# Advanced Real-Time Weld Monitoring Evaluation Demonstrated with Comparisons of Manual and Robotic TIG Welding Used in Critical Nuclear Industry Fabrication

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**Abstract.** Ensuring critical welded joint quality and repeatability is largely dependent on robust, well-designed Welding Procedure Specifications (WPS). Highly skilled manual welding engineers automatically recognise many imperfections, adjusting their responses according to inputs from vision, smell and sounds made during the welding process. Unfortunately, exceptional human ability does not guarantee performance when less predictable influences occur during welding processes. Human error and materials imperfections can result in defective welds for critical applications, commonly attributed to material surface impurities and contamination. Fault detection is problematic; the only finite method of weld testing is destructive testing which is not applicable to final product verification. Quality assurance and control is used to guarantee the welding process repeatability by production of a Procedure Qualification Record. This often-lengthy approval process restricts welding technology and materials application advancement. An alternative method of testing is the detection of flaws and defects in real-time to allow immediate process corrections. Development of real time welding evaluation instrumentation requires welding process parameters measurements combined with high-speed data processing. This real time monitoring and evaluation produces a weld defect fingerprint used to determine quality. We aim to highlight variations found in welding process quality using real-time monitoring and assess if it is within the acceptable standards for nuclear applications. To achieve this, we first must understand the human welding engineer using data taken from a series of manual weld trials. The trials use a common welding operation found in nuclear reactor pressure vessels. Reference data comparisons are made using identical trials with robotic welding equipment. Trial comparison results indicate that real time evaluation of welding processes detects flaws in weld quality. We then demonstrate how applications of welding process parameters are exceptionally effective methods for the control of robotic welding applications.

**Keywords:** Manual · Automatic · TIG welding · Nuclear

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# 1 Introduction

Single platform manufacturing involves reducing the overall cost, time and space required to manufacture a component by bringing all manufacturing tasks onto one common platform. This concept, successfully proven in other industries, such as automotive, demonstrates flexibility to adopt both conventional and advanced manufacturing tasks such as additive manufacturing. The motivation for new nuclear industry manufacturing are huge cost savings achieved by improvement, reliability and reduced scrappage of components that ultimately force changes in standardisation.

Process variations found in the welding operations of nuclear industry components currently prevent a holistic manufacturing process. Ensuring the quality and repeatability of critical TIG welded joints is largely dependent on robust, well-designed Welding Procedure Specifications (WPS). Highly skilled manual welding engineers automatically recognise many imperfections, adjusting their responses according to inputs from sight, smell and sounds made during the welding process.

Unfortunately, this exceptional human ability does not guarantee welding performance when less predictable influences occur before, during and after welding operations. Human error and minor materials imperfections can all result in a defective weld for critical applications. Defective welding process outputs are commonly due to surface impurities and contamination. Fault detection is problematic as the only finite method of weld testing is destructive testing which is impossible to apply to a final product for verification.

Extensive measures are taken with high investment in quality assurance (QA) and control (QC) to guarantee the welding process repeatability by production of a Procedure Qualification Record (PQR). This often lengthy approval process results in the over engineering of both materials and processes which in turn restricts welding technology and materials application advancement.

To enable an accurate understanding of the welding process, we must first analyse the human factors by analysing the welding engineers themselves. Effectively unpicking human inputs and adjustments during manual welding of any components is challenging. Therefore we must adopt new sensor technology, software development and advanced, high speed signal processing to produce accurate welding analysis. Added value found in this type of analysis can be later applied to both robotic welding technology and materials advancement.

Using a highly skilled manual welding engineer based at the Nuclear Advanced Manufacturing Research Centre (NAMRC) and research staff from the Department of Physics & Astronomy & Sheffield Robotics based in Sheffield, UK a series of collaborative research trials were made. The trials use a common tube to plate joint found in nuclear reactor pressure vessels. This data is compared with a series of identical trials using robotic welding equipment demonstrating repeatability.

The main objective of this research work is to provide elements for a turnkey automated solution that evaluates welding processes in real time and detects flaws in weld quality. The autonomous system should provide wear data as real-time welding evaluation data is applied to NDT using a novel technique [1, 2] to increase throughput and save the scrapping of nuclear reactor vessels. This data can be fed back to the manufacture of nuclear components to further both service life, design and efficiency.

## 2 Materials and Methods

### 2.1 TIG Welding

For the purpose of this research, automatic as well as manual Tungsten Inert Gas (TIG) Welding techniques are used. TIG Welding, also known as Gas Tungsten Arc Welding (GTAW), a technique using a stable, high voltage electrical arc maintained at a specified distance (arc gap) between a tungsten electrode and the work piece. During the welding process, the non-consumable tungsten electrode is surrounded in an inert environment by a shield gas supplied to both the electrode and the weld pool. This inert environment provided is to protect the weld seam until it has cooled to the point that oxidation no longer can occur. Argon gas with a purity of 99.998% Argon was used during each welding trial.

For the automatic orbital welding the power supply was controlled using an AMI Model 227 programmable GTAW portable pipe welding power supply designed for automatic orbital welding applications. The programming feature of this machine gives the user the ability to control both continuous or pulsed current, current amplitude, and rotation speed. During this research, the Model 96 weld head was used as a benchmark because of the self-supporting tube-to-tubesheet, pneumatically operated weld head, specifically designed for single and multi-pass automatic welds.

Manual welding equipment used in this research, considered the industry benchmark, the Miller Dynasty 350 TIG GTAW AC/DC inverter based power supply. This inverter technology is of a similar principle to all modern TIG welding power sources allowing control of AC balance and frequency, independent amplitude tuning, DC pulsing frequencies to help tailor the arc to each specific application. The power source was used in conjunction with a conventional TIG welding torch and wireless foot control.

Manual processes are still widely used because the remanufacturing industry relies on highly skilled welding staff to “feel” their way through a task [5]. Combined with existing manufacturers’ inability to utilise accurate component wear identification with good welding power supplies and non-destructive testing (NDT).

Weld monitoring provides an ideal opportunity to better utilise automatic systems. Existing solutions do not offer anywhere near the proposed level of intuition simply through the lack of development. By providing arc sensing and real-time monitoring, the system relieves dependency on the dwindling supply of highly skilled welding engineers through automation.

### 2.2 Tube-to-Plate

Automatic welds were performed using the AMI weld head tube-to-tubesheet (tube-to-plate). These plates found in nuclear reactors (see Fig. 1) are subjected to high pressure (720–1005 psi) and temperatures (510–574 F), which requires flawless welds to prevent leakage. Welding PQR and WPS in this case are based on the BS EN ISO

15614-1:2004+A2:2012, referring to the specification and qualification of welding procedures where Part 1 is for Arc and gas welding used in steels, nickel and nickel alloys [4]. Tubes of 3/32” thickness and ½” diameter were attached on a 2”plate. The material used for both the tubes and the plate was a 316 stainless steel.

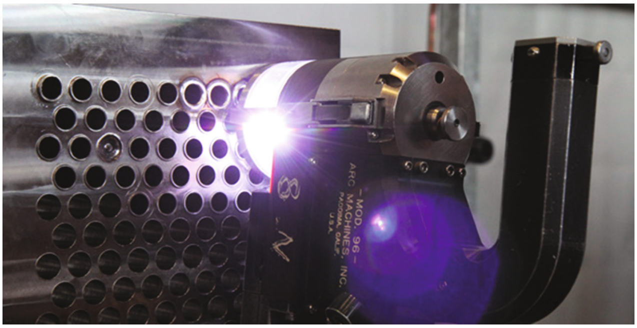


**Fig. 1.** Tubesheet welding. Specialised GTAW cell for autogenous welding of tubes and tubesheets [7]

# 3 The Collaboration

## 3.1 The Nuclear AMRC

The Nuclear AMRC has constantly grown and developed since its inception [3].

In July 2009, the UK government’s Low Carbon Industrial Strategy gave a commitment to “establish a Nuclear Advanced Manufacturing Research Centre that combines the knowledge, practices and expertise of manufacturing companies with the capability of universities”.

## 3.2 Flexible Manufacturing, Robotics and Automation Group

The Flexible Manufacturing, Robotics and Automation group is a joint venture between Sheffield Robotics and the Department of Physics at the University of Sheffield. The group leads a variety of research and development projects for aerospace, nuclear and scientific interdisciplinary research using advanced robotics, machine vision and advanced additive manufacturing systems.

# 4 Electric Measurements Analysis

## 4.1 High Speed DAQ

Electrical measurements of arc voltage, current and input power measurements of the VBCie system have been achieved thanks to the DAQ system developed by the University of Sheffield from 2006, see Fig. 2. The portable signal conditioning device is capable of measuring DC/AC welding current and voltage and can be used to evaluate fusion welding systems for Aerospace applications (funded by STFC in 2011 with their (IPS) Industrial Partnerships Scheme) produced by equipment manufacturers.

**Fig. 2.** Prototype High-speed DAQ system

Measurements are analysed in real-time and can be used to determine if a welded tube joint is successful. The IPS project developed the VBCie IP50-HMS Aero Auto to perform TIG orbital autogenous butt welds on tube joints in ultra-thin wall titanium and 316 L stainless steel tubes.

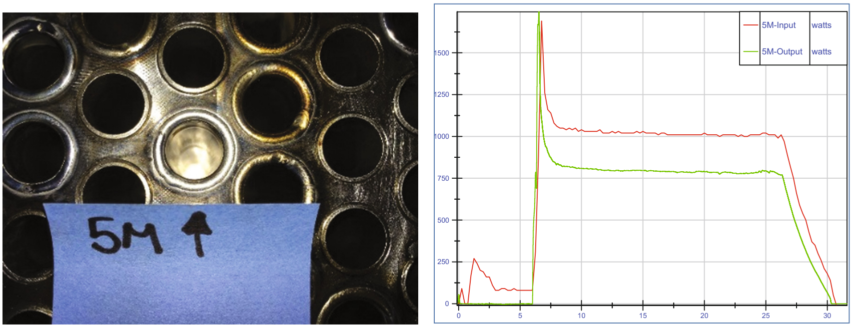
### 4.2 Automatic Welding

A series of automatic welds were performed on an 11-x-19 tube-to-plate worksheet using the automatic orbital welder described previously in Materials and Methods. These welds, and a second series to worksheet welds with deliberate defects were made in accordance with British welding standard BS 3915:1965.

The nature of intended defects included notches to both tube and plate, inert shield gas flow variations, and contamination. Welding system performance was monitored during the fusion process. Defect selection choice methodology was to simulate normally occurring problems found during tube-to-plate welding.

The coordination system that is used for identification of the tubes, has numbers 1–11 for the x-axis tubes and letters A–S for the y-axis tubes.

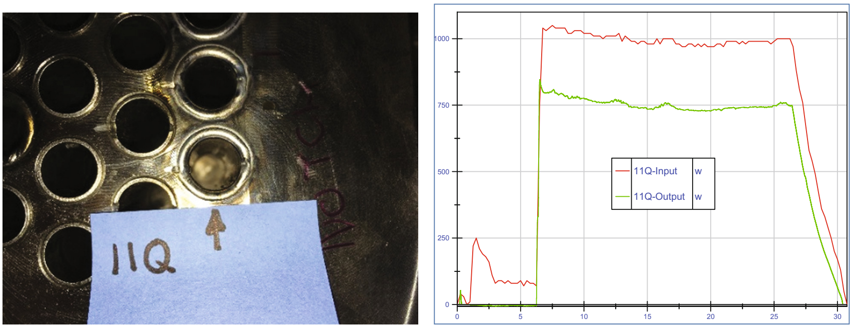
Measurements taken from the test sample 5 M (see Fig. 3) is joined using the correct welding procedure, will be compared with measurements taken from test samples with deliberate faults. We aim to determine the source of the variation that caused a pinhole at the start of the weld of 5 M by detecting similarities in the measurements in the time domain. All of the weld samples have been welded using a qualified WPS designed & proprietary to the Nuclear AMRC and carried out under controlled environmental conditions.



(a) (b)

**Fig. 3.** (a) Picture of a pool weld of a 316 L test structure representing the heat exchanger component found in a Nuclear reactor construction, (b) Power demanded by welding machine (in red) vs power delivered to weld (in green) η = 72%.

**Notch on the Samples.** One notch was cut into three test samples at a fixed point creating a defective joint. Normally this fault would not be detected when used in a robotic welding system. Material defects are a common flaw found during visual inspection by experienced welding engineers before attempting the welding operation. Visual inspection of the completed weld shows the presence of a pinhole (or lack of fusion) at the notch location. The active power deposited on the test sample (see Fig. 4) shows two peaks on the curve located at the exact time where the electrode is welding on top of the notch.

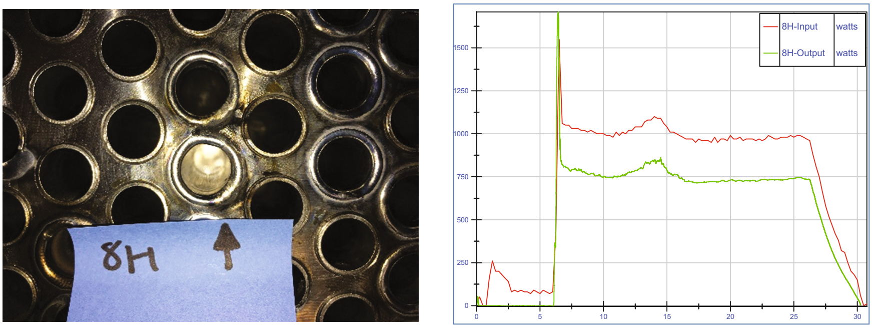


(a) (b)

**Fig. 4.** (a) Picture of a pool weld of a 316 L test structure representing the heat exchanger component found in a Nuclear reactor construction, (b) Power demanded by welding machine (in red) vs power delivered to weld (in green) η = 75%

Figure 4 highlights two peaks on the power delivered to the test sample (green curve in (b)). These two peaks are less noticeable on the power demand of the welding system (red curve in (b)) because the measurement frequency of the power input is low, just 4 samples/second.

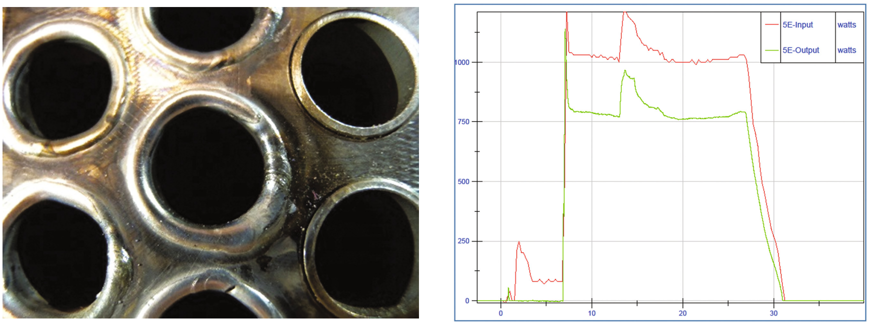
**Contamination of Samples (Grease).** A small amount of grease was introduced on the surface of the welding area in order to simulate possible contamination that can occur in a workshop. This type of common contamination is difficult to inspect by human welders and robots. Evaluating the data received from the welding of the contaminated area revealed a clear change in both, welding voltage and current that effects the arc power. Visually the test sample 8 H shows black colouring and pinholes where the grease contamination were located, see Fig. 5.



(a) (b)

**Fig. 5.** (a) Picture of a pool weld of a 316 L test structure representing the heat exchanger component found in a Nuclear reactor construction, (b) Power demanded by welding machine (in red) vs power delivered to weld (in green) η = 75%

**Quick Change of Shield Gas Concentration with Air Injection (1.5 s Perturbation 5 s after Arc Strike).** Inert shield gas flow disturbances by introducing air are made to simulate variations that occur during welding, either by mechanical malfunction or, human factors interrupting flow. A fast time change to gas concentration was introduced



(a) (b)

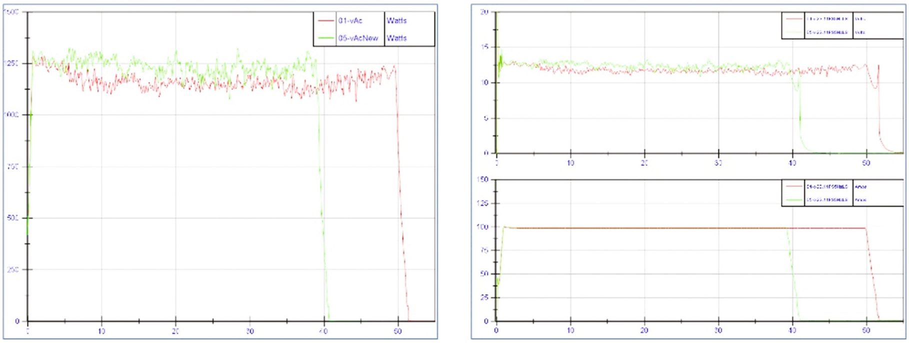
**Fig. 6.** (a) Picture of a pool weld of a 316 L test structure representing the heat exchanger component found in a Nuclear reactor construction, (b) Power demanded by welding machine (in red) vs power delivered to weld (in green) η = 75%.

5 s after the arc strike with a burst of compressed air. Data analysis of the welds with the shield gas flow revealed a voltage peak at the start of the arc air perturbation (see Fig. 6). A noise-like perturbation can also be seen in the welding current graph. As a result, the power output delivered to the sample test is higher than other variations. Visually, a bad weld, dark in colour (see picture in Fig. 6), and pinholes are observed at the end of the weld.

### 4.3 Manual Welding

Manual welds were performed on a series of 316 stainless steel plates. Using the same conditions and parameters for the automatic welding described previously, the aim of the trials was to simulate errors which occur during manual welding of nuclear industry components. This would be evidenced by the data generated and used in the identification and prevention of such flaws in the final products. Simulated errors comprised of using the wrong filler wire material and surface contamination. Wrong filler wire selection occurs through poor human judgment based on accidental selection due to similar visual appearance. Surface contamination occurs in the workshop due to substances like grease or debris. The data acquired from the defective welds are compared with data acquired from identical weld produced correctly using nuclear standards [6].

**Compare SS1 vs SSC4 (Clean 100 mm Long Steel Plate with Two Different Filler Wires).** There are no visible defects on a well prepared steel plate when using the right filler wire. However, when using a carbon filler wire on a steel plate more power is required to obtain correct penetration or fusion. Figure 7 shows a 20% increased welding speed when using the wrong wire (carbon) on a steel plate (100 mm long). The power output delivered to the plate is also higher (5%).

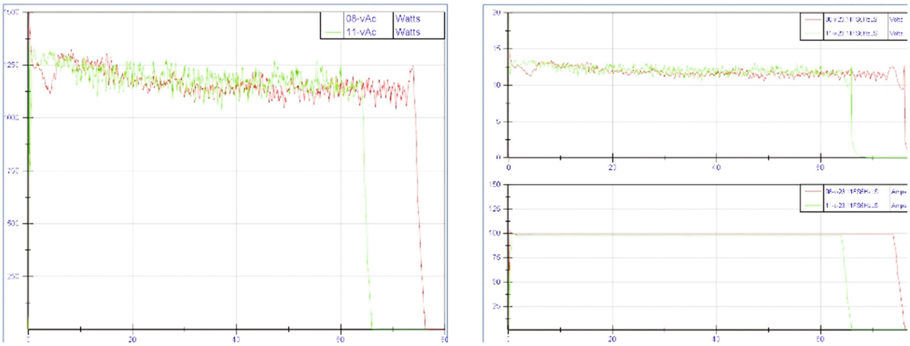


(a) (b)

**Fig. 7.** Welding voltage current of test sample SS1 (in red) using the right filler wire and SSC5 (in green) using a wrong filler wire (carbon).

**Compare SSCS2 vs SSCSW2 (Dirty 100 mm Long Steel Plate with Two Different Filler Wires).** Arc power delivery to the contaminated steel plate when using a carbon filler wire contains higher oscillations than when using steel filler wire on a dirty material. This is due to the welding machine trying to maintain stable arc and power outputs which can compensate for the contamination and the wrong filler wire.

Similar differences between welding speeds can be seen when welding with the wrong filler wire, see Fig. 8. Furthermore, it take longer to weld a contaminated material (35% longer). The welding machine delivers more power to the contaminated plate when using any of the filler wires.



(a) (b)

**Fig. 8.** Welding voltage current of dirty test sample SSCS2 (in red) using the right filler wire and SSCSW2 (in green) using a wrong filler wire (carbon).

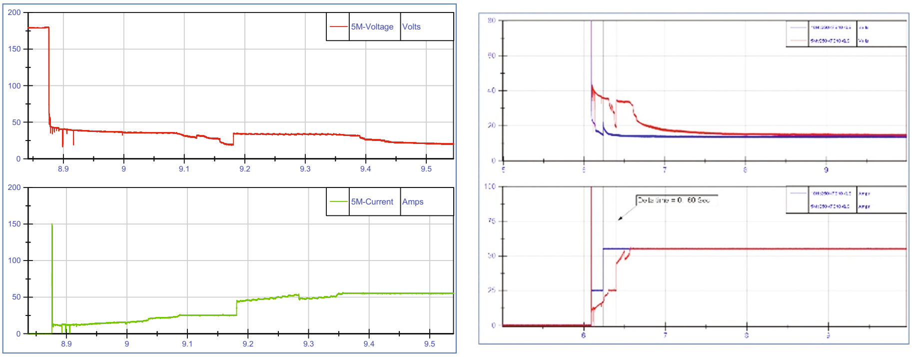
## 5 Some Welding Test Discussions

### 5.1 Evaluation of "Normal" Test Sample 5 M

Comparisons of the initial current and downslope using test sample 5 M are made with electrical measurement of the test samples produced without faults. Figure 9 shows how the transition between the arc strike and the initial current of test sample 5 M is delayed and not smooth compared with test sample 10H.

### 5.2 High Gas Flow Effecting Arc-Strike Disturbances

During the welding trials, the simulated inert gas flow variations used high gas flow which is similar to altering gas concentration with the introduction of air to achieve perturbation. High gas flow normally occurs from mechanical malfunctions of gas cylinder regulators used in welding. Unlike the previous shield gas disturbance which produced poor welds of a dark colour, visual inspection of weld sample 11 K revealed no defects. However, on-site there were indications (audible and visual) that the electrical arc was struggling to start. This is usually due to a high gas pressure/flow against the gap between the electrode of the torch and the work piece. Following the



(a) (b)

**Fig. 9.** (a) Voltage spike caused by welding machine trying to cope with the welding main arc current (55 Amps). (b) Welding voltage current of test sample 5 M (in red) not as smooth as test sample 10 H (in blue).

analysis of the data, there can be seen disturbances in both, welding voltage and current measurements, at the start of arc strike, see Fig. 10.

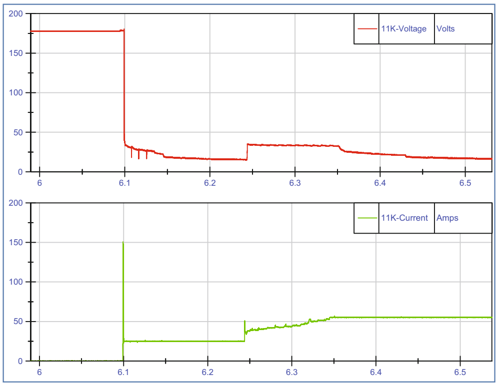


**Fig. 10.** Close-up of the welding voltage and current of 11 K measurement just after the arc strikes at 6.1 s.

# 6 Conclusions

Real time evaluation assessment of electrical parameters during manual or automatic welding is possible. It is possible to use this evaluation method for defect prevention during critical welding applications found in nuclear reactors and aerospace airframes and turbines. Previously a defects which can cause huge environmental and human loss could only be assessed by destructive testing.

Using real-time monitoring from the advanced High-Speed DAQ system developed by the University of Sheffield, the identification of a variety of defects was successfully achieved. Defects caused by contamination of the welding area, inert gas flow and changes in the mechanical characteristics of the surface were found to present unique characteristics in power-demand. Even in the case of high-gas pressure, when the visual inspection of the final product looked perfect, the acquired data revealed disturbances in the arc that affect weld quality.

The ability of accessing information in real-time and assessing the quality of the weld without destructive testing is building new foundations for the development of a monitoring system applicable to the global industrial sector. Using pattern recognition in voltage data reveals an infinite amount of possible applications. There are growing demands of monitoring systems in industry, where raw sensor data is transformed to higher-value information, establishing a benchmark technology for Industry 4.0 design principles. In the new era of manufacturing that involves collaborating robots with humans, welding monitoring and non-destructive testing, this has potential to be a game changing monitoring system.

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