ERBURIG^H Test Facility: The Next Step of Material Testing for H_2/O_2 Rocket Combustion Chambers

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Abstract
Material testing for H_2/O_2 rocket combustion chambers is important in the development of improved or new rocket engines. Due to the complex combustion atmosphere of H_2/O_2 combustion in terms of temperature, pressure and atmosphere composition, there are no testing methods that can simulate the exact conditions except for extreme costly full-scale tests. The EADS ERBURIG^H (Environmental Relevant Burner Rig – Hydrogen) test facility, which is presented in this paper, is the next step in small-scale testing that can simulate relevant material application temperature, composition of the combustion atmosphere, geometry, approximated gas velocity and the fluctuations of the oxygen-to-fuel-ratio (O/F-ratio) that is responsible for the Blanching mechanism.

1. Introduction

The development of new or improved rocket engines (especially for launcher application) is split in various sub-tasks. Basically, every engine component (e.g. pumps, turbines, thrust chamber etc.) is subject to constant development to improve the engine. Taking a closer look at the thrust chamber development, it is clear that material development and testing is a major aspect in improving the engines efficiency and performance. This is true for all kinds of rocket engines, from small rocket engines, e.g. orbital thrusters, which typically use refractory metals to withstand the high temperatures of the minimal cooled combustion chambers, to large rocket engines for launcher application that use copper-based alloys for combustion chamber material.

The trend chart (Figure 1) for small thrusters indicates that with a raise of the maximum working temperature the specific impulse, which is the synonym for the engine performance, can be increased. Efforts are being made to replace the refractory metals with Ceramic-Matrix-Composites (CMC) coated with Ultra-High-Temperature Coatings (UHTC). These CMC/UHTC material systems have to be investigated in detail to gain detailed knowledge of application limits (e.g. maximum working temperature, coating layer degradation, coating layer recession, chemical interaction of combustion chamber atmosphere with material, etc.). These investigations are currently underway at EADS Innovation Works and ASTRIUM Space Transportation [1], but are not further discussed in this article.

The aforementioned investigation of combustion chamber material for small thrusters was conducted using the EADS ERBURIG^K (Environmental Relevant Burner Rig-Kerosene) test facility. However, material testing for launcher combustion chambers can't be conducted with that test facility as the combustion atmosphere of hydrogen-oxygen (H_2/O_2) combustion differs from the small thruster combustion chamber atmosphere that normally uses carbon-containing fuels. But the principle of gaining more specific impulse by increasing the maximum working temperature still holds for launcher rocket engines. With that in mind, a new development, the EADS ERBURIG^H (Environmental Relevant Burner Rig-Hydrogen) test facility, was started on the basis of the EADS ERBURIG^K test facility. Using H_2 and O_2 for combustion, it will is suited to simulate relevant combustion chamber conditions for launcher rocket engines.

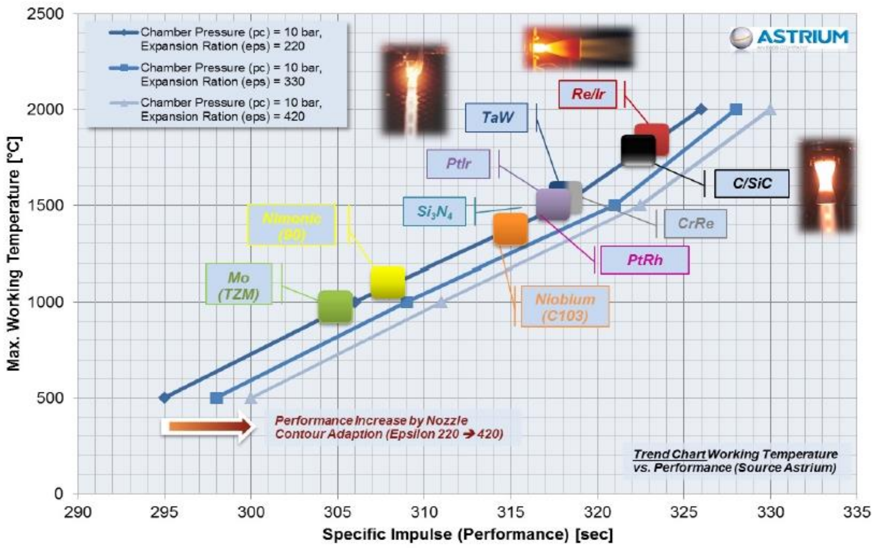

Figure 1: Trend chart of material working temperature over specific impulse for small rocket thrusters [1].

Material testing for H_2/O_2 combustion chambers, such as VULCAIN, can be divided in two parts: thermo-mechanical testing and thermo-chemical testing. In general, H_2/O_2 combustion chamber employs copper-based alloys, most notably copper-silver-zirconium (CuAgZr). The thermo-mechanical behavior of CuAgZr alloys have been studied in detail, most recently by S. Schwub [2].

The thermo-chemical behavior of copper-based alloys has been studied extensively by NASA (National Aeronautics and Space Administration) during the Space Shuttle era. While the oxidation of the material is quite well understood, there are areas on the hot gas wall of the rocket engine (after full-scale testing) that exhibit an extensive degradation during service. Figure 2 shows the area in question where the surface of the combustion chamber material changed from smooth to rough with cracks during operation. Upon closer inspection, the surface showed a sponge-like appearance which is thought to be caused by repeated oxidation and reduction of the material. The effect has a self-aggravating nature due to the fact that with increasing surface roughness the heat transfer from the hot gas is increased while the heat conduction through the material to the cooling chamber is reduced. This leads to higher material temperatures which again causes higher reaction rates for oxidation and reduction. Additionally, the higher material temperature has a negative effect on the thermo-mechanical behavior of the material. This surface degradation during service is called “Blanching Effect”.

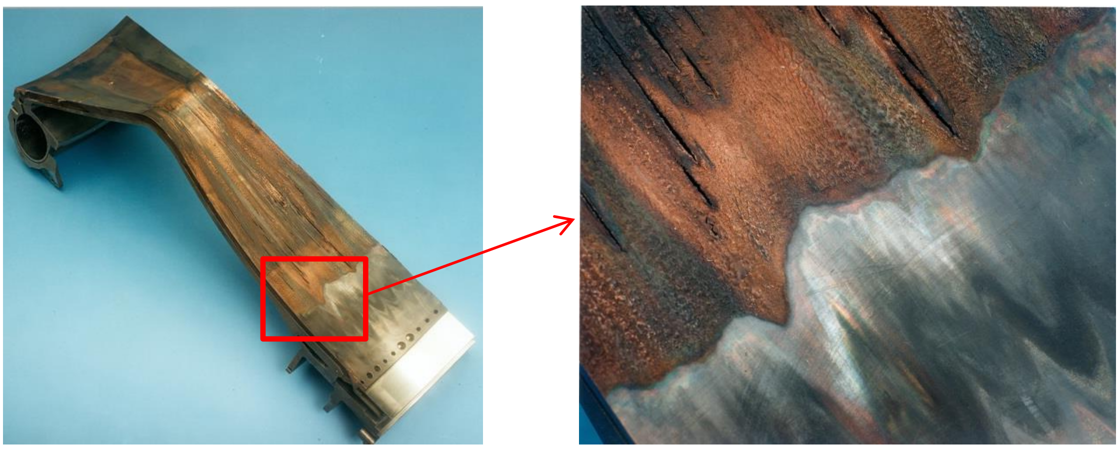

Figure 2: Change of CuAgZr surface appearance during HM60 engine operation (pictures provided by ASTRIUM Space Transportation).

The present article discusses a new innovative testing method for copper-based material for H_2/O_2 rocket combustion chambers which was developed by EADS Innovation Works and ASTRIUM Space Transportation to gain a more detailed insight into the working mechanism of the Blanching Effect with the goal to be able to implement this degradation effect into the in-house life-time simulation for H_2/O_2 rocket combustion chambers.

2. Frequently Used Material Testing Techniques

Due to the complex combustion chamber environment, only a few material testing techniques are available for material testing. Following, the most frequently used standard testing techniques are described briefly with exemplary results.

2.1 Thermogravimetric Analysis (TGA)

To evaluate the high temperature behavior of materials in certain atmospheres the thermogravimetric analysis (TGA) is most commonly applied. With this method material samples are heated in a furnace while the sample mass is recorded continuously. Depending on the future application of the material, various gases like O_2, SO_2, H_2, H_2S, H_2O, CO_2 [1] or air, can be used in the experimental set-up. The gained mass change data can give valuable information about reaction mechanisms and rate limiting steps of the overall reaction of the material sample with the reaction gases [4]. Figure 3 shows the schematic of such a TGA set-up as presented in [4]. A more detailed description of the working principle of the TGA can be found in literature, e.g. [4] [5]. In the following, several versions of TGA experiments (most notably with oxygen and hydrogen as reacting gases) that generate important information about the material behavior of combustion chamber material for H_2/O_2 combustion are shown.

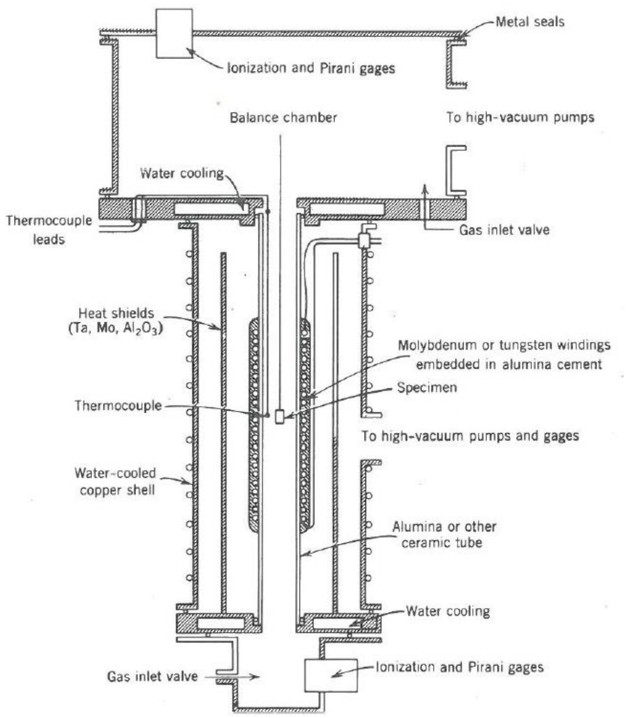

Figure 3: Working principle of thermogravimetric analysis [4].

2.1.1 TGA - Oxidative Atmosphere

The most commonly used version of TGA is with oxygen (O_2) as reacting gas. Although H_2/O_2 typically employ reducing (excess of H_2), the oxidation behavior of the material is important to fully understand the combustion chamber material. By varying temperature, oxygen content of the reacting gas and time, a good comparison of different combustion chamber materials can be established. The most extensive investigation of copper combustion chamber materials have been conducted by NASA. Suchlike comparisons of different materials can be displayed in various ways. Figure 4 shows an example for the comparison of the weight gain (relative to OFHC copper) of different copper-based alloys (GR-84: Cu-8wt.%Cr-4wt.%Nb; GC-60: Cu-1,1wt.%Al_2O_3; NAR-Z: Cu-3wt.%Ag-0,5wt.%Zr; GC-25: Cu-0.5wt.%Al_2O_3; GC-15: Cu-0.3wt.%Al_2O_3) at 0.25% oxygen-content (buffered with Ar) and a flow rate of 100cm³/min with respect to the material temperatures between 550°C and 700°C [6].

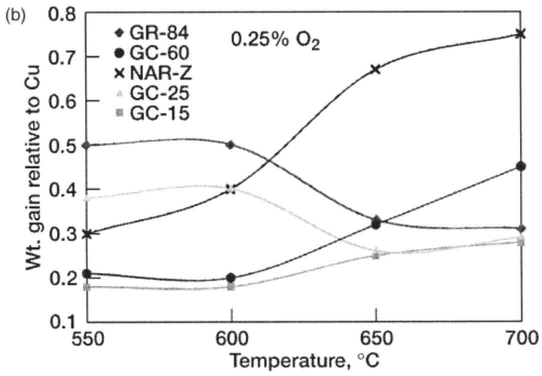

Figure 4: Comparison of relative weight gain of different Cu-alloys in 0.25% O_2 [6].

2.1.2 TGA - Temperature Cycling In Oxidative Atmosphere

Temperature cycling evaluates the behavior of the combustion chamber material with changing temperatures. Typically temperature cycling is performed between room temperature and application temperature. In case of rocket combustion chamber material, the test evaluates the behavior of the material concerning reignition of the rocket motor. For copper materials an enhanced weight loss, due to spallation of the oxide layer, is obtained. Figure 5 Comparison of Cu-alloy after cyclic oxidation in air at 600°C [7].Figure 5 shows an example for a cyclic oxidation study performed by L. Thomas-Ogbuji and co-workers [7] where several Cu-alloys have been submitted to cyclic oxidation in air at 500°C to 700 °C. Comparing the results for different materials, one can identify the material with the best resistance against spallation by identifying the material with the most oxide still on the surface.

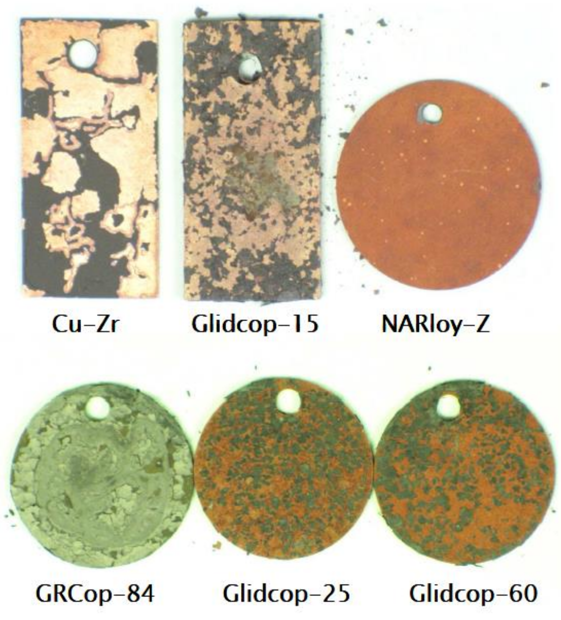

Figure 5 Comparison of Cu-alloy after cyclic oxidation in air at 600°C [7].

2.1.3 TGA - Oxidation-Reduction-Cycling

Modern H_2/O_2 rocket combustion chambers employ oxygen-to-fuel-ratios lower than stoichiometry (excess of H_2) to increase efficiency. This implies that no protective oxidation can be formed in the absence of free oxygen. Nevertheless, in service copper materials show signs of blanching. Blanching describes the repeated oxidation and reduction of the copper material. Close investigations of blanched areas reveal pits, cracks, fissures and a sponge-like appearance [8]. These surface changes lead to changes in material properties, e.g. thermal conductivity, heat transfer, etc.. The free oxygen needed for the oxidation part of the blanching process is provided through spatial and temporal fluctuations due to inhomogeneous mixing and turbulences.
In the experiment conducted by L. Ogbuji [8] at NASA Glenn Research Center (Cleveland, Ohio) a TGA set-up is modified to be able to switch from oxidizing gas (pure O_2) to reducing gas (4-5% H_2 buffered with Ar to be below the explosion threshold) and back at a gas flow rate of 40 ml/min. This simulates the fluctuations to reproduce the blanching effect. Figure 6 shows the comparison of different copper-based materials with respect to the testing time. During this time about 40 cycles of oxidation (0.1 min) and reduction (4.9 min) have been performed. An overall constant weight over the testing time implies a susceptibility to blanching while a weight gain implies a certain resistance to blanching. Thus, of all the materials tested only the CuCrNb materials imply resistance to blanching.

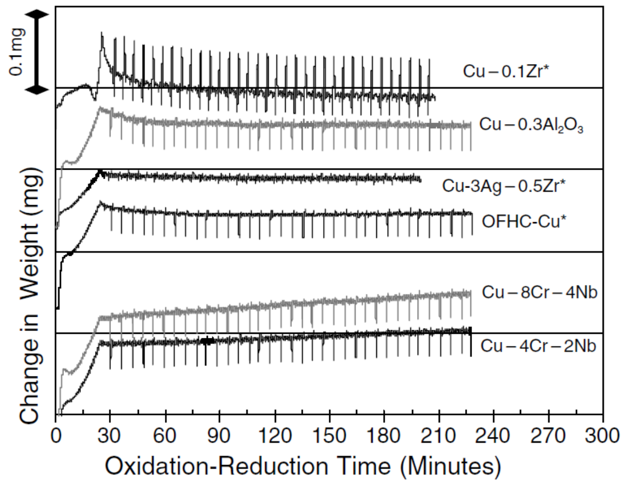

Figure 6: Comparison of weight change of different Cu-alloys after oxidation-reduction-cycling [8].

2.2 Full Scale Test

Full scale tests are the most effective tests to evaluate the behavior of the complete rocket engine. Despite this fact, these tests are only applied late in the development process as the tests are very expensive, laborious and time consuming. For comparison, NASA [9] compiled the testing costs of various engine developments. It is shown that development testing for LOX/LH (liquid oxygen / liquid hydrogen) rocket engines can easily range in the tens of millions of US dollars.
There are different ways to perform full scale tests. Firstly, testing only the rocket engine in special testing facilities and, secondly, performing flight tests on the actual rocket. Subsequently, these two methods will be described briefly.

2.2.1 Rocket Test Facilities

In the development of rocket engines, it is crucial to do thorough testing before the first flight. Every rocket developing nation maintains at least one rocket test facility. These test facilities usually consist of various test benches for different engine components and sizes.
The test facilities simulate the peripheral systems of the rocket engines. These are fired with combustibles from large storage tanks and their behavior is closely monitored by extensive diagnostic set-ups.

List of rocket test facilities:

- Germany: German Aerospace Center Lampoldshausen
- United States of America: NASA (National Aeronautics and Space Administration) Glenn Research Center, Ohio, OH
- Russia: NII-229, Zagorsk, Moscow Oblast
- India: Liquid Propulsion Systems Centre, Mahendragiri, Tamil Nadu
- Australia: Woomera Test Range, South Australia
- Japan: Noshiro Rocket Testing Center, Noshiro City

Figure 7: Test bench P8 at European research and technology test facility at German Aerospace Center in Lampoldshausen, Germany [10].

2.2.2 Flight Test

Flight tests are actual rocket launches that are equipped with a new evolution of an already existing or with a totally new rocket engine. To be able to conduct such a test, the engine in question has to proof a certain maturity beforehand. This is typically done by full-scale tests in rocket test facilities (see section 2.2.1).
The flight tests are often used as normal commercial missions for payload transportation to orbit. However, as there is no guarantee that the new rocket engine works properly, the flights are available at a lower prize while having lower liability for the payload carrier.

3. Environmental Relevant Burner Rig (ERBURIG) Test Facility at EADS Innovation Works

After developing the ERBURIG^{K} test facility [1] to conduct material testing for carbon-containing combustion atmospheres, the ERBURIG^{H} test facility was the next logical step. The test facility uses hydrogen and oxygen to emulate rocket combustion chamber-like conditions for material testing. The idea for the test facility can originally be traced back on the principle of a high-velocity-oxygen-fuel (HVOF) thermal spraying gun. With this process in mind, a new injection system for gaseous oxygen and gaseous hydrogen was developed with close resemblance to

the actual injection system of the VULCAIN II rocket motor. Typical H_2/O_2 HVOF thermal spaying gun do not possess a geometric combustion chamber in the way that rocket motors do. In addition, to achieve reliable and reproducible material testing conditions comparable to real combustion chambers the material testing has to be conducted inside the ERBURIG^H gun so that no ambient air/oxygen can pose any problems when studying the material behavior with lower than stoichiometry O/F mixtures. Hence, a new combustion chamber geometry, including a water cooling system for the injector head and the combustion chamber, was developed. In general, the working principle can be described to be the same as in an HVOF thermal spaying gun. At the face-plate, the injection system distributes the combustibles and, after the combustion, the hot gas is accelerated through a nozzle.
The test facility (Figure 8) is designed to be able to operate with combustion pressures between 7 bar to 12 bar with wall temperatures in the test section of the combustion chamber between 400°C and 600°C.

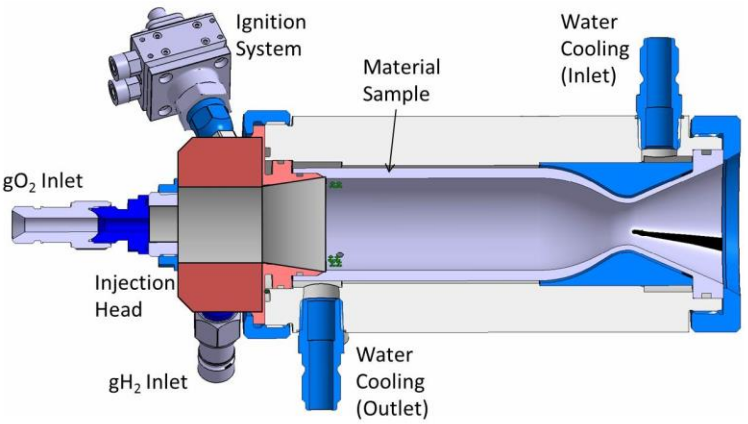

Figure 8: Schematic of ERBURIG^H set-up.

To get a deep understanding of the testing conditions, various diagnostic and numerical methods will be used characterize the ERBURIG^H test facility before initial material testing. These methods include numerical simulation by ASTRIUM Space Transportation of the combustion and gas flow inside the combustion chamber by use of a coupled simulation of ANSYS CFX and the ASTRIUM Space Transportation in-house code ROCFLAM II [11] for the combustion kinetics. Figure 9 illustrates an example of such a simulation. The simulations have been conducted for several operating conditions.

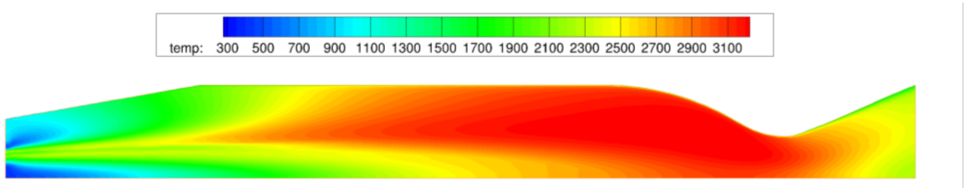

Figure 9: Exemplary temperature field for ERBURIG^H combustion chamber.

In addition to the numerical investigation of the test set-up, various diagnostic methods will be implemented to monitor the combustion chamber conditions, most notably temperature measurements of the hot gas wall by thermocouples and pyrometer and spectroscopic measurements for the hot gas composition.

First and foremost, the ERBURIG^H test facility was developed to study the effect of blanching of copper-based materials for rocket combustion chambers using hydrogen and oxygen as combustibles. Therefore, the naturally occurring temporal and spatial oxygen-to-fuel-ratio fluctuations in full-scale combustion chambers have to be simulated in the test facility. This is achieved through additional admixing of hydrogen or oxygen to generate higher, respectively lower, than stoichiometry oxygen-to-fuel-ratios.

In the next month, the focus will be on final manufacturing of the ERBURIG^{H} test facility with a subsequent implementation. Then initial testing will be conducted to check the diagnostic data of these first runs against the numerical results. Upon successful comparison, the material testing will be started.

4. Conclusion

Understanding the materials behavior in combustion chamber atmospheres is crucial to the development of improved or new rocket engines for launcher application. Due to the complex conditions inside the combustion chamber, a multitude of tests have to be performed to gain better understanding. The most important conditions in terms of material testing are temperature, composition of the combustion atmosphere, gas flow characteristics (turbulences/fluctuations of O/F-ratio, gas velocity, etc.) and geometry. Besides from full-scale testing (test facility or flight test) testing methods only simulate one or two relevant conditions at a time. As full-scale testing is extremely expensive, it is advisable to perform a series of smaller, less expensive and fast tests that simulate a combustion chamber relevant atmosphere before full-scale testing.
The typical TGA set-ups shown in section 2.1 can simulate temperature, composition of the combustion atmosphere and the fluctuation of the O/F-ratio. However, due to the small TGA sample size and the dimensions of TGA set-ups, realistic geometries and gas velocities cannot be achieved, which are relevant conditions for the material behavior.
With the new ERBURIG^{H} test facility of EADS Innovation Works it is now possible to perform cost-efficient (compared to full-scale tests) small-scale tests of combustion chamber material with respect to relevant material temperature, composition of the combustion atmosphere and geometry. In addition, the gas velocity of a real rocket engine can be approximated. For the fluctuations of the O/F-ratio, which is important to study the Blanching mechanism, it is possible to create a defined change in gas composition by varying the injection parameters during testing. In the next month, the ERBURIG^{H} test facility will be set up and initial testing will be started.

5. Acknowledgments

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