# Development of a Coupled Facility for High-Energy Proton Irradiation and High-Temperature, High-Pressure Water Corrosion

**Authors:** Liu, Miss Ying, Jiang, Ms. Xuefeng, Yan, Mr. Ku, Shi, Miss Xu'er, Jiao, Dr. Tingyu, Cao, Dr. Jiewei, Gu, Mr. Zhen Yuan, Liu, Ms. Yina, Dr. Chunjuan Li, Yang, Dr. Ming, For an academic context, **"Li, Dr. Wei" is not a standard form**. Use one of the following instead, depending on purpose and style:

1. **In the body of a paper / email salutation (with title):**
   - Dr Wei Li

   - Dr. Wei Li (with period, in American usage)
2. **In the body of a paper (without title):**
   - Wei Li
3. **In a reference list (author name format):**
   - Li, W.

   - Li, Wei (depending on the style guide)
4. **In formal address (speaking or writing a greeting):**
   - Dear Dr Li,

   - Dear Dr Wei Li,

So you should generally write **"Dr Wei Li"** (or **"Dr. Wei Li"** ) in formal text, and **"Li, W."** in reference lists., Yang, Dr. Ming

**Date:** 2026-01-06T11:20:48+00:00

## Abstract

To investigate the failure behavior of key pressurized water reactor (PWR) structural materials under coupled irradiation, high-temperature, high-pressure, and corrosive conditions, this study developed a test facility that integrates proton irradiation with a high-temperature, high-pressure aqueous environment, based on a 100 MeV proton cyclotron. The system safely extracts a high-energy proton beam into ambient atmosphere, thereby eliminating the risk of water ingress into the accelerator vacuum system.

The facility consists of three subsystems. The high-energy proton transmission subsystem enables wide-range tuning of proton energy from 4 to 96 MeV, controls the beam spot diameter to 25 mm, and provides real-time monitoring of beam current and specimen temperature. A multi-factor coupled specimen analysis model is established for 316L stainless steel under both low- and high-energy proton conditions, forming an analytical framework for evaluating its mechanical and thermal properties. The circulating water chemistry dynamic regulation subsystem employs a thermally insulated sealed autoclave and a closed-loop circuit, integrates electrochemical monitoring with solution parameter control and data logging, and supports comparative experiments in three regions (irradiated zone, corrosion zone, and non-irradiated zone).

This facility offers a safe and reliable experimental platform for elucidating the failure mechanisms of nuclear materials under the synergistic action of irradiation and corrosion.

## Full Text

## Preamble

### Development of a Coupling Facility for High-Energy Proton Irradiation and High-Temperature High-Pressure Water Corrosion

Ying Liu, Xuefeng Jiang, Ku Yan, Xu'er Shi, Tingyu Jiao, Jiewei Cao, Zhenyuan Gu, Yina Liu, Chunjuan Li, Ming Yang*, Wei Li*

National Key Laboratory for Metrology and Calibration Techniques, China Institute of Atomic Energy, Beijing 102413, China

## Abstract

To address the failure issues of key pressurized water reactor (PWR) materials under coupled conditions of irradiation, high temperature, high pressure, and corrosion, this study developed a testing facility that integrates proton irradiation with a high-temperature, high-pressure water environment, based on a 100 MeV proton cyclotron. The apparatus safely extracts the high-energy proton beam into ambient atmosphere, thereby eliminating the risk of water ingress into the accelerator vacuum system. The entire system comprises three subsystems: (1) The high-energy proton transmission system enables wide-range regulation of proton energy from 4 to 96 MeV, controls the beam spot diameter to 25 mm, and incorporates real-time monitoring of beam intensity and sample temperature. (2) A multi-factor coupled sample analysis model establishes an analytical framework specifically for 316L stainless steel under both low- and high-energy proton conditions, analyzing its mechanical and thermal performance. (3) The circulating water chemistry dynamic regulation system employs an insulated sealed autoclave and a closed-loop circuit, integrates electrochemical monitoring with solution parameter control and recording, and supports three-zone comparison experiments (irradiated zone, corrosion zone, and non-irradiated zone). This facility provides a safe and reliable experimental platform for investigating the failure mechanisms of nuclear materials under the synergistic effects of irradiation and corrosion.

**Keywords:** Irradiation accelerated corrosion, In situ proton irradiation, High temperature water

## 1. Introduction

The Pressurized Water Reactor (PWR) is the most prevalent reactor type among operational nuclear power plants globally, accounting for approximately two-thirds of total nuclear power capacity [?, ?]. The core structural materials of PWRs operate under long-term exposure to multiple extreme and coupled conditions, including high temperature, high pressure, irradiation, and corrosion. Consequently, material aging and failure induced by these factors have become critical concerns limiting the safety and lifetime of nuclear power plants [?], attracting significant attention from the industry. In the reactor cores of operating nuclear power plants in Europe, the United States, Japan, and other countries, numerous failure cases related to the combined effects of high temperature, high pressure, irradiation, and corrosion have been reported. Examples include irradiation embrittlement of reactor pressure vessel steels, irradiation swelling, and accelerated corrosion of fuel cladding, etc. [?]. To gain a deeper understanding of material degradation mechanisms under the combined action of multiple physical fields, and to more accurately evaluate material performance and predict service lifetime, it is essential to develop testing facilities capable of simulating coupled long-term service behavior under environments of irradiation, high temperature, high pressure, and corrosion.

At present, research and development of PWR environmental simulation facilities in the international community mainly follow two approaches: static water environment simulation devices and flowing water environment simulation devices. In 2011, Université Paris-Saclay [?] achieved coupled high-temperature irradiation and corrosion experiments in a static water environment, where they used a high-energy proton beam to investigate the role of water radiolysis on the corrosion of stainless steel in simulated PWR primary coolant conditions. In 2014, the University of Michigan [?, ?] designed and constructed an in-situ irradiation experimental facility capable of simulating high-temperature and high-pressure corrosion conditions in a flowing water environment. In the corrosive environment of flowing water, the vacuum protection scheme of the accelerator utilizes the sample as a barrier between the water solution and the vacuum environment, and is equipped with relatively expensive and complex double quick valves to reduce the risk of sample rupture. Once the sample is damaged, the vacuum level of the beam line will significantly decrease.

In this paper, based on the existing 100 MeV high-energy proton cyclotron accelerator facility, a high-energy proton beam extraction in-situ corrosion irradiation device with high temperature and high pressure is established. It mainly consists of three key technical modules: the high-energy proton beam transmission system, the multi-factor coupling sample analysis model, and the circulating water dynamic regulation system. The above design can simultaneously achieve the coupling technology of proton beam irradiation in the air environment and corrosion of flowing water under high-temperature and high-pressure conditions.

## 2. Experimental Design

To accommodate the research demands of various materials, it is necessary to regulate the proton beam energy in the test facility designed for coupling high-energy proton irradiation with high-temperature, high-pressure water technology. The objective of this regulation is twofold: to avoid localization of the Bragg peak within the sample, ensuring spatially uniform irradiation damage, and to subject the sample to a controllable flowing water environment with a maximum temperature of 320°C. To achieve this, the overall design comprises three integrated subsystems:

- **High-Energy Proton Beam System:** This system is responsible for proton beam energy regulation and collimation. It is also equipped with capabilities for real-time monitoring of both beam intensity at the sample and sample temperature.
- **Multi-Factor Coupled Sample Analysis Model:** This analytical component encompasses determining the correlation between sample thickness and incident beam energy, analyzing the thermomechanical response of samples under irradiation via finite element software, and calculating the subsequent beam transmission distance in water medium.
- **Circulating Water Dynamic Regulation System:** This subsystem includes the design of reactor vessel and integrated electrochemical monitoring. It provides precise control and continuous monitoring of key parameters within the high-temperature, high-pressure water circulation loop.

### 2.1. High-Energy Proton Beam System

This research was performed using the proton cyclotron platform at the Institute of Atomic Energy. Based on this facility, a high-energy proton beam system was constructed, as illustrated in Fig. 1 [FIGURE:1]. The system comprises two primary sections: (a) the Beam zone, which contains the existing proton cyclotron accelerator and the energy degrader; and (b) the Experimental zone, which houses a collimator, a finger ionization chamber, a Faraday cup, and an infrared thermometer. All devices within the experimental zone are mounted on an XYZ three-axis translational stage. This setup enables precise alignment of the sample to the beam spot center, facilitated by coordination with X-ray film. A 3-meter-thick shielding wall, featuring a central through-hole of 15 cm in diameter, separates the two zones to prevent direct irradiation of the entire experimental space by high-energy protons.

Within the system, the proton cyclotron accelerator delivers a beam with adjustable energy (70–100 MeV) and intensity (pA to $\mu$A), and an initial spot diameter of 5 cm. The energy degrader features a five-layer graphite configuration, with individual thicknesses of 0.63, 2.71, 4.09, 5.49, and 5.43 mm. Graphite was selected for its advantageous properties: small energy dispersion, low yield of short-lived radionuclides, and ease of machining. Stepwise proton energy adjustment is achieved by the pneumatic insertion or retraction of each graphite layer. When a proton beam passes through the graphite energy degrader, it loses energy via interactions with the material. This energy loss is not fixed but fluctuates around a mean value, following an approximately Gaussian distribution. The magnitude of these fluctuations—often termed energy straggling or energy spread—is characterized by the standard deviation $E_\sigma$. According to Bohr theory [**?**], $E_\sigma$ can be calculated using the following expression:

where $z$ is the atomic number of the incident particle, $Z$ is the atomic number of the target material, $e$ is the electron charge, and $N$ is the number density of target nuclei. After passing through a five-layer graphite degrader, the proton beam energy can be reduced to as low as 20 MeV. Fig. 2 [FIGURE:2] illustrates: (a) the variation of energy reduction with graphite thickness; (b) the relationship between energy reduction and the corresponding root mean square deviation of energy dispersion, $E_\sigma$; (c) the energy distribution obtained from Monte Carlo simulation, confirming the broadening of the energy spectrum after degradation. These results further indicate that greater energy reduction leads to a larger full width at half maximum (FWHM) of the Gaussian distribution, i.e., more pronounced energy dispersion.

Following graphite degradation, the proton beam traverses at least 3 m of air for further energy reduction, ultimately achieving continuous energy coverage from 4 MeV to 96 MeV in the sample irradiation area. This range fully meets the irradiation requirements for material systems of varying thicknesses.

After passing through the degrader, the proton beam enters the collimator via an aperture in the shielding wall. The collimator is made of graphite, with a thickness of 40 mm and a central hole diameter of 25 mm. This configuration provides a sufficiently large irradiation area for mechanical testing and analysis of materials while ensuring beam uniformity. As the proton beam spot expands due to scattering in the degrader and air, this collimator selects the most uniform and stable central region of the beam profile. To measure the beam intensity at the sample position, the system is equipped with a finger ionization chamber and Faraday cup, the latter being position-adjustable via a pneumatic device. In addition, an infrared thermometer is employed for non-contact, dynamic monitoring of the sample surface temperature field during irradiation.

Figure 4

Figure 1: Figure 4

## 2.2. Multi-Factor Coupled Sample Analysis Model

**2.2.1. Matching Sample Thickness to Incident Proton Energy** The sample thickness is designed according to the penetration depth of high-energy protons in the material, ensuring that the sample–water interface lies beyond the Bragg peak region to achieve uniform damage distribution. Fig. 3 [FIGURE:3] presents the damage (displacement per atom, DPA) and energy deposition profiles for 4 MeV and 96 MeV protons in 316L stainless steel, as simulated using the SRIM 2013 program [?]. Based on these penetration depths, a suitable thickness for 316L stainless steel samples under 4–96 MeV proton irradiation ranges from approximately 55 $\mu$m to 12 mm.

**2.2.2. Mechanical Condition Matching** Under low-energy irradiation conditions, the sample needs to be maintained in a relatively thin configuration. It is therefore essential to ensure that the sample can withstand the design pressure of 15 MPa under pressurized water reactor (PWR) operating conditions. Meanwhile, to investigate the effect of water radiolysis on the material, the corrosion zone was designed to be slightly larger than the irradiation zone, enabling comparative analysis of experimental conditions in the irradiation zone, corrosion-affected zone, and the non-irradiated zone. Based on the above considerations, the diameter of the irradiation zone is set to 25 mm, and that of the corrosion zone to 30 mm.

Subsequently, a finite element model was established using ANSYS software to simulate the stress distribution when a water pressure of 15 MPa acts on the corrosion area with a diameter of 30 mm. By varying the sample thickness, the relationship curve between maximum stress and thickness was obtained, as shown in Fig. 4

. The simulation results indicate that the maximum stress in the sample decreases with increasing thickness. The dashed line in the figure denotes the yield strength of 316L stainless steel at 320°C. The sample must be designed such that the material yield strength is not exceeded under experimental conditions. As shown in Fig. 4, the maximum stress curve intersects the yield strength line at a thickness of 3 mm. Hence, when subjected to 15 MPa water pressure on a 30 mm diameter area, the minimum safe thickness of the 316L stainless steel sample should be no less than 3 mm.

To further assess the structural safety of the sample under service conditions, the rupture pressure of the 3 mm thick specimen was evaluated using the analytical model proposed by Vodyanik [?]:

$$2\Delta U$$

Figure 5

Figure 2: Figure 5

where $p$ is the rupture pressure, $\Delta$ is the sample thickness at burst, $D$ is the sample diameter, and $\sigma_{UTS}$ is the ultimate tensile strength of 316L stainless steel, taken as 485 MPa. Substituting a thickness of 3 mm and a diameter of 30 mm yields a calculated rupture pressure of approximately 97 MPa for the sample. This value significantly exceeds the 15 MPa working pressure of the experiment, confirming that the designed specimen possesses a substantial safety margin under the intended operating conditions.

A working pressure of 15 MPa was used in all experiments to ensure water remained in the liquid phase, thereby maintaining stable and controllable corrosion conditions at the maximum operating temperature of 320°C and preventing boiling.

Based on the SRIM simulation results, a sample thickness of 3 mm necessitates an incident proton energy of 45 MeV to avoid positioning the Bragg peak within the material. Consequently, for an irradiation zone diameter of 25 mm and a corrosion zone diameter of 30 mm, the feasible sample thickness range is 3–12 mm, corresponding to an incident proton energy range of 45–96 MeV. From this relationship, the functional dependence among the actual energy deposited in the sample, sample thickness, initial proton beam energy, and degrader thickness can be established, as summarized in Table 1 .

**2.2.3. Thermal Characteristics** To investigate the thermal response of the sample under high-energy proton irradiation, a transient thermal analysis was performed using ANSYS software. A 12-mm-thick 316L stainless steel sample was modeled under one-side irradiation by a 96 MeV, 250 nA proton beam, with the opposite side subjected to a circulating water flow boundary condition at 320°C. The simulation duration was set to 10 hours. The results are presented in Fig. 5

, which shows the temperature evolution of the irradiation zone over time as well as the corresponding temperature distribution contour. The simulation indicates that the temperature in the irradiated region rises rapidly to approximately 341.8°C and stabilizes within a short period. At this temperature, 316L stainless steel retains its microstructural and mechanical stability, thereby satisfying the operational requirements under the investigated conditions.

Under the combined influence of proton irradiation and the high-temperature aqueous environment, the temperature in the irradiated zone rose rapidly to approximately 341.8°C within about 30 minutes and subsequently reached a steady state.

**2.2.4. Travel Distance of the Beam in Water after Sample Penetration** To mitigate radiolysis effects in the aqueous solution and prevent the proton beam from irradiating the reference and auxiliary electrodes positioned behind the sample, it is essential to minimize the penetration depth of protons in water after traversing the sample. The residual range of proton beams with varying initial energies was simulated and optimized using SRIM 2013 for different sample material thicknesses. The results are presented in Fig. 6 [FIGURE:6].

In this study, proton incident energies of 45 MeV and 96 MeV were selected, impinging on 316L stainless steel samples of varying thicknesses to evaluate their subsequent penetration distance in water. Simulations revealed that for 316L stainless steel thicknesses of 3 mm and 12 mm, respectively, the residual proton range in water is minimized, measuring approximately 3 mm and 9 mm. Reducing the sample thickness below these optimal values—for example, using a 10 mm sample instead of the optimal 12 mm—results in a significant increase in the penetration depth in water, reaching about 18 mm. Conversely, increasing the sample thickness beyond the optimal value causes the Bragg peak to deposit excessive energy within the 316L stainless steel, leading to non-uniform irradiation damage. Such non-uniformity is undesirable for studies focused on material performance under irradiation.

These simulation outcomes also provided critical data for the subsequent design of the electrochemical cell, enabling the placement of the reference and auxiliary electrodes as close to the sample as possible while remaining outside the direct radiation range.

## 2.3. Dynamic Regulation System for Circulating Water

**2.3.1. Design of the Corrosion Cell** To withstand an internal pressure of 15 MPa (corresponding to a water boiling point of 340°C) while offering good mechanical strength and corrosion resistance, the main cell body is constructed from 316L stainless steel. The internal volume for the aqueous solution is 100 mL, with a designed circulation flow rate of 5 L/h.

The internal configuration for electrical isolation and sealing of the sample within the high-pressure aqueous environment is illustrated in Fig. 7 [FIGURE:7]. The sample is mounted between two polyimide gaskets. This polymer material, capable of withstanding temperatures up to 350°C, provides the necessary elasticity to maintain a watertight seal under high pressure. Furthermore, an insulating ceramic sleeve is employed to ensure complete electrical isolation between the sample and the metallic cell body.

To facilitate system operation and data acquisition, the corrosion cell is equipped with six machined ports. These include an inlet, an outlet, drain ports, as well as ports for thermocouple and electrochemical monitoring probes.

The electrochemical detection system comprises a CorrTest CS310M electrochemical workstation, a $Cu/Cu_2O$ reference electrode, and a platinum wire auxiliary electrode. The reference electrode is positioned 15 mm from the sample surface, and the distance between the reference and auxiliary electrode is set at 13 mm. This spatial arrangement is based on the SRIM simulation results presented in Section 2.2.4. Specifically, for a proton incident energy of 94 MeV penetrating a 12 mm thick 316L stainless steel sample, the subsequent travel distance of the proton beam in water is approximately 9 mm. The designed electrode spacing ensures that both the reference and auxiliary electrodes remain outside this irradiation range, therefore preventing irradiation-induced damage and avoiding interference with electrochemical measurements.

**2.3.2. Regulation and Monitoring of Solution Parameters in the Water Circulation System** A simplified schematic of the designed water circulation loop is presented in Fig. 8 [FIGURE:8]. The system provides fully automated, closed-loop control of the temperature, pressure, and flow rate of the aqueous solution passing through the reaction cell. An automatic shutdown mechanism is integrated to protect against abnormal operating conditions, ensuring operational safety.

The working fluid is an ultrapure water solution (conductivity $ $0.2 μS/cm) with trace elements such as boron and lithium. This solution is held in a 20 L experimental tank, which is continuously purged with nitrogen for deoxygenation. Critical water quality parameters, including dissolved oxygen (DO) concentration and conductivity, are monitored in real time using a Honeywell UDA2182 analyzer. Following the nitrogen purging process, the DO concentration in the solution is maintained at $ $10 ppb, with a conductivity of approximately 20 μS/cm.

During operation, the aqueous solution is circulated from the storage tank through the following sequence: it is first pressurized by a high-pressure pump, then passes through a pulse damper to suppress pressure fluctuations, and is subsequently heated by a preheater before entering the reaction vessel. After the reaction takes place, the effluent is cooled by a condenser and depressurized via a back-pressure valve. Prior to returning to the tank, the solution flows through a secondary set of dissolved-oxygen and conductivity sensors for online monitoring. If the dissolved-oxygen level remains $ $10 ppb, the solution is returned to the storage tank to continue circulation. If the value exceeds 10 ppb, the stream can be diverted to a wastewater tank. All key components mentioned in this circulation loop were supplied by Bairoe Co.

## 3. Experimental Results

Following the design outlined in Section 2, photographs of the complete experimental facility are presented in Fig. 9 [FIGURE:9]. Fig. 9(a) shows the beam collimation system, comprising a graphite beam collimator, an infrared thermometer, a Faraday cup, and the corrosion cell with the installed sample. All components are mounted on an XYZ three-axis translational stage to enable precise alignment between the sample and the proton beam. Fig. 9(b) illustrates the beamline section, which mainly consists of an infrared laser for initial optical alignment, the beamline channel, and a finger-type ionization chamber for monitoring beam intensity. Fig. 9(c) displays the water circulation and dynamic regulation system, arranged from left to right as a chiller unit, the main water circulation loop, and the integrated control cabinet. Housed inside the control cabinet is the electrochemical workstation, which is responsible for the closed-loop control of all water chemistry parameters and the acquisition of electrochemical signals during irradiation.

Prior to irradiation, the proton beam path must be calibrated to compensate for potential deviations from the beamline central axis, caused by magnetic deflection and beam conditioning. The alignment is performed in two stages. First, an infrared laser is used for preliminary optical alignment, ensuring that the center axes of the beamline channel, collimator, Faraday cup, and sample are co-linear. Subsequently, an X-ray film with a marked center is placed at the beamline exit. A low-current proton beam (~1.6 nA) is applied for short irradiation to expose the film (about 10 min). The developed film is then analyzed to determine the precise location of the beam center. Finally, the XYZ three-axis translation stage is adjusted to align the sample exactly with this calibrated beam position, guaranteeing accurate irradiation of the sample area.

For the irradiation-corrosion coupling experiments, a 100 MeV proton beam (without deliberate energy degradation) was employed. Following confirmation of system integrity, the test conditions were established by pressurizing the system to 15 MPa and heating the water to 130°C. Under these steady-state conditions, sequential irradiations were conducted at beam currents of 100 nA, 200 nA, and 300 nA, each for a duration of 15 minutes. Subsequently, the temperature was increased to 320°C while maintaining the pressure at 15 MPa, and the same sequence of beam currents (100, 200, 300 nA) was applied, with each irradiation step lasting 10 minutes. Key parameters, including the Electrochemical Potential (ECP), DO, and conductivity, were monitored and recorded synchronously throughout the entire experiment.

Fig. 10 [FIGURE:10] presents the synchronous variation of water temperature, conductivity, and DO content recorded during the experiment. The active irradiation periods at each beam current are marked by distinct background colors: yellow for 100 nA, cyan for 200 nA, and orange for 300 nA.

During the 130°C phase, neither conductivity nor DO exhibited significant changes with increasing beam current or irradiation time, indicating stable system conditions. This suggests that, at this temperature, boric acid ionization had reached equilibrium, and proton irradiation in the range of 100–300 nA was insufficient to markedly alter the bulk ionic composition of the solution. Radiolysis products such as ·H and ·OH [**?**], potentially generated by the proton beam, likely underwent rapid recombination in the liquid phase or were consumed by reactions with the container and sample surfaces, thus failing to accumulate as stable ionic species that could affect conductivity.

When the temperature was raised to approximately 268°C during a non-irradiation interval, conductivity displayed a stepwise increase from 19.0 $\mu$S/cm to 20.3 $\mu$S/cm, then stabilized. This change is attributed solely to a temperature effect: the dissociation of boric acid is endothermic, and the temperature rise shifts the equilibrium toward increased concentrations of $H^+$ and $B(OH)_4^-$ ions [**?**], thereby raising the conductivity.

After stabilization at 320°C and resumption of irradiation, conductivity remained largely unchanged under 100 nA and 200 nA irradiation but showed a distinct increase to approximately 24 $\mu$S/cm under 300 nA irradiation. At 320°C, water radiolysis becomes more pronounced. While the ion yield from radiolysis at lower currents (100/200 nA) may have been buffered by the boric acid-lithium system, the 300 nA irradiation likely exceeded a threshold, producing a detectable increase in conductive ions. Therefore, the overall conductivity trend was primarily governed by temperature-dependent boric acid dissociation, with high-current proton irradiation at elevated temperature superimposing a measurable additional effect.

Throughout the experiment, DO was maintained at a consistently low level ($ $10 ppb) via continuous nitrogen purging, confirming the effectiveness of the environmental control system.

Fig. 11 [FIGURE:11] illustrates the evolution of the ECP of 316L stainless steel under proton irradiation at beam currents of 100 nA, 200 nA, and 300 nA, tested at 130°C and 320°C. Two distinct response regimes are evident: (1) **Controlled negative shift at 130°C:** During irradiation at all three currents, the ECP exhibited a steady, nearly linear drift in the negative direction. The extent of this shift increased with beam current, ranging from approximately -0.0274 V at 100 nA to -0.031 V at 300 nA. According to mixed potential theory [**?**], the incident protons function as an externally applied cathodic current. To maintain charge balance, the anodic dissolution rate is suppressed, resulting in a negative ECP shift. The stable, linear drift suggests a relatively stable surface state at this temperature, with irradiation primarily acting as an external polarizer. (2) **Enhanced negative shift and fluctuation at 320°C:** At 320°C, the ECP stabilized at a substantially more negative potential (approximately 300 mV lower than at 130°C) and displayed pronounced dynamic fluctuations. The overall negative shift is ascribed to the combined effects of elevated temperature—which modifies the oxide film structure and reaction kinetics [**?**] and accelerates electrode processes—and the more reducing environment induced by radiolysis products (e.g., $H_2$, ·H). The observed fluctuations reflect a dynamic competition at the surface: proton bombardment continuously damages the oxide film, momentarily exposing fresh metal and shifting potential negatively, while the high-temperature aqueous environment promotes rapid repassivation, shifting potential back positively. Variations in local concentration of radiolysis products further contribute to this unstable equilibrium. Higher beam currents amplified this dynamic behavior, resulting in slightly wider fluctuation ranges.

To quantify the influence of temperature on corrosion kinetics under irradiation, potentiodynamic polarization curves were measured at 130°C and 320°C under a proton beam current of 300 nA (Fig. 12 [FIGURE:12]) and fitted using the Tafel extrapolation method [?]. The fitted parameters reveal a pronounced enhancement of corrosion in the high-temperature irradiated environment. Compared to 130°C, the corrosion potential ($E_0$) at 320°C shifted negatively by approximately 260 mV (from -0.062 V to -0.322 V), indicating a significantly increased thermodynamic tendency for corrosion. Simultaneously, the corrosion current density ($I_0$) increased by a factor of about 2.85, from 1.58$×10^{-5}$ A/cm$^2$ to 4.51$×10^{-5}$ A/cm$^2$, reflecting a marked acceleration of the corrosion rate. Moreover, the absolute value of the cathodic Tafel slope ($b_c$) also increased from 89.5 mV/dec to 162.1 mV/dec, suggesting a change in the cathodic reaction mechanism, possibly toward a more inhibited process. These alterations are attributed to the synergistic effects of elevated temperature and irradiation: temperature accelerates reaction kinetics (Arrhenius effect), while irradiation-induced defects (e.g., vacancies, interstitials) degrade the integrity of the protective oxide film, thereby promoting the penetration of corrosive species and ion transport, and reducing the film resistance.

It should be emphasized that the electrochemical responses observed at 320°C do not result from temperature alone. They reflect the cumulative effect of a sequential experimental history: pre-irradiation damage at 130°C, followed by heating, and subsequent irradiation at 320°C. This procedure more realistically simulates the progressive in-service exposure of reactor materials, making the resulting data more relevant for engineering assessment than those obtained by testing a pristine sample directly at high temperature. The results clearly demonstrate the synergistic acceleration of corrosion by irradiation and elevated temperature—a key concern in irradiation-assisted corrosion research. Moreover, with this continuous experimental sequence, the internal comparison between data obtained at 130°C and 320°C remains valid for isolating temperature as the primary variable of interest.

## 4. Summary

This study successfully developed a novel in-situ experimental facility based on a 100 MeV proton cyclotron. This system is designed to investigate the synergistic effects between high-energy proton irradiation and high-temperature, high-pressure water corrosion under simulated PWR primary water chemistry conditions (with boron and lithium additions, and deaerated). The facility features an atmospheric-beam-extraction scheme, which effectively eliminates the risk of water ingress into the accelerator vacuum system during irradiation experiments. It integrates multiple key functions: proton energy regulation, dynamic closed-loop control of high-temperature, high-pressure water chemistry, electrochemical monitoring (capable of measuring dissolved oxygen, conductivity, ECP, etc.), and a three-zone comparative experimental design.

Using this platform, systematic coupled irradiation-corrosion experiments were conducted on 316L stainless steel at 130°C and 320°C with varying beam currents. The preliminary results demonstrate a significant synergistic accelerating effect of elevated temperature and proton irradiation on both the electrochemical behavior and corrosion rate of the material.

In conclusion, this newly developed facility provides a fully functional, safe, and reliable experimental platform. It enables in-depth investigation into the failure mechanisms of nuclear structural materials under coupled conditions of irradiation and water chemistry that closely mimic the actual PWR primary water environment.

**Author Contributions:** All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Ying Liu, Xuefeng Jiang, and Ku Yan. The first draft of the manuscript was written by Ying Liu, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Declarations:** Conflict of interest The authors declare that they have no conflict of interest.

## References

[1] S.J. Zinkle, G.S. Was, Materials challenges in nuclear energy, Acta Materialia 61(3) (2013) 735-758 https://doi.org/10.1016/j.actamat.2012.11.004

[2] W.N. Association, World Nuclear Power Reactors & Uranium Requirements, 2024. https://world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx. (Accessed 1 October 2025).

[3] S. Lapuerta, N. Bérerd, N. Moncoffre, N. Millard-Pinard, H. Jaffrézic, D. Crusset, D. Féron, The influence of relative humidity on iron corrosion under proton irradiation, Journal of Nuclear Materials 375(1) (2008) 80-85 https://doi.org/10.1016/j.jnucmat.2007.10.011

[4] M.B. Lewis, J.D. Hunn, Investigations of ion radiation effects at metal/liquid interfaces, Journal of Nuclear Materials 265(3) (1999) 325-330 https://doi.org/10.1016/S0022-3115(98)00885-X

[5] M. Kawaguchi, K. Ishigure, N. Fujita, K. Oshima, Effect of radiation on release of corrosion products in high temperature aqueous system, Radiation Physics and Chemistry (1977) 18(3) (1981) 733-740 https://doi.org/10.1016/0146-5724(81)90196-5

[6] P.L. Andresen, G.S. Was, 5.08 - Irradiation Assisted Stress Corrosion Cracking, in: R.J.M. Konings (Ed.), Comprehensive Nuclear Materials, Elsevier, Oxford, 2012, pp. 177-205.

[7] R. Gérard, F. Somville, Situation of the Baffle-Former Bolts in Belgian Units, International Conference on Nuclear Engineering, 2009.

[8] E.P. Simonen, S.M. Bruemmer, Radiation effects on environmental cracking of stainless steels, JOM 50(12) (1998) 52-55 10.1007/s11837-998-0309-3

[9] G.S. Was, P.L. Andresen, Stress Corrosion Cracking Behavior of Alloys in Aggressive Nuclear Reactor Core Environments, Corrosion: The Journal of Science and Engineering 63(1) (2007) 19-45 https://doi.org/10.5006/1.3278331

[10] H.K. Zhang, Z. Yao, G. Morin, M. Griffiths, TEM characterization of in-reactor neutron irradiated CANDU spacer material Inconel X-750, Journal of Nuclear Materials 451(1) (2014) 88-96 https://doi.org/10.1016/j.jnucmat.2014.03.043

[11] B. Muzeau, S. Perrin, C. Corbel, D. Simon, D. Feron, Electrochemical behaviour of stainless steel in PWR primary coolant conditions: Effects of radiolysis, Journal of Nuclear Materials 419(1) (2011) 241-247 https://doi.org/10.1016/j.jnucmat.2011.08.051

[12] S.S. Raiman, A. Flick, O. Toader, P. Wang, N.A. Samad, Z. Jiao, G.S. Was, A facility for studying irradiation accelerated corrosion in high temperature water, Journal of Nuclear Materials 451(1-3) (2014) 40-

[13] S. Raiman, Irradiation Accelerated Corrosion of 316L Stainless Steel in Simulated Primary Water, 2016.

[14] Q. Yang, D.J. O' Connor, Z. Wang, Empirical formulae for energy loss straggling of ions in matter, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 61(2) (1991) 149-155 https://doi.org/10.1016/0168-583X(91)95454-L

[15] J.F. Ziegler, The Stopping and Range of Ions in Matter (SRIM), 2013.

[16] V.I. Vodyanik, Design of safety rupture discs, Chemical and Petroleum Engineering 8(6) (1972) 586-588 10.1007/BF01139117

[17] W. Thomas, J. Sunnerberg, M. Reed, D.J. Gladstone, R. Zhang, J. Harms, H.M. Swartz, B.W. Pogue, Proton and Electron Ultrahigh-Dose-Rate Isodose Irradiations Produce Differences in Reactive Oxygen Species Yields, International Journal of Radiation Oncology*Biology*Physics 118(1) (2024) 262-267 https://doi.org/10.1016/j.ijrobp.2023.07.042

[18] H. Arcis, J.P. Ferguson, L.M.S.G.A. Applegarth, G.H. Zimmerman, P.R. Tremaine, Ionization of boric acid in water from 298K to 623K by AC conductivity and Raman spectroscopy, The Journal of Chemical Thermodynamics 106 (2017) 187-198 https://doi.org/10.1016/j.jct.2016.11.007

[19] M. Behazin, S.A. Briggs, F. King, Radiation-induced corrosion model for copper-coated used fuel containers. Part 1. Validation of the bulk radiolysis submodel, Materials and Corrosion 74 (2023) 1834 - 1847

[20] R. Hanbury, The Role of Displacement Damage in Irradiation Affected Corrosion of 316L Stainless Steel,

[21] E. McCafferty, Validation of corrosion rates measured by the Tafel extrapolation method, Corrosion Science 47(12) (2005) 3202-3215 https://doi.org/10.1016/j.corsci.2005.05.046