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Review Article

Advanced Applications of Fuel Cells during the COVID-19 Pandemic

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COVID-19 was identified all over the world as a pandemic in December 2019. This novel coronavirus affects the lower respiratory area, which causes pneumonia in the human body and transfers from human to human. Every day, the number of new patients and the number of deaths are increasing immensely, while specific drugs for this virus are still being developed. Hospitals are struggling to accommodate patients, resulting in a large number of temporary hospitals. These makeshift hospitals need an uninterrupted power supply to continuously maintain all the electrical facilities. Fuel cells, especially solid oxide fuel cells, play an essential role in meeting the additional energy needs of humankind during this critical moment. SOFCs are able to supply power to those makeshift hospitals from the main hospital building, as well as supplying electricity to locked-down residential areas to ease the strain on the electrical grid during this pandemic situation. As a result of their extensive applicability and numerous uses, SOFCs can be used to address electrical needs challenges in various sectors.

1. Introduction

The COVID-19 pandemic has caused the deaths of millions of people. There have been relentless undertakings in order to save lives in all parts of the world. In Wuhan, China, the first outbreak of a disease caused by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) was detected and later it was named “Coronavirus Disease 19 (COVID-19)” [1]. On 17 November 2019, the first patient was diagnosed with COVID-19 with an initial symptom of pneumonia in China [2], and subsequently, several patients were admitted to hospitals with initial symptoms of pneumonia in December 2019 as reported by the World Health Organization (WHO) [3]. Thereafter, the number of patients increased rapidly across China and almost among the whole world [4, 5]. On 11 March 2020, the WHO declared COVID-19 as a pandemic [6]. As of 9 March 2021 (GMT 05:58 am), 117,751,038 cases had been reported globally and the death toll was 2,612,196. In the United States, the cumulative number of COVID-19 cases rose to 29,744,652, exceeding the cases in France (3,909,560), Russia (4,333,029), the UK (4,228,998), Spain (3,160,970), Italy (3,081,368), and China (90,002) as of 9 March 2021 [7]. This new virus has since spread to more countries than the 2003

SARS-CoV [8]. Figure 1 shows the most affected nations in the world due to COVID-19.

The COVID-19 virus is a novel beta RNA coronavirus (size: 60–140 nm diameter with backbone projections) that causes respiratory syndromes. Coronavirus sufferers may additionally have a fever with severe respiratory problems and cough, and some patients had also suffered gastrointestinal complications and symptoms (diarrhoea, vomiting, and stomach pain) [9–11]. Patients who have cancer, excessive blood pressure, cardiac problems, asthma, and diabetes, as well as older people and people with digestive disorders, are at a high chance of being impacted by COVID-19 [12, 13]. With the advent of new strains, several attempts have been made to produce COVID-19 vaccines [14], but certain problems with vaccine development on a large scale in the future and long-term storage stability will arise [15]. Researchers are still trying to develop the drugs for this novel virus [16]. This virus causes severe acute respiratory symptoms that spread by human-to-human contact. Due to its nosogenic nature, self-isolation, wearing sterile face masks, and social distancing are mandatory for preventing the spread of COVID-19 [17]. Each country has introduced quarantine rules (which usually lasts 14 days) to prevent the spread of this disease as much as possible [18].

It has been discovered that the long-term air pollution found in major cities accelerates the rate of infection of COVID-19, and there is a strong correlation between the mortality rate of infected persons and the amount of air pollution [19]. During the pandemic, almost all industries were temporarily closed down, and due to stay-at-home orders by governments, there have been fewer vehicles on the road, leading to lower emissions of CO_2, NO_2, and other toxic elements. It has been found that air pollution was one of the reasons for the high mortality rate due to the coronavirus in the USA [20]. The gaseous pollutant can damage the cellular and immune system by causing respiratory stimulation, cough, throat irritation, and breathing problems to the human body [21]. It was also found that the affected and death rates for COVID-19 were higher in Northern Italy due to the higher levels of air pollution [22].

During the COVID-19 period, the number of new cases abruptly rose globally, and hospitals became incapable of admitting all of the affected patients. Therefore, governments have had to erect mobile hospitals with beds. Each bed had to contain ventilators in order to supply an adequate amount of artificial ventilation for the patient. They also need the external power supply for the ventilators, along with other electrical equipment (including air-conditioners). In addition, due to the work-from-home notices, people have to stay at home, increasing the demand for electricity. This is a critical time to prioritize the supply of electrical energy to meet this additional demand [23]. Efforts are being made to adapt to the rate at which energy demand increases every day. Sustainable renewable energy sources are needed to meet this growing energy demand, and one of the most viable sources of green energy is fuel cells for this purpose. Figure 2 depicts the solid oxide fuel cell (SOFC) power supply chain from hospitals to makeshifts.

These fuel cell technologies for the next-generation hydrogen economy can be utilized with zero combustion [25]. The choice of the fuel cell is key to a successful installation. Fuel cell applications can replace most internal combustion engines, providing static and portable power. Fuel cells are a technological advancement since the twentieth century [26]. The principles of a fuel cell were first developed in 1839 by William Grove, who researched water electrolysis for hydrogen and oxygen production. He discovered that, when switched off, an electrolysis cell constructed with sulfuric acid and platinum catalysts produced a small current. Mond and Langer first composed the appellation "fuel cell," where, in 1889, they developed an electrolyte-supported cell with porous Pt electrodes that operated on H_2 and O_2 [27]. The operating temperature, efficiency, electrolyte content, applications, and ionic transport mechanism are all used to classify fuel cells.

Solid oxide fuel cell (SOFC) offers relatively very high competence among all the types of fuel cells, fuel flexibility (hydrogen, natural gas, biogas from biomass [28–32], and gases made from coal), and low emissions, which led to the use of SOFCs as future power generation technology [33, 34]. It shows high efficiency (>60% efficiency) with clean environment credentials [35]. Hence, SOFCs can be used as one of the most suitable, sustainable energy sources. SOFC can also be used as an extensive power generation system and cogeneration application combined with the micro-CHP system. Portable power generation [36] and easy transportation [37] are other advantages of SOFC. In addition, SOFCs can support patients in hospitals and also supply power to residential areas at the same time. Such heterogeneous use may be available in SOFC [38]. There are several large manufacturers of SOFCs that can meet the electricity needs of people during this pandemic (as seen in Table 1). Each company manufactures different types of SOFCs, depending on each usage scenario.

In the current pandemic situation, the use of SOFC is essential in meeting this enormous energy demand. Thus, SOFC will play an important role by producing sufficient portable energy that is more sustainable than current fossil fuels.

2. Solid Oxide Fuel Cells (SOFCs)

Highly polluting fossil fuels are a concern for both environmental and economic reasons. This has resulted in more attention being paid to fuel cells, which are widely believed to be the future of electricity generation and are an area of extensive research in the scientific field. An electrochemical device known as a solid oxide fuel cell (SOFC) is capable of converting chemical energy to electricity directly [48–50]. An electrolyte composed of ceramic material separates the anode and cathode. The oxidation of fuel occurs at the anode, whereas the reduction of oxygen occurs at the cathode, and the transport of ions occurs throughout the electrolyte [51]. During oxidation at the anode, the electrons are released. The cathode then receives these electrons, and the reduction process occurs. This movement of electrons between the anode and the cathode generates electricity [52]. Thus, the

Figure 1: The most affected countries with COVID-19 in the world [7].

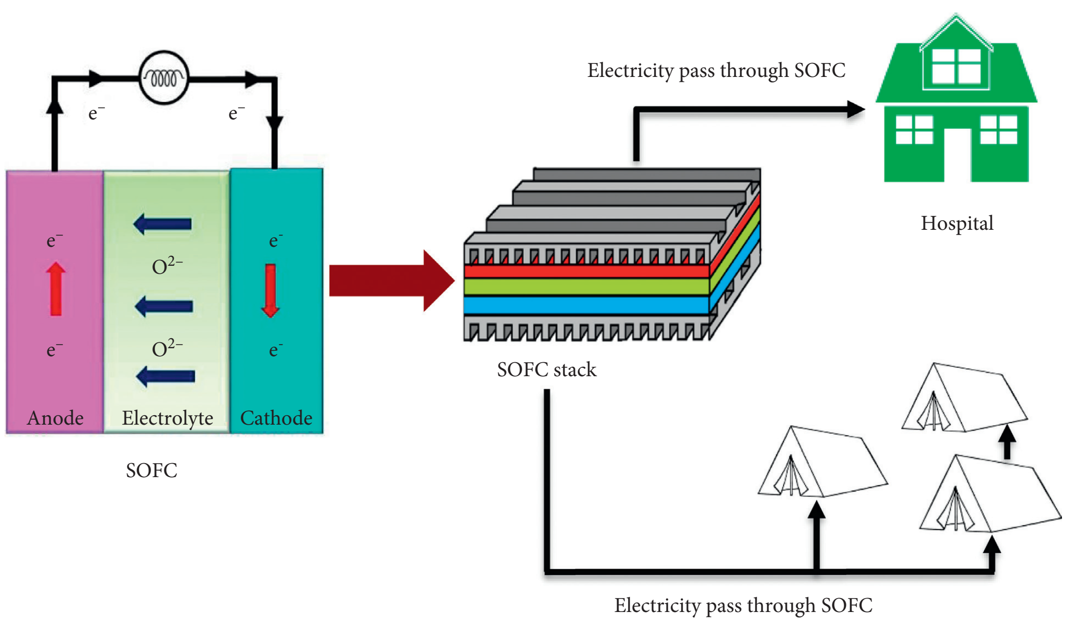

Figure 2: Power supply systems based on solid oxide fuel cells from the main building of the hospital to the temporary hospital extensions [24].

Table 1: List of SOFC companies with applications.

Company name	Applications	Origin	Ref.
Adelan Ltd.	Portable and mobile products	UK	[39]
Bloom Energy Corporation	200 to 300 kilowatts of power operating 24 × 7 with the highest efficiency of power solution used in on-grid and off-grid sections	USA	[40]
Ceres Power Limited	CHP (combined heat and power) for commercial and residential buildings	UK	[41]
Convion Ltd.	50–300 kW range of power output for distributed power generation and industrial self-generation purposes	Finland	[42]
Elcogen AS	High-power range SOFC stack from kilowatt range to megawatt systems used in residential areas, commercial and industrial transportation, and energy storage	Estonia	[43]
FuelCell Energy, Inc.	2.8 MW of ultraclean power to supply directly to the electric grid	USA	[44]
Hexis AG	1000 watts as electrical output for the public grid	Germany	[45]
SOLIDpower S.p.A.	Micro-CHP unit combined with SOFC for residential and small commercial buildings	Germany	[46]
Sunfire GmbH	Off-grid power	Germany	[47]

conventional solid oxide fuel cell (SOFC) can be used for energy generation with zero polluting emissions, with water as its only emission, as shown in Figure 3.

The oxidation takes place at the anode side [54]:

$$H_2 + O^{2-} = H_2O + 2e^- \tag{1}$$

and the reduction occurs at the cathode as

$$\frac{1}{2}O_2 + 2e^- = O^{2-} \tag{2}$$

Therefore, the overall reaction is

$$H_2 + \frac{1}{2}O_2 = H_2O \tag{3}$$

It is noteworthy that the whole efficiency of a SOFC depends on the inputs (H_2 as fuel and O_2) and outputs (electricity, heat, and water). For input parameters, mass and energy balance must be considered to analyze the cell efficiency. For output parameters, energy and mass balances for water, electrical, and heat energy should also be considered. All these terms can be effectively determined via the current and voltage of the whole cell.

An ion-conducting oxide membrane is typically used in solid oxide fuel cells (SOFCs). This oxide ion-conducting SOFC performs between 700°C and 1000°C, which is a very high-temperature range. SOFCs have numerous benefits when operated at high temperature. In essence, expensive platinum (Pt) and ruthenium (Ru) catalysts are not needed [35], and high temperatures prevent sulfur poisoning in fuels [55].

In SOFC, the anodes play a crucial role in providing reactive sites for fuel oxidation to occur in oxide anions delivered by the electrolyte. The anode must be stable at high temperatures in reducing atmospheres consisting of H_2 to gaseous hydrocarbons, depending on the fuel source used. The anode cermet Nickel-YSZ (Ni-YSZ) was a vital discovery for the development of SOFCs [56]. This material meets all the required benchmarks for the anode. The development of a cheap, suitable material for the SOFC anode is an enduring effort [57, 58].

The SOFC electrolyte plays a vital role in conducting ionic species between the electrodes, completing the electrical circuit [59, 60]. The material should have sufficiently high ionic and low electronic conductivity to avoid a short circuit across the cell. Additionally, the material must be stable in oxidizing and reducing atmospheres at the functioning temperature and be capable of forming a thin, dense film. Currently, 8 mol% yttrium doped ZrO_2 is the electrolyte of choice for high-temperature fuel cells because of its ionic conductivity, stability, and compatibility with other cell components. However, YSZ is limited to high-temperature operations due to its poor ionic conductivity at temperatures below 800°C. A target temperature for SOFC operation is 500°C, reducing the requirement for high-temperature materials and lowering the cost [61]. This improves the balance so that the generation of heat may be used for further energy production, therefore maximizing the device's efficiency. These variables have driven the advancement of a few other materials for intermediate- and low-temperature SOFC electrolytes. The development of low-temperature SOFCs has been encouraging, for instance, the fabrication of small portable devices, e.g., laptops, industrial scanners, battery chargers, cell phones, camcorders, and other electronic devices that require extended operating life [62, 63].

Cathode materials for SOFC have been well established over the past 50 years, with extensive work done to optimize conductivity, thermal stability, and facilitating the oxygen reduction reaction. Cathode materials should be chemically compatible with the electrolyte system and have sufficiently high conductivities (typically S/cm) to enhance reactivity. The combination of ionic and electronic conductivity is required to increase the size of the triple-phase boundary (TPB), the reactive sites at the cathode where oxygen is reduced and transferred to the electrolyte. In a purely electronic conducting cathode, such as $La_{0.8}Sr_{0.2}MnO_3$ (LSM), the TPB sites are limited to the interface of cathode-electrolyte [64]. Additionally, the cathode must be chemically stable at different temperature ranges and adequate porosity to efficiently distribute gaseous oxygen through the cathode to the cathode/electrolyte interface [65].

SOFCs offer several advantages compared to other fuel cell devices. Direct utilization of hydrocarbon fuels, which can be used without any pretreatment, is one of the main benefits of SOFCs [66]. High-temperature SOFCs can be operated with different types of fuels, not only relying on pure H_2. This fuel flexibility is derived not only from the facility of direct oxidation at high temperatures but also from the high-temperature internal reforming at the anode, readily converting the natural fuels into available hydrogen or methane. Along with being fuel flexible, a solid, thermally, and mechanically stable electrolyte is another major advantage of SOFCs. Another significant benefit of SOFCs combined with heat and power (CHP) systems is to produce electricity in heating households and residential blocks. Given the fact that residential heating has been recognized as a challenging sector in the fuel cell sector to decarbonize, solid oxide fuel cells, combined with micro-CHP units, can drastically reduce associated emissions [67]. The overall efficiency of SOFC can be up to 90–95% when the heat is utilized. In the UK, the cost of gas is around £4 per kWh. If we convert it to electricity at 60% efficiency, it will cost £6 per kWh to generate electricity in the homes. In contrast, the grid's electricity cost is £14 per kWh, whereas the standard electricity cost was 16.6 p/kWh in the UK in 2019 [68]. In the USA, the electricity cost per kWh using SOFC will be around only 9 cents by the end of 2021 [69], whereas the average standard electricity cost is 13.19 cents per kWh [70]. Therefore, it is handier to use SOFCs for producing electricity from the gas at a decreased price, and the excess electricity produced from SOFC can be handed to the grid.

3. Role of SOFCs during the Pandemic COVID-19

In COVID-19, the healthcare workers are at the highest risk of transmission from the patient. The USA, the most affected

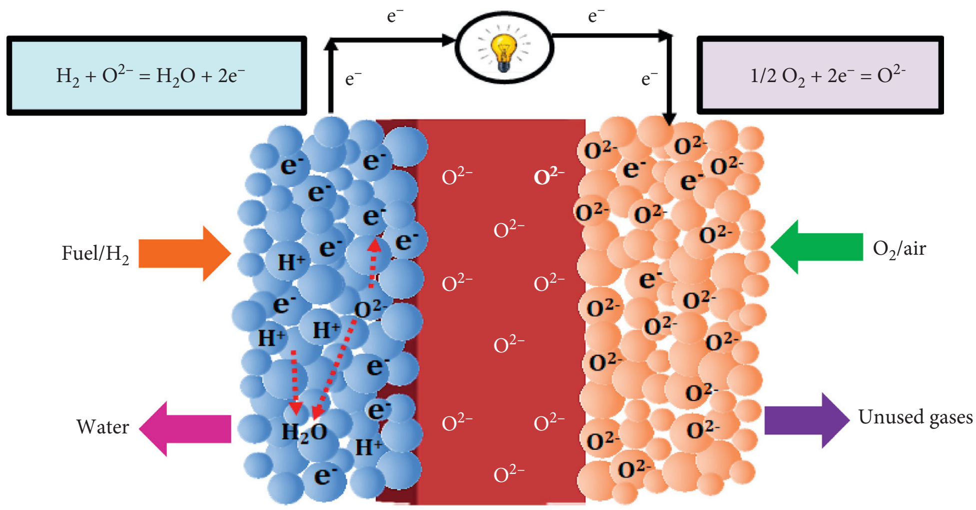

Figure 3: Schematic representation of a solid oxide fuel cell (SOFC) [53].

country as of 9 March 2021, is at the forefront of the highest affected and mortality during this pandemic, where almost 28.6 million cases were found [71]. Around 1,738,812 people were affected only in New York (as of 9 March 2021), where the number of people who died is 48,643 [72]. There are 213 hospitals in New York City [73]. Due to COVID-19, the bed numbers were increasing but still insufficient to meet demand. New York state government has already made temporary hospitals, and the hospital's main branch accommodates and treats all the affected patients. These makeshift tents need a continuous power supply to activate the ventilation systems and operate the other electronic services on time. Fuel cells can overcome these challenges and provide uninterrupted power generation at a low cost.

According to the data from the Institute of Health Matrices and Evaluation, 80,076 beds (and a total of 9,508 ICU beds) were needed to treat COVID-19 patients on 9 March 2021, in the USA, which is a much higher number [74]. College hostels, convention centers, hotels, and stadiums have been turned into hospitals to cope with the stress of COVID-19 patient's overflow, especially for those patients whose symptoms do not require intensive or emergency care. Moreover, these temporary hospitals need a continuous power supply system. The California government has ordered the administration to provide a constant power supply to the additional state-of-the-art hospitals built to deal with this disaster. Bloom Energy, one of the largest SOFC/fuel cell companies globally [75], has made a microgrid using the fuel cell system capable of powering a hospital with its makeshifts to accommodate the patient overflow. Bloom Energy has already installed a 400 kW fuel cell-based microgrid to power a temporary hospital that contains almost 100 beds in California [76]. As the SOFC system involves distributed power generation, it can easily be operated without electricity distribution lines and provided a continuous power supply during any natural or human-made disasters [77]. Therefore, this distributed electricity system, after removing the temporary tents, can be used elsewhere when the pandemic is over.

The amount of electricity bills that have to be paid every year is relatively high. As electricity is costly and vulnerable, a fuel cell-based CHP system can be used to generate electricity as much as we needed without the hassle of billing and putting the extra power on the grid. The fuel cell micro-cogeneration system is a home energy system that provides sustainable and portable energy in residences [53]. Simultaneously, social distancing is a significant issue, and people have to stay home for an extended period during this COVID-19. Countries with cold weather can mitigate their energy demand through SOFC-based micro-CHP systems. SOFC is already being applied to the individual residence with a micro-CHP system [67] in Europe. Italy, UK, Germany, and so many European countries suffer from this COVID-19, severely affected and causing financial loss. These places can expand their home electrification with micro-CHP systems [78] during this lockdown period.

It was observed that countries having hot and humid weather could also curb the death toll at a lower rate reported by Wang et al. [79]. Countries from Asia usually have a sweltering and humid atmosphere. Though the people from these regions are affected mainly due to the novel coronavirus, the death rate is relatively low concerning Europe and North America from the WHO website. Although the death toll in hot climates is low, the number of victims is high. To accommodate such a large number of patients, the hospitals also need an adequate amount of beds with all emergency treating equipment and an uninterrupted power supply. Micro-CCHP and micro-CHP, both systems, can be attractive technology for energy generation in these regions [80, 81]. Figure 4 depicts how SOFCs cogenerated with micro-CHP generate electricity for the residence and pass extra power to the grid. The use of renewable fuel with low-cost materials and the system's operational flexibility will undoubtedly increase the product demand.

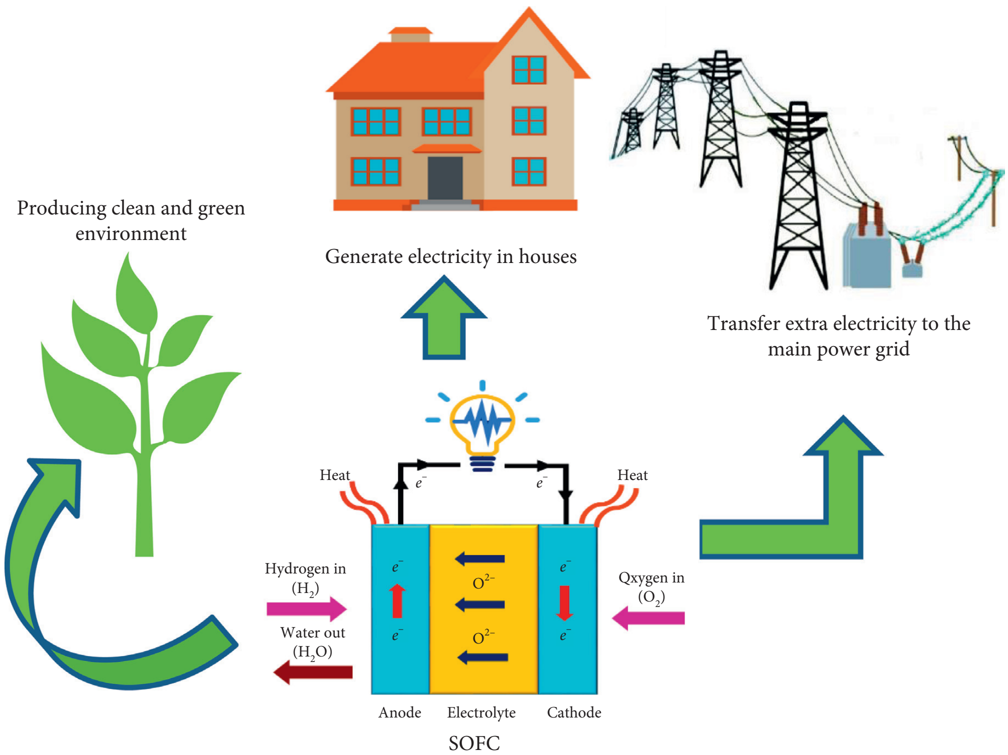

FIGURE 4: Schematic diagram of generating electricity through SOFC micro-CHP.

SOFC is one of the least expensive options for electricity generation [82–84]. That is why SOFC developers have been able to develop a variety of designs and integrations and market it commercially at a low cost. By changing the cell design, the overall cost of SOFC can be reduced. Therefore, the role and use of SOFC in energy production and sustainability are undeniable if this issue is taken seriously in commercialization. In addition, not just in the time of pandemic COVID-19 or any natural disaster, SOFCs have the potential to help satisfy the rising need for electricity in daily life.

4. Conclusions

At this moment in time, the whole world is struggling because of the COVID-19 pandemic. In order to cope with this pandemic, it is necessary to build public awareness about maintaining social distancing and alleviate the increased energy demand. As doctors and health workers are relentlessly trying to save lives, the role of fuel cells, mainly SOFCs, in meeting the need for extra energy in this challenging time is vital. As SOFCs can provide both on-grid and off-grid energy storage, it can be interconnected to create larger systems capable of supplying energy in an emergency. SOFCs generate an enormous amount of heat as a byproduct during its operation, which can be very useful for hospitals' heating and hot water supply. Even when the pandemic eventually ends and the mobile hospitals will be closed, these SOFC-distributed power arrangements can be used elsewhere to supply continuous electricity. The implementation of SOFCs has the added benefit of being sustainable as well as having zero pollutant emissions.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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