Reactor Core Monitoring at the McMaster Nuclear reactor with Nitrogen-16 Gamma and Neutron Flux Measurement

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Abstract

Three power measurement systems at the McMaster Nuclear Reactor are compared: i) Thermohydraulic measurement involves measuring the difference in coolant temperatures of inlet and outlet as well as the mass flow rate; ii) Neutron flux measurements outside the core, which is proportional to the core neutron flux; iii) Nitrogen-16 (N-16) gamma measurements that measure the amount of N-16 produced by from the oxygen in the coolant at the exit pipe. The amount of gamma radiation measured from the N-16 will be proportional to the power. Data from these three measurement systems were taken simultaneously at the McMaster Nuclear Reactor and analysed. Thermohydraulic power measurements are shown to be reliable for steady state operation due to their small uncertainty, but not for quick changes in power. Ex-core neutron-based power measurements are imprecise due to low neutron counts but respond to changes immediately. N-16 gamma measurements respond quickly and are precise but have other unique challenges due to the finite N-16 lifetime.

Background and Experimental Apparatus

Motivation

Neutron flux measurements of the core are proportional to the power, but they are also affected by the core composition. [1] Isolating this effect requires a different measurement of the power. More accurate and reliable measurement of the power might make measurement of the core composition through neutron flux measurements possible although this has proven difficult at the MNR in the past [1].

McMaster Nuclear Reactor (MNR)

The MNR is a 5MW open pool type reactor that uses low enriched uranium fuel and light water for cooling and moderation [2]. The MNR is a research reactor and is designed as a neutron source [2]. The MNR SDS1 emergency shutdown system includes a central control rod that is dropped into the core [3]. The SDS1 system has several automatic triggers, one of which is the power reaching 125% [3] of the maximum steady state power level.

Thermohydraulic measurement

By measuring the temperature of the coolant water, at the inlet and outlet as well as the mass flow rate, one can estimate the core power with the heat capacity equation. Where $\dot{m}$ is the mass flow rate, c_{water} is the heat capacity of water and the difference in outlet (T_{outlet})and inlet (T_{inlet}) temperatures is relatively small, the following relation can be used:

$$\boldsymbol{Q = \dot{m}c_{water}(T_{outlet} - T_{inlet})}.$$

In the MNR inlet, the temperature is measured with a total of four thermocouples, two at the inlet and two at the outlet and the flow is measured with a flow meter [1].

Neutron flux measurements

The neutron flux in the core is proportional to the power of the reactor [1]. The neutron flux outside the reactor shielding is proportional to that inside the core if the shielding remains constant. This means that the neutron flux at any point in the reactor building will be proportional to the reactor power. The neutron flux was measured with two He-3 neutron detector arrays placed at two different locations in the reactor hall, one of which is shown in figure 1.

Figure 1 He-3 neutron detector set up in MNR.

Neutrons are neutral particles which make them difficult to detect. He-3 has a relatively high neutron capture cross section [4].

$He^3 + n^1 \rightarrow H^1 + H^3 + Q$

For this reaction the energy released is Q = 764 keV [4]. This energy ionizes the helium in the detector. Ionized helium is then measured at a high voltage line and neutrons can be counted. The neutron flux is also dependent on the fissile inventory of the core [5].

N-16 gamma measurements

In the core the isotope oxygen-16 in the water undergoes a nuclear reaction when hit with fission neutrons which produces a proton and N-16 [6].

$^{16}O + n \rightarrow {}^{16}N + p$

Nitrogen-16 is a radioactive isotope with a half-life of 7.13s [7]. The decay of nitrogen-16 releases gamma rays that was measured by a NaI crystal scintillation detector at the exit pipe as shown in Figure 2. The amount of N-16 is proportional to the power of the reactor [2].

Figure 2 NaI detector shielded by lead

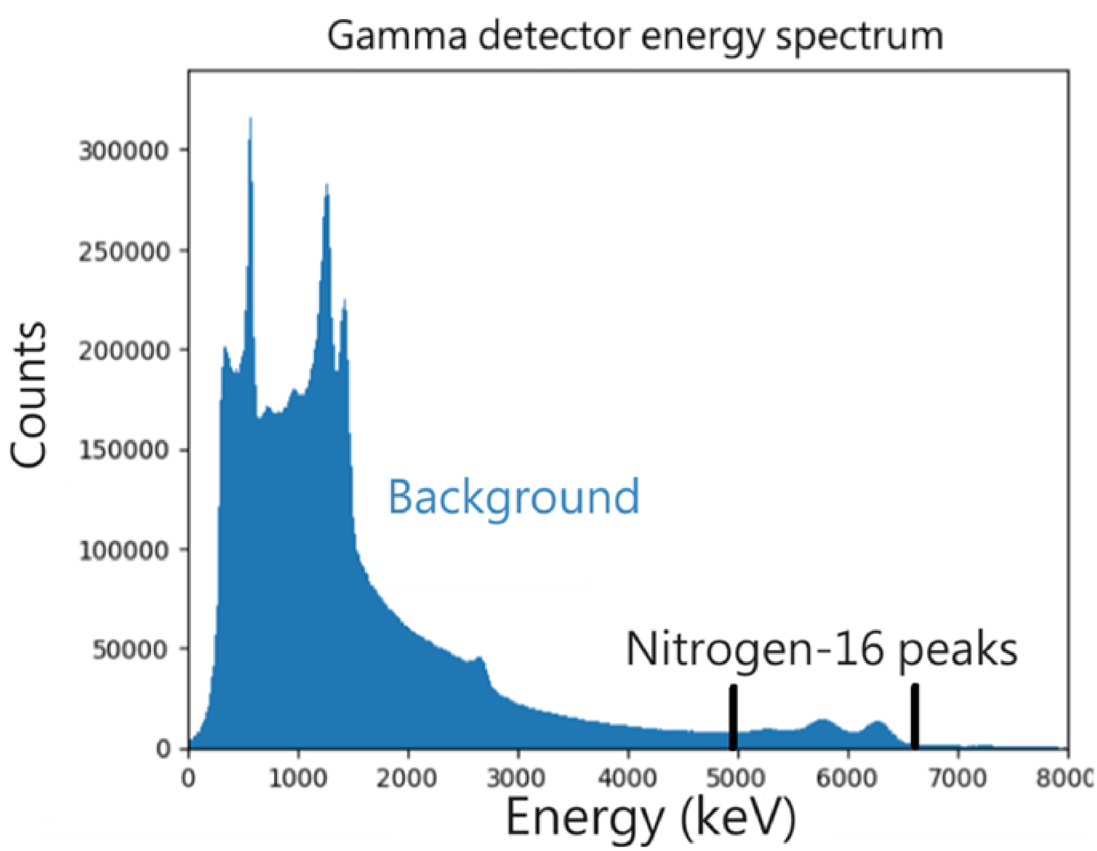


Figure 3 Example gamma spectrum

The NaI detector was shielded with lead bricks, with an open slot pointed towards the exit pipe to increase the amount of gamma rays seen by the detector from the outlet pipe relative to the background. This slot is further covered by a thin sheet of lead to reduce deadtime. Nitrogen-16 decay gammas have an energy of 6129 keV [8] which is the highest clearly visible peak in Figure 3. The next two highest peaks in Figure 3 are a result of the escape of one or both of the gammas from the annihilation of the positron pair-produced by the initial gamma.

Steady state

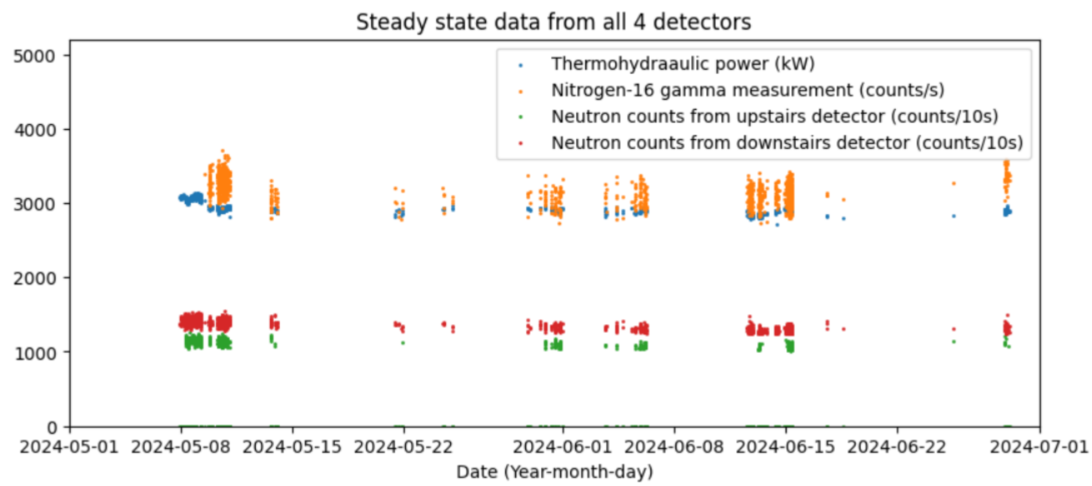


Figure 4 Steady-state data

Figure 4 shows the steady state data for 2024 May and June when there are data from all four detectors. From this data there is no significant variance in different power measurement systems while at steady state. This data can be used to find the ratios of the different measurement methods over time as well. It is found that these also remain consistent over time with no significant changes in neutron flux counts per thermohydraulic power, N-16 counts per thermohydraulic power or neutron counts per gamma count. The expected changes due to fissile inventory change with burnup are only a few percent [1], so, we would not be seen without more data and improving the precision of this work.

Reactor shutdown analysis

SDS1 tests are useful events for studying power monitoring system due to the linear power increase and sharp drop.

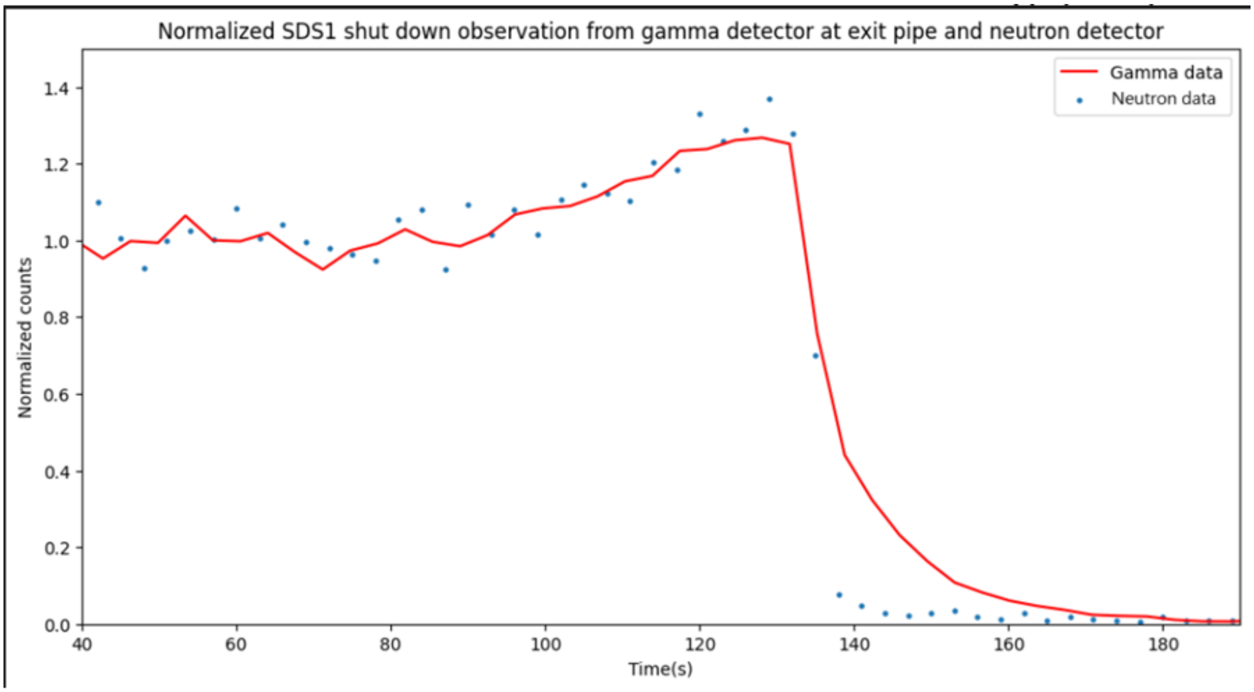


Figure 5 Normalized data for SDS1 shutdown

Figure 5 shows the data from one such event, where the reactor goes through a period of linear power increase before shutting down. The gamma data are a summation of all counts within a range of energies that contains all three N-16 peaks.

There are residual neutrons that are observed after shutdown by the neutron detectors. To account for these residual neutrons the approximate number of expected gammas per neutron at steady state is scaled to the number of residual neutrons detected and then subtracted from the gamma data. Then an exponential curve is fit to the gamma data (see Figure 6).

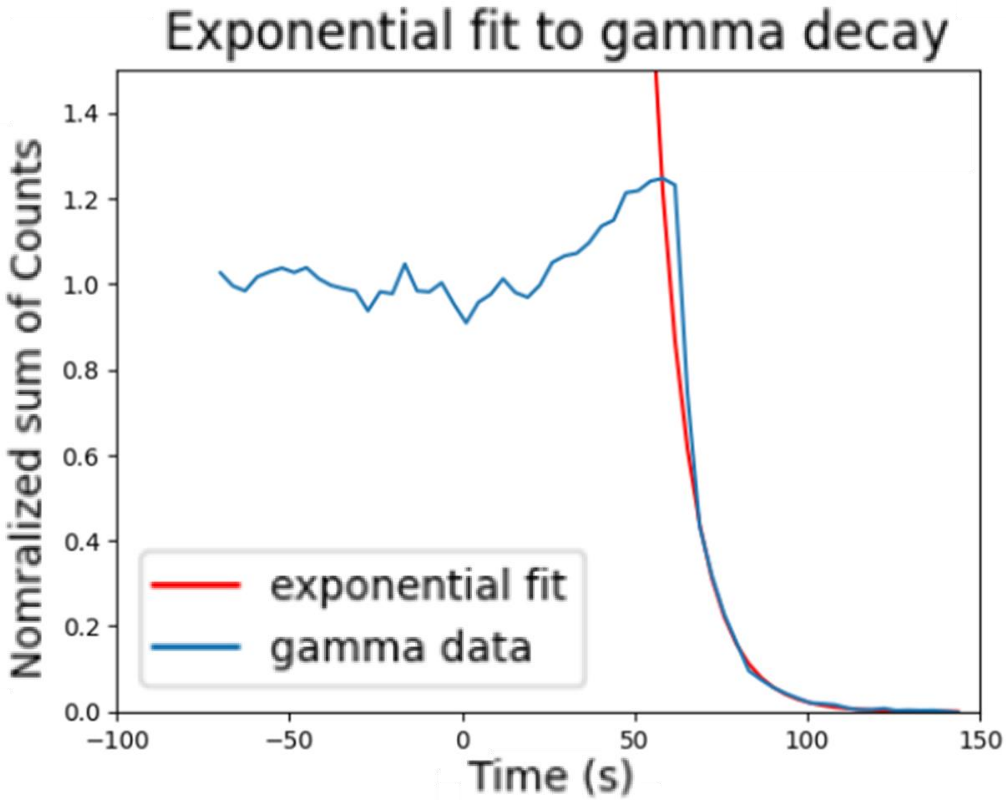
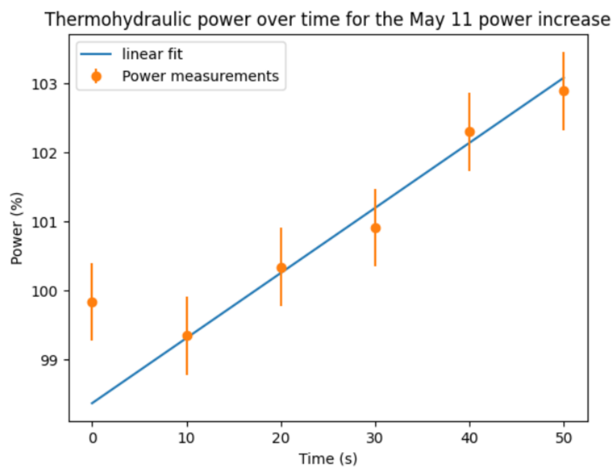


Figure 6 Exponential fit to gamma decay

After accounting for the neutrons, we find a chi squared value for the fit of 1.6 per degree of freedom (DOF) compared to 4.28 per DOF before accounting for the neutrons. The fit also has a lower RMS error of 13.5 counts/s compared to 173 counts/s before the neutrons are accounted for. We measure a half life of N-16 of 7.23 ± 0.1s. This agrees well with the published N-16 decay rate of 7.13s [7] The process of accounting for the neutrons introduces an error to the result from the error in the neutron curve fit and the error in the expected number of gammas per neutron. This same process also assumes that the expected number of gammas per neutron will be the same between steady state pre shutdown and after the shutdown. There is further an error from background that has the same energy as the nitrogen-16 peaks.

Linear increase of reactor power

Before the shutdown there is a linear increase in the reactor power up to 125% before the reactor trips.



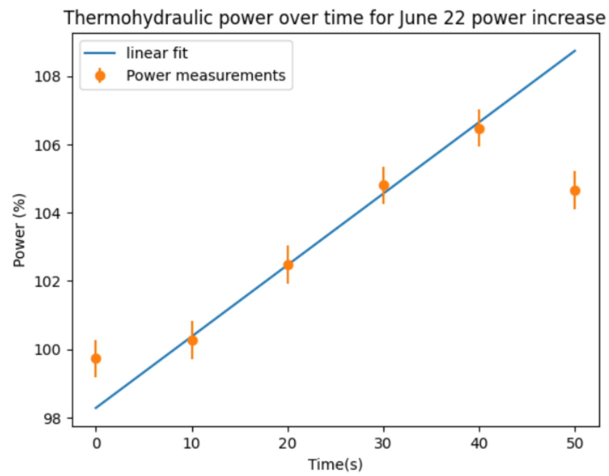
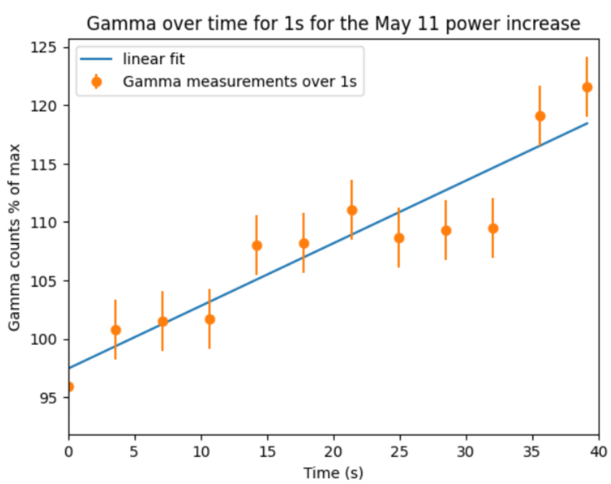


Figure 7 Thermohydraulic power increase May 11

Figure 8 Thermohydraulic power increase June 22

In the thermohydraulic measurements (Figures 7 and 8) linear fits have slopes of 6.06 ± 0.3 kW/s and 2.8 ± 0.3kW/s and chi squared values of 2.4e-06 and 4.7e-07 for May 11 and June 22, respectively. The thermohydraulic power measurement does not reach 125% as expected.

However, 125% of steady state was reached before shutdown in the N-16 data.



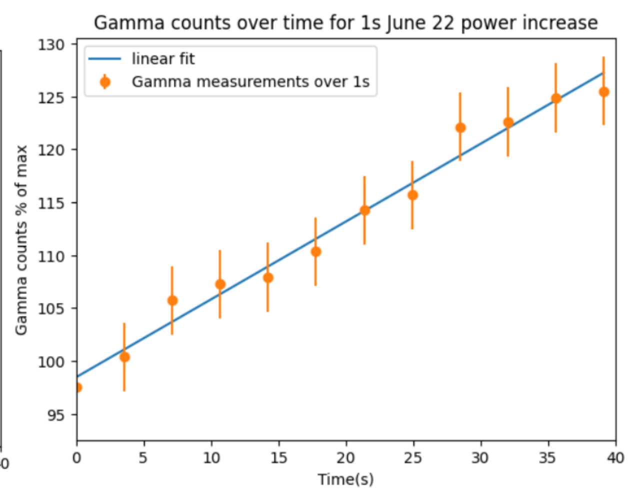


Figure 9 Nitrogen-16 power increase May 11

Figure 10 Nitrogen-16 power increase June 22

The N-16 data (Figures 9 and 10) also fits to lines with slopes 24.5 ± 1.2 counts/s^2 and 17.5 ± 2.2 counts/s^2 for May 11 and June 22 respectively. These fits also have very low chi squared values of 2.4e-7 and 2.5e-6.

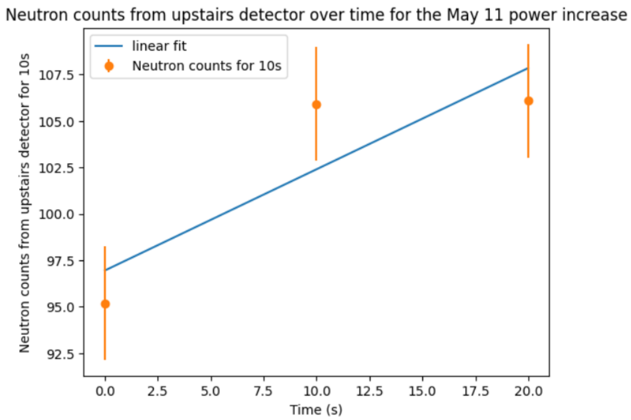


Figure 11 Neutron power increase May 11

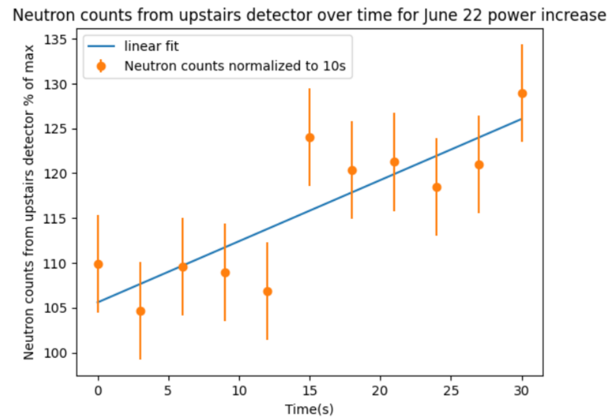


Figure 12 Neutron power increase June 22

The slopes for May 11 and June 22 in the measured neutron flux (Figures 11 and 12) are 6.25 ± 3.5 counts per 3s /s and 7.4 ± 1.6 counts per 3s /s. The chi square values for these fits also indicate a less than perfect linear fit of 1.9 and 0.6 per DOF for the two power increases.

Gamma measurements systems-based analysis

The measurement at the gamma detector will be a response to the power change in the core. The measured signal from the detector will be a convolution of the power and the transfer function associated with the detector set up. The transfer function is a deconvolution between idealized versions of the exponential decay (Figure 14) and the shutdown (Figure 13).

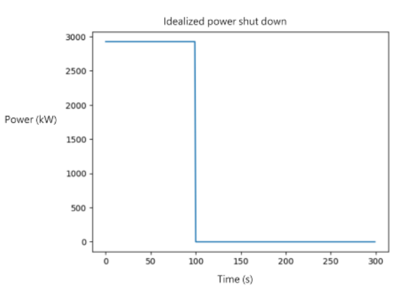


Figure 13 idealized shutdown

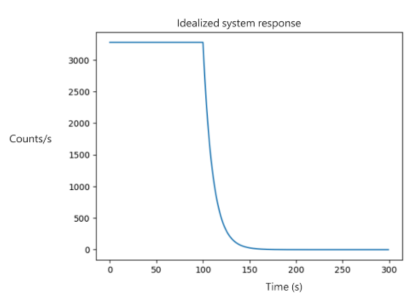


Figure 14 idealized gamma response to shutdown

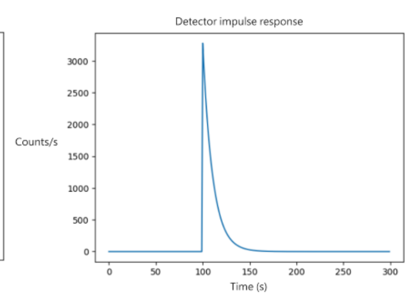


Figure 15 system impulse response

The impulse response (Figure 15) can be convoluted with the measured power from the neutron measurements as well as the power measurements and then compared to the results of our measured gamma signal. Using a ramp function with the slope and steady state value taken from our thermohydraulic measurements gives us an expected gamma measurement, see Figure 16.

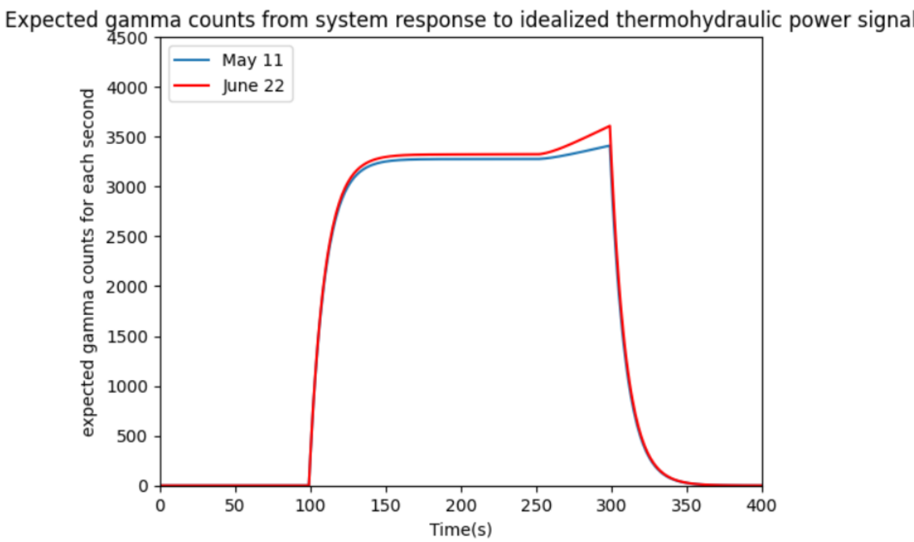


Figure 16 Expected Gamma measurements from the thermohydraulic power

The slopes for the May 11 and June 22 shutdowns are 2.92 ±0.34 counts per s/s and 6.59 ±0.31 counts per s/s. These are very far from our measured slopes in the gamma signal.

Repeating the process with the idealized neutron signal as our power increase gives us a different expected gamma measurement, in Figure 17.

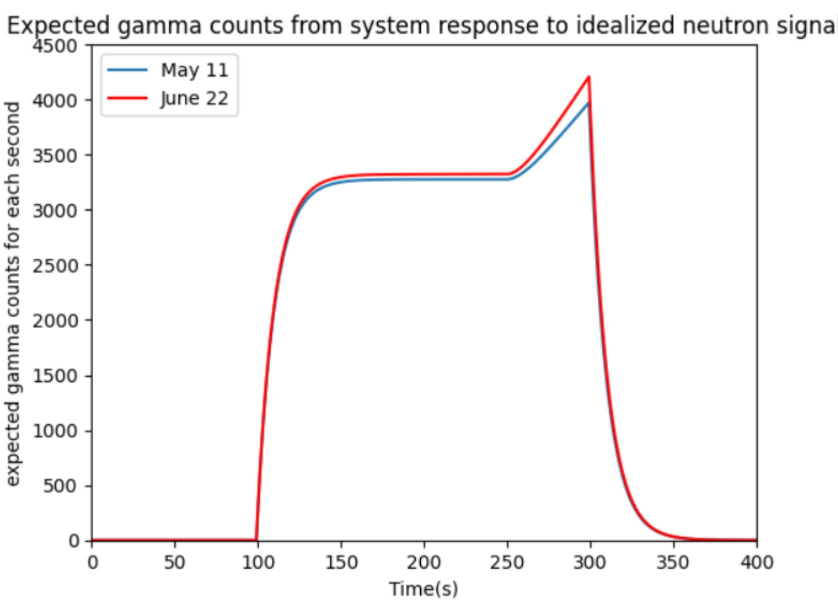


Figure 17 Expected Gamma measurement from neutron signal

The slopes for the May 11 and June 22 shutdowns are 16.84 ± 9.42 counts per s/s, and 21.4 ± 4.56 counts per s/s. These results are within the error of our measured gamma slopes, seen in the previous section. Notably the error bars on the slope are very large due to the low number of neutron measurements taken over the power increase as well as the high variance on each measurement.

Conclusions

Thermohydraulic power measurements have the lowest variance. This makes thermohydraulic measurements the most precise way of measuring steady state power. However, these thermohydraulic measurements do not reflect changes in power very accurately, due to thermal time lag. The systems-based approach shows that while the neutron measurements and gamma measurements are correlated as expected, the thermohydraulic measurements are not. This along with the fact that the thermohydraulic power does not reach 125% indicates that they do not respond accurately to changes in power. Neutron-based power measurements have the largest variance of any of the three systems used, due to relatively low neutron counting rates. Neutron flux measurements do respond in real time to changes in power; neutrons move very fast so the flux at the core is proportional to the flux at the detector at the time scale of reactor power changes. Neutron flux measurements are also influenced by other factors, the amount of shielding in the reactor building as well as the fissile composition of the core. These effects also limit the usefulness of neutron-based power measurements. The nitrogen-16 gamma-based power measurements have lower variance than the neutron counts. The nitrogen-16 signals respond well to changes in the core power. This makes nitrogen-16 a potential best of both worlds measurement system for reactor power. This measurement does have a few unique limitations; however, the exponential decay of nitrogen-16 must be accounted for in any changes of power, this can be done quite easily with deconvolutions.

Next steps

Measuring the power level of the MNR at different power levels is necessary to further validate nitrogen-16 power measurements. Comparing steady state thermohydraulic power to the neutron counts and gamma counts at different power levels would show how these power measurements reflect the power at steady state through different power levels. [9].

Sources

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