SHARP PHASE CHANGE IN SHAPE MEMORY ALLOY THERMAL ACTUATORS FOR SUBSEA FLOW CONTROL

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ABSTRACT

Gas-lifted oil wells are susceptible to failure through malfunction of gas lift valves (GLV). One failure mode occurs when the GLV check valve fails and product passes into the well annulus, potentially reaching the wellhead. This is a growing concern as offshore wells are drilled thousands of meters below the ocean floor in extreme temperature and pressure conditions and repair and monitoring become difficult. The authors have previously developed a thermally-actuated safety valve to prevent product backflow into the annulus in the event of check valve failure. The safety valve uses shape memory alloy (SMA) wires to translate a temperature change into a displacement and, based on commercially available SMA wire material properties, requires a $6^{\circ}C$ *temperature change to fully actuate. In some wells, however, check valve failure may result in less than* $6^{\circ}C$ *temperature change. In this paper a new concept is developed to sharpen the austenitic phase change in SMA actuators. The concept has broad practical implications because it will allow thermally-activated devices, such as fluid control valves, to become much more precise, i.e., translating a small temperature change into a large displacement. The new concept uses the fact that SMA transition temperatures are stress dependent. By specifically controlling stress in the wire, the temperature difference required for austenitic transition can be decreased. This is achieved with a negative-differential spring - a spring that exerts a decreasing amount of force as it is displaced. The concept is tested experimentally by conductively and electrically heating SMA wires connected to a negative-differential spring. Results show a* $2.9^{\circ}C$*-*$5^{\circ}C$ *reductions, respectively, in the temperature difference required for austenitic transition.*

Introduction

Gas lift is an artificial lifting method used to produce oil from wells that do not flow naturally. Gas is injected through the well annulus and into the well tubing at a down-well location (as shown in figure 1). The gas mixes with the oil in the tubing, aerating the oil and causing it to rise to the surface [1].

Gas lift valves are one-way valves that allow gas to pass from the annulus to the tubing but prevent oil from passing through to the annulus [1]. Most valves contain a pressurized bellows and an internal check valve (see figure 2). The bellows opens when the injection gas is pressurized above a threshold value, and the internal check valve prevents oil from passing through the gas lift valve [8] .

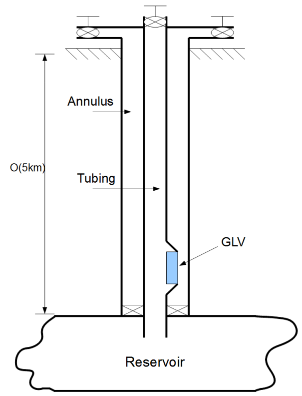

Figure 1. Schematic of oil well with gas lift valve (GLV). Top of figure represents sea floor.

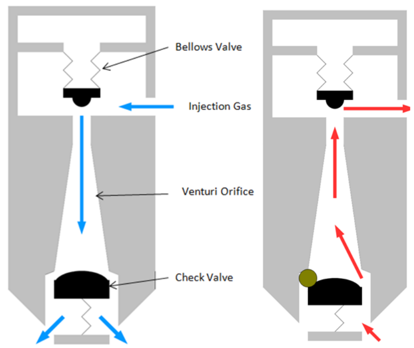

Figure 2. Gas lift valve model. Normal operation (left) and failure (right)

Proper function of gas lift valves is very important for the safety of the well and surface operations. If hydrocarbons flow through the wrong path (i.e. backflow from the tubing into the annulus, through a gas lift valve leak), they can reach the wellhead and create an undesired accumulation of high-pressure combustible material. Leaking gas lift valves are thought to have played a significant role in the 1988 accident on the Piper Alpha North Sea production platform, which led to an explosion and fire killing 167 men [7]. Even now, two decades after the Piper Alpha accident, gas lift valves are still susceptible to leakage [2], with seal corrosion being a major contributing factor.

The authors have previously developed a thermally-actuated safety valve [3] that prevents a backflow event in the case of gas lift valve failure. The safety valve is a shape-memory-alloy (SMA) -actuated trunnion ball valve that closes when heated and opens when cooled. It relies on the fact that injection gas is cooler than produced fluids, and that the gas lift valve will heat up during a backflow event. The safety valve is completely passive, requiring no communication from the surface and no external power source.

Using commercially-available shape memory alloys, the design requires a temperature change of at least 6° C to actuate. Some wells may have less than a 6°C temperature difference between normal operation and a backflow event, and the current design could not be applied to those wells.

In this paper we propose a new invention that will allow the safety valve to actuate with less than a 6° C temperature change. More broadly, this invention would allow any device actuated by SMAs to become much more precise, i.e. translating a small temperature change into a large displacement.

Background

In the thermally-actuated safety valve the SMA wire contracts when it heats from A_s (Austenite start temperature) to A_f (Austenite finish temperature), and expands when cooled from M_s (Martensite start temperature) to M_f (Martensite finish temperature. See figure 3.

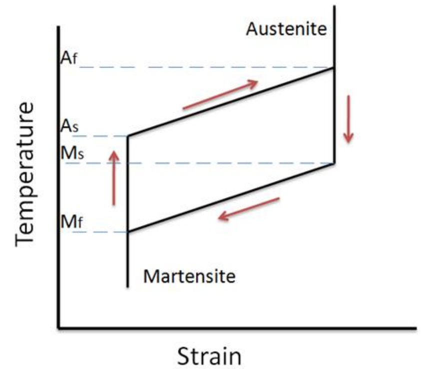

Figure 3. Shape memory alloy hysteresis

In this paper we describe how the new design is applicable to the austenitic transition. The transition temperatures A_s and A_f are dependent on stress, σ, applied to the wire, as

$$A_{s\sigma} = A_s + \frac{\sigma}{C} \tag{1}$$

Where $A_{s\sigma}$ is the Austenite start transition temperature under external stress σ, A_s is the Austenite start transition temperature under no external stress, and C is a constant dependent on the material [5]. Similarly,

$$A_{f\sigma} = A_f + \frac{\sigma}{C} \tag{2}$$

where the subscript f denotes Austenite finish transition temperature. Equations 1 and 2 show that increasing external stress on an SMA wire increases the A_s and A_f transition temperatures, while decreasing the external stress decreases the A_s and A_f transition temperatures.

Sharp Phase Change Concept

The temperature change required to completely actuate an SMA wire is equal to the difference $A_f - A_s$. Based on the constitutive equations, it is theoretically possible to reduce this temperature difference by externally applying a high stress when the wire is near the A_s transition temperature and a low stress when the wire is near the A_f transition temperature. This will raise A_s, while not significantly changing A_f. Thus the difference $A_f - A_s$ will be reduced and the phase change from Austenite to Martensite will be sharpened.

This external stress characteristic can be realized by using a negative-differential spring - a spring that exerts a decreasing restoring force as it is displaced. This is the opposite force characteristic as a positive spring, which exerts an increasing restoring force as it is displaced. Physical examples of negative-differential springs include a mass on a lever rotating from horizontal to vertical, a coiled metal ribbon of decreasing width, and wire rotating a cam of decreasing radius.

To the authors' knowledge a negative-differential spring has not been used to sharpen the phase change of conductively-heated SMA wires. A similar concept is used in differential SMA actuators [6] for electrical applications. These actuators rely on the fact that shape memory alloys can undergo an Austenite-Martensite transformation induced by stress under a constant temperature [5], as shown in figure 4. When the external stress applied to the SMA exceeds σ_{Ms} and σ_{Mf} it transitions to Martensite, and when the external stress is lowered below σ_{As} and σ_{Af} it transitions back to Austenite.

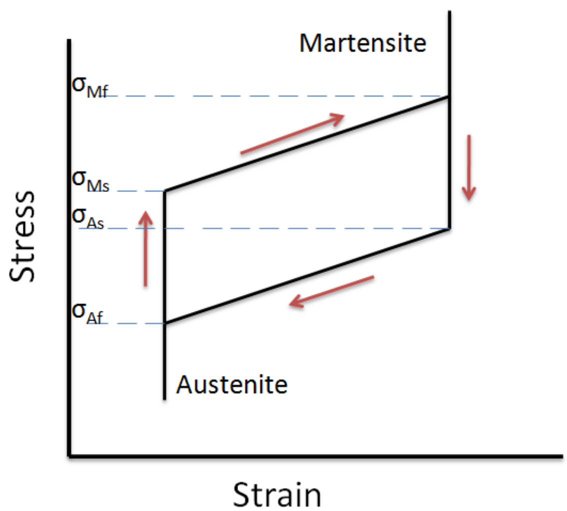

Figure 4. Stress-induced shape memory alloy hysteresis

In the differential SMA configuration, two SMA wires are attached antagonistically and each electrically heated independently. One wire is used as the actuator while the other used as the restoring wire. As the actuating wire is heated and contracts, the restoring wire is pulled in tension and undergoes stress-induced Martensitic transformation. The restoring wire has a high initial stiffness, and then a lower stiffness after Martensitic transformation. Thus the restoring wire acts as a negative-differential spring and decreases the amount of temperature change necessary to transform the actuating wire.

The restoring wire is then heated electrically and acts as an actuator in the reverse direction while the other wire acts as the restoring wire. The main use of differential SMA actuators is to shorten cycling time of the actuation system. This setup, however, is not directly suited to an application where only conductive heating is available, such as the gas-lift safety valve application.

The concept of using a bias element to reduce the transformation temperature of SMA wires is mentioned in [4], where the SMA wires are used as jewelry and heated by body heat. However, there is no explanation of how the bias element would be physically realized, and no experimental tests or prototypes are described.

Experimental Setup

The sharp phase change concept is tested experimentally using a mass on the end of a rotating lever to act as the negative-differential spring, and heating the SMA wire by electrical heating and by conduction through water.

Electrical Heating

The concept is first tested using electrical heating. An SMA wire is connected on one end to ground and the other to a circular section of a rotating lever. See figure 5.

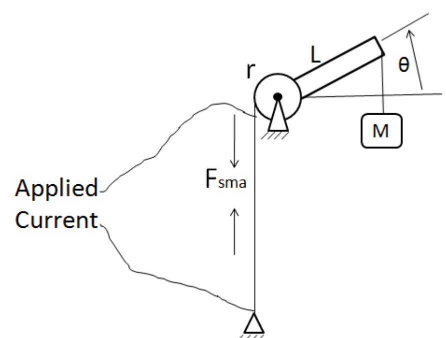

Figure 5. Electrical heating experimental setup

A mass is connected to the other end of the lever, with a pivot point in between. The circular section has radius r and the mass M is connected at a distance L from the pivot point. An electric current is applied across the SMA wire to heat it resistively. In this setup, the stress in the SMA wire, σ_{SMA} is given by the force, F_{SMA}, divided by the wire area:

$$\sigma_{SMA} = \frac{MgL}{Ar} cos\theta \tag{3}$$

where g is the gravity constant, A the cross-sectional area of the wire, and θ is the lever angle measured from horizontal. To achieve a negative-differential spring stress characteristic, the lever is initially started at a positive angle θ between zero and 90 degrees. As the SMA wire is heated it contracts, rotating the lever up to a final angle also between zero and 90 degrees. The cosine of the angle decreases as the angle increases, and thus the external stress applied to the wire decreases as the wire heats up.

To achieve a positive spring, the lever is initially started at a negative angle between negative 90 degrees and zero degrees. As the SMA wire is heated and contracts it rotates the lever up to a final angle also between -90 degrees and zero degrees. The cosine of the angle increases in this scenario, meaning the external stress in the wire increases as the wire is heated.

In the first type experiment the lever was started at an initial angle of 40 degrees to achieve a negative-differential spring, and current was applied to the wire until it completely transitioned from Austenite to Martensite. A 0.5-kg mass was used, with a 0.1-m lever and 0.51-m initial SMA wire length. Current was increased approximately linearly over a 20-minute time interval. A Crossbow CXTA01 inclinometer was used to measure the rotation of the lever, and a BK Precision 1672 DC Power Supply used to provide electrical current to the wire. A representative plot of current versus time for one trial is shown in figure 6, and a plot of lever angular rotation versus time for the same trial is shown in figure 7. Both plots are unfiltered.

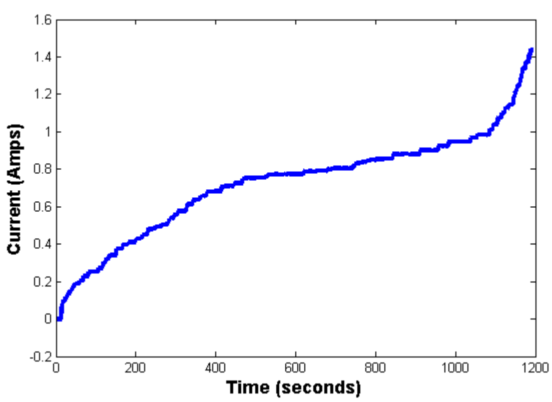

Figure 6. Electrical current applied to SMA wire vs time. Data is unfiltered.

The second type of experiment was identical to the first except the lever was started at -40 degrees to achieve a positive spring. Each experiment was repeated five times and the average of the results are shown in figure 8, with the positive spring results shown in red and negative-differential spring results in blue. To average the data, each trial was resampled to give the same number of data points per trial, and then the average was taken. A second-order butterworth filter with cutoff frequency 0.05 was applied to the averaged data to smooth out sensor noise.

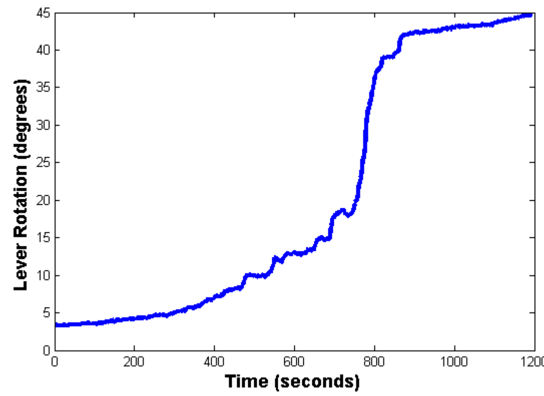

Figure 7. Lever rotation vs time. Data is unfiltered

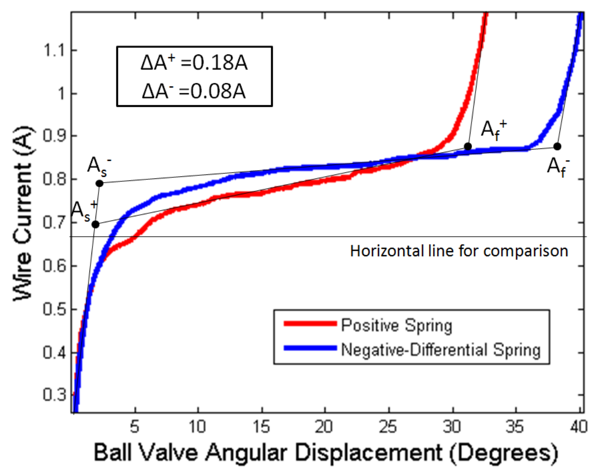

Figure 8. Electrical heating results for positive spring and negative differential spring. Plots are the average of all trials and are filtered to reduce noise.

The positive spring transition currents are represented by A_s^+ and A_f^+ (as determined by extending the slopes of the initial and middle sections of the red curve [5]), and the negative-differential spring transition currents by A_s^- and A_f^-.

For the positive spring the A_s^+ - A_f^+ difference is 0.18 Amperes, while for the negative-differential spring the A_s^- - A_f^- difference is 0.08 Amperes. If current is assumed to be roughly proportional to temperature in the wire above ambient (i.e., heat transfer is predominantly convective), then this 0.1-Ampere difference would correspond to an approximately 5°C decrease in $A_s - A_f$ spread. Thus, the thermally actuated safety valve is potentially applicable to wells with gas-oil temperatures less than 6°C. A second and interesting finding is that the SMA wire contracts more in the negative-differential spring scenario. This is possibly because, at the end of the heating cycle the wire contraction must overcome a smaller restoring force with a negative-differential spring than with a positive spring. This finding could allow less SMA wire length to be used in the gas lift safety valve application.

Repeatability Figure 9 shows the data for each trial. Data are resampled so that each trial has the same number of data points for comparison, but data are not filtered. The vertical axes of the positive spring and negative-differential spring trials are offset so the graphs can be seen more clearly.

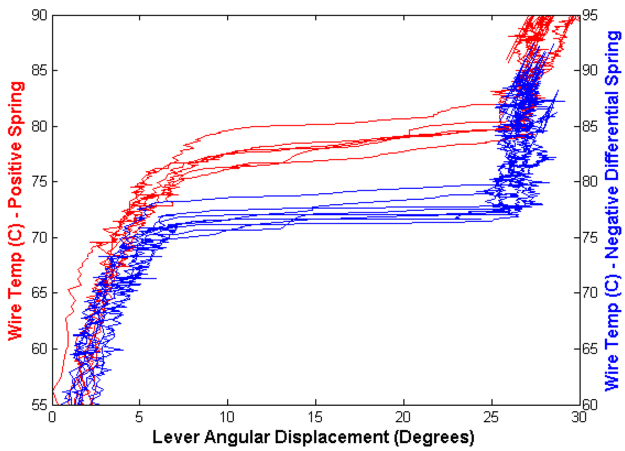

Figure 9. Electrical heating repeatability. Data unfiltered

Conductive Heating

Similar experiments were conducted by heating the SMA wire conductively. In this set of experiments the SMA-lever-mass setup was immersed in water and the water was heated by an electric resistive heater. See figure 10. For these experiments a 0.1-kg mass was used, with a 0.1-m lever length and 0.51-m initial SMA wire length.

Water was pumped from a reservoir, through an electric heater, and into the container with the SMA wire. It then drained back into the reservoir. The water was well mixed and the temperature of the water near the SMA measured to approximate the temperature of the SMA wire. An Omegadyne 6 kilowatt TruHeat STFT-6000-240 heater was used to control water temperature, and a National Instruments T-type thermocouple model 746061-01 was used to measure water temperature. The thermocouple was calibrated to ambient air temperature of 20C. In the negative-differential spring set of experiments the lever was started at 40 degrees tilt and the water gradually heated over approximately 40-minutes until the wire transitioned from Austenite to Martensite. A representative plot of water temperature versus time for one heating trial is shown in figure 11, and a plot of lever rotation versus time for the same trial is shown in figure 12. Data is unfiltered in both plots. In figure 12 the data is much noisier than the angle data from the electrical heating experiments, and this is likely because of the added noise of the pump and 6-kilowatt water heater affecting the inclinometer output.

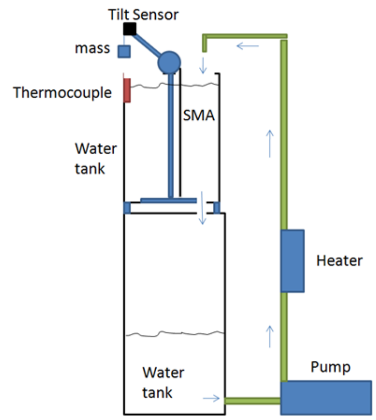

Figure 10. Conductive heating experimental setup

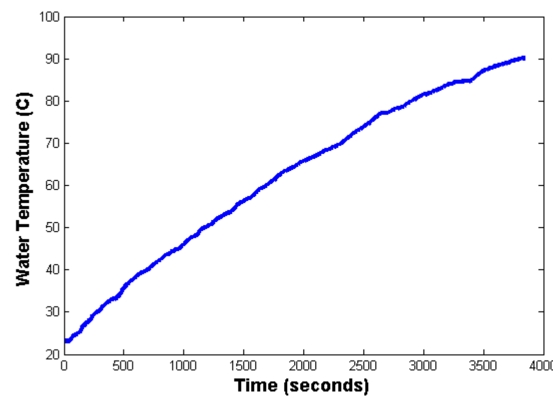

Figure 11. Water temperature vs time. Data is unfiltered.

In the positive spring set of experiments the lever was started at negative 40 degrees and the water heated until the SMA wire transitioned from Austenite to Martensite. Six trials were averaged for the positive spring experiments and eight trials for the negative-differential spring experiments. To average the data, each trial was resampled to give the same number of data points per trial, and then the average was taken. A second-order butterworth filter with cutoff frequency 0.05 was applied to the aver-

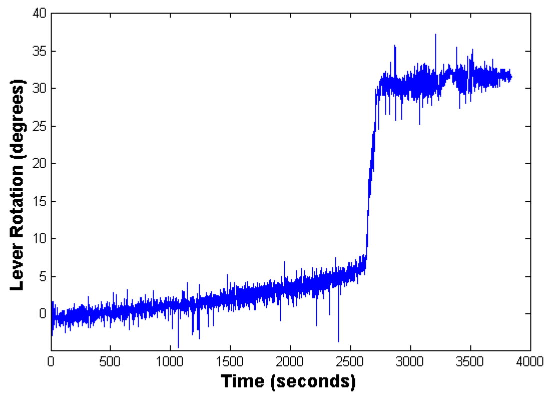

Figure 12. Lever rotation vs time. Data is unfiltered

aged data to smooth out sensor noise. Results are shown in figure 13 in a plot of wire temperature versus lever angle. The positive spring profile is shown in red and the negative-differential spring in blue.

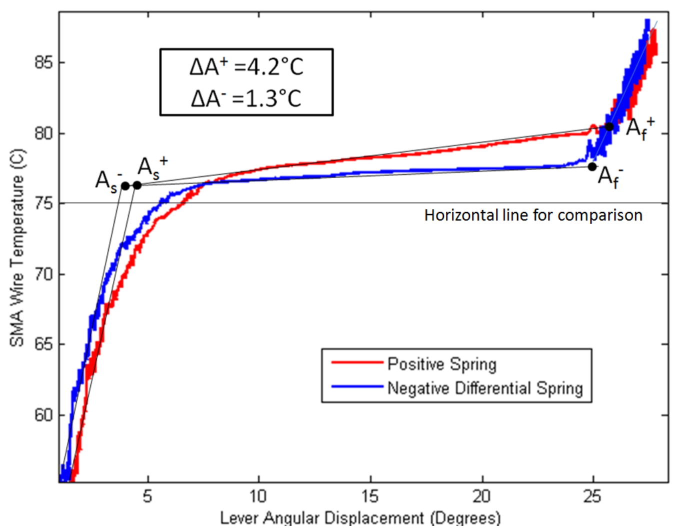

Figure 13. Conductive heating results for positive spring and negative differential spring. Plots are the average of all trials and are filtered to reduce noise.

This plot is analyzed similarly to the electrical heating plot. For the positive spring the A_f^+-A_s^+ temperature difference is 4.2°C, while for the negative-differential spring the A_f^--A_s^- temperature difference is 1.3°C. Thus the negative-differential spring decreased the $A_s - A_f$ temperature difference by 2.9°C. In this plot, unlike the plot in figure 8, the profiles for the negative-differential spring and positive spring reach approximately the same angle. This is possibly because in the conductive heating experiment a smaller mass was used than in the electric heating experiment (0.1-kg instead of 0.5-kg), and this may have lessened the difference in restoring force between the two scenarios near the end of the heating cycle.

Repeatability Figure 14 shows the data for each trial. Data are resampled so that each trial has the same number of data points for comparison, but data are not filtered. The vertical axes of the positive spring and negative-differential spring trials are offset so the graphs can be seen more clearly.

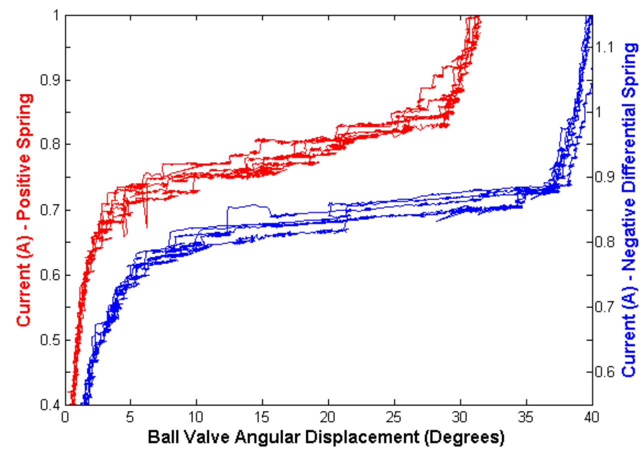

Figure 14. Unfiltered data from six positive spring trials and eight negative-differential spring trials.

Discussion of Results

The experimental results show that it is possible to reduce the temperature change needed to actuate an SMA wire by 2.9°C-5°C by conductive and electric heating respectively using a negative-differential spring. Thus, the thermally-actuated gas lift safety valve described earlier could theoretically be applicable to wells with less than 6°C temperature differences between normal operation and backflow events. Future work should focus on integrating a negative-differential spring into the existing gas lift safety valve design.

Acknowledgments

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