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Comparison of the Neutronic Performance of IRP-1 and IRP-2 at SNS

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Neutron Technologies Division

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1. INTRODUCTION

The Spallation Neutron Source (SNS) operated from start-up, in May 2006, through December, 2017 before replacing the Inner Reflector Plug (IRP). This component is the most costly and time-consuming "regular maintenance" replacement foreseen in the operation of the First Target Station (FTS). The IRP includes beryllium reflector blocks, steel and aluminum support structures, aluminum moderator vessels (which in turn include gadolinium and cadmium neutron poisons) and water coolant systems. The lifetime of this multi-million dollar component is driven by poison and decoupler burnup in moderator vessels. [1, 2, 3, 4] The moderators include these neutron poisons to best match neutron beam performance with scattering instrument needs. The burnup that comes with use changes the performance of the moderators until they no longer server their intended purpose. The reasonable desire to maximize the IRP lifetime means that the moderator performance at the Beginning Of Life (BOL) is significantly "over poisoned" and different from the performance at moderator End Of Life (EOL). Upon installation of the second IRP article, IRP-2, the SNS Neutronics team characterized the performance of the neutron beamlines in order to assess the differences between them, primarily by comparing the EOL performance of IRP-1 to the BOL performance of IRP-2. While IRP-2 was largely similar to IRP-1 in its conceptual design, there were some differences in the specific design of IRP-2 to support enhanced manufacturability, and the change from IPR-1 to IRP-2 coincided with the replacement of the light water in the IRP cooling loop with heavy water, as had been intended in the SNS design but not implemented during construction because of heavy water availability. [5, 6]

2. IRP DESCRIPTION

The Inner Reflector Plug (IRP) assembly in the SNS target station is a replaceable component which contains the moderator vessels (aluminum, with cadmium and gadolinium decouplers and poisons), the moderator media (liquid water at approximately 300 K and liquid hydrogen at approximately 20 K), beryllium blocks, aluminum and steel structural components, steel shielding, and reflector coolant (light water in IRP-1 and heavy water in IRP-2). The IRP is desired to last as long as possible, since it is expensive and its replacement requires significant downtime. The IRP lifetime is driven primarily by the burnup of the gadolinium and cadmium neutron poisons used on some of the moderators to tailor the neutron beam performance to optimize instrument performance, with a secondary driver arising from radiation damage in the moderator vessels. The IRP is inserted in the monolith vertically, and then a target module is horizontally inserted through the monolith into position within the IRP. Target modules are anticipated to last approximately one half-year of operation, while IRPs are anticipated to last several years of operation.

1. IRP-1 was designed to last 30 GW-hours based on detailed neutronics calculations.
2. IRP-2 was nominally designed to the same 30 GW-hour goal—that is, poison and decoupler thickness were intended to be consistent.
3. The construction of IRP-2 was somewhat more closely monitored than was IRP-1, and the thickness, density, and coverage of decoupler materials in IRP-2 was found to be less self-consistent, and less consistent with the design, than we hoped for, whether or not that was the case with IRP-1.
4. The replacement of IRP-1 with IRP-2 happened at the same time as the replacement of light water

cooling (for the IRP) with heavy water cooling (as was intended from the beginning of SNS operation). This replacement was intended to increase the neutron beam intensity by somewhere between 20 and 25% [5], which coincidentally matched the expected loss in performance of IRP-1 over its anticipated lifetime - that is, the BOL–IRP-2 intensity was anticipated to be very similar to the EOL–IRP-1 intensity, without making any significant changes in pulse widths.

5. Manufacturing problems with IRP-2 necessitated running IRP-1 past its intended life of 30 GW-hours; it was instead used for 40.5 GW-hours.
6. Anecdotal evidence from instrument teams suggested notable degradation in decoupled moderator performance (in terms of instrument resolution) at about 35 GW-hours.
7. More detailed, complete calculations of moderator performance as a function of burnup were developed when it became clear that there would be difficulties installing IRP-2 according to the original schedule. These refined calculations [4] suggested later burnout, indicating lifetimes of 33 GW-hours on the water moderator poison plate and 39 GW-hours on the decoupled-poisoned hydrogen moderator decoupler.

3. CHARACTERIZATION MEASUREMENTS

In general, the characterization measurements performed on individual neutron scattering instruments that reflect changes in the IRP include:

1. incident beam spectral distribution, as measured using time-of-flight with beam monitor style detectors (either incorporated into the neutron scattering instrument itself or temporarily installed specifically for the measurement);
2. emission time distributions, as measured using crystal analyzers in time-focused or near-backscattering configurations directing a wavelength-analyzed beam into a temporarily installed detector; and
3. typical neutron scattering experiments, in which a characteristic typical or calibration measurement on the neutron scattering instrument may be repeated.

The incident beam spectral distributions are typically measured in such a way as to facilitate absolute normalization, although it is not always possible to provide an exact comparison over time, since instruments are upgraded and modified to reflect scientific priorities and ongoing improvement projects. Emission time distributions can be challenging to measure accurately in the presence of guides, especially curved guides.

3.1 Decoupled Poisoned Hydrogen

The Top Upstream moderator is composed of liquid hydrogen at approximately 20 K, is decoupled from the reflector with cadmium, and is poisoned at the centerline of the roughly 50 mm thick volume with gadolinium. [7] This moderator serves beamlines 1–3 and 10–12. This moderator is optimized primarily for higher resolution (as opposed to higher intensity), so special attention is paid to the emission time distributions, which are both more sensitive to poison and decoupler burnup and more relevant to instrument performance as compared to spectral intensity changes.

The SNS Neutronics Team measured emission time distributions and spectral intensities repeatedly on beamline 3, where the SNAP instrument is installed. SNAP is a relatively short straight instrument, with a fairly open instrument design within a cave, and is well-suited to the setup of temporary characterization equipment. Figure 1 shows the measured pulse widths at the middle of IRP-1 operation (MOL), the end of IRP-1 operation (EOL), and the beginning of IRP-2 operation (BOL).

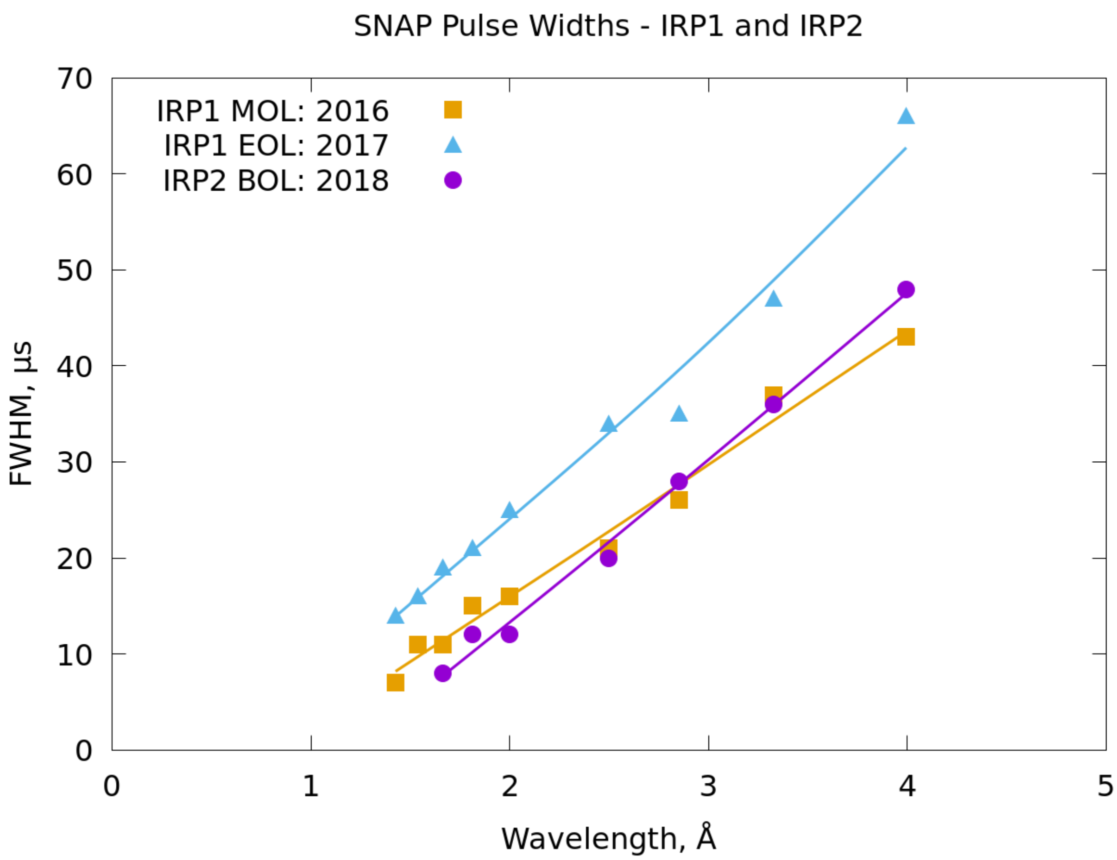

Figure 1. Pulse widths (FWHM) as measured at beamline 3 at various stages of IRP-1 and IRP-2 operation. Points indicate measured values, while the lines only serve to guide the reader's eye. Note that by the end-of-life for IRP-1, pulse widths had increased by almost 40%—IRP-2 restored the original performance.

Another perspective on the IRP replacment comes from the spectral intensity measured on beamline 3 (generally at the same time as the emission time distributions are measured), as appears in Figure 2. The spectral intensity through the final beamline aperture before the sample is very similar, indicating that the use of heavy water reflector coolant very nearly offset the restoration of decoupler and poison materials in the (new) IRP-2 assembly. It is worth noting that Figure 1 and Figure 2, taken together, show that, for example, at 4 Å the BOL–IRP-2 intensity is comparable to that of EOL–IRP-1, despite the EOL–IRP-1 pulse width being 40% larger, implying a much greater *peak* intensity from BOL–IRP-2. These changes

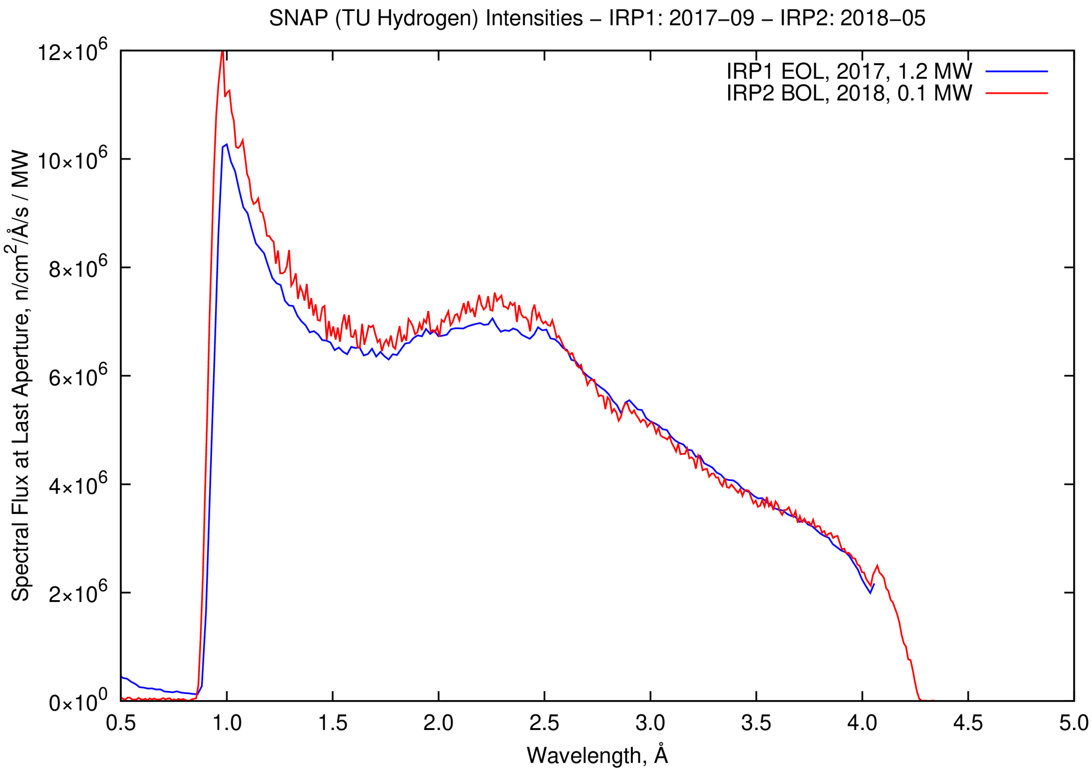

Figure 2. Spectral intensity as measured at beamline 3 at IRP-1 End of Life and IRP-2 Beginning of Life. The power-normalized intensity is very similar, indicating that the change to heavy water reflector coolant approximately offset the restoration of moderator poison and decoupler.

are consistent with the decoupler and or poison for the hydrogen moderator "burning out" by the end-of-life of IRP-1.

3.2 Decoupled Poisoned Water

Spectral and emission time distributions were also measured repeatedly on beamline 7 (the VULCAN instrument) viewing the decoupled poisoned water moderator. The VULCAN instrument provides a working example of the long-term variation in instrument configuration complicating consistent comparison of beam characteristics; the VULCAN instrument was upgraded in 2013 with the addition of a ninth guide segment. [8] The measurements reported here are all after that change.

Spectra and pulse widths measured in 2013, 2017, and 2018 are shown in Figures 3 and 4, respectively. The changes in pulse width, an increase of around 10–25% in FWHM for only the final 39 GW-hr

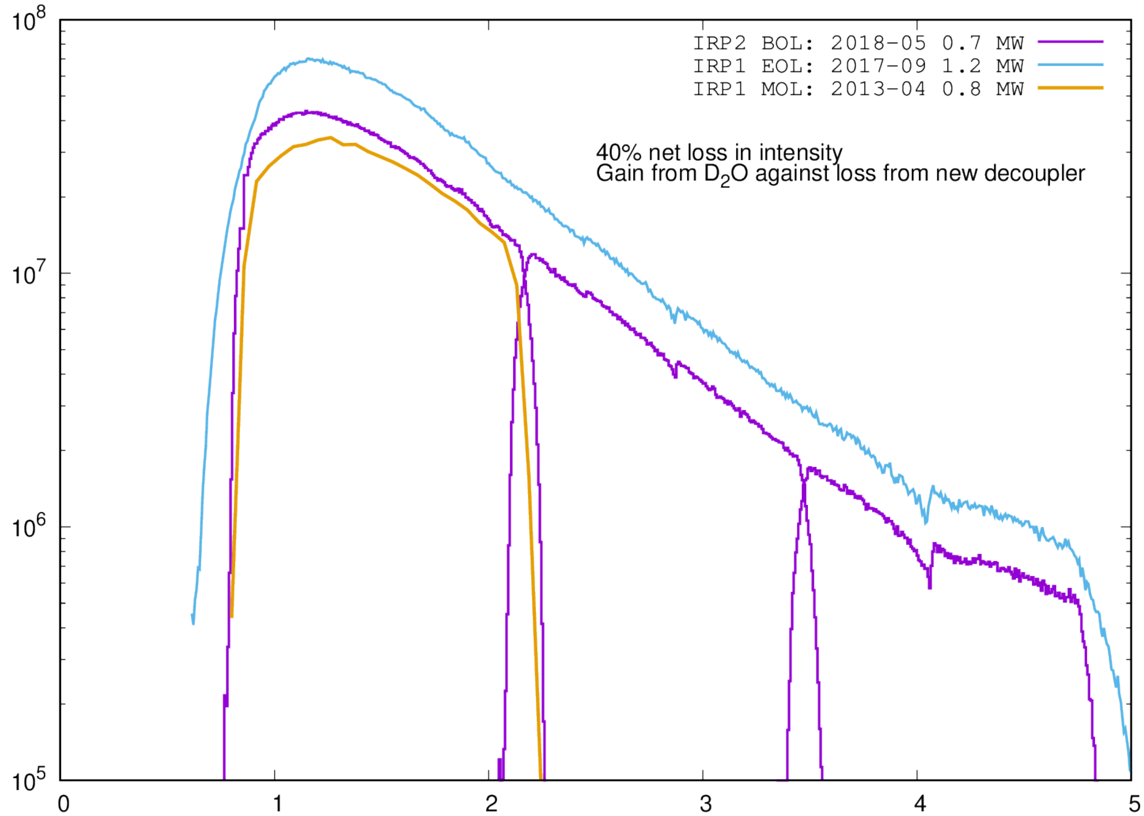

Figure 3. Spectral changes at beamline 7 (VULCAN) between IRP-1 at middle-of-life and end-of-life and IRP-2 at beginning-of-life. Note the significant increase in apparent intensity from IRP-2 at the end of life, where the decoupler and poison are nearly depleted. The change to heavy water reflector cooling partially offsets the penalties associated with the fresh decoupler and poison layers in IRP-2.

measurement, are consistent with simulation predictions. There are additionally significant changes in spectral intensity scale (but not shape) as a function of burnup. The apparent intensity at 3 Åincreases by around 60% between the MOL–IRP-1 and the EOL–IRP-1 measurement. The replacement of the reflector coolant (light water in IRP-1 and heavy water in IRP-2) is expected to increase the intensity by around 20–25%, partially offsetting the loss associated with a fresh decoupler and poison (note that the BOL–IRP-2 measurement is somewhat higher than the MOL–IRP-1 measurment).

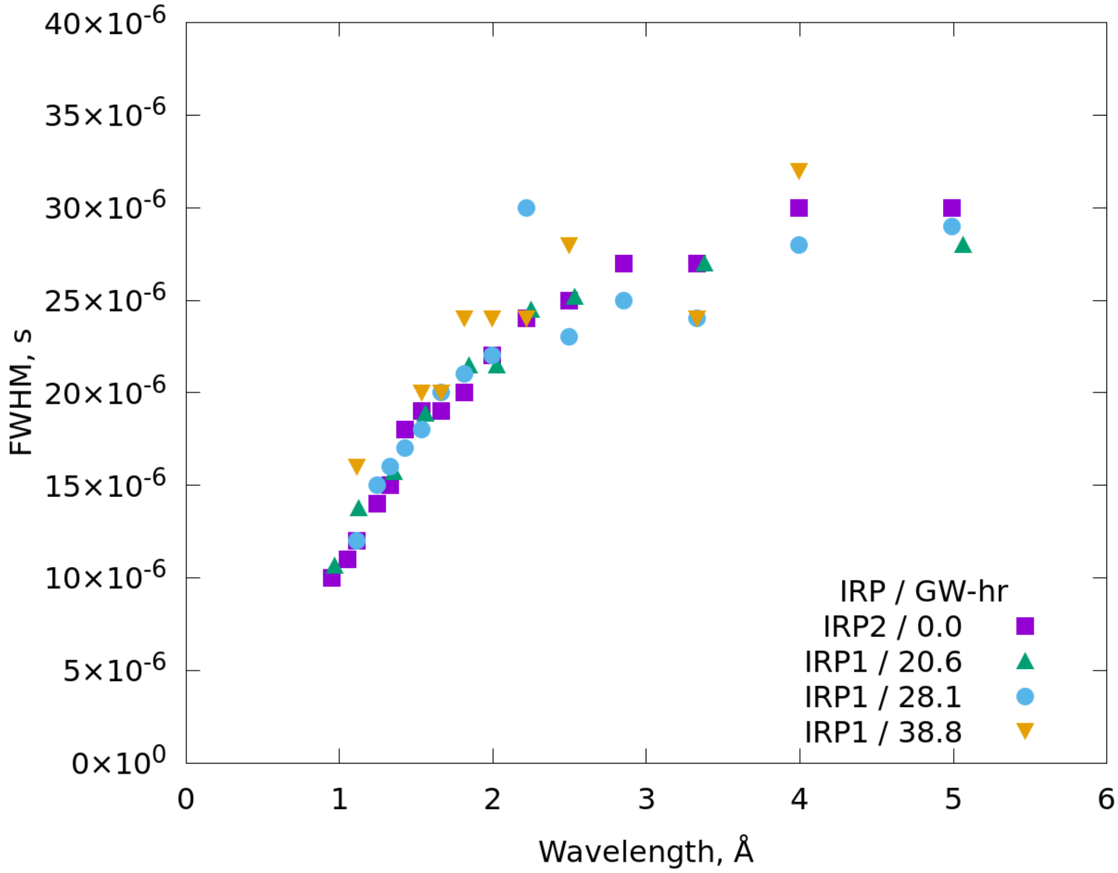

Figure 4. Pulse widths (FWHM) measured at beamline 7 at IRP-2 Beginning of Life and at various stages of IRP-1 operation. The pulse widths over that time-frame did not change significantly until the final measurement, which took place at approximately 39 GW-hr, and then increased by 10-25% suggesting burnout issues arising between 30 and 40 GW-hr.

Other observations involving the water moderator also indicate significant burnout near the end of life of IRP-1. Figure 5 shows vanadium calibration measurements taken on SEQUOIA, a direct geometry inelastic neutron spectrometer viewing the water moderator via beamline 17. While the overall pulse width at an incident neutron energy of 55 meV did not change significantly between the two measurements taken using EOL–IRP-1 (in 2017) and BOL–IRP-2 (in 2018) the appearance of long-lived low-intensity "tails" on the incident beam pulse shape results in significant degradation of the instrument performance. The inelastic feature around -20 meV is significantly obscured by this degradation.

Given the totality of the observations on the water moderator, we can conclude that the decoupler on the water moderator did indeed suffer burnout.

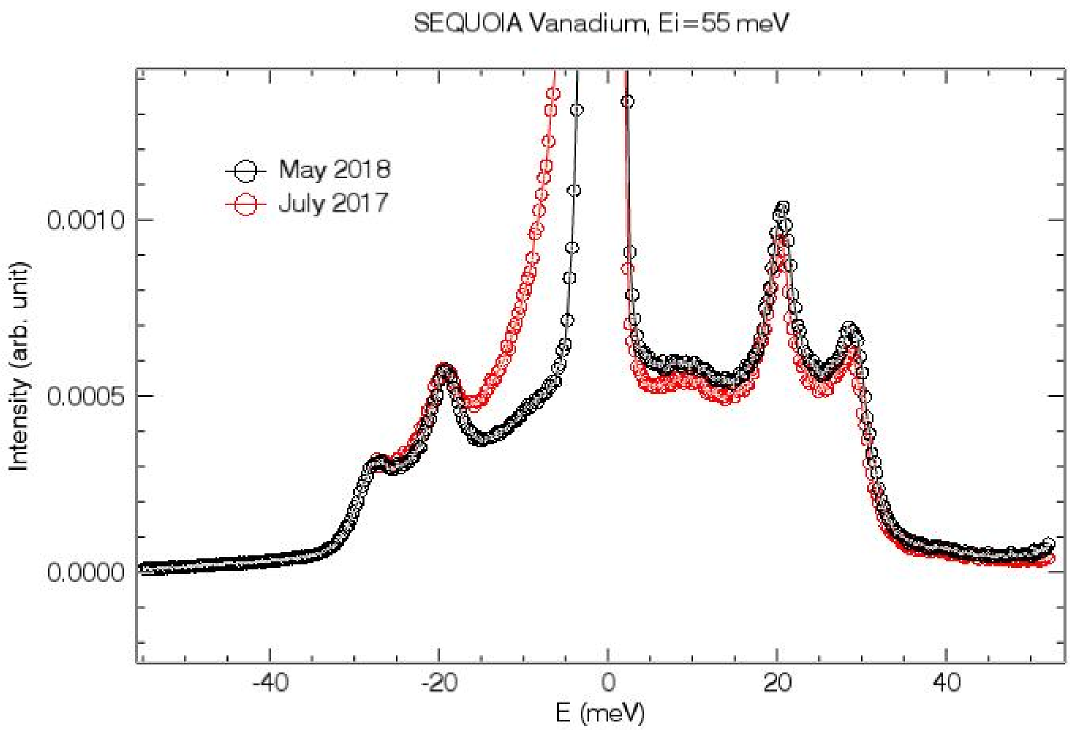

Figure 5. Vanadium calibration measurements on the SEQUOIA instrument taken using EOL–IRP-1 (2017) and BOL–IRP-2 (2018). The elastic line (around energy transfer of 0 meV) is not wider as quantified by the FWHM metric, but there is a significant "tail" arising from tails in the underlying pulse shape coming from the moderator. This tail significantly impacts the measurement of low energy transfers and degrades the overall performance of the instrument.

4. COMPARISON OF IRP-1 AND IRP-2 PERFORMANCE

Our neutronics simulations indicated that the poisons and decouplers in IRP-1 should have lasted around 33 GW-hours for the water moderator and 39 GW-hours for the decoupled hydrogen moderator before reaching burnout, where emission time distributions change dramatically, impacting instrument resolution. (Changes in overall intensity were expected to be significant, but relatively continuous, with no particular sudden change in performance. Spectral distributions were not foreseen to change dramatically below approximately 100 meV.) In practice, by some 40 GW-hours, we saw that the decoupled hydrogen moderator performance as characterized by pulse width changed dramatically, impacting the resolution of instruments viewing that moderator, while the water moderator performance as characterized by long-lived pulse shape tails, impacting the resolution of instruments viewing that moderator in a different, but no less significant fashion. Both moderators showed changed intensity as well. Altogether these observations suggest that both decoupled moderators experienced burnout. This change in performance over lifetime was anticipated.

From an instrument performance perspective, however, the replacement of IRP-1 with IRP-2 appears to have “restored” the initial instrument performance in terms of beamline resolution (that is, pulse widths and pulse shape tails, etc.) while not having a particularly severe impact on the beamline intensities due to the restoration of poison layer thicknesses. That is:

- IRP-2 installation restored pulse widths and pulse shape tails to match that of the initial IRP-1 characteristics, and
- IRP-2 installation maintained intensities at EOL–IRP-1 levels for the decoupled hydrogen moderator, avoiding dramatic sudden intensity loss, by offsetting the intensity penalties associated with fresh poisons by benefits arising from the use of heavy water coolant in IRP-2. The intensity loss on the decoupled water moderator upon IRP replacement, arising from fresh decoupler / poisons, was only partially offset by the replacement of the reflector coolant (heavy water for light water).

From a beamline / instrument characterization perspective, these results indicate a consistent ongoing need for both beamline and instrument characterization campaigns that incorporate:

1. emission time distributions providing metrics describing pulse width (e.g., FWHM) as well as metrics describing the prominence of pulse shape tails,
2. consistently normalized spectral intensity measurements, and
3. frequently repeated measurements at different times during operation in consistent operating conditions.

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