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DYNAMIC FIBER OPTIC SENSORS UNDER INTENSE RADIOACTIVE ENVIRONMENTS*

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ABSTRACT

A liquid mercury target will be used as the neutron source for the proposed Spallation Neutron Source facility. This target is subjected to bombardment by short-pulse, high-energy proton beams. The intense thermal loads caused by interaction of the pulsed proton beam with the mercury create an enormous rate of temperature rise (~10^7 K/s) during a very brief beam pulse (~0.5 μs). The resulting pressure waves in the mercury will interact with the walls of the mercury target and may lead to large stresses. To gain confidence in the mercury target design concept and to benchmark the computer design codes, we tested various electrical and optical sensors for measuring the transient strains on the walls of a mercury container and the pressures in the mercury. The sensors were attached on several sample mercury targets that were tested at various beam facilities: Oak Ridge Electron Linear Accelerator, Los Alamos Neutron Science Center–Weapons Neutron Research, and Brookhaven National Laboratory's Alternating Gradient Synchrotron. The effects of intense background radiation on measured signals of each sensor are described and discussed. Preliminary results of limited tests at these facilities indicate that the fiber optic sensors function well in this intense radiation environment, whereas conventional electrical sensors are dysfunctional.

1. INTRODUCTION

A liquid mercury target will be used as the neutron source for the proposed Spallation Neutron Source (SNS) facility.[1] This target will be bombarded by short-pulse (~0.5-μs), high-energy (1-GeV) proton beams (10^{14} protons/pulse) at a repetition rate of 60 Hz. Liquid mercury is chosen over solid target materials primarily because of its capability to handle high beam powers. One of several important issues[1–2] for liquid targets is the ability to withstand the intense thermal loads (17 kJ in ~0.5 μs) caused by interaction of the pulsed proton beam with the mercury. Although the resulting average temperature rise is relatively small (<10 K) during this very brief beam bombardment, the rate of temperature rise is enormous (~10^7 K/s). The resulting pressure waves in the mercury that will interact with the walls of the mercury target may lead to large stresses in the target vessel.

To gain confidence in the mercury target design concept and to benchmark the computer design codes used to predict the effects,[1–2] tests are needed to measure the transient strains on the walls of the mercury container and pressures in the mercury. Thus, one of the primary research and development efforts for SNS is measuring these parameters.

Several sample mercury targets have been prepared for tests[3–10] at various beam facilities: Oak Ridge Electron Linear Accelerator (ORELA), Los Alamos Neutron Science Center–Weapons Neutron Research (LANSCE–WNR), and Alternating Gradient Synchrotron (AGS). The goal of these tests is to explore potential measurement techniques that would function in the intense radiation and fast response (~1-μs) environment. The LANSCE–WNR and AGS facilities can provide the desired key thermal shock test parameters, including the intense radiation. At the ORELA facility, the background radiation (about 10^{13} high-energy X-ray photons due to bremsstrahlung of the 150-MeV electron beams) exceeds that of the other two proton beam facilities. Thus, ORELA is an ideal facility

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for evaluating the feasibility of sensors chosen for measuring strains and pressures in the sample targets.

To measure fast transient signals (in the microsecond timescale) on a sample target, we chose dynamic and responsive sensors (with a response frequency above 200 kHz), such as electrical strain gages, piezoelectric pressure gages, and fiber optic (FO) strain gages. The details of the strain measurement technique using FO strain gages were reported elsewhere.[7–8] Each sensor and its processing instrument were checked out on a sample target for the fast response. Subsequent tests of the sample target with sensors were conducted in a beam facility. In the following sections, we describe and discuss instrumentation preparation at ORNL facilities, including ORELA, and preliminary results for targets tested at the LANSCE–WNR and the AGS facilities.

2. INSTRUMENTATION PREPARATION

The goal of the instrumentation preparation is to select dynamic sensors viable for measuring transient pressures and strains in the microsecond timescale and in the presence of a high-radiation field. To prepare the instrumentation, we fabricated a small stainless steel sample target (about 50 mm in diameter, 100 mm in length, and 1.5 mm in wall thickness). One metallic foil resistance strain gage (conventional electrical strain gage) was bonded midway along the length of the cylindrical target. One PCB piezoelectric pressure gage (made by PCB Piezotronics, Inc.) was installed on the back plate of the target. This sample target was then filled with water and positioned in the electron beam path on a rack inside the Target Room of the ORELA facility. These gages on the target and their processing equipment at the diagnostic station in the Electron Room were connected by 40-m long electrical cables. In addition, an FO telemetry unit was used for studying effects of intense radiation on transmitting optical signals between the sample target and the diagnostic station. The gating signal of the electron beam accelerator was used to trigger the FO telemetry unit. This telemetry unit provided an output signal with a pulse width of 3-μs. Within such a short time frame, a 150-MeV electron beam was formed and injected at the sample target. We used a Tektronix Digital Oscilloscope TDS 420 to record output signals of the gages. The preliminary results of the initial tests at the ORELA facility are summarized below.

1. Results confirmed that the FO telemetry unit performed well under the intense radiation background in the ORELA facility. Whenever the 150-MeV electron beam pulse was formed, the output pulse of the telemetry unit showed a tiny transient spike (<1 μs). The tiny transient spike (~5% in magnitude) at the instant of the 150-MeV beam pulse was superimposed on its smooth waveform of the output pulse.

2. At the instant of the beam pulse, the output waveforms of process instruments for the strain gage and the PCB pressure gage showed very large electrical signals. (The PCB gage signal was similar to that shown in Fig. 1). For the small thermal loading of the beam pulse, these signals were not real and must be classified as noise. The noise could be associated with ionization effects of the intense radiation background. The noise decay time was within 10 μs for the strain gage signals, but

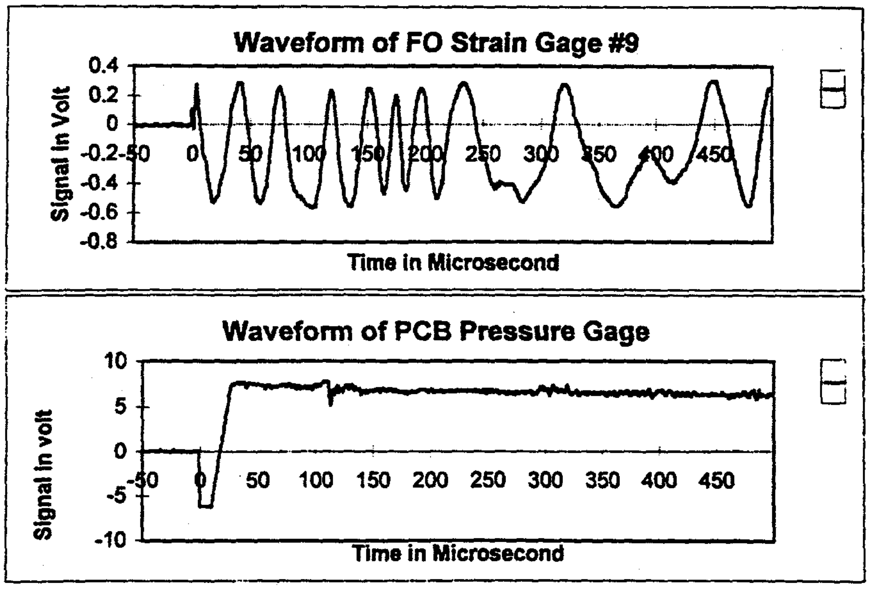

Fig. 1. Signal waveforms for FO strain gage 9 (SN9) and PCB pressure gage.

over seconds for the PCB pressure gage signals. The large step in voltage (>5 V or 7 MPa) on the PCB gage signals that appeared at the instant when the beam was on could be used for triggering the instruments. The oscillatory nature of the strain gage noise indicated the dynamic variations of the gage circuit impedance due to the intense radiation background. The undesired noise masked the real signals and made these gages dysfunctional for measuring beam-induced strains and pressures within the microsecond timescale. These initial tests indicated that alternative sensors for measuring strains and pressures of mercury targets are needed.

As mentioned above, the signals of the FO unit revealed an insignificant effect of the background radiation. That motivated us to explore the potential of using FO sensors for our tests. Subsequently, we attached three FO strain gages[7] on the target cylinder along its axis (approximately 120° apart). To test the functionality of these FO gages, the sample water-can target was then installed in a single-stage pneumatic pellet injector facility. A 4-mm plastic pellet that was accelerated to ~350 m/s impacted on the front face of the target. The impact created a measurable strain signal, as shown in Fig. 2. The signal waveforms reveal that the FO strain gage responds to the initial pressure waves in the steel vessel and to the slow sound waves of the water, while the PCB gage measures vibration waves of the water in the target. These preliminary tests gave us the confidence that the FO strain gages were applicable for our mercury target development tests.

To calibrate the FO strain gage,[6] we installed a set of four in two pairs on a tungsten target plate. Off-line tests showed that the strain value measured with FO gages agreed within 5% of those measured with conventional electrical strain gages. Further tests of radiation effects at the ORELA facility revealed that the noise signal corresponding to the beam pulse is small in magnitude (<30 mV peak-to-peak or <5% operational value) and of short duration (of a few microseconds) in decay time. (This phenomenon is similar to that of the FO unit described previously.) Such a small noise presented little or no limitation to the application of these new FO strain gages in measuring the transient strains of target structures under intense proton beams in the LANSCE–WNR and the AGS facilities.

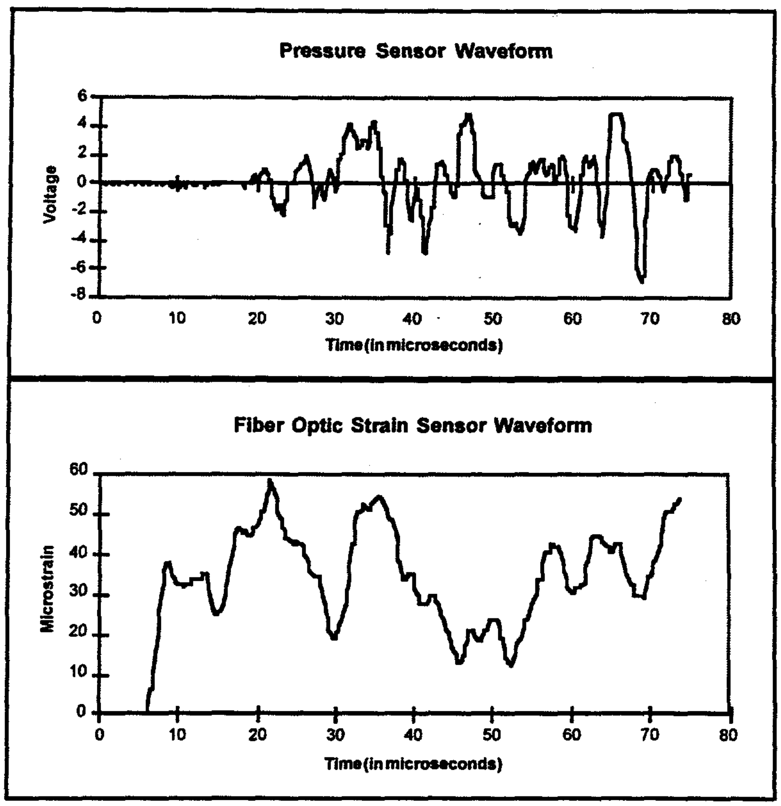

Fig. 2. Temporal variations of strain measured by an FO strain gage and pressure signals measured by PCB pressure gage.

3. RESULTS OF TESTS AT LANSCE–WNR

A cylindrical-shaped mercury target vessel that was used for tests at the LANSCE–WNR is shown in Fig. 3. It was constructed from a section of stainless steel type 304L–Schedule 10 pipe with welded end caps. The length of the target is 203 mm, the inner diameter is 108 mm, and the wall thickness is 2.7 mm. The front end cap closest to the beam entrance is 6.4 mm thick, whereas the rear end cap is 9.5 mm thick. The FO strain gages were calibrated by measuring the peak-to-peak voltage of each gage that was made at a constant gain of the signal amplifier and a constant laser exciting current in the FOSS I processing instrument. (The same FOSS I setting was used for tests at the LANSCE–WNR facility.) A cover plate with a handle for transporting the target is provided to protect the delicate FO strain gages from damage. A secondary container was used to contain any unexpected spill of mercury from its vessel. In the secondary container, the target vessel rested in a set of support baffles that ensured correct alignment of the target to the centerline of the beam. The secondary container was placed on a lift table that could be moved up or down remotely from the diagnostics station (~30 m away).

The LANSCE–WNR facility is capable of injecting 2.5×10^{13} protons per pulse at 800 MeV and 0.250 μs. The beam current and pulse length can be adjusted to control total beam particles (protons) on the target. During target tests, a magnetic loop and a video camera (provided by LANL) monitored proton beams. The magnetic loop measured the proton beam current as a function of time during the pulse. The video camera recorded the profile of the proton beams, using beam-induced light emission from a phosphor plate placed on the front of the target. The strains on the target structure and pressures in the mercury were measured by using nine FO strain gages (as shown in Fig. 3) and a PCB piezoelectric pressure gage submersed in the mercury (not shown).

The beam profile, which was roughly the same for all pulses during the target tests, was measured to have a full-width at half maximum (FWHM) value of 27-mm diameter. The experiment was done for 21 single-pulse beam shots varying from 0.2×10^{13} to 2.5×10^{13} protons per pulse or shot. Under the full LANSCE beam condition (2.5×10^{13} protons per pulse), the facility was operated for collecting strain and pressure data for 13 beam shots. Typical signal waveforms of the FO strain gage 9 (SN9) and the PCB pressure gage are shown in Fig. 1. The step signal of the PCB pressure gage reveals the presence of intense radiation during the interaction of 800-MeV proton beams with the mercury target. The corresponding signals of gage 9 indicate that the optical gage is immune to the radiation.

In Fig. 4, output signals for the FO strain gages 9, 4, 5, and 8 were recorded at a small timescale of 0.02 μs per data point and reveal the following.

1. The initial spikes on gage signals of 9 and 4, using FOSS processing instrument I, are lower in amplitude than those on gage signals of 5 and 8, using FOSS processing instrument II. These initial spikes occur within 1 μs after the beam is on target.

2. The spike amplitude of the gage signals of 5 and 8 is larger than the calibrated peak-to-peak amplitude that was done by using the FOSS processing instrument I, and so it is not optically possible and must be considered as noise. The noise could be either electrical noise of the FOSS processing instrument or optical noise of the sensors and cables. Optical noise is

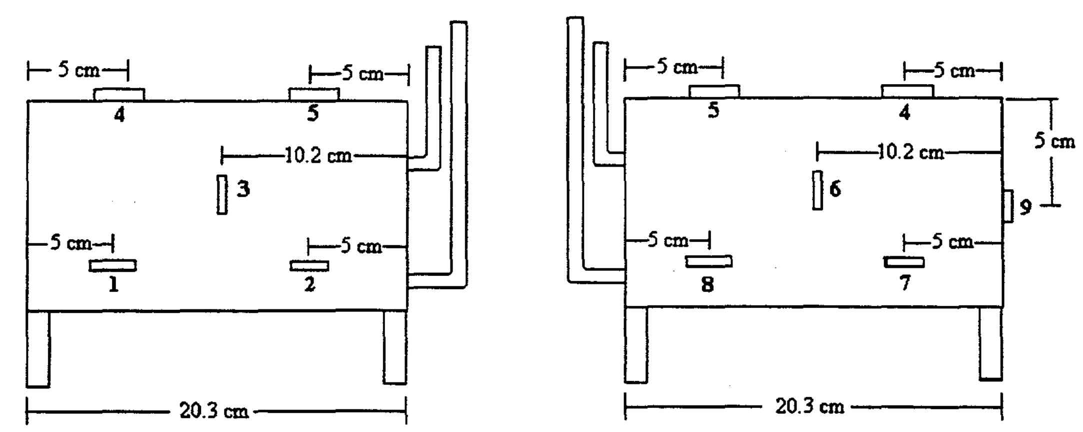

Fig. 3. Sketch of nine FO strain gages attached on the mercury target tested at the LANSCE–WNR facility.

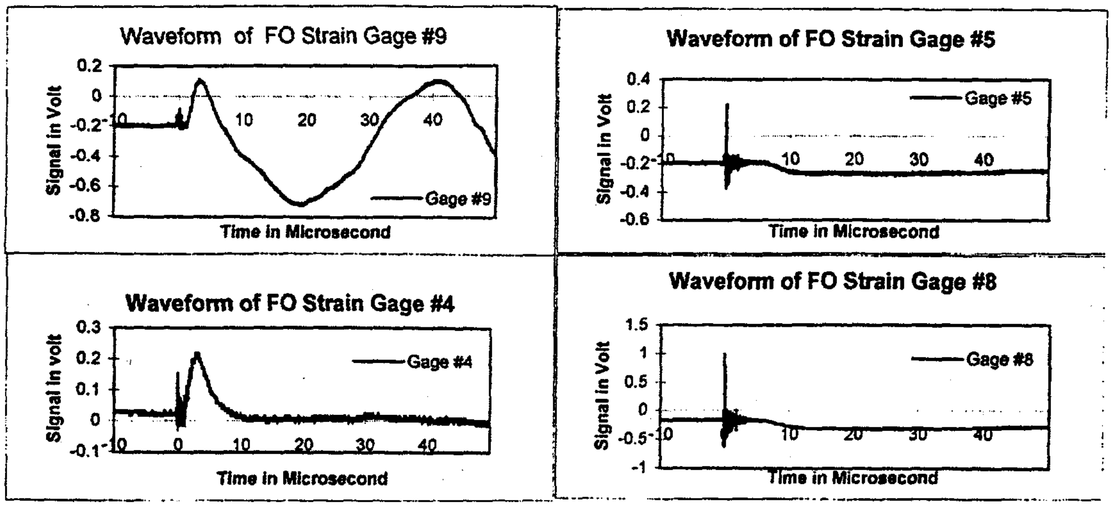

Fig. 4. Signal waveforms of strain gages 9, 4, 5, and 8.

probably caused by ionization and scintillation of the optical fibers and sensors.

3. The noise signals following the initial spike on signals of gages 4, 5, and 8 decay away within ~10 μs. The strain waves should arrive at FO gages after ~10 μs of beam impact. Thus, the real strain signals that appear after ~10 μs can be used to deduce target strains.

The strain gage 9 that was attached on the front end cap of the target produced the strongest signal in responding to the beam pulse. The measured peak value of 300 μ-strain corresponded to an axial stress component in the vessel of about 60 MPa. The frequency of the strain response is about 1 kHz. The above test results indicated that the FO strain gage technique is a viable method for measuring the fast strain response of the mercury target vessel in this severe radiation environment.

4. RESULTS OF TESTS AT AGS

A series of mercury target tests[3–9] were conducted at the Brookhaven National Laboratory (BNL) AGS facility in 1997, as part of the AGS Spallation Target Experiment (ASTE) collaboration. Various laboratories throughout the world provided equipment, instrumentation, and personnel support to conduct these tests. In addition to participating in the foil irradiation tests for studying neutrons produced, ORNL has also participated in the "thermal shock" tests. The goals of the thermal shock tests were to measure strains using a set of FO strain gages on the outside surfaces of the mercury target.

The ASTE mercury target vessel, which was fabricated by Forschungszentrum Julich GmbH (FzJ), is cylindrically shaped with a hemispherical dome welded on the end facing the 24-GeV proton beams. The length of the vessel is 1000 mm, its diameter is 200 mm, and its wall thickness is 2.5 mm. On the ASTE target, we attached 12 FO strain gages. The location and the identification number of these gages are shown in Fig. 5.

More than 70 waveforms were collected on 8 different gages using 4 FOSS I processing instruments and 2 LeCroy oscilloscopes. Waveforms from FO strain gages 4, 11, and 12 were measured for a series of nine beam pulses with 23-GeV proton beams that contained about 3×10^{12} protons per pulse. Typical dimensions of the beam profile were reported to be 50 mm vertical by 25 mm horizontal. Based on Ni's calculation,[10] the peak energy density in the mercury is estimated to be 3 MJ/m^3 compared to a value of 11 MJ/m^3 expected for SNS.

A typical strain waveform for the FO gage 11 is shown in Fig. 6. This gage is located about 0.17 m downstream of the front of the target and is oriented axially. The timescale of t = 0 is the instant that the beam arrives at the target. The strain wave arrives at the gage 11 at ~70 μs after the beam is on. The strain oscillates very rapidly at a frequency of ~20 kHz. The entire strain oscillation waveform only lasts for ~3 μs, thus indicating that significant damping takes place on about a 1-ms timescale. The peak axial strain measured is about 36 μ-strain, corresponding to an axial stress of ~7 MPa. This peak strain occurs at ~100 μs. These results are in reasonable agreement with the Japan Atomic Energy Research Institute (JAERI) measurements.[9] The JAERI data and the ORNL data were taken at different test conditions. Uncertainties in the test conditions and strain measurements make detailed comparisons difficult. Nevertheless, note that the

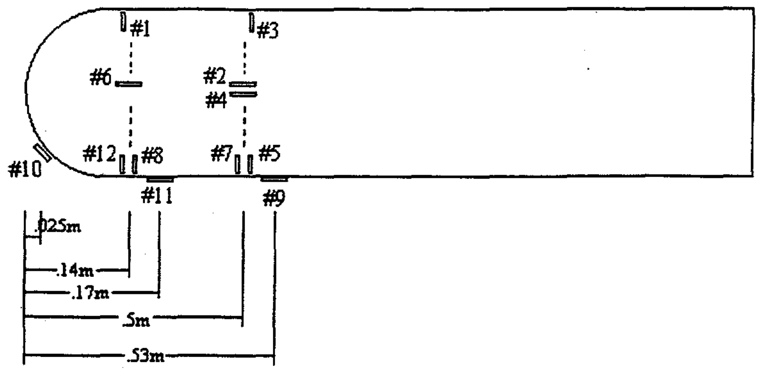

Fig. 5. Sketch of 12 FO strain gages attached to the ATSE mercury target at AGS.

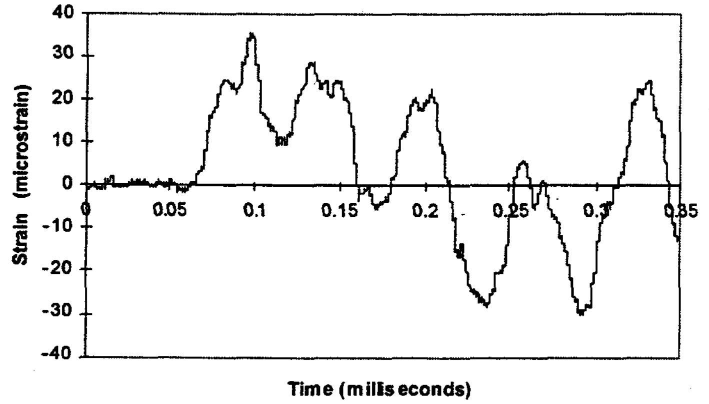

Fig. 6. A typical strain waveform for the FO strain gage 11 as a function of time.

measurements agree within a factor of 2 or 3 with the predictions made by Ni of PSI,[10] for the first 150 μs. Also note that Ni's calculations were performed for a proton current 2.4 times greater than that actually achieved in the tests.

The FO gage 4 that is located at 0.5 m measured a strain response starting at ~150 μs, which is significantly later than that of the FO gage 11, due to its more downstream location. The signal at this location is also much smaller than for gage 11 because the heating is a factor of 2 lower at this location and gage 4 is located near a large port flange. Ni's results[10] show a similar reduction at this location, and its initial response time of about 130 μs for this location is in agreement with the measured data.

5. CONCLUSION

Based on the results of these limited tests, it is concluded that the FO strain gage technique is a viable method for measuring fast strain response in the structure of a mercury target vessel in the severe radiation environment. The PCB piezoelectric pressure gage is dysfunctional in the intense radiation environment.

The initial noise signals experienced with the FO strain gages in the tests at the LANSCE–WNR (and to a much lesser extent in the ASTE tests at AGS) indicated the possibility of both the electrical and the optical noises. The intensity of the electrical noise depends upon the FOSS processing instruments. The optical noise could be associated with the ionization of the optical sensor and the scintillation of its connecting optical cables. Understanding of this phenomena, which may lead to reduction or elimination of this noise, will be attempted in future tests. In addition, future tests at these facilities will be conducted with more extensive FO strain gage instrumentation and with development of innovative FO pressure-sensing techniques. Our recent effort[6] toward improving the design, calibration, and signal analysis of the FO strain and pressure gages is also presented in this conference.

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