

some drivers beyond their attentional capacity. Such effects of attentional overload have been demonstrated in driving simulations, naturalistic driving studies, and closed-course evaluations (6).

Research on the effects of emotional distraction upon the driving task is limited, but there are a few studies that support the hypothesis. This research often relies on self-report and surveys of past driving incidents, making causal attributions difficult. Laboratory and simulation studies must attempt to induce a particular emotion to study its effect. One simulator study of the effects of auditory messages of positive and negative emotion (7) showed that negative words reduced driving speed and worsened lateral control compared with positive words. Evoked response potentials used to assess the allocation of attentional resources across tasks showed that positive and negative stimuli were processed differently. Similar studies suggest that negative billboard images can degrade driving performance (8, 9). One simulator study showed that induced happiness and anger each caused more driving errors compared with neutral and fear conditions, but subjective workload was similar across the affective states (10). Conversely, other studies suggest that drivers will modulate their glances to billboards based on the situational demands of the driving task (11, 12). Whether the same modulation occurs for messages presented on DMSs during times of high attentional demand is unknown.

Another plausible hypothesis for the results obtained by Hall and Madsen is that it is the overall design of the traffic safety messages, including fatality numbers, which collectively contributes to an information overload situation that has adverse effects upon driving behavior. Messages must be limited in length and formatted to ensure that motorists can quickly read and correctly process the information presented during limited viewing time. Guidelines and regulations have been developed on how to best design DMS messages reporting things like traffic incidents, special events, and road-work activities (13). Similar guidance does not yet exist for traffic safety messages. These messages are often unclear in terms of how drivers should respond to the information. It has commonly been assumed that drivers simply read and then quickly disregard messages that they deem unnecessary. However, the results of Hall and Madsen suggest that drivers may continue to try and assess how they are supposed to use that information for a much longer period of time after reading the message.

Although not something that Hall and Madsen could explicitly test with the Texas dataset, this hypothesis would help explain

why a message containing fatality numbers could impede a driver's cognitive abilities and adversely affect their driving performance but not influence their attitudes or conscious driving behaviors. This hypothesis would also suggest that similar effects would be expected when using other numbers in traffic safety messages, such as the number of speeding tickets issued, the percentage of crashes involving impaired motorists, etc. (again, a hypothesis that Hall and Madsen could not test with the existing Texas dataset). Although not necessarily in response to the Hall and Madsen results, it should be noted that the US Federal Highway Administration in 2021 discouraged the use of fatality numbers and other statistics in traffic safety messages displayed on DMSs (14).

The crash data presented by Hall and Madsen clearly demonstrate a safety effect of showing fatality numbers on DMSs. However, the mechanism for this safety effect is not clearly elucidated by the data presented in the paper. Additional analyses regarding crash types and documented causal factors in the crash reports might yield more insights. For example, the authors treated all types of crashes as equal and only separated single-vehicle from multiple-vehicle crashes. The assertion that emotional salience caused distraction would predict a pattern of crash types that would be the result of distraction, such as rear-end crashes resulting from delayed response to a slowing lead vehicle. Examining the pattern of specific crash configurations would be a stronger test of the distraction explanation posited by the authors. ■

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#### ELECTROCHEMISTRY

# Electrifying membranes to deliver hydrogen

An electrochemical membrane reactor enables efficient hydrogen generation

By Arthur J. Shih and Sossina M. Haile

The developed world has had a vacillating interest in hydrogen ( $H_2$ ) as the green fuel of the future. Today, the interest is being renewed as the climate crisis becomes increasingly evident (1). A key challenge with hydrogen, presuming that it can be generated by using sustainable electrical power, is its economical delivery. The daunting cost of installing a hydrogen infrastructure has been a major driver behind the decision of policy-makers in the United States and elsewhere to put the hydrogen effort on hold (2). On page 390 of this issue, Clark *et al.* (3) address head-on the hydrogen infrastructure need by exploiting electrochemical membrane reactors to strip hydrogen from more convenient carriers, including ammonia ( $NH_3$ ), methane ( $CH_4$ ), and biomass. These fuels could potentially be delivered to a point of need by using an existing infrastructure, where they could then be converted to hydrogen for use in fuel cells.

The concept of using liquid or easily liquified hydrogen carriers to fulfill hydrogen delivery needs has gained traction in recent years (4–6). Ammonia as the carrier is attractive because the cycle is entirely carbon free; whereas methane is attractive because the locally produced carbon dioxide can potentially be sequestered; and biomass is attractive because if deployed alongside sequestration, it results in a carbon-negative cycle. Among the reactor types available for extracting hydrogen from hydrogen-bearing compounds, electrochemical membrane reactors based on proton ceramic electrolytes offer distinct advantages. Such reactors combine thermochemical

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catalysts that facilitate decomposition of the carrier with electrochemical pumping of hydrogen across a proton-conducting solid-state membrane (5, 7). Because only protons, which emerge in the form of hydrogen gas upon undergoing oxidation at the hydrogen evolution electrode, can be delivered across the membrane, one can reasonably anticipate that every electron delivered to the membrane will result in the production of hydrogen in a 1:2 ratio. Furthermore, because of the solid-state and gas-impermeable nature of the membrane, one can expect the hydrogen produced to be entirely free of impurities—in particular, of unreacted carrier molecules, species that simply cannot get to the other side of the membrane. Another added benefit is the ability to pressurize the hydrogen by only increasing the current.

applications, challenges emerge. As noted by Clark *et al.*, managing the temperature profile across the reactor is particularly difficult. The process of pumping hydrogen across an electrochemical membrane leads to an increase in temperature because of the changes in hydrogen concentrations. At the same time, the decomposition reactions are inherently endothermic and drive the temperature down. Consequently, in a reactor with a simple linear flow, the upstream regime will be much cooler than the downstream regime. Such a temperature gradient introduces efficiency penalties.

Clark *et al.* meet this challenge by engineering a counterflow geometry that enables transfer of the heat generated at the downstream portion of the reactor, as a consequence of the electrochemical pumping, to the upstream portion of the reactor, where

values in the literature. Although extraction efficacy is not a commonly discussed metric, it is useful for describing the overall performance of a catalytic membrane reactor and can be calculated by multiplying the carrier conversion fraction by the hydrogen recovery fraction. Another important metric is the pressure difference across the membrane. In traditional catalytic membrane reactors, in which mechanical pumps pressurize the reactant supply, the permeate emerges at a pressure lower than that of the feed. Therefore, additional mechanical pumps are required to pressurize and compact the hydrogen for storage and transport. Clark *et al.* demonstrated an integrated system in which chemical transformation, purification, and pressurization are all achieved in a single device, an accomplishment that is only possible in an electrochemical membrane reactor. The combination of hydrogen extraction efficacy and exhaust gas pressurization achieved in their system are truly unprecedented. Future efforts will likely be directed toward increasing the hydrogen flux, which remains moderate for their electrochemical system and does not factor into the extraction efficacy or pressurization metrics.

Today, the main application of hydrogen is in oil refining, which accounts for about 55% of all hydrogen consumption, and about 93% of hydrogen is produced by using methane (1). Consequently, technological advances in methane steam reforming may inadvertently prolong the global reliance on fossil fuels. By directing greater attention to ammonia, one of the hydrogen carriers demonstrated by Clark *et al.*, future electrochemical catalytic reactors may allow use of hydrogen without incurring carbon emissions. ■



As water electrolysis for hydrogen fuel production ramps up, the energy sector is in increasing need of efficient ways to deliver that hydrogen using convenient carriers such as ammonia and methane.

In contrast to their electrochemical counterparts, traditional catalytic membrane reactors use a membrane that is hydrogen-permeable, typically made with palladium (Pd) or a Pd alloy, rather than one that is proton-permeable (8–15). Hydrogen is driven across a traditional membrane by mechanical pressure, which creates a chemical potential gradient. In the electrochemical membrane reactor, protons are driven across the membrane by application of a voltage (or current), which indirectly drives the flux of hydrogen gas.

Recent advances in electrochemical membrane reactors (5, 7) have spurred the race to implement “hydrogen-on-demand” solutions. In devices scaled up for practical

the carrier decomposition reactions cool the system (3). Beyond the use of a counterflow design, thermal gradients are mitigated by formulating an interconnect material that provides excellent heat transfer as well as electrical contact between adjacent cells in the reactor. The interconnect composition is also designed to match the thermal expansion behavior of the electrochemical components of the reactor, contributing to its long-term stability. With these advances in reactor design and material components, the authors achieved an unprecedented combination of carrier gas conversion, hydrogen recovery, system size, and reactor lifetime.

The >99% hydrogen extraction efficacy of the system of Clark *et al.* exceeds all other

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## Electrifying membranes to deliver hydrogen

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