An Assessment of the Implications of 10CFR851 on Vacuum Systems at the National Synchrotron Light Source

MICHAEL ESPINOZA (Stony Brook University, Stony Brook, NY 11794)
EDWIN HAAS (Brookhaven National Laboratory, Upton, NY 11973)

Abstract

As of February 9, 2007, the U.S. Department of Energy required that its' facilities comply with Section 10 of the Code of Federal Regulations, part 851 (10CFR851). This code requires vacuum vessels to be considered pressure vessels due to their potential for backfill pressurization and it specifies clearly that vacuum systems must comply with applicable American Society of Mechanical Engineers (ASME) B31 series and Boiler and Pressure Vessel (B&PV) codes. The B&PV codes were not formerly used for vacuum systems.

Historically, vacuum systems at the NSLS have been assembled from standard vacuum components. Vacuum vessels already in use at NSLS were often connected to pressurized fluid sources, and although pressure relief was used, the pressure relieving devices were usually not National Board (of Boiler and Pressure Vessel Inspectors) certified (as required by ASME code), or non-UHV compatible. If internal pressure sources are used and specific exemptions cannot be claimed, ASME Section VIII code requires the vacuum vessels be built as pressure vessels by certified manufacturers only. According to Section VIII code, each pressure vessel must be registered and 'U' stamped after inspection and testing. NSLS vacuum vessels are not U-stamped and this cannot easily be done retroactively. This caused much concern at the National Synchrotron Light Source (NSLS): few (if any) vacuum vessels could comply with Section VIII of the B&PV code and thus 10CFR851.

The response at NSLS was first to study these ASME codes, make use of any exemptions stated within them, then inspect existing vacuum systems. All NSLS beamlines were included in this study. Of biggest concern were vacuum vessels with an internal diameter or diagonal dimension greater than six inches with sources of pressure such as water or pressurized gas. These systems were inspected for code-compliant pressure-relieving devices. If needed, ASME-compliant safety devices were sized, specified, and located using an Excel spreadsheet that calculated the pressure relief requirements and output graphs of flow rate and pressure versus time. This effort assures that NSLS is compliant with 10CFR851 and its' vacuum systems are safe.

Introduction

The U.S. Department of Energy(DOE) required its' facilities to be compliant with Section 10 of the Code of Federal Regulations, part 851 (10CFR851) as of February 9, 2007. 10CFR851 codifies DOE's worker protection program requirements established within DOE Order 440.1 which seeks to reduce or prevent accidents, injuries, illnesses, and accidental losses by providing employees and contractors with a safe and healthful workplace. 10CFR851 specifically addresses construction safety, fire protection, explosives safety, pressure safety, firearms safety, industrial hygiene, biological safety, occupational medicine, motor vehicle safety, and electrical safety (nano-technology safety and workplace violence protection shall be included at a later date).

The U.S. DOE defines pressure systems in the following terms: “Pressure systems are comprised of all pressure vessels and pressure sources including cryogenics, pneumatic, hydraulic, and vacuum. Vacuum systems should be considered pressure systems due to their potential for catastrophic failure due to backfill pressurization. Associated hardware (e.g. gauges and regulators), fittings, piping, pumps, and pressure relief devices are also integral parts of the pressure system.” 10CFR851 requires that all “pressure vessels, boilers, air receivers, piping and supporting systems conform to the applicable American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PC) code sections I through XII including applicable code cases.” Also stated within 10CFR851 is compliance with the strictest of state and local codes. The consequence of treating vacuum vessels as pressure vessels is that they must potentially comply with the ASME B&PV Section VIII code, which formerly was not used for vacuum systems, unless a specific code exclusion clearly applies. One exclusion specified within Section VIII are systems with maximum differential pressures less than 15 psi (including in failure modes). 10CFR851 specifies “when national consensus codes are not applicable (because of pressure range, vessel geometry, use of special materials, etc.) contractors must implement measures to provide equivalent protection and ensure a level of safety greater than or equal to the level of protection afforded by the ASME or applicable state or local code.” 10CFR851 further specifies measures to be taken if ASME Code is not applicable (i.e., design by a PE, qualified personnel used to perform examinations and inspections, documentation and accountability for each pressure vessel).

NSLS vacuum systems are generally assembled from standard components and include diagnostics, controls, and regulating components (e.g. vacuum valves). Beamlines at NSLS often include large vacuum vessels for mirrors, monochromators, and end stations which may utilize water (often with unlimited make-up capacity) or cryogenic cooling for internal components. Pressurized gas sources within these vacuum vessels are common. A sample monochromator is shown in figure 1. When fluid lines enter a vacuum chamber, the potential for internal pressurization exists, especially when the cooling system has sufficient capacity for internal pressure to rise above atmospheric pressure. This invokes 10CFR851.

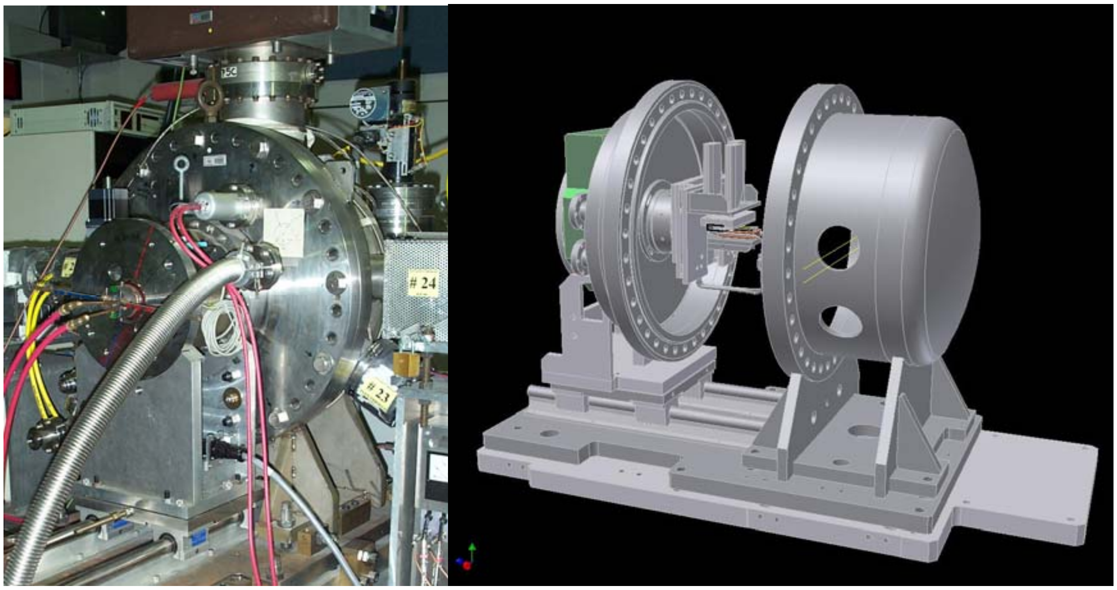


Figure 1: X22C Monochromator (a) actual installation, (b) 3D computer model

Beamlines have many such sources of pressurized fluid. Shutters, collimators, apertures, masks, and slits may transmit pressurized fluid through vacuum chambers.

Figure 2 shows a sample water-cooled aperture.

Figure 2: Water Cooled Aperture

Vacuum/Pressure boundaries and barriers

The NSLS Vacuum Group also uses bleed-up systems that have 1-2 psig pressure relief capability to prevent internal pressurization. Wherever the possibility for internal pressurization exists, either the entire system must be designed for the maximum pressure that could be encountered, or National Board certified pressure relief must be provided.

Although vacuum valves are not water-cooled, some Granville-Phillips valves use sealed, concentric, axial bellows chambers that when pressurized, apply sufficient force to seal the vacuum valve. These valves are designed with integral pressure relief, but their integral 'burst disks' are not National Board certified as is required by ASME code. Since they are no longer manufactured, they are slowly being phased out at NSLS and replaced by VAT all-metal seal valves. The Vat valves do not use gas pressure for sealing. Figure 3 shows these two types of valves.

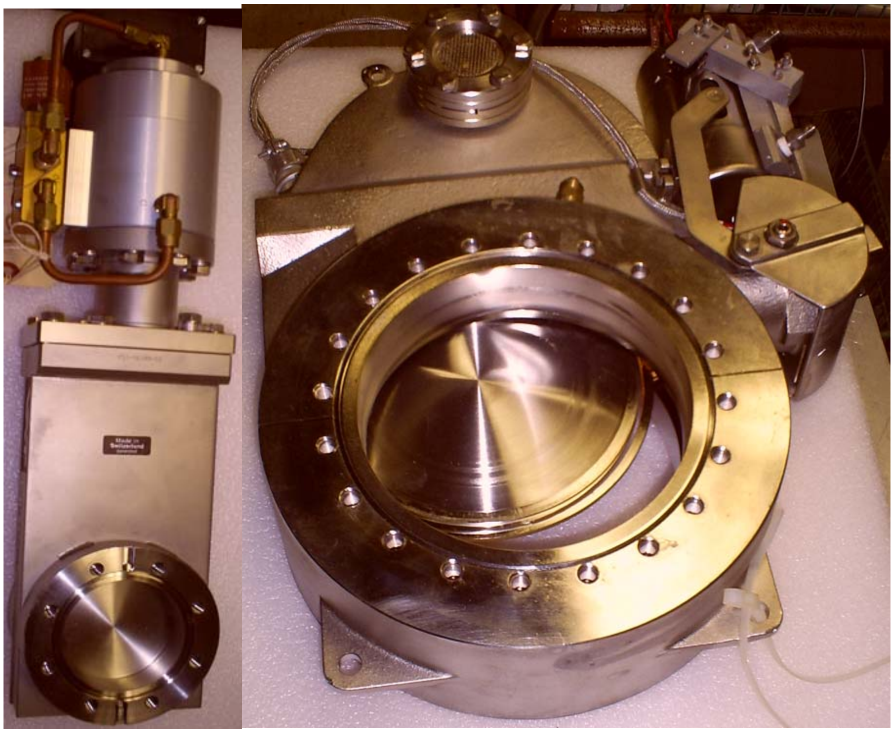


Figure 3: (a) Vat Valve (b) GP Valve

The impact of treating vacuum vessels as pressure vessels

Vacuum vessels are often designed as an assemblage of standard components welded to a pressure vessel shell. The design and manufacturing techniques have become standard in the vacuum industry so that UHV vacuum levels can be achieved efficiently and cost-effectively, but these vacuum vessels cannot meet Section VIII requirements. If they did, they would have been much more costly and potentially would not have performed well for UHV operation. Vacuum flanges and “nipples” use continuous internal welds and, when needed, stitch welds only are used on the outside opposite the continuous internal welds. The welds are designed to carry adequate loads for vacuum service while assuring that no “trapped volumes” exist that can cause “virtual leaks.” The wall thickness on standard vacuum components does not meet ASME Section VIII B&PV code requirements. Similarly, the ASME Section VIII code requirements for full radiographic weld testing, material certifications, and third party National Board (of Boiler and Pressure Vessel Inspectors) certified inspection are not performed on vacuum vessels. The ASME requirement for material traceability for example cannot be performed retroactively. For existing vacuum chambers, the welds and wall thickness of the standard vacuum components would not be sufficient for ASME Section VIII certification. At NSLS, when purge gases are connected to these vacuum vessels, for example during bleed-up, 1-2 psig pressure relief valves are included on the bleed-up systems. New vacuum vessel designs could meet Section VIII requirements, but as mentioned, this would be much more costly and more virtual leak problems would be anticipated.

Procedure

The research work for this effort started with an assessment of the relevant ASME codes and a review of applicable fluid mechanic principles. After developing and programming the equations using Excel spreadsheets, a study of each beamline was undertaken. Of highest concern were pressure sources that penetrated into vacuum space within components such as monochromators, slits, and beryllium windows. Pressurized cooling water sources connected to make-up water, nitrogen, helium, and process gas sources were examined and the pressure and flow information was calculated. Each isolatable section with a potential pressure source required a pressure relief device. Within each section, the weakest component was generally identified. Glass view ports and beryllium windows for example were usually the components which would be expected to fail at the lowest internal pressure. This process was repeated for each beam line. Due to the amount of calculation necessary, the information gathered from each of the beam lines was input into Excel spreadsheets. The spreadsheets calculated the pressure relief requirements and output graphs of flow rate and pressure versus time.

Where vacuum vessels having a greater diameter than six inches are used, detailed inspection was needed to assure that no sources of pressure either were (or could be) added which could cause internal gauge pressure to reach or exceed 15 psi. All beam line segments having sources of internal pressure, such as water (with adequate capacity or make-up capability) or a pressurized gas were inspected for ASME-compliant pressure relief devices. If needed, ASME-compliant safety devices were identified, sized, and located to assure compliance with 10CFR851. Since ASME/National Board certified, UHV-compatible pressure relief devices were required, a related effort was undertaken to acquire such devices which were not commercially available at that time.

MDC Vacuum Products has since introduced two new burst disks which will relieve pressure at 9-11.5 psi, both are National Board-certified and UHV compatible; one is offered on a 1.33" Conflat mini-flange, and the other on a 2.75"OD Conflat flange. These two particular burst disks were used when sizing the pressure relief capacity for each NSLS vacuum vessel.

Fluid Mechanics Analysis

In order to automate the process since many beamlines and vacuum vessels were involved, the necessary fluid mechanics equations were developed and programmed into an Excel spreadsheet so that only the necessary variables for each vacuum vessel had to be input. The Excel spreadsheet then output the burst disk information needed.

Starting with the 'equation of state', the amount of gas in a certain volume can be calculated: $PV = mRT$

where P = pressure (psi)

V = volume (in^3)

T = temperature (°R)

m = mass (lb_m)

R = Universal gas constant (1545 ft lb_f/[lb_{mole}°R]/molecular wt, which for dry air is 28.97 lb_m/lb_{mole}, thus R = 53.3 ft lb_f/[lb_m°R] in US customary units)

The maximum flow rate attainable occurs when the flow is 'choked' and the fluid approaches sonic velocity. At choked flow, $\mathbf{W = PC_dAC}$ (lb_m/s or lb_m/hr)

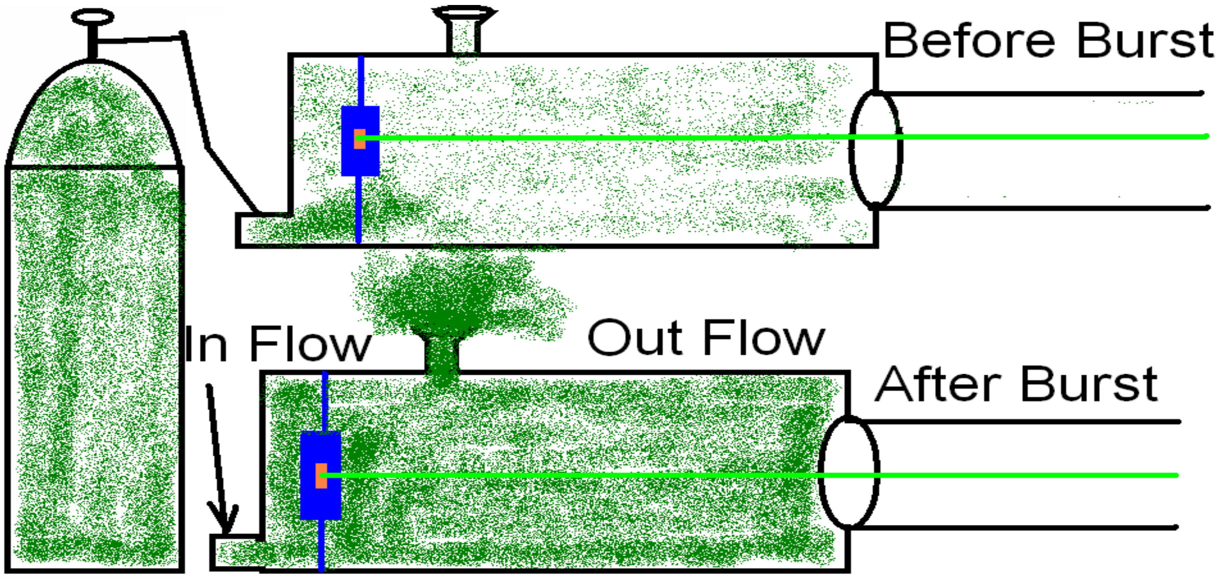
where P is the inlet pressure (psi)

C_d = coefficient of discharge or the frictional coefficient

A = area of the inlet orifice (in^2) and

C (a constant) = $\sqrt{\frac{Kg}{RT}\left(\frac{2}{K+1}\right)^{\frac{K+1}{K-1}}}$ where k = specific heat ratio (c_p/c_v) and g = gravity.

This equation is the maximum flow rate attainable which is an upper bound for flow.



Using PV=mRT the object is to develop an expression for the pressure in the tank versus time. Taking the derivative with respect to time:

dP/dt = dm/dt RT/V.

whereby R (the ideal gas constant), T (the temperature), and V (the volume) all remain constant during this process. The mass flow rate **dm/dt** = **W = PC$_d$AC**, the rate of flow out of the tank. Substituting results in **dP/dt = WRT/V = PC$_d$ACRT/V**. Moving around the variables and solving for P this equation becomes $\int \frac{dP}{P} = \int \frac{C_dACRT}{V} dt$

Solving this integral from the initial pressure P_i to the final pressure P_f, and from the initial time, zero and the final time, t, we get $P_f = P_i e^{\frac{C_dACRT}{V}t}$. This expression is $P_{tank}(t)$ which varies with time. C_d, the coefficient of discharge or the resistance of the fluid flow, is the equivalent of the resistance in an electric circuit. The resistance depends on the flow path between the pressurized fluid supply tank (or source) and the vacuum chamber. For pressurized gases, a regulator is usually used on the gas supply tank and a length of tubing connects it to the vacuum chamber. Assuming a worst-case scenario whereby the regulator fails completely open, no flow resistance contribution is assumed from the regulator and therefore it is not added to the C_d. The only resistance to calculate is the tubing. The tubing has a κ factor which depends on length, diameter, amount of bend, and the tubing material roughness. The formula for κ is **κ =fL/d** where f is the friction of the material.

To assure that pressure will not rise unacceptably within a vacuum vessel, the flow rate out of the tank needs to be calculated, and it should be greater than the sum of maximum flow rates into the vacuum chamber. Since the pressure in the tank is constantly decreasing with time and the flow rate depends on the pressure in the tank, the flow rate into the vacuum chamber will vary with time. The governing equation therefore becomes

$W = P_i e^{\frac{C_d ACRT}{V} t} C_d AC$. This is also $dm/dt = P_i e^{\frac{C_d ACRT}{V} t}$ **$C_d AC$**

To determine the flow rate into the vacuum chamber, a similar process is followed. Taking the derivative of PV=mRT with time and using **$dP/dt = dm/dt\ RT/V_2$** where V_2 is the volume in the vacuum chamber (not in the pressurized tank). Substituting **dm/dt = W** and integrating from initial pressure in the chamber, zero, to final pressure $P_{chamber}$ and from time zero to final time t for P. $\int dP = \frac{P_i C_d CART}{V_2} \int e^{\frac{C_d ACRT}{V} t} dt$

results in $P_{chamber} = \frac{P_i C_d V}{V_2}\left(1 - e^{\frac{C_d ACRT}{V} t}\right)$. As you can see from this equation, as time goes on, the pressure will increase only up a maximum, $\frac{P_i C_d V}{V_2}$.

Now in order to plot the pressure versus time in the chamber, we need to find at what time the burst disk will open. The way to do that is to plug in the burst pressure in the formula and solve for t. **When the burst disk ruptures, the flow rate out of the**

tank has to be calculated and compared to the flow rate into the chamber. This is done iteratively using an Excel spreadsheet.

When the burst disk opens, there is both a flow rate in and a flow rate out. The flow rate in is at choked flow because of the large difference in pressures between the tank and the vacuum chamber. The gas discharge out of the tank is initially choked, but as the tank empties, the flow velocity transitions from sonic to subsonic.

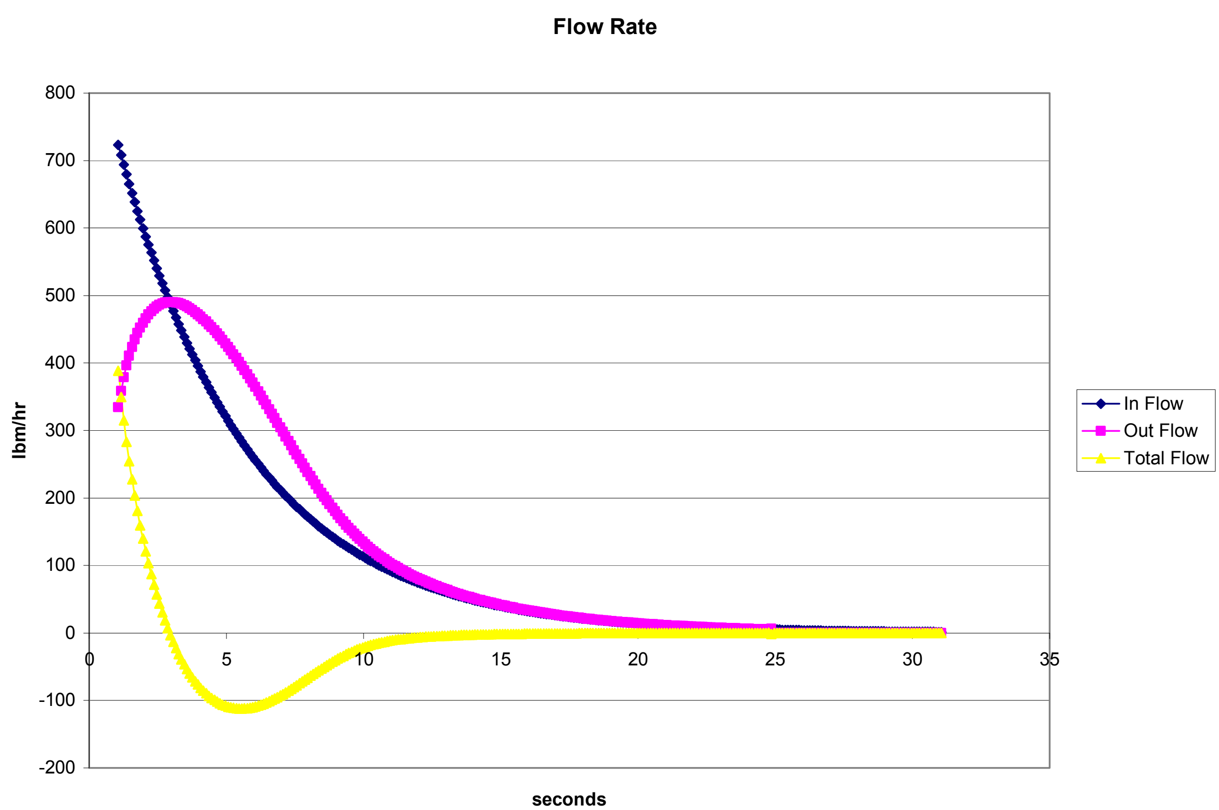
After the burst disk opens, $dm/dt = W_{in} – W_{out}$. W_{in} was determined previously while W_{out} uses a different formula since it's not at choked flow (at least not initially). The formula for non-choked flow is $W = C_d A P_1 \sqrt{\frac{2Kg}{(K-1)TR}\left(\left(\frac{P_2}{P_1}\right)^{\frac{2}{K}} - \left(\frac{P_2}{P_1}\right)^{\frac{K+1}{K}}\right)}$. Therefore the total change in pressure is $dP/dt = (W_{in}-W_{out})RT/V_2$. This equation is solved iteratively by incrementing the time interval dt. The smaller the time interval, the more accurate the answer. At t = 0 the burst disk hasn't opened yet, the time of interest is when the burst disk opens. For one example, this occurred at approximately 1 second. Figure 4 shows this. The pressure it starts off with is the burst pressure.

Time	**Flow Rate In**	**Flow Rate Out**	**Total Flow**	**Change in Pressure**	**Pressure in Vessel**	**Gage Pressure**
s	**lbm/hr**	**lbm/hr**	**lbm/hr**	**dP**	**Psia**	**psig**
1.0609933	723.14719	334.47303	388.67416	1.0886475	23.088648	8.0886475
1.1609933	708.25631	358.65351	349.6028	0.9792116	24.067859	9.0678591
1.2609933	693.67207	378.90852	314.76355	0.8816294	24.949488	9.9494885
1.3609933	679.38814	396.12494	283.2632	0.7933992	25.742888	10.742888
1.4609933	665.39834	410.89918	254.49917	0.7128333	26.455721	11.455721
1.5609933	651.69662	423.65499	228.04163	0.6387277	27.094449	12.094449
1.6609933	638.27704	434.70619	203.57085	0.5701869	27.664636	12.664636
1.7609933	625.13379	444.29274	180.84105	0.5065224	28.171158	13.171158
1.8609933	612.26118	452.60299	159.6582	0.4471908	28.618349	13.618349
1.9609933	599.65365	459.80525	139.8484	0.391705	29.010054	14.010054
2.0609933	587.30572	466.0987	121.20703	0.3394919	29.349546	14.349546
2.1609933	575.21207	471.55324	103.65882	0.2903407	29.639886	14.639886
2.2609933	563.36744	476.21809	87.149348	0.2440989	29.883985	14.883985

2.3609933	551.76671	480.13998	71.626733	0.2006212	30.084606	15.084606
2.4609933	540.40486	483.36332	57.041545	0.1597691	30.244376	15.244376
2.5609933	529.27697	485.93029	43.346679	0.1214108	30.365786	15.365786
2.6609933	518.37823	487.88098	30.49725	0.0854205	30.451207	15.451207
2.7609933	507.70391	489.25341	18.450495	0.0516785	30.502885	15.502885
2.8609933	497.24939	490.08372	7.1656705	0.0200705	30.522956	15.522956
2.9609933	487.01015	490.40619	-3.396039	-0.009512	30.513444	15.513444

Figure 4: Pressure verses time points

This example shows an unacceptable pressure relief capability. The internal pressure rose above 15 psig whereby ASME Section VIII codes apply to this vacuum vessel. Notice that after the pressure reaches 15.52 psi it starts to diminish. This is the maximum pressure that will be reached in the chamber. At this point, the flow rate in goes below the flow rate out and the total flow becomes negative, therefore emptying the chamber. With the graphs of pressure verses time produced by the Excel spreadsheets as shown below in figure 5, the pressure relief needs for each vacuum vessel can be assessed.



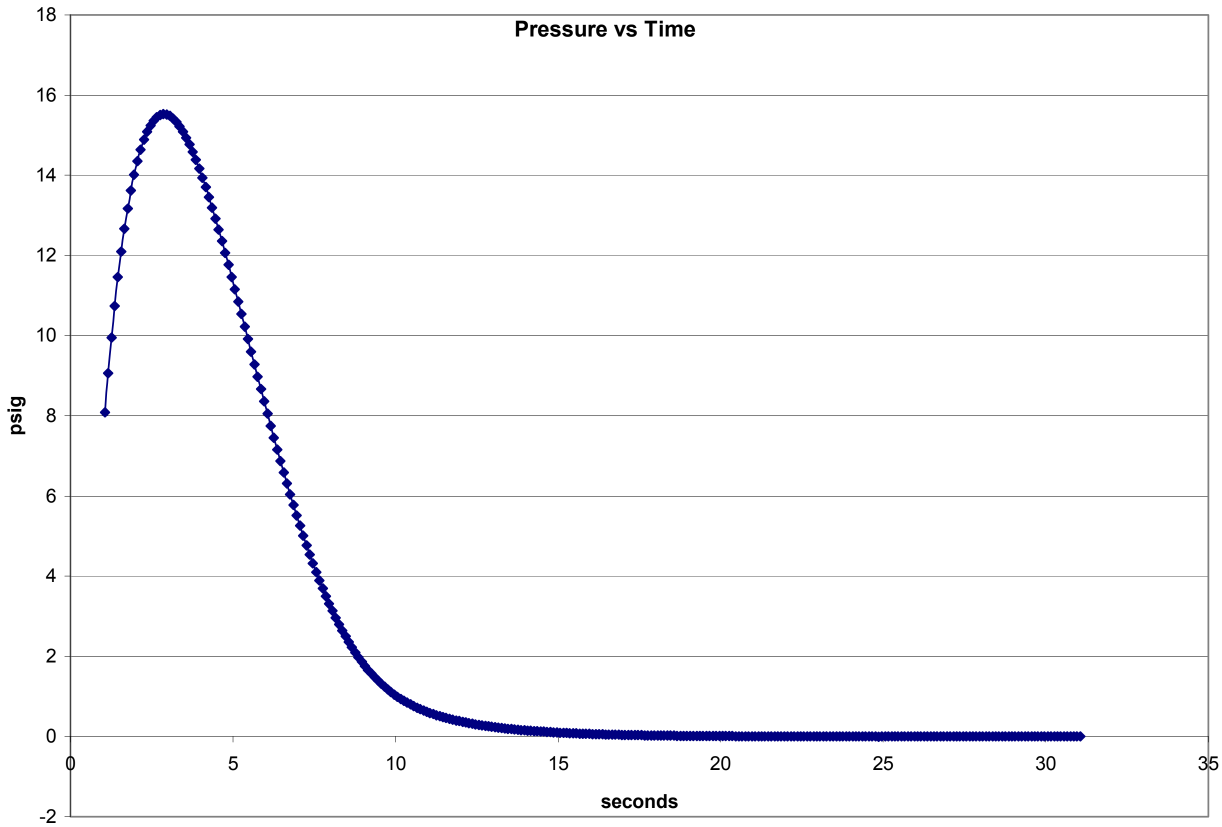


Figure 5: (a) Flow rates and (b) pressure versus time

Actions taken at NSLS

Using these Excel spreadsheets, an inspection of every beam line was undertaken from the first X-ray beam line. Each vacuum vessel was identified and every potential source of pressure was located. Most common sources of pressure were process gases and water-cooling lines within slits, apertures, and beryllium windows. Since beryllium windows separate vacuum chambers, both sides of the beryllium windows were considered. There were many more sources of water pressure than nitrogen or helium, and even though it may be unlikely that a segment of beamline could fill entirely with water, ASME code requires that this be considered when cooling fluid was coming from a process water system with unlimited make-up as opposed to coming from a chiller with limited capacity that simply cools a fixed quantity of fluid and circluates it repeatedly after passing through a heat exchanger. Many monochromators used chillers which had insufficient capacity to over-pressurize the monochromator's vacuum vessel. Some monochromators used liquid helium as a source of cooling. They required pressure relief since the helium expands rapidly if released into the warm monochromator.

Conclusions

Using Excel spreadsheets, the required pressure relief was calculated for NSLS vacuum vessels using nitrogen, helium, and process gasses. It is recommended that burst disks as specified in the attached output be added to each vacuum vessel indicated so that discharge is directed downward and away from personnel. If this is not possible, provisions may be added to protect personnel from discharge effluents.

The analyses done provides specific recommendations for each beamline to assure compliance with 10CRF851 and assure personnel at NSLS are safe.

Acknowledgements

This paper describes the efforts of many people:

- Ron Beauman, NSLS Utilities Engineer
- Conrad Foerster and Jih-perng (Eugene) Hu, NSLS Vacuum Engineers
- Anthony Lenhard, Chief Beam line Technical Supervisor at NSLS
- Walter deBoer, Chris Lanni and other NSLS Technicians
- Andrew Ackerman and Bob Casey, NSLS Safety engineers
- Sal Pjerov and the NSLS Design Room staff