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Vacuum system upgrade for extended Q-range small-angle neutron scattering diffractometer (EQ-SANS) at SNS

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ABSTRACT

The Extended Q-range Small-angle Neutron Scattering Diffractometer (EQ-SANS) instrument at the spallation neutron source (SNS), Oak Ridge, Tennessee, incorporates a 69 m³ detector vessel with a vacuum system which required an upgrade with respect to performance, ease of operation, and maintenance. The upgrade focused on improving pumping performance as well as optimizing system design to minimize opportunity for operational error. This upgrade provided the following practical contributions:

- Reduced time required to evacuate from atmospheric pressure to 2 mTorr from 500 to 1000 min to 60–70 min
- Provided turn-key automated control with a multi-faceted interlock for personnel and machine safety.

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Original system configuration and performance

The EQ-SANS detector tank incorporates a double-walled design to facilitate the use of light concrete between the walls for fast neutron shielding as well as sintered boron carbide inside the tank for shielding of slow neutrons [5]. Initial evacuation of the tank was through a 10 m long, 160 mm diameter line by a Leybold SP250 screw pump boosted by a Pfeiffer roots-type blower with a rated

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speed of 754 cubic feet per minute (CFM). A Pfeiffer Model TMH521 turbomolecular pump with a rated pumping speed for air of 510 (l/s) backed by a Varian Tri-Scroll 300 dry scroll pump performed further evacuation. A convection-enhanced Pirani gauge on the blower inlet at the pump-end of the 160 mm diameter, 10 m long roughing line monitored pressure from atmosphere to low vacuum while a wide range cold cathode gauge attached at the pump-end of the high-vacuum line monitored the pressure once it reached high vacuum.

Since pumping on one end of a long tube results in a pressure gradient along the length of the tube [2], neither of these pressure readings accurately represented the true pressure in the tank during normal operations. In molecular flow, the pressure at distance X from the pump end of the tube is represented by

$$P_x = q\pi D \left(\frac{-X^2}{2CL} + \frac{X}{C} + \frac{L}{S} \right) \quad (1)$$

Where q is the outgassing rate per unit area, P is pressure, D is tube diameter, X is distance from pump end of tube, C is conductance, L is the length of the tube, and S is the pumping speed [2]. Values of X/L = 0.125, 0.25, 0.50, and 0.75 yield the following, respectively:

$$P_{0.125} = q\pi D \left(\frac{0.2344}{2C} + \frac{1}{S} \right) \quad (2)$$

$$P_{0.250} = q\pi D \left(\frac{0.4375}{2C} + \frac{1}{S} \right) \quad (3)$$

$$P_{0.500} = q\pi D \left(\frac{0.75}{2C} + \frac{1}{S} \right) \quad (4)$$

$$P_{0.750} = q\pi D \left(\frac{0.9375}{2C} + \frac{1}{S} \right) \quad (5)$$

Therefore, for a given pumping speed, conductance, outgassing, and tube diameter, the pressure gradient along the length of the tube is significant.

Electro-pneumatic gate valves mounted on the blower inlet and turbo pump inlet isolated the tank along with both the rough and high vacuum pumping lines. A custom software application on a Direct Logic 06 Koyo PLC with a 4-channel analog input attachment module controlled and monitored the evacuation cycle. A separate PLC controller monitored the tank pressure via two convection-enhanced Pirani gauges attached to the tank and provided a dry-contact closure interlocked to the neutron detector high voltage supply when the tank pressure was above 700 Torr or below 2 mTorr. However, this pressure monitor was not tied to the Koyo PLC controlling the vacuum system. Venting of the tank was accomplished by stopping the evacuation cycle on the PLC and manually opening a 25 mm manual angle valve.

An aluminum neutron window separates the detector tank from the sample environment and incoming neutron guide [5]. Consequently, separate vacuum systems evacuated these defined regions. A Pfeiffer Cube with a rated pumping speed of 80 l/s attached to the guide and sample environment via a manual isolation valve. This system had no pressure monitoring instrumentation other than separate pressure instrumentation included within the neutron chopper systems installed within the neutron guide.

The original detector tank vacuum system offered several opportunities for improvement. Primarily, the time required to evacuate the 69 m³ detector vessel to 2 mTorr was 500–1000 min, as shown in Fig. 1.

The water vapor load in the detector tank was such that it adversely affected the life of the dry scroll pump [4] used to back the turbo pump. Secondly, the isolation valve for the Leybold roughing package

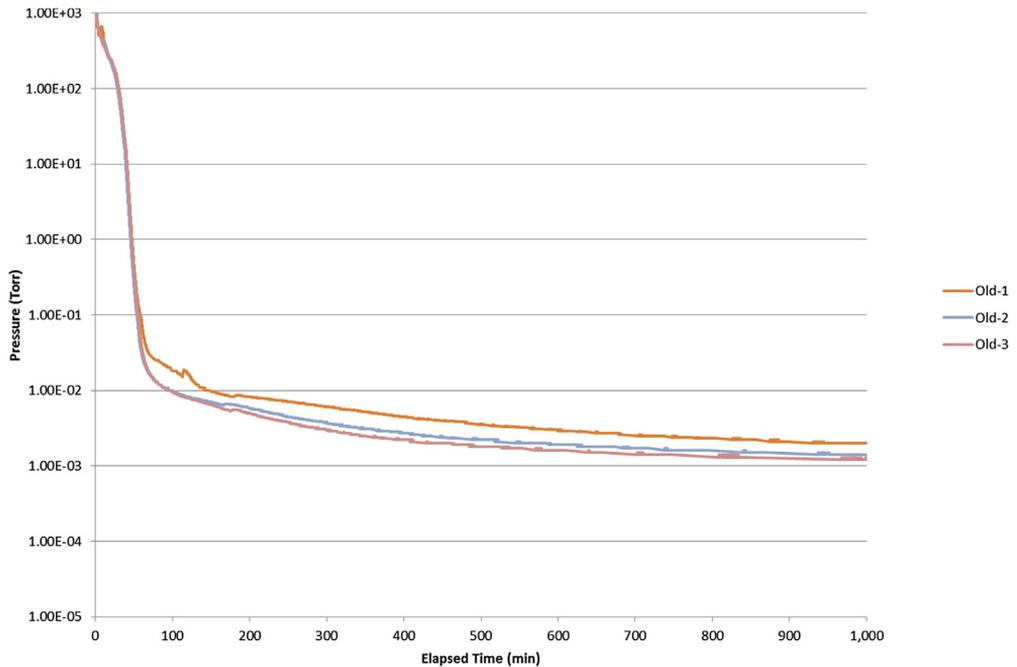


Fig. 1. Prior to vacuum system upgrade, the detector tank took 500–1000 min to reach an operating pressure of 2 mTorr.

was located directly on the blower inlet port that allowed the entire roughing line, which is 10 m long and includes eight LF160 O-rings, to be common to the tank during run-time operations, thereby unnecessarily increasing the total gas load during operations. High voltage for the neutron detectors in the tank was interlocked to two convection-enhanced Pirani gauges, with setpoints at 700 Torr and 2 mTorr, even though 2 mTorr is very close to the low end of a Pirani gauge’s useful range. Thirdly, venting of the detector tank was a manual process that had no integral machine safety interlocks.

Fig. 2 depicts a graphical representation of the original vacuum system for EQ-SANS. The vacuum system for the sample tank and upstream neutron guide, which is shown on the right-hand side of the figure, also offered opportunity for improvement. The upstream guide section was isolated from the sample environment via a manual gate valve. Once this valve closed, the sample environment was completely isolated from all vacuum pumps and pressure instrumentation. The only means available to re-evacuate the sample tank was manually reopening this gate valve, sending the resulting “slug” of air into the upstream guide. Careful attention was necessary not to damage other pressure-sensitive components in this guide as well as the small turbo pump used for evacuation. In addition, the manual gate valve in question was in an access-controlled radiological buffer area and had no position indication so that beamline operators/staff could determine the state of the valve remotely. Of equal importance, the original vacuum pumps and instrumentation in use were unique, not used anywhere else on the SNS site. Recently, vast upgrading has occurred to “standardize” all vacuum hardware thus minimizing the spare parts inventories in response to uptime requirements as well as budget constraints.

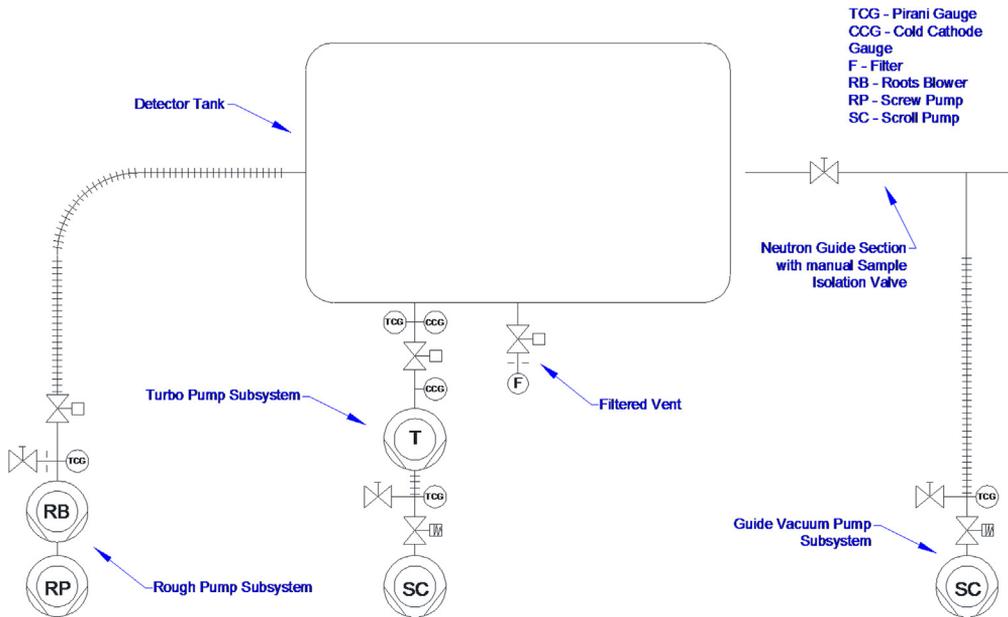


Fig. 2. Schematic of original vacuum system for EQ-SANS, showing roughing system on the left, turbomolecular system in the center, and the separate neutron guide pumping system on the right.

Criteria for upgrade

In order to result in a successful project, the team factored several criteria in determining the goals and scope of the upgrade.

Improve vacuum performance

The length of time required to achieve an operational pressure of 2 mTorr was unacceptable from a performance as well as a maintenance standpoint. Because the detector tank had to be vented in order to access the neutron detectors and subsequently re-evacuated, normal detector maintenance took upwards of 2–3 days. Furthermore, the base pressure for the detector tank, as measured by the Pirani gauges, was in such close proximity to the lower operational setpoint of 2 mTorr that minor aberrations in system performance easily resulted in crossing the setpoint and shutting down the neutron detectors. Therefore, the upgrade required a lower base pressure for the detector tank and improved pressure instrumentation for the neutron detector interlock that would reliably monitor the pressure in the tank.

Standardization of equipment

Reflecting the need of a working and reliable vacuum system as well as the budget constraints, several improvements made at SNS in recent years have “standardize” vacuum hardware thus minimizing spare parts. The benefits include improved response time for the vacuum system maintenance by having on-the-shelf replacement parts with which the technician staff is knowledgeable and familiar. Therefore, the upgrade must utilize vacuum components that are common to other vacuum systems at SNS.

Automation

Opportunity for improvement existed in the original vacuum systems with respect to automation. While the detector tank vacuum system had a simple PLC control scheme, manual intervention to complete an evacuation cycle was required and the high voltage interlock for the neutron detectors was not integrated. While the initial evacuation of the detector tank was relatively automated, venting the detector tank was completely a manual process. Therefore, the upgrade must incorporate automated, “single-click” evacuation and vent cycles. The interlock for neutron detectors high voltage must require enhancements to incorporate checks for nominal pump performance in addition to the previous pressure setpoint. Furthermore, the new control system must include a maintenance function with automatic flags for preventative maintenance including a password-protected manual/troubleshooting mode.

Description of new hardware utilized in upgrade

Fig. 3 depicts a graphical representation of the new vacuum system for EQ-SANS, including that for the upstream guide and sample environment. The extent of the upgrade is multi-faceted, incorporating improvements in performance as well as ease-of-use.

Rough vacuum system

The original Leybold SP250 screw/Pfeiffer roots-type blower (754 CFM) package was replaced with an SP250/WSU1001 (589 CFM) package that is configured identically to SP250/WSU1001 packages used at several other beamlines at SNS. While this new configuration results in less nominal pumping speed at the pump, the original roughing system configuration was conductance-limited at low pressure so no net negative effect in delivered pumping speed resulted (Fig. 4). The roughing pump change does allow EQ-SANS to be serviced by a “drop-in spare” roughing package kept on site to service other beamlines in the event of a pump failure.

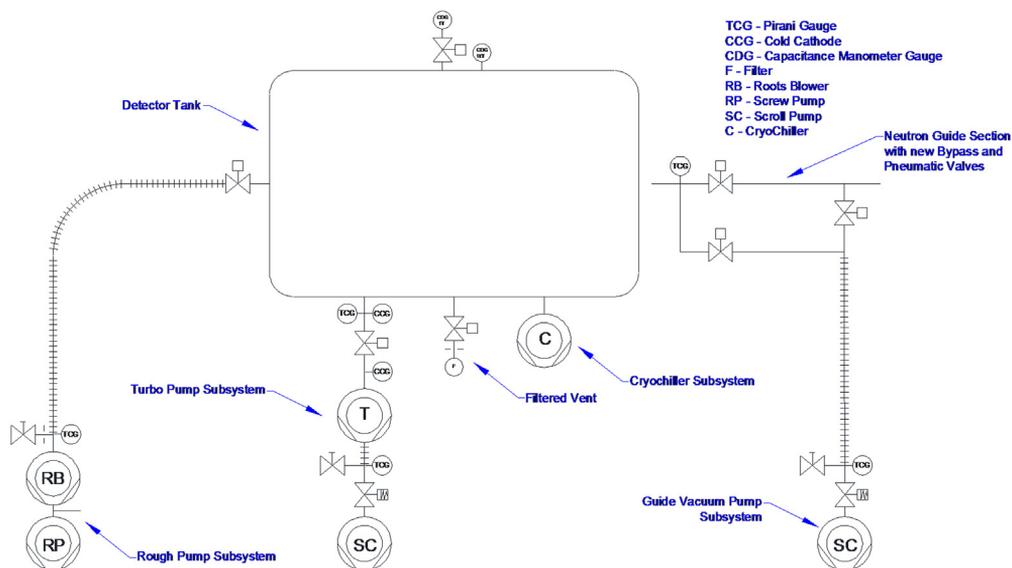


Fig. 3. Schematic of upgraded vacuum system for EQ-SANS instrument, showing roughing system on left, turbomolecular and cryo pumping systems in center, and the separate neutron guide pumping system on the far right. At the top, the 1 Torr and 1000 Torr capacitance manometers are shown.

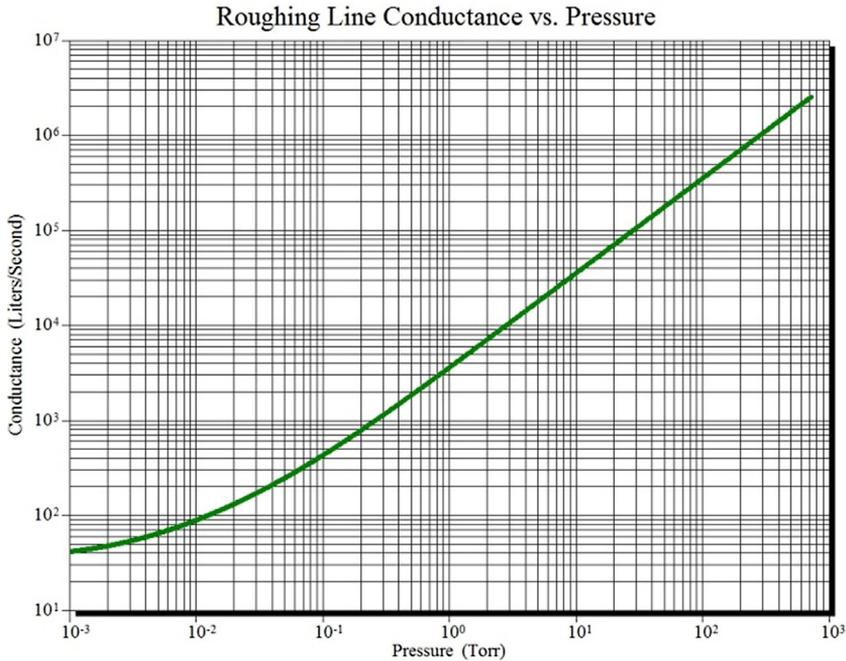


Fig. 4. Plotting conductance of the EQ-SANS roughing line as a function of pressure shows that the roughing system with a 278 l/s (589CFM) pumping package does not become conductance limited until a pressure of approximately 0.060Torr is reached. For the EQ-SANS application, turbomolecular and cryo pumping are initiated prior to reaching this pressure.

Moving the isolation valve from the blower inlet and mounting directly on the tank eliminated the 10 m long roughing line, its associated O-rings, and their gas-load from being common with the tank during normal operation. Convection-enhanced Piranni gauges added to the blower inlet and outlet monitor blower performance.

High vacuum system

The original Pfeiffer TMH521 (510 l/s) turbomolecular pump was replaced with a new Pfeiffer HiPace 700 (685 l/s), which is used on several other beamlines at SNS and of which SNS has spares on the shelf. Analysis of the line connecting the turbo pump to the tank (Fig. 5) indicated that the additional pumping speed was not limited by line conductance until the pressure drops below 0.006 Torr. Since the line conductance stays at 600 l/s or above throughout the operational pressure range for the tank, the larger (685 l/s) pump does provide better performance than did the original pump (510 l/s).

New gauge spools before and after the turbo isolation gate valve (on the detector tank) eliminated several O-rings and their respective gas loads as well as allowed for installation of “standard” cold cathode and Convection-enhanced Piranni gauges on CF-style flanges. Again, the use of “standard” instrumentation serve to minimize downtime in the event of equipment failure.

The keystone to this vacuum upgrade was the addition of a cryo-cooler with a copper evaporator coil mounted inside the detector tank. In regards to the shape and location of the coil in the tank, close attention was paid to neither hinder operations nor complicate maintenance of the detectors inside the tank while maintaining enough coil surface area to utilize the full 200,000 l/s pumping capacity of the cryo-cooler for water vapor. This was accomplished by using a curved coil, which was mounted at the back of the tank, beyond the farthest most travel of the detector carriage. Using a high-speed, high-capacity cryo-coil to trap water vapor greatly reduced the water vapor load on the turbo pump and, more importantly, its dry scroll foreline pump. As the cryo-cooler is a high-cost, long-lead component that is used in multiple beamlines, SNS has an on-the-shelf spare.

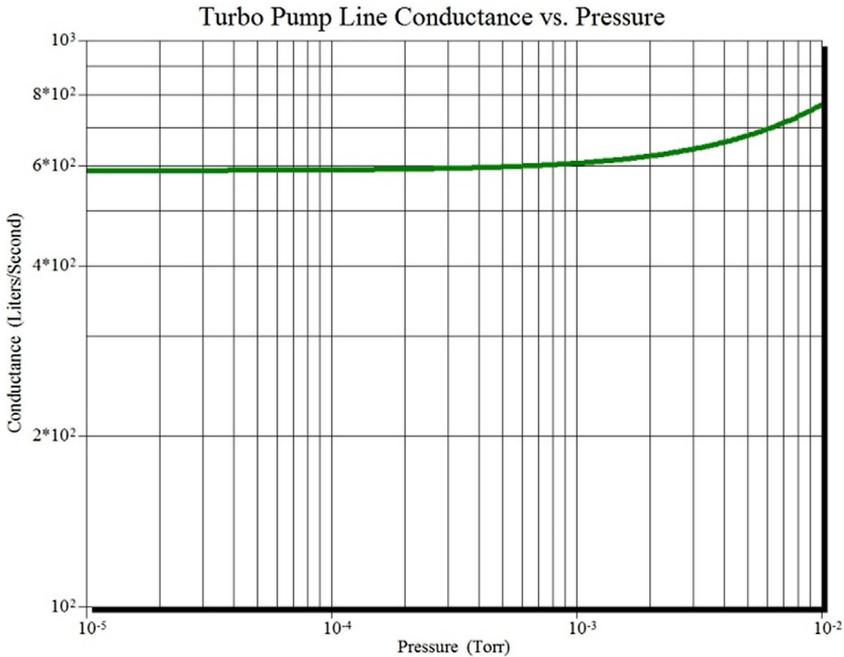


Fig. 5. Plotting conductance of the EQ-SANS high vacuum line as a function of pressure shows that the turbomolecular pumping system with a 685 l/s pumping package is not conductance limited above 0.006 Torr.

Instrumentation

Where appropriate throughout the vacuum system, utilization of “standard” cold cathode and Convection-enhanced Pirani gauges with their “standard” rack-mount controllers occurred. However, a pair of capacitance diaphragm gauges (CDG) was used for pressure monitoring during initial evacuation as well as in the interlock for neutron detectors. CDG’s offer higher accuracy than their Pirani counterparts as well as gas-independent measurement [1]. The series of CDG’s selected give 4 decades of usable measurement, so a 1000 Torr (full scale) CDG monitors pressures down to 0.1 Torr and a 1 Torr CDG monitors pressures down to 1E-4 Torr. In order to protect the 1 Torr CDG from potential zero-shift due to diaphragm deformation [3], an electro-pneumatic valve isolates the CDG when the tank pressure approaches 1 Torr.

Upstream guide and sample environment

The original configuration for the upstream guide vacuum utilized a small (80l/s) Pfeiffer turbo pump albeit through a low-conductance connection. A dry scroll pump replaces the turbo pump and modifying the line connecting the pump to the guide increases the conductance. To eliminate the issues surrounding the manual isolation valve between the sample environment and the guide, a pneumatic valve with an auxiliary port replaces the manual valve. The auxiliary port on the new valve connects to a “bypass” line that incorporates a Pirani gauge and connects to the scroll pump via a pneumatic isolation valve. The addition of a pneumatic valve to the line coming from the upstream guide to the pump (Fig. 3) protects the guide and neutron choppers from the “slug” of air when the sample environment is evacuated. Because of these changes, monitoring and controlling the valve status as well as pressures in the upstream guide are completed via the same PLC as the

detector tank vacuum system uses. Furthermore, the pneumatic gate valve on the sample environment is tied to the neutron detector interlock preventing the beamline from accepting neutrons with the valve closed, eliminating the possibility of striking the valve gate with neutron beam.

Controls

The new control scheme for the EQ-SANS vacuum system consists of one vacuum rack to service the sample environment, upstream guide, and the detector tank. The vacuum rack uses an Allen-Bradley CompactLogix PLC with a touch PanelView for the operator interface. The PLC provides interlocks and control for all pumps and valves. The PLC uses Ethernet/IP to communicate to the PanelView and upgradeable for connection to the network to obtain access to the PLC tags in the future. All vacuum controllers (gauge and pump) are hardwired to the PLC I/O and are controlled through the touch panel.

The software on the PLC controls the automated evacuation and vent cycles as well as interlocks to the separate neutron detector high voltage and cooling systems. The software also has a maintenance log for the various pumps, a manual/troubleshooting mode, and an automated “regeneration cycle” for the cryo-cooler, all of which is password-protected for maintenance personnel use only.

Performance summary

Figs. 6 and 7 show data representing the performance gain for the EQ-SANS vacuum system. The pressure setpoint for neutron detector operation is 2 mTorr, so the time required to get to that pressure is used as the basis for comparison.

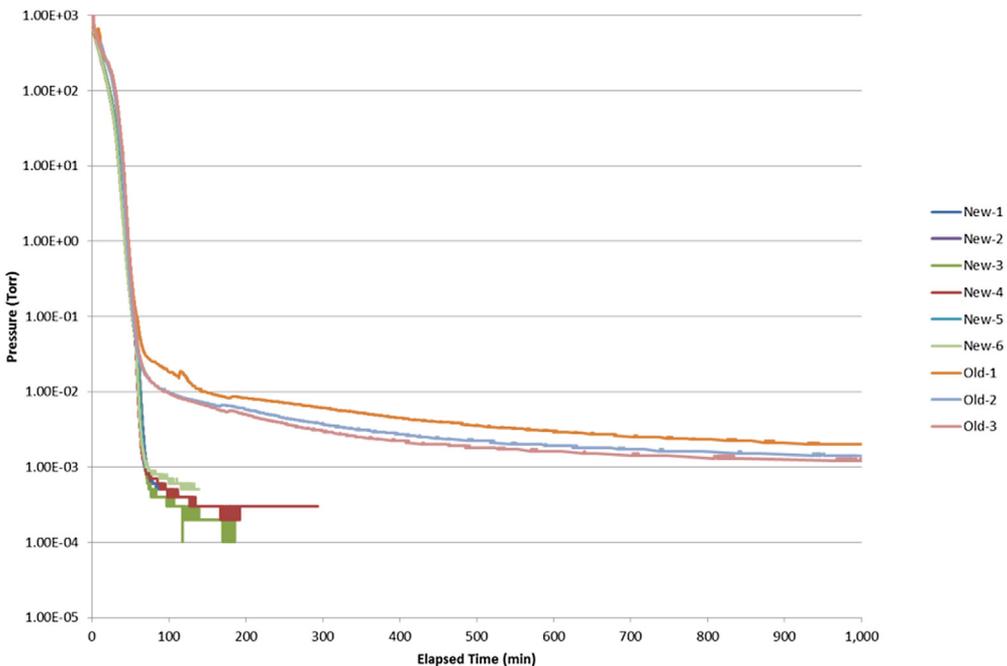


Fig. 6. The result of the vacuum system upgrade is a drastic reduction in the time needed to reach an operational pressure of 0.002 Torr in the detector tank.

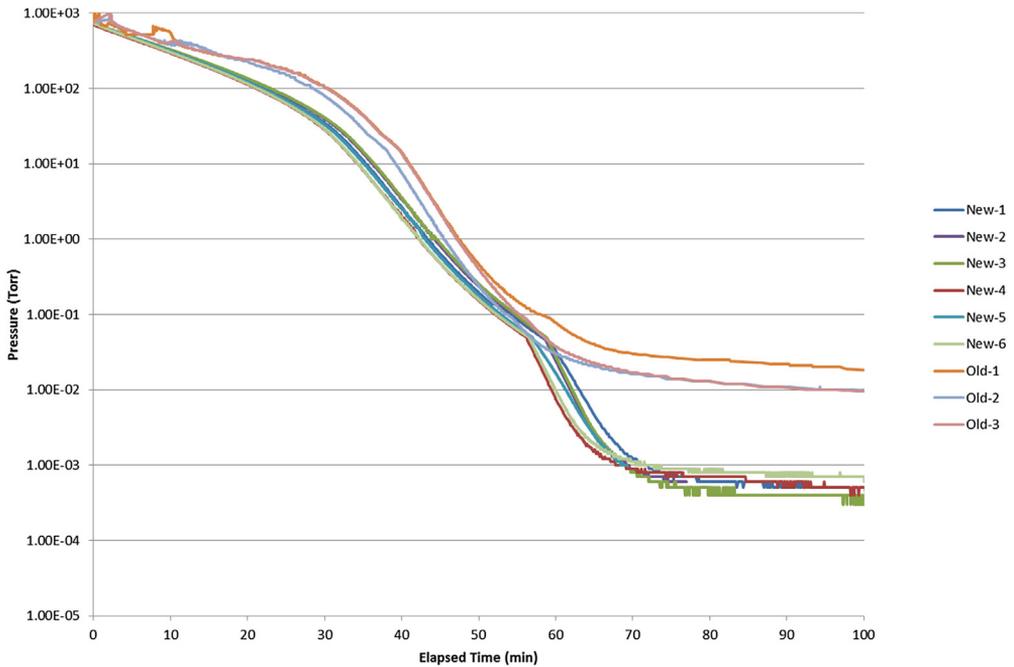


Fig. 7. The result of the vacuum system upgrade is a drastic reduction in the time needed to reach an operational pressure of 2 mTorr in the detector tank. This close-up of the first 100 min of evacuation shows that before the upgrade, the tank pressure was still in the 0.1–1.01 Torr range, while after the upgrade the tank has already surpassed the operational pressure setpoint of 0.002 Torr.

Shown are the archival data from the last three evacuations of the detector tank prior to the upgrade as well as the first six evacuations of the tank with the upgraded equipment installed. Of note, for the new evacuation sequence, the cryo-cooler is enabled at a tank pressure of 0.2 Torr and the turbo pump is enabled (isolation valve opened to tank) at 0.050 Torr in the data shown.

Conclusions

With the original vacuum system, evacuating the detector tank from atmospheric pressure to 0.002 Torr took 500–1000 min. The new vacuum system accomplishes evacuating the detector tank in 60–70 min. The benefits to this improvement are numerous and should prove useful to fellow scientists at other SANS facilities by offering a guideline on how to improve the vacuum performance and serviceability of their respective instruments.

- Detector maintenance inside the tank, which requires venting the tank to allow personnel access then re-evacuating afterwards, can now be accomplished one standard 8 h shift as opposed to several days. Since this occurs on average 4 times per calendar year, this results in 8–12 additional days of uptime per year.
- The automation of the evacuation and vent cycles reduces the opportunity for human error.
- The use of “standard” pumps and gauges facilitates prompt service when a component fails with drop-in replacement components already in-house and on the shelf.
- Specifically designing the hardware and controls to be similar in operation to those used on other beamlines makes maintenance a smoother task.

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