| **DOE Hydrogen Program Record** | |
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| **Record #:** 21004 | **Date:** May 5, 2021 |
| **Title:** Increased Design Life for High-Pressure Stationary Hydrogen Storage Vessels through Development of Empirically Based Design Curves | |
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| **Approved by:** Laura Hill and Jesse Adams | **Date:** November 12, 2021 |

## Item

Fatigue crack growth rate design curves were developed at Sandia National Laboratories and accepted into ASME Section VIII Division 3 Code Case 2938 in December 2018. The design curves are for steels used in high-pressure hydrogen storage vessels commonly installed at hydrogen refueling stations (HRS) (e.g., Type 1 and 2) [1, 2]. The use of these design curves enables approximately three times longer design life of typical hydrogen storage vessels compared to previous industry designs. The use of specified design curves reduces costs by enabling longer pressure vessel life, removes need for expensive and challenging testing, and provides harmonization of design curves.

## Supporting Information

Hydrogen pressure vessel design, according to American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Section VIII Division 3 Article KD-10 [3], utilizes a fracture mechanics design approach and fatigue crack growth rate information to determine the number of cycles that pressure vessels can undergo during the operating lifetime. Fracture mechanics assumes the structure has an initial flaw based on non-destructive evaluation (NDE) and assesses the growth of this initial flaw. A safety factor of two is assigned to the calculated design cycles as per ASME BPVC VIII-3 which provides for additional tolerance.

Fatigue crack growth rate is defined as the crack extension per load cycle (da/dN) and increases as a function of the driving force to extend the crack, typically characterized by the cyclic stress intensity factor range ($\Delta K$). The stress intensity factor (K) is a fracture mechanics parameter representing the stress, size, and geometry of a crack in the structure and is transferrable between laboratory tests and engineered structures. Typically, $\Delta K$ is greater for a larger crack; thus, as a crack grows, $\Delta K$ increases, and the rate of fatigue crack growth also increases.

Article KD-10, which is used for ASME hydrogen pressure vessel design, requires extensive fatigue crack growth testing in gaseous hydrogen at pressure equal to or greater than the design pressure, including replicate testing of steels from multiple heats of steel to develop data for the design basis. The resulting fatigue crack growth data represent the principle design basis for structural integrity assessment and lifetime prediction for fatigue service. Prior to Code Case 2938, SA-372 Grade J was the only alloy with publicly accessible design data that satisfied Article KD-10 [4, 5]. Figure 1 shows the publicly accessible data that could be used for design prior to Code Case 2938, which is limited to ΔK >10 MPa $m^{1/2}$. Prior to the Code Case, each designer would establish with their own fit to available data and extrapolate to ΔK <10 MPa $m^{1/2}$, which characterizes the majority of the life of high-pressure vessels. In Figure 1, a dashed line represents an upper bound fit of the data and has been extrapolated to cover the full design space of a pressure vessel. In principle, as there was no guidance in the code, each designer could develop their own curve in this range of ΔK <10 MPa $m^{1/2}$, resulting in a lack of harmonization in curves used for pressure vessel design.

In a partnership with several international stakeholders and supported by the Hydrogen and Fuel Cell Technologies Office (HFTO) Safety, Codes and Standards subprogram, Sandia developed a test campaign to assess two important questions: (1) what is the fatigue crack growth response of pressure vessel steels at low ΔK (<10 MPa $m^{1/2}$); and (2) can a wider range of steels be considered for this application?

The outcome of the testing campaign was three-fold and demonstrated in Figure 2:

1) Fatigue crack growth at low ΔK was found to be up to ten times lower than extrapolation of previous data.
2) Additional pressure vessel steels were found to behave similarly, including SA-723 pressure vessel steels of interest to the industrial stakeholders.
3) The fatigue response of common pressure vessel steels (SA-372 and SA-723) can be characterized by a robust design curve, represented by the solid curve in Figure 2.

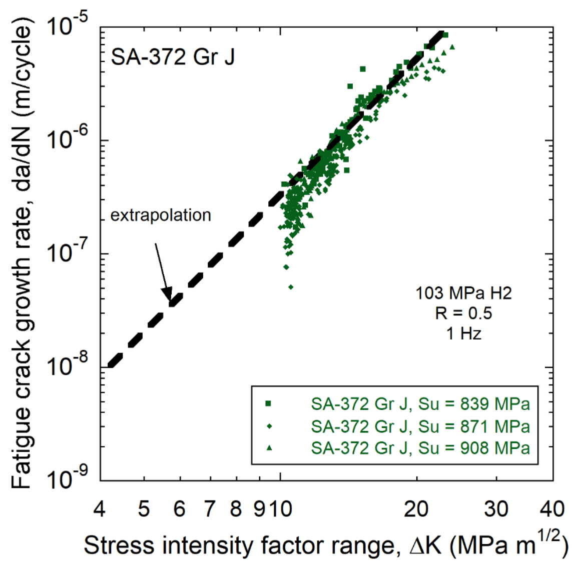


Figure 1. Historical fatigue crack growth rate data for ASME SA-372 Grade J steel measured in gaseous hydrogen at pressure of 103 MPa. Prior to Code Case 2938, these data represented the publicly available data that could be used as a design basis for pressure vessels at hydrogen refueling stations. When necessary, these data were extrapolated to low stress intensity factor ranges.

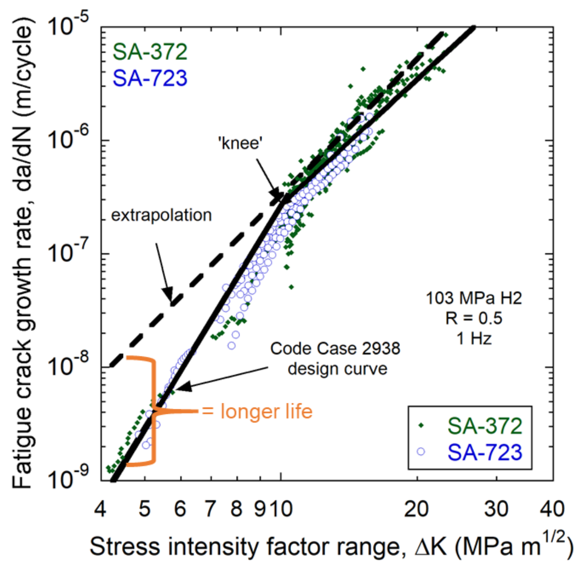


Figure 2. Fatigue crack growth rate data for six different batches of ASME SA-372 and SA-723 steel measured in gaseous hydrogen at ≥103 MPa. The Code Case 2938 design curve (solid line) is a better representation of the data than the extrapolated curve. By using the Code Case 2938 curve design, tank life can be increased because slower and more accurate crack growth rates are used for design.

The new data clearly identified a 'knee' in the fatigue response of the pressure vessel steels, which represents a transition point to significantly lower crack growth rates than the previously extrapolated results. Using the new data generated at low ΔK (Figure 2), fatigue design life calculations result in a significantly greater number of design cycles as compared to calculations using the overly conservative extrapolation shown in Figure 1. The exact difference in design life will depend on the specific design and operation of the vessel. Revised design life calculations for an in-service HRS pressure vessel revealed nearly three times longer design life when the Code Case 2938 design curves were used compared to the original design basis (e.g., extrapolated curve) [8]. The approval of Code Case 2938 eliminates the need for additional costly testing of ASME pressure vessel steels (SA-372 and SA-723) in gaseous hydrogen by providing design curves that can be used in up to 106 MPa hydrogen pressure and are dependent on load ratio (e.g., pressure swing). The use of specified design curves provides harmonization in the design basis since all manufacturers can now use the same design curves.

**References**


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