Exploring Electrochemical Charging: A Potential Substitute for Hydrogen Gas in Hydrogen Embrittlement Testing?

Catalina H. Musinoi Hagen[1], Erik Koren[2], Anette B.Hagen[1], Bård Nyhus[1], Roy Johnsen[2], Antonio Alvaro[1], Vigdis Olden[1]

[1]SINTEF Industry, Trondheim, Norway
[2]Norwegian University of Science and Technology

Corresponding author's e-mail address: Catalina.Hagen@sintef.no

- **Keywords:** *Hydrogen uptake and diffuson (through metals and polymers). Hydrogen-affected mechanical properties (e.g. hydrogen embrittlement of steels, rapid gas decompression damage of polymers)*

ABSTRACT

This paper evaluates the potential of electrochemical charging as an alternative to hydrogen gas charging in hydrogen embrittlement (HE) testing. Conducted collaboratively by SINTEF Industry, the Norwegian University of Science and Technology (NTNU), and Kyushu University, our study compares these methods regarding hydrogen uptake and diffusion in X65 pipeline steel—a material prevalent in the oil and gas industry.

Utilizing the hydrogen permeation technique, we measured critical parameters such as the effective hydrogen diffusion coefficient (D_{eff}) and sub-surface hydrogen concentration (C_{0R}) during gas charging at pressures up to 100 bars. These measurements enabled a direct comparison with traditional hydrogen gas charging pressures by calculation of the equivalent hydrogen pressure (p_{H2eq}) for electrochemical charging. A specialized dual-membrane permeation cell was constructed to ensure precision, introducing an innovative experimental methodology to bridge and verify the correlation between electrochemical and gaseous hydrogen charging. Our findings indicated a robust correlation between the calculated p_{H2eq} from electrochemical methods and the measured pressures in gas charging, validated through equilibrium pressure measurements in the novel custom-made setup.

Electrochemical charging conditions, notably cathodic protection at –1050 mV vs. Ag/AgCl, were found equivalent to a hydrogen pressure of approximately 15-20 bar. The inclusion of recombination poisons escalated the equivalent pressure to about 200 bar, aligning with the desired pressures for hydrogen gas transportation in pipelines. We also simulated the electrochemical production of hydrogen and its diffusion into the steel using a transient, 1-D diffusion model. This model, validated with experimental data, predicts the evolution of hydrogen pressure and the effects of operational and material parameters, such as pressure changes with more negative potentials and the time required to reach a steady state in larger volumes.

Furthermore, preliminary mechanical toughness tests were conducted on the same X65 material under both hydrogen gas and electrochemical charging conditions. These tests aimed to assess the impact of each method on the steel's mechanical properties, particularly its toughness and ductility. The outcomes indicated that both charging methods resulted in similar effects on material integrity, thereby supporting the theoretical equivalency of electrochemical and hydrogen gas charging in the context of HE-testing.

The significance of these findings lies in the potential for electrochemical charging to replace hydrogen gas charging in HE tests, which are essential for ensuring the safe use of materials in hydrogen-related applications. Electrochemical charging offers a more accessible, safer alternative that could facilitate broader research and testing activities, especially in environments where handling high-pressure hydrogen gas is logistically challenging or hazardous. This shift could significantly impact the standard methodologies used in HE testing, enhancing safety and efficiency in research and industrial contexts.

Acknowledgements
This work has been supported by the Research Council of Norway and the industry company partners through the HyLINE project (294739) and through internal fundings in SINTEF and NTNU. The authors gratefully acknowledge the financial support from the strategic SINTEF Industry project number 102026529 SEP HYSAT:" Determination of equivalent hydrogen cracking Severity from hydrogenating media". The authors would also like to thank Nils-Inge Johan Nilsen and Morten Høgseth Danielsen for their support in the experimental work

References
1. Koren, E., Hagen, C. M., Wang, D., Lu, X., Johnsen, R., & Yamabe, J. (2023). Experimental comparison of gaseous and electrochemical hydrogen charging in X65 pipeline steel using the permeation technique. *Corrosion Science*, *215*, 111025.
2. Koren, E., Hagen, C. M., Wang, D., Lu, X., & Johnsen, R. (2024). Investigating electrochemical charging conditions equivalent to hydrogen gas exposure of X65 pipeline steel. *Materials and Corrosion*, *75*(3), 315-321.
3. Anette B. Hagen, Bård Nyhus, Michael R. Gerhardt, Catalina H. Musinoi Hagen, Gaute Stenerud, Antonio Alvaro, Philippe Mainçon, Vigdis Olden, *International Journal of Hydrogen Energy*, accepted for publishing.