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# Laboratory experimental platform for studying renewable energy integration using green hydrogen

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**Abstract.** The integration of renewable energy–based sources into the electrical power system presents challenges arising from the inherent uncertainty in their generation, particularly in the case of wind or photovoltaic power plants due to their high variability. These challenges can be mitigated through the use of large-scale energy storage systems. Hydrogen emerges as an attractive energy vector with significant development potential; its wide availability, ease of production, storage, and conversion into thermal and electrical energy position it as a feasible solution. However, the potential of hydrogen is not matched by the availability of adequately trained technicians capable of designing, managing, or maintaining facilities in which hydrogen is produced, stored, or transformed to electrical energy. This article presents an educational device developed by the authors, designed to facilitate the understanding and practical application of the process of converting hydrogen into electrical energy through the use of proton exchange membrane fuel cells. The device, which combines low cost, safe operation, and scalability, is currently being used by final-year undergraduate students in the Electrical Engineering degree program, with very satisfactory educational results.

**Key words.** Energy storage systems, green hydrogen, engineering curricula, renewable energy integration.

## 1. Introduction

The large-scale integration of renewable energy–based power plants into the power system has become one of the major challenges of the energy transition. The increasing penetration of technologies such as solar photovoltaic and wind power contributes to decarbonization and reduces dependence on fossil fuel–producing countries. However, this growing penetration also introduces technical challenges arising from the variability and uncertainty of renewable generation. Some studies indicate that adequate planning, together with the use of advanced operational tools, is required to ensure the stability and reliability of the power system [1].

Large-scale energy storage is widely regarded as the main solution for helping to the integration of highly variable energy sources, such as most of those based on renewable-based technologies [2]. Energy storage systems enable the decoupling of renewable generation from load, thereby providing flexibility and enhancing the reliability of the power system. Several technologies can be used for energy storage to facilitate the integration of renewable energy into the electric power system, with hydrogen-based storage being one of the most promising options [3], [4]. Although water electrolysis is not currently a commercially competitive alternative, due to its lower energy efficiency relative to fossil fuels and the high cost of some of the materials required for its development (for example, a PEM electrolyzer costs around 2200€/kW), it is emerging as a key technological solution for the energy transition, providing an energy source free of greenhouse gas emissions and a high-purity fuel. For instance, Toyota uses a hydrogen fuel cell to power its Mirai model.

The effective deployment of a new technology with high development potential requires professionals trained in its fundamentals, operation, and maintenance. In this regard, energy storage technology in the form of hydrogen (particularly the so-called "green hydrogen", understood here as hydrogen produced from electricity generated in renewable energy plants and subsequently stored as an energy carrier), starts at a disadvantage compared to more mature solutions, such as electrochemical storage in batteries. It is currently difficult to find university programs that offer a high level of training in this technology, which may lead to a worrying shortage of engineers skilled in its use in the near future [5].

Part of the solution to this potential shortage lies in incorporating into current electrical engineering curricula the fundamental concepts, skills, and competencies needed for future professionals to be able to operate with a reasonable degree of autonomy in this emerging technology. Comprehensively revising an academic curriculum is often a complex task, as it requires the agreement of multiple stakeholders, from educational authorities to broader society, and involves long implementation times. However, addressing key aspects of the new technology within the framework of one or more elective courses can be accomplished in just a few months. In the international literature, several contributions have proposed short courses combining theoretical instruction with hands-on laboratory activities, forming structured learning sequences that can be incorporated into elective course curricula [6]. However,

few initiatives implement an electrochemistry teaching methodology that promotes students' active participation in the study of sustainable energy devices, their components and operating conditions, and the discussion of their performance.
This paper presents an educational kit, together with instructional materials, for the laboratory testing and analysis of a proton exchange membrane (PEM) fuel cell, designed for use in undergraduate teaching laboratories. The main design objectives of the system developed by the authors were low fabrication cost, ease of scalability, and safe operation. This equipment has strengthened the experimental facilities of our university's engineering laboratories by providing students with an environment in which they can experiment with, understand, analyse, and apply the fundamental principles of converting hydrogen stored in a small tank into electrical energy. Although the power levels involved in the conversion process of the prototype are relatively small, the intended scalability of the design makes it possible to build similar units capable of operating at significantly higher power levels.
The remainder of this paper is organized as follows. Section 2 presents the fundamentals of converting stored hydrogen into electrical energy by means of a PEM fuel cell. Section 3 describes the experimental setup. Section 4 outlines the operating procedure used to carry out an experimental test. Section 5 discusses the skills and competencies that students are expected to acquire. Finally, Section 6 presents the main conclusions.

## 2. Operation of a PEM fuel cell

A PEM fuel cell is an electrochemical device capable of converting gaseous hydrogen into electrical energy. It can also operate in reverse, generating hydrogen from distilled water when supplied with energy from an external power source. A fuel cell is similar to a rechargeable battery, with the exception that in this case the reactants are fed from the outside; otherwise, its operation is largely comparable. The production of electrical energy is continuous as long as hydrogen is supplied to the anode and oxygen to the cathode of the fuel cell. The advantage of this method is clear: recharging is extremely fast, the range is greater, and the number of charge-discharge cycles is higher than that of a conventional rechargeable battery.
The active component of a fuel cell is the Membrane Electrode Assembly (MEA), which is constructed using two porous graphite electrodes onto which small quantities of platinum (approximately 0.5 mg/cm²) are deposited to act as a catalyst for the oxidation–reduction processes.
Between the two electrodes, a polymer membrane made of a material commercially known as Nafion is placed; its function is to allow only the passage of protons from the anode to the cathode. The thickness of the membrane–electrode assembly is only about 0.2 mm.
The membrane–electrode assembly is joined to two highly porous carbon-paper supports (anode backing and cathode backing) with thicknesses ranging from 100 to 300 microns. The pores in these materials enable the gas to reach the electrodes. Finally, the assembly is compressed between two end plates, which serve the dual purpose of conducting electricity to the outside and directing the gases toward the membrane–electrode assembly. Figure 1 shows the structure and components of a PEM fuel cell.
The hydrogen entering the cell comes into contact with the anode (the negative terminal), and, thanks to the platinum catalyst, the oxidation of the gaseous hydrogen takes place, as shown in reaction (1).

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (1)$$

On the other hand, when oxygen comes into contact with the cathode (the positive terminal), together with the electrons arriving from the external circuit, the reduction of oxygen occurs, forming two $O^=$ ions, as expressed in reaction (2). These two ions, along with four protons that cross the polymer membrane, produce two molecules of water, as shown in reaction (3).

$$O_2 + 4e^- \rightarrow 2O^= \quad (2)$$

$$2O^= + 4H^+ \rightarrow 2H_2O \quad (3)$$

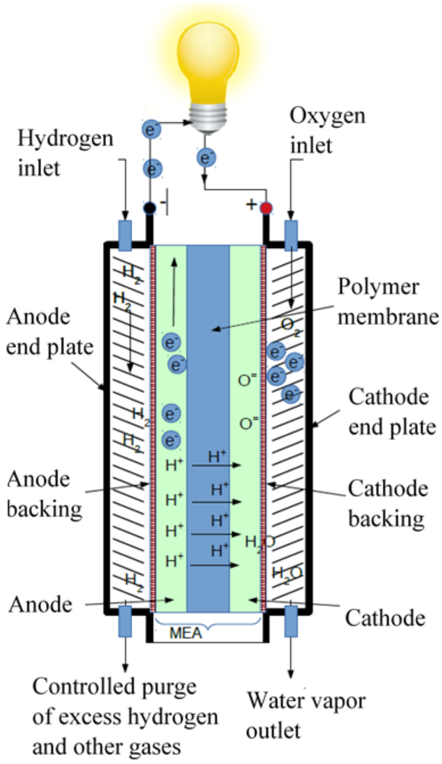


Fig. 1. Schematic diagram of a PEM fuel cell.

The process continues as long as the reactants are supplied to the fuel cell. The higher the current drawn by the external circuit, the greater the consumption of reactants within the cell, since a larger number of electrons is involved and, consequently, a greater number of redox reactions take place (fuel cell dynamics).
For continuous operation of the cell, it is necessary to purge the anode regularly in order to remove water vapor, nitrogen, and other gases that accumulate over time. This process is carried out by means of a solenoid valve that vents the anode for a sufficiently short period to minimize hydrogen losses as much as possible.
The platinum catalyst is essential for achieving acceptable reaction rates at both the anode and the cathode. Although

it is an expensive material, it is indispensable for the fabrication of this type of device. As an example, the reactions (4) and (5) show those that occur at the anode.

$$H_2 + 2Pt \rightarrow 2Pt - H \quad (4)$$

$$2Pt - H \rightarrow 2Pt + 2H^+ + 2e^- \quad (5)$$

The movement of protons is carried out through the electrolyte membrane, whose effectiveness is limited at low temperatures (below 80 °C), which are typical of these devices. In addition, oxygen reduction is one hundred times slower than hydrogen oxidation.
A proton exchange membrane (PEM) fuel cell provides between 0.2 and 0.7 A/cm², and its typical operating voltage ranges from 0.6 to 0.84 volts. By multiplying these parameters, it is possible to obtain power densities on the order of 0.12 to 0.54 W/cm². Considering that the thickness of the MEA is approximately 0.2 mm, it becomes clear that compact devices with high power densities can be achieved.
The electrical behaviour of a fuel cell is characterized by its polarization curve, which represents the terminal voltage (ε) as a function of the delivered current (I), as shown in Figure 2. A portion of the energy available from the electro-chemical reaction is required to drive the reaction at the desired rate, while an additional fraction is consumed in overcoming ohmic losses occurring between the two electrodes within the cell. As a consequence, the operating voltage is lower than the equilibrium voltage.

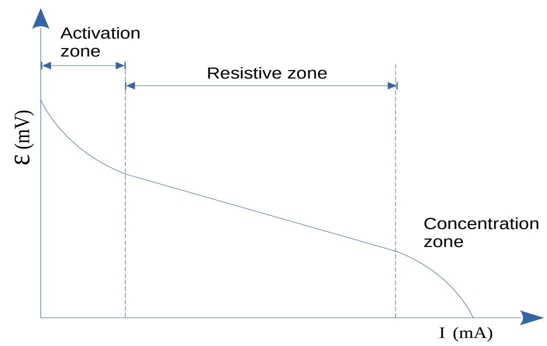

Fig. 2. Polarization curve of a PEM fuel cell.

Each of the voltage losses that take place is referred to as an overpotential or polarization. In a fuel cell, three types of overpotentials can be identified:

a) Activation overpotential: associated with driving the charge-transfer reaction so that it proceeds at a given rate.
b) Concentration overpotential: generated in the interfacial region near the electrode, where a reduction in the concentration of charge carriers occurs.
c) Ohmic overpotential: resulting from ohmic losses within the cell, which lead to internal heating. It is caused by ionic and electronic resistances in the fuel cell and can contribute significantly to the total losses.

## 3. Description of the educational device

To address the lack of educational equipment for teaching hydrogen technology, the authors developed several devices, one of which, due to its versatility and ease of use, is presented in this article. The device is designed to perform a series of experiments related to the conversion of hydrogen into electrical energy. This device is shown in Figure 3.

The device incorporates several components, including the following key elements:

- The fuel cell (I). It consists of an educational single-cell PEM fuel cell.

Its negative terminal (black) acts as the anode when the device operates in electric generator mode. It includes two ports: one is directly connected to the hydrogen reservoir, while the other is connected to a syringe that allows purging of the undesired generated gases when the device operates.
The positive terminal (red) acts as the cathode. It also includes two ports: one is connected either to the oxygen reservoir or to the air pump. The second port acts as an outlet for residual gases (water vapor).

- The hydrogen and oxygen tanks (A and B, respectively).

Both tanks are equipped with graduated scales that enable easy visualization of the filling level. The oxygen tank includes a red LED and the hydrogen tank includes a blue LED to facilitate identification and improve the visibility of the scale markings. Their nominal capacity is 12 cc, and this amount of hydrogen does not pose any safety risk in the laboratory environment.

- Measurement equipment (C).

Consisting of a voltmeter and an ammeter, which allow the electrical parameters of the system to be measured.

- Electric loads (G and H).

The equipment includes two resistive electrical loads. One of them is an adjustable resistor ranging from 0 to 10 Ω, and the other is a fixed 1 Ω resistor. It also includes a small DC motor that allows the visualization of electrical energy generation. The availability of both fixed and variable resistors makes it possible to obtain a sufficient number of points for the fuel cell's polarization curve.

- Regulable power supply (D).

A variable power supply adjustable in both voltage (E) and current (F), with short-circuit protection. It was included for the potential use of the PEM fuel cell as an electrolyzer. It will not be used in the experiments described in this paper.

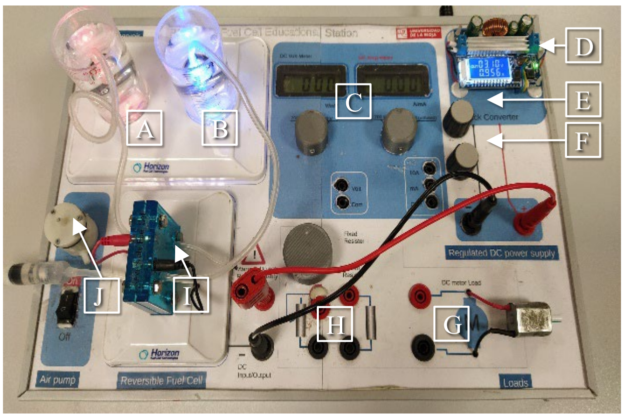

Fig. 3. Appearance of the fully assembled educational device.

## 4. Execution of the laboratory teaching session

In this section, two experiments conducted using the designed device are described. These experiments focus on obtaining the polarization curve of the PEM fuel cell and on determining its efficiency when operating as an electrical generator.

*4.1. Determination of the polarization curve.*

The aim of this experiment is to obtain the polarization curve of the PEM fuel cell, that is, to experimentally determine the relationship between the voltage and current at the electrical terminals of the cell while it electrochemically converts the chemical energy of hydrogen into electrical energy. In other words, the objective is to characterize the behaviour of the fuel cell as an electrochemical generator. To this end, a 10 Ω variable resistor is used to set different operating points of the fuel cell, at which the corresponding voltage and current values are measured. In parallel, the generation of electrical energy can be illustrated more visually by connecting a small direct-current electric motor.

In a first stage, the fuel cell must be prepared to operate in generator mode, which requires a sufficient amount of stored hydrogen and oxygen to perform the experiment. If the tanks are not filled, the required gases can be produced by operating the PEM fuel cell as an electrolyzer or using an external electrolyzer. The detailed procedure is described in another article by the authors, also presented at this conference. Briefly, the tanks are filled as follows:

1. The gas collection bells are placed inside the graduated tanks and filled with distilled water up to the level marked as 0, without connecting the silicone tubes to the cell. Once all air has been completely removed, the tubes are connected to the cell, and the membrane is hydrated with distilled water on the oxygen side using a syringe.
2. The power supply is set to a maximum current of 1 A and a maximum voltage of 3 V.
3. The lower ducts of the cell are sealed. On the oxygen side, the syringe itself can be used as a plug, while on the hydrogen side a short piece of silicone tubing and a stopper are employed.

Once the reservoirs are filled, the fuel cell can be operated at different operating points. The first operating point is established with the fuel cell under open-circuit conditions, that is, with only the voltmeter connected to its electrical terminals. The voltmeter reading corresponds to the first point in the activation overpotential region of the polarization curve and represents the maximum achievable voltage. The subsequent points of the polarization curve are obtained by connecting the 10 Ω variable resistor to the fuel cell through the ammeter. The external resistance is adjusted from its maximum value (10 Ω) down to zero, with the measuring instruments being read at each step. A minimum of 20 different values of the external resistance should be selected, corresponding to an equal number of distinct operating points, in order to clearly trace the polarization curve. Using the table of voltage and current measurements corresponding to the different operating points, the polarization curve of the PEM fuel cell can be directly plotted. In addition, the electrical power generated at each operating point can be determined from the measurement table.

Fig. 4 shows the polarization curve (black color) and the generated power curve (red color). The polarization curve clearly shows the three overpotential regions. For example, the ohmic overpotential region corresponds to a current range between 40 mA and 440 mA and a voltage range between 750 mV and 450 mV. In the case of the power curve, it exhibits a maximum that takes place at the operating point corresponding to the boundary of the ohmic overpotential region, with a value of 200 mW.

Carrying out this experiment helps students to practically reinforce their understanding of the operational limits of the PEM fuel cell, the dependence of the generated power on the selected operating point, and the existence of a maximum power operating point.

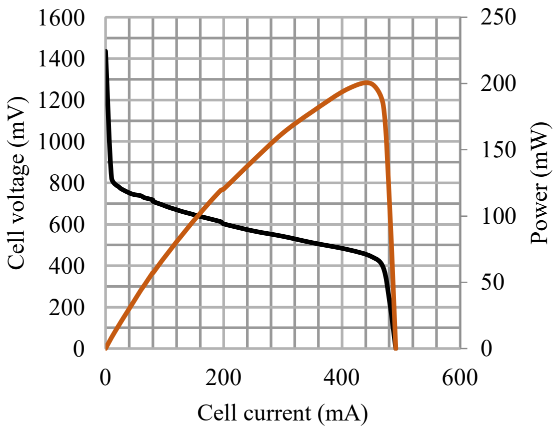


Fig. 4. Polarization and generated power curves.

*4.2. Determination of the efficiency.*

Once the polarization curve experiment has been completed, the next step is to determine the electrical energy generated and the efficiency of the fuel cell. The hydrogen and oxygen tanks will be refilled, setting the hydrogen volume to 10 cm³. A fixed 1 Ω resistor will be used as the electrical load. The fuel cell will be connected to the load, and a stopwatch will be used to record the elapsed time for each 2 cm³ increment of hydrogen consumption. The voltage and current delivered by the fuel cell will also be recorded. These measurements are then used to calculate the energy delivered in each interval, as shown in Table I. The energy for each interval is computed using the average power over that interval.

Table I. – Experimental results.

| Vol. H (cc) | Time (s) | Cell Volt. (mV) | Cell Current (mA) | Power (mW) | Δt (s) | Energy (J) |
|---|---|---|---|---|---|---|
| 10 | 0 | 625 | 245.0 | 153.1 | | |
| 8 | 47 | 621 | 245.2 | 152.3 | 47 | 7.18 |
| 6 | 104 | 617 | 245.0 | 151.2 | 57 | 8.65 |
| 4 | 169 | 611 | 242.0 | 147.9 | 65 | 9.72 |
| 2 | 230 | 603 | 239.0 | 144.1 | 61 | 8.91 |
| 0 | 287 | 593 | 235.0 | 139.4 | 57 | 8.08 |
| **Total** | | | | | **287** | **42.53** |

Using a spreadsheet, the electrical power-versus-time curve will be plotted (Fig. 5). As shown clearly in the

figure, the electrical power output decreases slightly over time. This behaviour is mainly due to two factors: (i) the drop in pressure in both gas tanks (hydrogen and oxygen) as they are depleted, and (ii) the accumulation of water vapor at the fuel-cell cathode. The area under this curve corresponds to the energy delivered, expressed in joules.
Over the process values presented as an example in Table I, the total energy generated was 42.53 J, and the volume of hydrogen consumed was 10 cm³ under normal conditions. The energy contained in this volume of hydrogen can be calculated from the hydrogen density and its lower heating value using (6).

$$\boldsymbol{E_{H_2}} = \boldsymbol{LHV_{H_2}} \cdot \boldsymbol{\rho_{H_2}} \cdot \boldsymbol{Vol_{H_2}} \qquad (6)$$

where $\boldsymbol{E_{H_2}}$ is the energy contained in the volume $\boldsymbol{Vol_{H_2}}$ of hydrogen, $\boldsymbol{LHV_{H_2}}$ is the lower heating value for hydrogen, and $\boldsymbol{\rho_{H_2}}$ is its density in normal conditions.

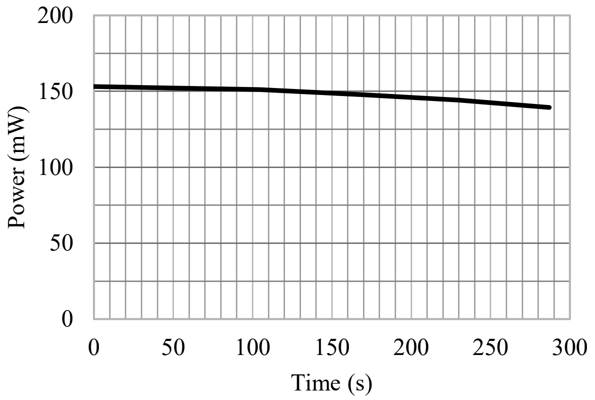


Fig. 5. Electrical power generation vs. time.

The efficiency is calculated as the ratio between the electrical energy generated and the energy content of the hydrogen consumed during the process. For the example presented in Table I, the efficiency was 39.41%.

## 5. Skills and competencies developed by students

Hydrogen produced from renewable sources (primarily solar and wind) can be stored and transformed at times different from when it is generated to produce electrical energy. A renewable-based power plant that integrates hydrogen generation, storage, and conversion can therefore evolve from an intermittent resource into a controllable one, adjusted to demand requirements, thereby contributing to the stability and reliability of the electrical power system. Accordingly, knowledge of the electrochemical devices and phenomena that enable the conversion of hydrogen into electrical energy should be included as a core component of university-level training programs in hydrogen technologies. The experiments described in Section 4, conducted using the device presented in Section 3, focus on this conversion process using a PEM fuel cell. Developing a solid understanding of its operating principle through hands-on experimentation requires the acquisition of a set of theoretical competencies, including the expressed in the next paragraphs.

Theoretical competencies (prior knowledge):

a) Identify of the main components of a proton exchange membrane (PEM) electrolyzer.
b) Understand the anodic and cathodic oxidation–reduction (redox) electrochemical reactions.
c) Explain the role of noble-metal catalysts (platinum, iridium, and ruthenium).
d) Describe the behaviour and function of the polymer membrane (e.g., Nafion).

Technical and experimental competencies developed through the laboratory sessions:

e) Develop proficiency in operating reversible PEM cells, including configuring the electrolyzer used for hydrogen production as an electrochemical generator for electrical power production (fuel cell mode).
f) Operate laboratory instrumentation (e.g., voltmeters and ammeters) to monitor process conditions and record electrical parameters.
g) Select and handle electrical loads to obtain accurate operating points.
h) Modify operating conditions safely to obtain results suitable for analysis.
i) Apply critical maintenance and safety procedures to preserve equipment integrity and ensure correct operation, including:
    - membrane hydration,
    - electrical operating limits,
    - equipment maintenance,
    - housekeeping and cleanliness,
    - work-environment conditions, and
    - personal protective equipment (PPE).

Analytical and modelling competencies:

j) Obtain and plot the voltage–current (V–I) relationship (polarization curve), identifying the three fuel-cell loss regions: activation, ohmic, and concentration overpotentials.
k) Determine the maximum power point based on the fuel cell V–I curve.
l) Calculate the total energy delivered by the fuel cell from the area under the power-versus-time curve.

Efficiency assessment competencies:

m) Compute energy efficiency by comparing the electrical energy generated with the stored chemical energy using the lower heating value (LHV) of hydrogen.
n) Quantify critical design parameters such as current density and power per unit membrane area.
o) Calculate the mass of hydrogen consumed and the specific fuel consumption per unit of energy produced (stoichiometry and consumption rates).

This laboratory experiments complement activities focused on electrical energy generation from hydrogen and the analysis of the associated internal losses. These experiments are guided by a worksheet that describes the procedure to be followed and includes a set of questions intended to promote the acquisition of the competencies described above. Students are required to submit a report presenting their results and responses to the proposed questions as part of the assessment.

## 6. Conclusions

Practical training is essential for preparing future engineers to use PEM fuel cells for electrical energy generation and storage, as it enables them to gain an applied understanding of electrochemical phenomena, operational limitations, and the design criteria that determine system performance. Through laboratory experiments, students acquire competencies in handling hydrogen production systems, storage processes, membrane hydration, control and safety procedures, and optimization of the operating point.

Carrying out the proposed experiments is of particular interest because they link PEM fuel cell technology with renewable energy sources. This connection reinforces the view of hydrogen as an energy storage and conversion vector, highlighting its usefulness for transforming surplus wind or solar electricity into stored energy that can later be recovered through fuel cells. This storage and recovery capability can provide flexibility, stability, and backup capacity to power systems with a high penetration of renewable energy.

Improved training in the use and applications of green hydrogen technology would accelerate the transition from the classroom to the implementation of decarbonized energy solutions.

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