the change in surface temperature over time as the part responds to excitation to detect and image subsurface features.

Modern thermographic NDI systems range from simple handheld configurations (e.g. a heat gun and IR camera manually applied and viewed by the inspector) used for field inspection of aircraft, pipelines and watercraft, to fully automated production cells for quality assurance of turbine blades. However, the underlying principle behind all of these systems is the same. Heat deposited by the system at the sample surface flows toward the cooler interior, and the presence of a subsurface flaw, such as a void or delamination, blocks the flow of heat and causes the nearby surface to cool more slowly than flaw-free areas. The result is a transient "hot spot" in the IR image sequence.

For many years, hot spot detection was the standard procedure for IR NDT, and it is still used for some applications such as detection of trapped water in aircraft honeycomb sandwich structures and significant material loss due to subsurface corrosion in aluminum aircraft and steel marine structures. However, it is not sensitive to small or subtle subsurface flaws and, because it is highly dependent on the subjective interpretation of the IR image by the operator, it is difficult to automate or reduce to a standardized procedure. For automated or more advanced applications, additional processing is required.

SINGLE PIXEL BEHAVIOR

In “hot spot” detection, data from the IR camera is treated as a sequence of images to be viewed by the operator as a movie. However, additional information can be obtained by treating each pixel as an independent time varying signal, so that a 600-frame sequence (e.g. 10 seconds at 60 Hz frame rate) from a camera with a 640 x 512 focal plane array is treated as 327,680 individual time histories, each with 600 samples. A considerable amount of information about the subsurface state of the sample can be gained from inspection of a single pixel time history without reference to rest of the image. As an example, consider the temperature-time history of the 3 samples (Figure 1). For an infinitely thick, flaw-free sample (left), the time history, shown on a logarithmic scale, is a straight line with slope -0.5, which represents ideal one-dimensional thermal diffusion. The presence of a back wall that obstructs the flow of heat (center) causes the straight line to gradually become a horizontal (slope = 0) line. The intersection of the 2 straight lines defines a time t*, which characterizes the thickness of the material and its thermal diffusivity (the rate at which heat travels through it). While these 2 cases represent limiting cases of free and completely obstructed heat flow, the presence of a finite-sized flaw (right) is an intermediate case. All 3 cases initially behave identically, however, both the flaw and wall cases diverge from the straight line (slope -0.5) at time t*. After time t*, the flaw gradually falls back towards the original slope -0.5 behavior.

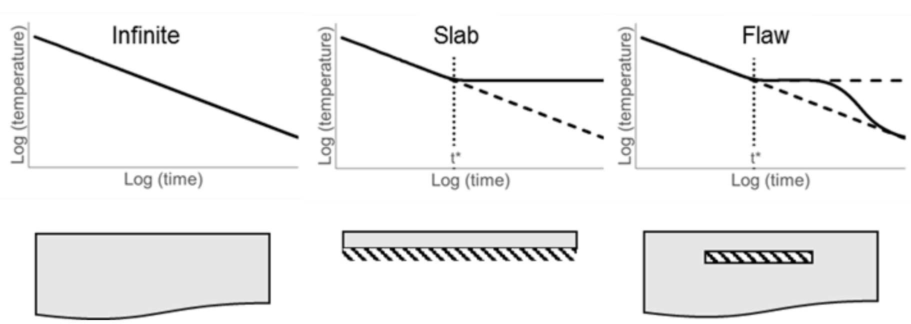

Figure 1: Logarithmic surface temperature-time response to flash heating for an infinitely thick solid (left), slab with an insulated back wall (center) and thick solid with an internal insulating flaw (right).

THERMOGRAPHIC SIGNAL RECONSTRUCTION

Actual data from a thermographic NDI system is susceptible to noise, temperature contributions from the background, and emissivity variations in the part under test, which may be a complex nonplanar, multilayer structure. The Thermographic Signal Reconstruction (TSR) method builds on the single pixel approach to address these issues, providing both noise reduction and signal enhancement. In TSR, each logarithmic pixel time history is replaced by a low order polynomial, which reduces temporal noise. The noise-reduced replica of each pixel time history is then differentiated with respect to time (Figure 2), removing emissivity and background artifacts. The 1st and 2nd derivatives of the infinitely thick sample are straight horizontal lines with amplitude -0.5 and 0, respectively. For the sample with the insulated back wall, the first derivative transitions between the horizontal lines with amplitudes -0.5 and 0, with the midpoint of this transition occurring at time t*. The 2nd derivative of the wall case is a symmetric function that is closely approximated by a Gaussian, with its peak at time t*. The presence of a flaw that obstructs the flow of heat breaks the symmetry of the derivatives and can reduce the maximum and minimum amplitudes of the signals, compared to the infinite or wall cases.

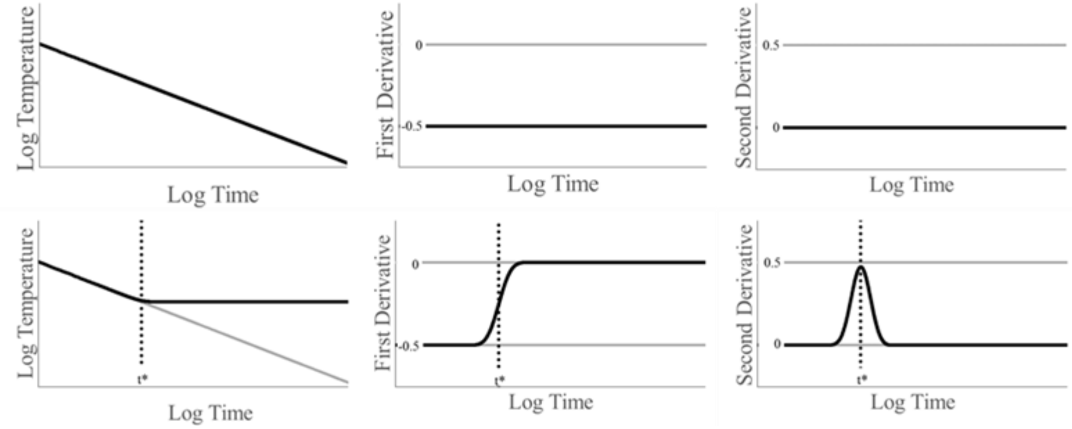

Figure 2: TSR pixel time history response to flash excitation. surface temperature vs. time (left), first (center), and 2nd (right) derivative response of an infinitely thick sample (top row) and a slab with an insulated back wall (bottom).

THERMOGRAPHIC NDI OF GROUND VEHICLE CORROSION

Thermography is widely used in aerospace applications for detection of material loss due to corrosion on the inner wall of primary structure, where a deviation from specified performance can result in catastrophic failure of the aircraft. In ground vehicles, prevention and detection of internal corrosion, or corrosion originating at the interior wall is also a significant concern, however, corrosion originating at or near the vehicle exterior wall is a prevalent problem that results in reduced service lifetime and increased maintenance and repair costs. Simple NDI methods, e.g. visual and tap testing, are widely used to perform fast, qualitative inspection of military ground vehicles to identify instances of surface corrosion, or hidden corrosion near the surface (Fig. 3). Although inexpensive and easy to perform, these methods lack the sensitivity to detect early stages of corrosion, when repair or rework may be viable, and are limited to detection of advanced corrosion, when vehicle structural integrity or functionality may already be compromised, and extensive replacement and/or rework is required. Visual inspection is further complicated by false positive indications due to surface scratches, markings, debris or discoloration. More advanced NDI methods such as eddy current or ultrasound are capable of detecting hidden early stage corrosion, but these are point scanning techniques, which are time consuming when applied on the scale of an entire vehicle.

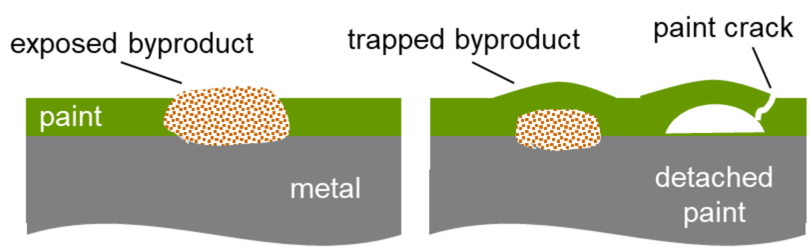

Figure 3: Simple corrosion can be detected using conventional NDI methods: (left) By-product exposed at paint surface. (right) Displacement of paint surface due to trapped by-product disbonded from the metal substrate.

Detection of hidden subsurface corrosion requires more precise control of thermal excitation and higher sensitivity to rapid changes in the IR signal response since the transit time of thermal energy through paint layers or near surface metal may be on the order of tens of milliseconds. Flashlamps emitting several kilojoules of light and near IR energy over a period of a few milliseconds, and high-speed IR camera operating at 100 – 400 Hz frame rates in the mid-IR spectrum (2-5 um) may be required for optimum sensitivity and probability of detection. Data processing using TSR to reduce noise and enhance detected subsurface anomalies allows detection of many anomalies that do not appear in the unprocessed sequence as hot spots, e.g. small low aspect ratio voids or inclusions (e.g. voids filled with corrosion by-product), or extended flaw conditions, where an entire area is affected and no boundaries appear to provides shape cues or allow comparison to an unaffected background. The TSR derivatives also provide a basis for quantitative measurement of material loss, as t*, the inflection point of the first derivative and maximum of the second derivative indicates the time at which a discontinuity occurs, thus allowing calculation of the material thickness loss.

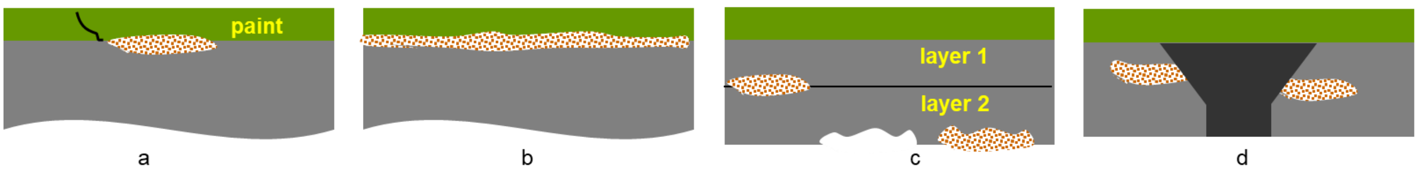

Figure 4: Corrosion scenarios under paint (a) Discrete corrosion b) distributed corrosion c) corrosion at a bonded metal-metal interface d) exfoliation adjacent to fastener.

In practice, the fact that ground vehicles are normally painted for corrosion protection or signature reduction is helpful to thermographic NDI methods. The presence of the paint improves IR emissivity and absorption of light from the flashlamps, compared to aircraft inspection where many planes are not painted, and inspection of bare aluminum is difficult due to optical reflection and low IR emissivity. Strategies for thermographic NDI of painted ground vehicles will vary, depending on the type and thickness of the paint, the part geometry and the likely defect mechanism. Some common examples are shown in Figs. 4-5:

a. Discrete corrosion at paint-metal interface: May present as a by-product filled inclusion or as a void if byproduct has escaped. Large indications may be detectable as hot spots using heat gun and handheld uncooled camera. However, small indications may be highly transient, and require flash/high-speed/TSR to detect, and to discriminate from superficial features on, rather than below, the surface.
b. Distributed corrosion at paint-metal interface: Requires flash/high-speed/TSR and statistical analysis of early signal behavior.
c. Discrete corrosion and bonded metal-metal interface or inner wall. Difficulty of detection will depend on feature aspect ratio (ratio of depth below paint-metal interface to minor axis of flaw size). Features with aspect ratio ~ > 6 are likely to be detectable using heat gun / uncooled camera. Features with aspect ratio < 6 may require flash/high-speed/TSR.
d. Exfoliation adjacent to fastener: Features may be small and highly transient, requiring flash/high-speed/TSR for detection.

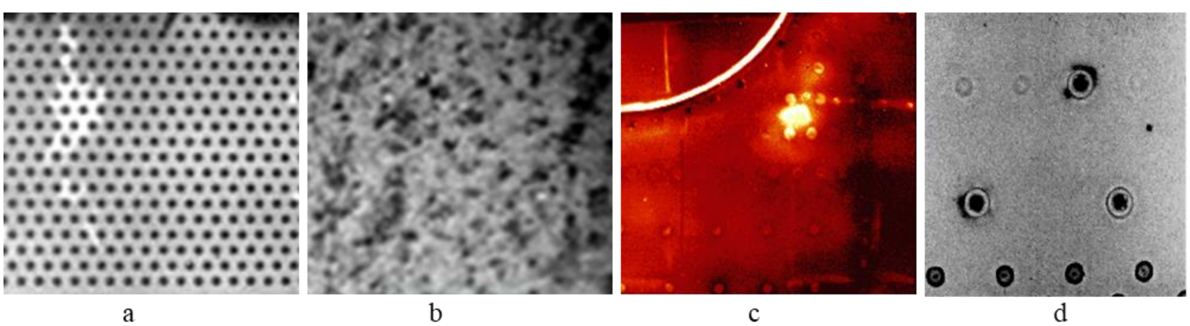

Figure 5: Flash thermography examples: a) Corrosion at paint-metal interface of a perforated Al panel; b) Distributed corrosion on a CARC painted Al panel after salt-fog exposure; c) Discrete corrosion at the back wall of a 0.25” thick steel panel; d) exfoliation corrosion adjacent to fastener.

Corrosion at the Paint-Metal Interface

A common mechanism for the initiation of corrosion occurs when paint is removed by a scratch or scrape and the underlying metal surface is exposed. Corrosion that begins at the exposed surface may extend under the paint, so that the actual extent of the corrosion is significantly greater than the visual indication. However, by-product from the exposed area may also extend onto the paint over an uncorroded area, creating a false indication of the extent of actual corrosion (Figure 6). Flash thermography provides an effective means for identifying subsurface corrosion extending from exposed metal.

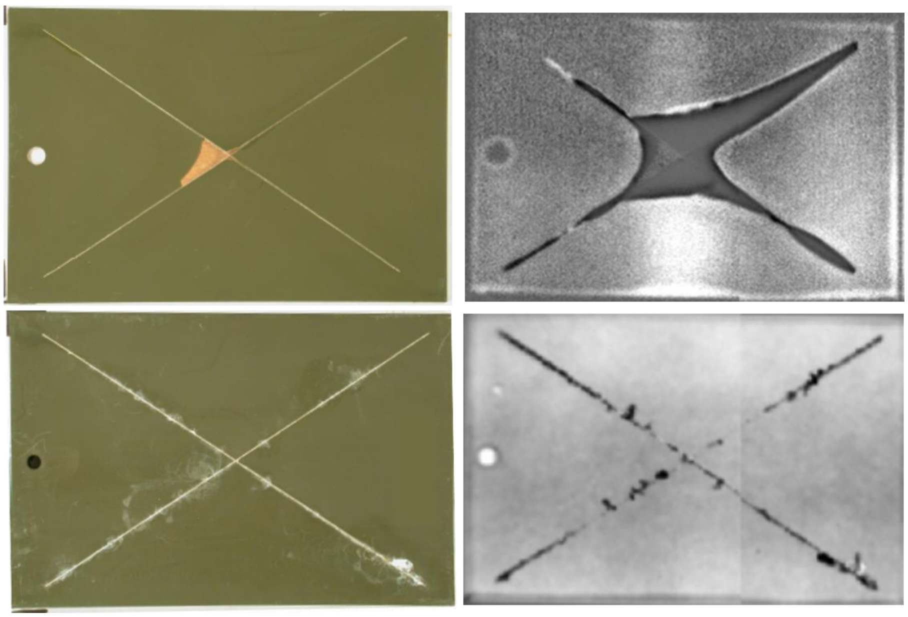

Figure 6: Visual (left) and flash thermography (right) images of painted Al panels after 1000-hour salt-fog exposure. Corrosion in the top panel extends far beyond the scribe marks. In the bottom panel, visual by-product indications on the surface are superficial, but dark thickening and discrete extensions of the scribe marks indicate corrosion under the paint.

A more challenging problem occurs when an entire surface under paint becomes corroded, since there are no distinct edges or shape cues to guide the inspector in identifying corrosion. In many cases, this problem

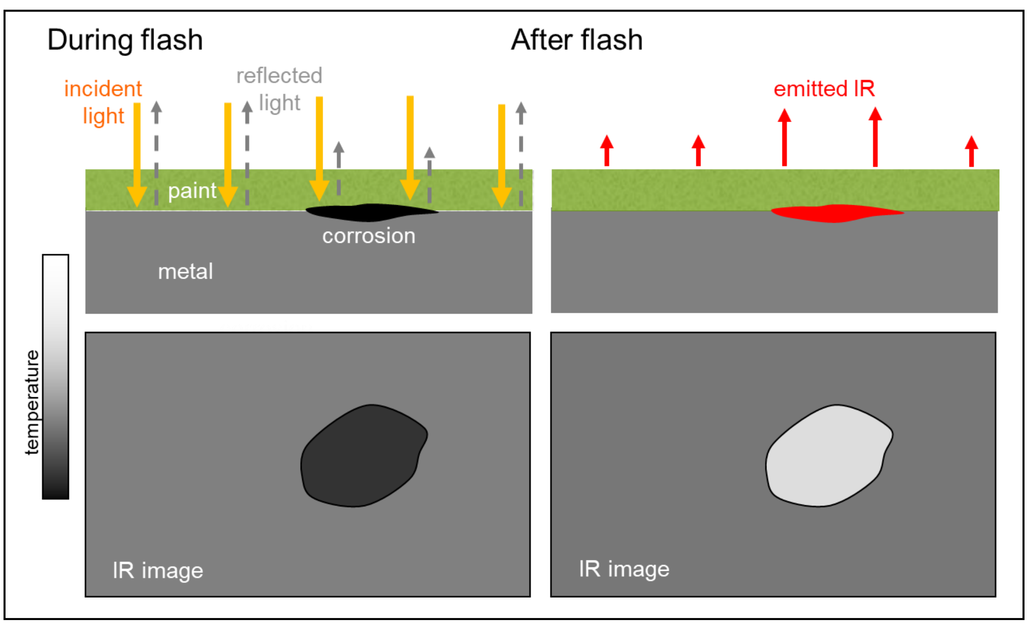

Figure 7: Surface corrosion under a translucent paint. Left: During flash heating, light from flash passes through the paint. IR spectral component is reflected from clean areas and partially absorbed by corrosion by-product or rough surface, resulting in a transient cold spot in the IR image (bottom); Right: After the flash, the corroded area is warmer than surrounding clean areas, resulting in a hot spot in the IR image (bottom).

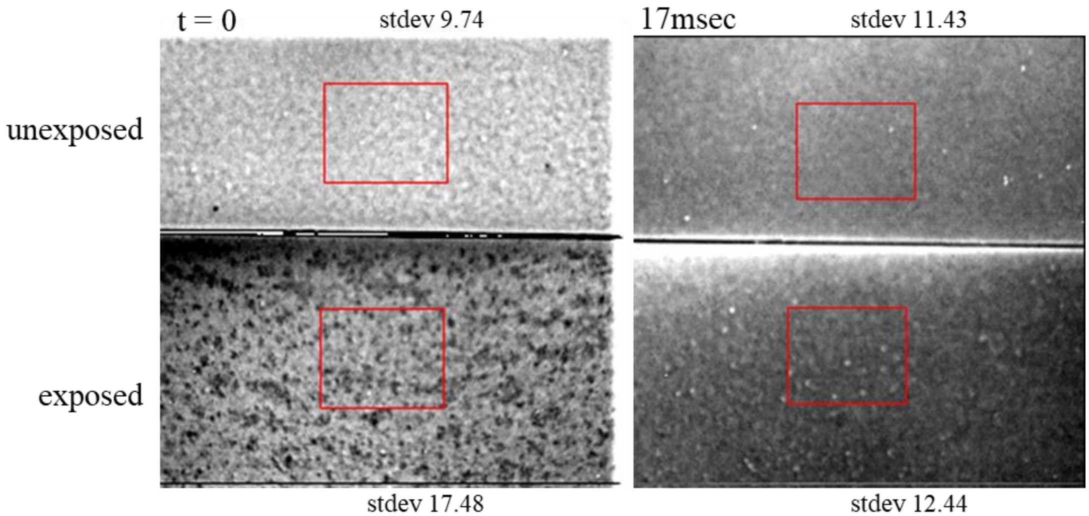

Figure 8: (top) TSR images of a clean CARC painted steel panel during (left) and immediately after excitation by a truncated 1-msec rectangular flash pulse; (bottom) Similar images of an identical panel after 1000-hour salt-fog exposure. Standard deviations are calculated over the indicated red rectangles.

can be addressed by exploiting both the temporal and spectral characteristics of the flash, which is typically generated by a plasma discharge in a tube filled with xenon gas. The flash pulse carries energy in both visible and IR spectral ranges, but in most cases, absorption occurs at the target surface, heating it nearly instantaneously relative to the rate of thermal diffusion in the target material and the sampling rate of the IR camera. The full width, half maximum duration of the flash pulse is on the order of a few milliseconds, but the IR component of the flash persists longer than the visible component, emitting IR energy that is detectable with an IR camera for tens of milliseconds. Using dedicated flash truncation hardware, it is possible to reduce the duration of both visible and IR components to form a near-rectangular pulse with duration of 1 msec or less. This precision control of flash timing offers enables a useful opportunity for NDI of ground vehicles where near-IR translucent paint has been applied. In such cases, during or immediately after the flash pulse, the IR component of the flash passes through the paint and is reflected off of the clean metal surface and absorbed by corrosion byproduct or a rough surface where pitting has occurred. An IR image acquired in this highly transient state, the corroded area will act as a poor IR reflector, and appear cold. However, a few milliseconds later, a "phase reversal" will occur, as the clean surface will appear cool, and the corroded area will appear hotter, warming the surrounding paint and causing increased IR emission at the surface (Figure 7). The net effect is a "hot spot" in the image at the corrosion site. Using the truncated flash to exploit paint translucence during the flash, it is possible to evaluate distributed corrosion at the paint metal interface (Figure 8). Corrosion under the paint results in a rapid reduction in surface variance of the flash response and immediate post flash TSR images.

DISCUSSION AND SUMMARY

Thermographic NDI of ground vehicles poses a unique set of challenges that differ from those encountered in aerospace maintenance and manufacturing, where the technique is widely used. Aside from differences in requirements and the materials involved, aerospace NDI typically involves interrogation of relatively clean surfaces to find internal deeper internal problems, while ground vehicle inspection often involves structures where corrosion, wear and damage are evident on the surface, and the task is to determine the extent and severity of that damage. Many basic GV NDI tasks can be accomplished using a simple thermography configuration comprising a heat gun and an uncooled IR camera, where the inspector views the camera output in real time to identify hot spots associated with voids created by paint that has separated from the surface, or inclusions at the paint-metal interface that are filled with corrosion by-product. However, the domain of GV applications can be extended significantly through the combination of flash thermography, high speed IR cameras and TSR signal processing. The combination of these elements enables quantitative evaluation of results and comparison of invariant thermophysical properties through the use of the TSR derivatives, reducing the burden of interpretation of results on subjective evaluation by the operator.

Thermography offers a fast, easy-to-implement alternative compared, in comparison to existing technology for ground vehicle NDI. However, broader implementation of thermographic NDI for corrosion will depend largely on whether the advanced detection capabilities provided by flash excitation, high speed IR cameras and TSR signal processing can be achieved with portable, low-cost uncooled cameras and excitation sources suitable for use in the field.

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