# Novel Water-Loaded Rig for Characterising Materials in Future Fusion Reactor Windows

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**Abstract**

The development of fusion energy is a critical step towards sustainable and clean energy production. One of the key components in fusion reactors, such as ITER, is the vacuum vessel window, which is part of the first safety wall and experiences extreme mechanical and thermal loads over extended periods under radiation. The failure of these windows due to subcritical crack growth (SCCG) can be life-limiting, and understanding this behavior is crucial for the design and operation of future fusion reactors. This paper presents a novel water-loaded test rig for characterizing the SCCG of materials, specifically focusing on silica, a candidate material for vacuum vessel windows. In this study, we conducted tests on silica at two different loading rates to better understand its behavior under varying conditions. Additionally, we developed a Python code to interpret the test data using the Weibull approach.
**Introduction**

Fusion energy holds promise as a clean and virtually limitless source of power. However, the realization of this technology depends on overcoming numerous engineering challenges, including the design and durability of vacuum vessel windows. These windows, part of the safety wall, must withstand high temperatures, radiation, and mechanical stresses over extended lifetimes. Previous studies have shown that SCCG can be a significant failure mechanism in fields such as dental ceramics and that radiation can impact the SCCG rate in alumina. However, the combined effects of radiation, high temperatures, and long durations on SCCG in materials like silica remain unclear. Understanding the behavior of materials under these conditions is essential for designing windows that can withstand the harsh environment of a fusion reactor.

**The Jules Horowitz Reactor (JHR)**

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The Jules Horowitz Reactor (JHR) is a new research Material Testing Reactor (MTR) under construction in Cadarache, France. It is designed to provide high-intensity neutron flux for a wide range of experimental campaigns, including material and fuel experimental irradiation studies. The JHR will be equipped with a variety of irradiation devices. These devices are designed to simulate the conditions experienced by materials in fission or fusion reactors, including high neutron fluency, irradiation temperature, and mechanical loadings.

The FUSERO project, a collaboration between UKAEA (Oxford, UK) and CEA (Cadarache, France), aims to develop test devices and associated sample holders dedicated to investigating material irradiations more suited to the "fusion community." In addition to "cook and look" irradiation type, the project is divided into three main components: FUSERO A, FUSERO B, and FUSERO C, irradiation devices with in-situ measurements. FUSERO A focuses on the current challenges for ITER and future fusion reactor diagnostic windows, particularly addressing structural issues and investigating further Sub-Critical Crack Growth (SCCG). Given the brittle nature of ceramics, these materials can suffer from premature failure when stressed due to surface cracks and imperfections. FUSERO B and FUSERO C expand on this work by exploring additional materials and conditions, respectively at very low temperatures and under thermomechanical fatigue under radiation environments, to better understand the long-term behavior of materials in fusion reactor conditions.

**Methodology, Materials, and Testing**

In the framework of FUSERO development, a novel water-loaded test rig used in this study enables cost-effective testing at scale with acceptable measurement accuracy. These rigs are designed to simulate the conditions experienced by vacuum vessel windows in fusion reactors. By changing the pump speed, the rigs can gather fracture data at various stressing rates, bringing the dataset closer to the requirements of standard BS EN 843-3. In this study, we focused on testing silica ($SiO_2$) at room temperature under two different loading rates to better understand its behavior under varying conditions. Silica is a candidate material for vacuum vessel windows due to its high strength, low thermal expansion coefficient, and excellent resistance to radiation damage. However, the behavior of silica under subcritical crack growth conditions is not well understood. The tests were conducted on silica specimens with dimensions of 50 mm x 10 mm x 5 mm. The specimens were subjected to a constant load at two different loading rates: 100 N/s and 1000 N/s.

**Weibull Analysis**

The Weibull distribution is a widely used statistical model for describing the strength of materials. It is particularly useful for analyzing the strength of brittle materials, such as ceramics, which exhibit a high degree of variability in their strength. The Weibull distribution is defined by two parameters: the shape parameter (m) and the characteristic strength ($\sigma 0$). The shape parameter (m) describes the variability in the strength of the material. A low value of m indicates a high degree of variability, while a high value of m indicates a low degree of variability. The characteristic strength ($\sigma 0$) is the strength at which 63.2% of the specimens fail. The Weibull parameters were estimated using the maximum likelihood estimator (MLE) method. The MLE method involves finding the values of $\sigma 0$ and m that maximize the likelihood function, which is the probability of observing the given data.

**Results and Discussion**

The results indicate that the characteristic strength between datasets varies by approximately 10%, with the uncertainty around individual measurements being around 4-5%. This suggests that the increase in strength observed between the datasets is mostly due to the change in loading rates, highlighting SCCG phenomena. The water-loaded test rigs have proven to be a valuable tool for gathering data under conditions relevant to fusion reactors.

Additionally, we developed a Python code to interpret the test data using the Weibull approach. The Python code for Weibull analysis was developed using the SciPy library, which provides a suite of mathematical and statistical functions. The code takes the strength data as input and returns the estimated Weibull parameters ($\sigma 0$ and m) and their uncertainties. The code first calculates the natural logarithm of the likelihood function and then uses the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm to find the values of $\sigma 0$ and m that maximize the likelihood function. The more specimens used to estimate the fit, the more accurate the fit parameters are likely to be. The estimated parameter calculated directly from a finite number of observations is referred to as 'biased'. It needs to be 'unbiased' by multiplying with an unbiasing factor (UF). This brings the expected (or mean) parameter value for a finite sample size closer to the 'true' parameter of the entire population. For the Weibull distribution, the tabulated unbiasing factors from the standard ASTM C1239-13 were applied. In the data analysis of this study, no adjustment was made for the characteristic strength, because it is generally negligibly impacted by bias. This code allows for the fitting of a Weibull formalism and a parameters convergence approach.

The sensitivity analysis shows that the height of the sample is the most important contributor to the combined uncertainty of stress, followed by the tolerance on the span between the inner supports. A coverage factor of k=2 (equivalent to 2 standard deviations) was selected to produce an uncertainty interval with a confidence of approximately 95%.

**Conclusion**

The findings from this study justify and inform future designs of subcritical crack growth (SCCG) tests for ceramics in irradiated conditions. The novel water-loaded rigs provide a cost-effective and accurate method for testing materials under conditions similar to those experienced by vacuum vessel windows in fusion reactors. Additionally, the development of a Python code to interpret the test data using the Weibull approach enhances the accuracy and reliability of the results. This work is a significant step towards understanding the long-term behavior of materials in future fusion reactors and ensuring their safe and reliable operation. The future work will include a testing program to include irradiation experiments, in JHR as an example, which will allow for the study of the effects of radiation on the SCCG behavior of materials. The Python code for Weibull analysis will also be further developed to include additional features, such as the ability to handle censored data and to perform statistical tests for comparing the Weibull parameters of different datasets. This work will enable a more comprehensive analysis of the test data and a better understanding of the factors that influence the SCCG behavior of irradiated, and under irradiation, materials.

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