Disassembly of a Vacuum System for Mechanical Refurbishment.

Presented to the faculty of Lycoming College in partial fulfillment
of the requirements for Departmental Honors in
Astronomy and Physics.

By
Melany Lauren McGillvray
Lycoming College
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ABSTRACT:
The vacuum system belonging to the Lycoming College Astronomy and Physics department was disassembled for maintenance and mechanical refurbishment due to its analyzed inefficiency in prior testing. Lab director and Lycoming College Alumnus, Jeff Garrett ('81), from Outgassing Services International (O.S.I.) in Mountain View, California, supplied many of the custom upgraded components that were necessary for the system's modernized redesign.

INTRODUCTION:

This paper reports the comprehensive reasoning behind the disassembly of an insufficient vacuum system. It includes pre-disassembly calculations of internal chamber pressure and serves as a guideline for diagnostic testing on all vacuum chamber apparatus, with a few altercations depending on the system. It was observed that once the chamber was isolated and vacuum pumping was terminated, the internal chamber pressure plummeted over the duration of a three-hour test. For this reason, the vacuum system was then refurbished and redesigned to improve internal chamber pressure efficiency. Experimental reassessment of initial research was conducted post-reassembly to verify a significant change in the chamber's ability to reach and maintain lower pressures.

TEST APPARATUS:

[See Fig. 3 in Appendix]

Original Test Chamber.

The top of the test chamber was sealed by a 4-cm thick by 51-cm diameter glass lid. Below the lid was a stainless steel chamber "collar," which housed eight holes to which external instrumentation could be affixed. Directly underneath the chamber collar was an open-ended thick glass cylinder, having dimensions of approximately 8.3-cm in height by 45.5-cm in diameter. The bottom plate of the test chamber, made of stainless steel, was 51-cm in diameter with a 14-cm diameter hole cut out of its center.
[See Fig. 4 a, b, c in Appendix]

Pumping Mechanism.

Directly below the stainless steel chamber plate, covering completely its center hole, was a baffle valve and mercury vapor trap, respectively, that lead to a diffusion pump, all of which have sat unused for twenty-six years. The baffle valve [model no. H7L4A, serial no. 495] was attached to the bottom plate of the test chamber via six bolts 0.8-cm in diameter, having a bolt circle diameter (B.C.) of 23.3-cm and a flange groove, 0.6-cm wide by 0.5-cm deep, which housed a rubber O-ring. Below the baffle valve was a mercury vapor trap that fed into a diffusion pump [model no. B04]. [See Fig. 6 a, b, c in Appendix]

The main pumping mechanism used to evacuate the test chamber from atmospheric pressure was a mechanical Duo-Seal Vacuum Pump, which optimally spun at 300 revolutions per minute. [See Fig. 9 a, b in Appendix]

Additional Equipment.

A manually operated stainless steel SPEEDIVAC valve was located to the left of the main test chamber having three outputs; one that connects the valve to the chamber, another to successive stainless steel SPEEDIVAC vacuum lines and to a second valve and more vacuum lines that led to the mechanical pump, and the last to vacuum lines connecting a third valve leading to an exhaust cylinder tank. Adjoining vacuum lines were clamped together by stainless steel half-circle shaped SPEEDIVAC flanges. [See Fig. 10 in Appendix]

Rubber hosing is used directly from the vacuum pump and exhaust cylinder tank to connect to the stainless steel vacuum lines.

Internal chamber pressure is measured by an analog thermocouple gauge control manufactured by Veeco Instruments Inc. [model no. TG-7]. It reads pressure values through a Veeco Thermocouple Gauge Tube [Type DV-1M] that sits affixed on a vacuum line running between the test chamber and pumping mechanism. [Note: In this particular setup, the thermocouple gauge control was not reading the actual internal chamber pressure, but the pressure of the vacuum line running between the main chamber and the vacuum pump.]

An external fan is used to cool the vacuum pump in the event that overheating should occur.

Unused Components.
[See Fig. 5 in Appendix]

The aforementioned baffle valve, vapor trap, and diffusion pump sat relatively inactive underneath the main test chamber for an extended period of time.

It should be noted that when the baffle valve knob was turned to either the “open” or “closed” designation, the valve mechanism itself did not function, but remained permanently in the closed position.

[Note: All unused components were registered by SPEEDIVAC, made in England by Edwards High Vacuum Ltd.]

TEST PROCEDURE:

Test Chamber Preparation.

The glass lid is removed from the chamber apparatus and the stainless steel components are cleaned with a solvent [here, dichloromethane] prior to testing. The lid is then placed and centered over the chamber for a secure fit. The valves running between the test chamber and vacuum pump are manually opened so that air is free to be evacuated through the vacuum lines. The thermocouple gauge control is activated to start reading internal chamber pressure. The vacuum pump is then turned on and the external fan is used to cool the pump from possible overheating.

Prior to test commencement, the vacuum system was left to run 24 to 48-hours overnight to achieve the minimum pressure possible; approximately 9-mTorr for the current set up.

TESTING:

Two tests were performed, each over a period of three hours. Once initial pressure was recorded at the zero time mark, the valve located between the vacuum pump and thermocouple gauge tube was closed before pumping terminated. Isolating the chamber in this manner ensured that immediate leaking would not occur through the vacuum lines once the pump had been turned off. The successive pressure measurements were then recorded post-pump termination at fifteen-minute intervals for the duration of the test.

DATA PROCESSING:

The successive change in pressure is calculated by,

$$\Delta P = (P_n - P_{n-1}) \qquad [1]$$

where P indicates a recorded pressure in mTorr and the subscripts n and n-1 represent the most recent pressure measurement and the measurement just before, respectively.

The instantaneous leak rate is determined by calculating, similarly, the change of internal chamber pressure as a function of time by,

$$R_{PL} = \Delta P/15\text{-min, or} \qquad [2]$$

$$R_{PL} = (P_n - P_{n-1})/15\text{-min} \qquad [3]$$

where R indicates the calculated rate at which pressure leaked, identified respectively by the subscripts PL.

The total pressure loss percentage is measured by:

$$TPL\ (\%) = [(P_f - P_i)/P_{atm}]*100, \qquad [4]$$

$$P_{atm} = 825\text{-Torr or } 825\text{x}10^3\text{-mTorr}$$

where P indicates a measured pressure in mTorr and the subscripts f and i indicate the final and initial pressure recordings, respectively, for the entire three-hour test duration. The subscript atm indicates the pre-experimental atmospheric pressure present in the chamber.

RESULTS:

Table 1: Test 1 - Analog Thermocouple Pressure Efficiency.

Pressure Reading No.	Time Elapsed	Pressure	ΔP ($P_n - P_{n-1}$)	Instantaneous Leak Rate [($P_n - P_{n-1}$)/15min]
P_n	(min)	(mTorr)	(mTorr)	(mTorr/min)
P_i	0	7	---	---
P_2	15	49	42	2.8
P_3	30	90	41	2.73
P_4	45	135	45	3.0
P_5	60	175	40	2.67
P_6	75	215	40	2.67
P_7	90	255	40	2.67
P_8	105	290	35	2.33
P_9	120	340	50	3.33
P_{10}	135	375	35	2.33
P_{11}	150	400	25	1.67
P_{12}	165	450	50	3.33
P_f	180	490	40	2.67

Average ΔP: (mTorr)	Total ΔP: (mTorr)	Average Leak Rate: (mTorr/min)	Total Pressure Loss (%):
40.25	483	2.68	0.058_5

Table 2: Test 2 - Analog Thermocouple Pressure Efficiency.

Pressure Reading No.	Time Elapsed	Pressure	ΔP ($P_n - P_{n-1}$)	Instantaneous Leak Rate [($P_n - P_{n-1}$)/15min]
P_n	(min)	(mTorr)	(mTorr)	(mTorr/min)
P_i	0	9	---	---
P_2	15	60	51	3.4
P_3	30	110	50	3.33
P_4	45	155	45	3.0
P_5	60	200	45	3.0
P_6	75	250	50	3.33
P_7	90	290	40	2.67
P_8	105	325	35	2.33
P_9	120	375	50	3.33
P_{10}	135	400	25	1.67
P_{11}	150	445	45	3.0
P_{12}	165	480	35	2.33
P_f	180	500	20	1.33

Average ΔP: (mTorr)	Total ΔP: (mTorr)	Average Leak Rate: (mTorr/min)	Total Pressure Loss (%):
40.92	491	2.73	0.059_5

[Note: The leaking phenomenon here involves air escaping from the rubber gaskets between connecting vacuum lines, weak O-ring seals, etc. The analog thermocouple gauge control used in this experiment also created large error in that it became difficult to approximate pressure readings as the test reached longer durations.]

DISASSEMBLY:

The reason for the vacuum system's disassembly was to perform maintenance on all of its components. During that time, it was determined that many of the rubber components, such as O-rings and various seals, had vastly deteriorated over the years. It was also noted that the vapor trap and diffusion pump had considerable amounts of debris and/or rust coalescing on their internal surface area.

The following components were then removed from the original vacuum system due to the aforementioned reasoning:

1. SPEEDIVAC Baffle Valve [model no. H7L4A, serial no. 495]
2. SPEEDIVAC Mercury Vapor Trap
3. SPEEDIVAC Vapor Diffusion Pump [model no. B04]
4. All stainless steel wing nut assemblies turn style valves, and existing vacuum lines.
5. SPEEDIVAC flanges
6. Stainless steel chamber collar blank plates, or "blanks"
7. Rubber hosing components
8. VEECO Thermocouple Gauge Tube* [Type DV-1M]

[*Note: the thermocouple gauge tube was not completely removed from this system, but relocated to the inside of the test chamber to measure the internal chamber pressure more accurately.]

REASSEMBLY:

[See Fig. 12 in Appendix]

Replacement Parts.

Due to the removal of all SPEEDIVAC vacuum equipment, the hole on the bottom stainless steel plate of the main test chamber was left uncovered. To compensate for this exposed area, a custom stainless steel plate, fabricated by DV Manufacturing, was placed underneath the already existing stainless steel plate. [See Fig. 13 in Appendix]

A Swagelok bellows valve [SS-4BK] replaced the one of the SPEEDIVAC valves, which indirectly connected the chamber to the exhaust tank through adjoining vacuum lines. [See Fig. 14 in Appendix] The Swagelok valve directly affixes on the chamber collar and connects to the exhaust tank via Teflon tubing. A manually operated Nor-Cal Products valve [ILV-1502-CF] replaced the other SPEEDIVAC valves, which now directly connects the test chamber to the vacuum pump via a 1-m long DV Manufacturing stainless steel bellows. [See Fig.15, 18 in Appendix]

Nor-Cal Products wing nut assemblies replaced the SPEEDIVAC flanges. The design of the replacement clamps completely encases adjoining parts so that little leaking should occur. [See Fig. 11 a, b in Appendix]

New stainless steel chamber collar blanks replaced the older versions for upgraded consistency. [See Fig. 16 in Appendix]

A Duniway Stockroom mini convection module, or digital thermocouple gauge control, is affixed to the chamber collar to record precise pressure readings at any given moment, in accordance to the existing thermocouple gauge tube and analog control for experimental comparisons. [See Fig. 17 in Appendix]

New Equipment.

The bottom of a DV Manufacturing foreline trap connects to the mechanical vacuum pump by a small portion of rubber hosing 8-cm in length, having an outer diameter of 3.0-cm and an inner diameter of 1.5-cm. The top of the trap connects to the new stainless steel bellows. Its purpose is to trap any small particles or oil residue from contaminating the main test chamber. [See Fig. 18 in Appendix]

[See Table 7 in Appendix for complete inventory.]

EXPERIMENTAL REASSESSMENT:

Using the same aforementioned methodology for internal chamber pressure analysis, two three-hour tests are performed. The first test replicates past pressure analysis identically, with the additional digital thermocouple gauge pressure measurements. It was found that the analog thermocouple gauge was consistently reading approximately 10-mTorrs less than the actual pressure measured by the digital version. Due to this variation, the Veeco thermocouple gauge tube was removed from the internal chamber and disconnected from the analog thermocouple gauge control before the second reassessment commenced. A new blank and O-ring seal then replaced the exposed hole on the chamber collar. The second reassessment was performed routinely with only the digital thermocouple.

RESULTS:

Table 3a: Reassessment 1a - Analog Thermocouple Pressure Efficiency.

Pressure Reading No.	Time Elapsed	Pressure	ΔP ($P_n - P_{n-1}$)	Instantaneous Leak Rate [($P_n - P_{n-1}$)/15min]
P_n	(min)	(mTorr)	(mTorr)	(mTorr/min)
P_i	0	>1	---	---
P_2	15	27	N/A	N/A
P_3	30	59	32	2.13
P_4	45	85	26	1.73
P_5	60	110	25	1.67
P_6	75	140	30	2.00
P_7	90	160	20	1.33
P_8	105	180	20	1.33
P_9	120	200	20	1.33
P_{10}	135	225	25	1.67
P_{11}	150	250	25	1.67
P_{12}	165	270	20	1.33
P_f	180	290	20	1.33

Average ΔP: (mTorr)	Total ΔP: (mTorr)	Average Leak Rate: (mTorr/min)	Total Pressure Loss (%):
23.91	289	1.59	0.035

Table 3b: Reassessment 1b - Digital Thermocouple Pressure Efficiency.

Pressure Reading No.	Time Elapsed	Pressure	ΔP $(P_n - P_{n-1})$	Instantaneous Leak Rate $[(P_n - P_{n-1})/15min]$
P_n	(min)	(mTorr)	(mTorr)	(mTorr/min)
P_i	0	5	---	---
P_2	15	38	33	2.20
P_3	30	69	31	2.07
P_4	45	94	25	1.67
P_5	60	121	27	1.8
P_6	75	148	27	1.8
P_7	90	173	25	1.67
P_8	105	191	18	1.20
P_9	120	215	24	1.60
P_{10}	135	237	22	1.47
P_{11}	150	258	21	1.40
P_{12}	165	278	20	1.33
P_f	180	295	17	1.13

Average ΔP: (mTorr)	Total ΔP: (mTorr)	Average Leak Rate: (mTorr/min)	Total Pressure Loss (%):
24.17	290	1.61	0.035

Table 4: Reassessment 2 - Digital Thermocouple Pressure Efficiency.

Pressure Reading No.	Time Elapsed	Pressure	ΔP $(P_n - P_{n-1})$	Instantaneous Leak Rate $[(P_n - P_{n-1})/15min]$
P_n	(min)	(mTorr)	(mTorr)	(mTorr/min)
P_i	0	3	---	---
P_2	15	18	15	1.00
P_3	30	32	14	0.93
P_4	45	44	12	0.80
P_5	60	57	13	0.87
P_6	75	69	12	0.80
P_7	90	79	10	0.67
P_8	105	91	12	0.80
P_9	120	104	13	0.87
P_{10}	135	117	13	0.87
P_{11}	150	129	12	0.80
P_{12}	165	140	11	0.73
P_f	180	150	10	0.67

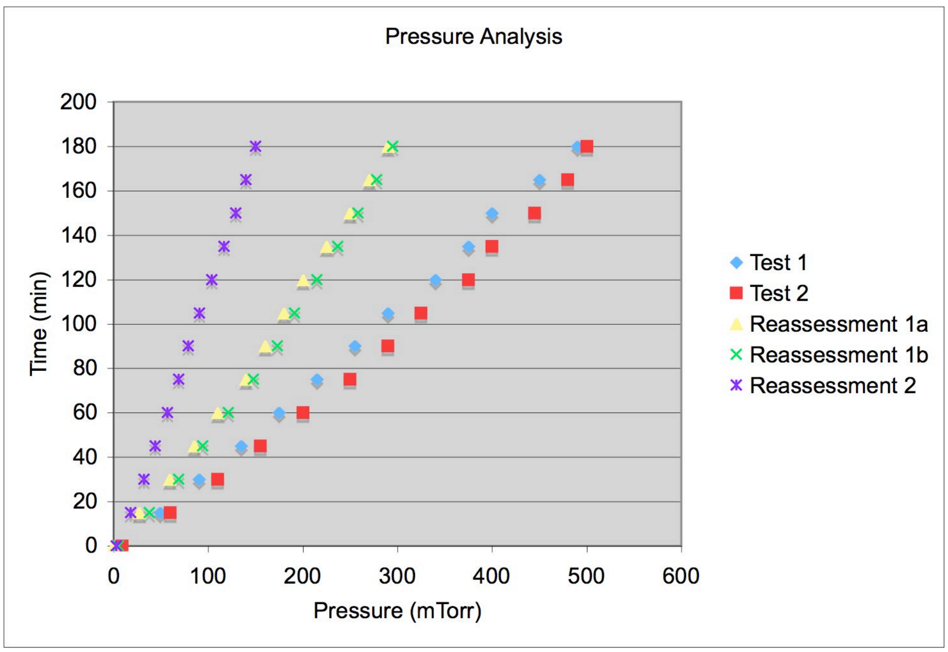
Average ΔP: (mTorr)	Total ΔP: (mTorr)	Average Leak Rate: (mTorr/min)	Total Pressure Loss (%):
12.25	147	0.817_5	0.018

Table 5: Internal Chamber Pressure Analysis.

		P_i	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_f
Test	**Thermocouple Model**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**
Test 1	Analog	7	49	90	135	175	215	255	290	340	375	400	450	490
Test 2	Analog	9	60	110	155	200	250	290	325	375	400	445	480	490
Reassessment 1a	Analog	>1*	27	59	85	110	140	160	180	200	225	250	270	290
Reassessment 1b	Digital	5	38	69	94	121	148	173	191	215	237	258	278	295
Reassessment 2	Digital	3	18	32	44	57	69	79	91	104	117	129	140	150

* Measurement disregarded due to inaccuracy.

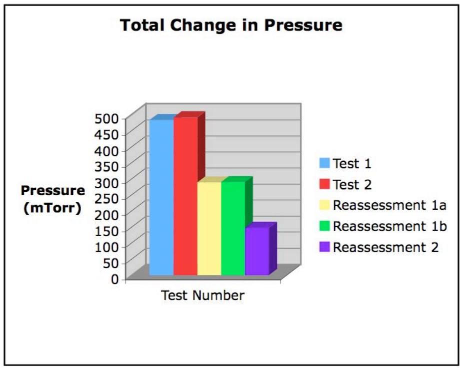
Pressure Analysis.



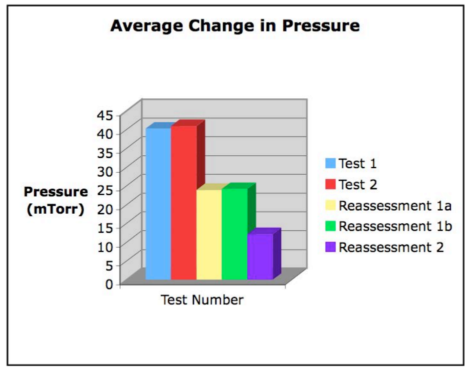
[Fig. 1]

Table 6: Other Calculations.

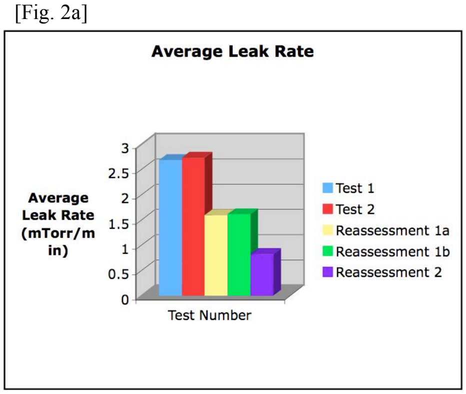
Test	Thermocouple Model	Total ΔP (mTorr)	Average ΔP (mTorr)	Average Leak Rate (mTorr/min)	Total Pressure Loss (%)
Test 1	Analog	483	40.25	2.68	0.058_5
Test 2	Analog	491	40.92	2.73	0.059_5
Reassessment 1a	Analog	289	23.91	1.59	0.035
Reassessment 1b	Digital	290	24.17	1.61	0.035
Reassessment 2	Digital	147	12.25	0.817_5	0.018



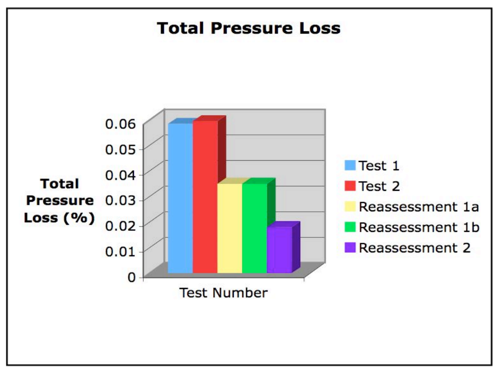
[Fig. 2a]



[Fig. 2b] Per 15-minute interval.



[Fig. 2c]



[Fig. 2d]

DISCUSSION.

[See Fig. 19 a, b in Appendix]

The decision to remove the baffle valve, vapor trap, and diffusion pump was based primarily on the fact that they had been idle for many years and their functionality was questionable. Prior to disassembly, the baffle valve knob proved to be useless. Once taken apart, a whir of pressure was released and the valve became functional. It is believed that because the diffusion pump, and therefore the mercury trap and baffle valve, sat inactive for such an extensive period of time, the mechanical vacuum pump acted on the idle components, creating a mini-vacuum atmosphere within them. Though the components could have been reassembled and tested prior to complete disassembly, the problem of using mercury in a classroom setup (vapor trap) posed hazardous consequences, as some mercury may still exist in the trap.

The VEECO stainless steel flanges, valves, and vacuum lines were removed, as they were major sources of pressure leaking. Also contributing to the leaking phenomenon were the rubber hosing components that dried out and cracked over the years. However, most of the pressure leaked through the vacuum lines that ran between the chamber and thermocouple gauge tube housing. The vacuum tube was then initially removed from the external vacuum line and placed inside the main test chamber.

After the system's reassembly and previous analysis was reassessed, the analog thermocouple gauge control proved to read inaccurate measurements of pressure. [See table 3 a, b] With the digital version directly connected to the chamber collar, a comparison was made and showed that the analog thermocouple read approximately 10-mTorr less than the actual internal chamber pressure. Because of this inaccuracy, the decision was made to remove the thermocouple tube from inside the chamber and disconnect the analog thermocouple gauge from the system completely. A blank plate was then fastened over the exposed hole on the chamber collar, and reassessment continued.

By removing the thermocouple gauge tube, the test chamber achieved a new minimum pressure (3-mTorr) compared to the previous reassessment (5-mTorr). This change also helped achieve a lower change in pressure, or, a greater ability to maintain lower pressures [See Table 5].

It can be seen from Fig. 1 and 2 (a, b, c, and d) that pressure leaking is less abundant in the updated system.

FUTURE WORK.

The vacuum system originally belonged to former physics professor Dr. Morton Fineman, who had used it for molecular beam experiments in inert atmospheres.

In the years after his retirement, Dr. Fisher began using the vacuum system to store metal samples that he had created during his graduate school research. The chamber was an ideal place to store such materials, as the vacuum system created a miniature "clean room" atmosphere. He also used the system to demonstrate simple experiments to introductory PHYS 225/226 classes.

Departmental majors had not used the vacuum system for research purposes since Fineman. With the redesign and improved internal chamber pressure efficiency, students will now be able to create laboratory experiments of their own and conduct a kind of research that is not familiar with the current Lycoming College faculty. It will give students an opportunity to venture outside hypothetical classroom work and have sufficient hands-on laboratory experience.

With sufficient funding and resources, a future student, or students, could further my work in updating the mechanical vacuum pump to an even better turbo molecular pump. This would result in achieving lower pressures comparable to the system used at O.S.I.

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Marshmallow TML (%) Under Vacuum Conditions.

M.L. McGillvray
Lycoming College, Williamsport, PA 17701

The effect of vacuum conditions on three marshmallow samples was studied by measuring sample total mass loss (TML%) using three different test time intervals: 2 hours, 24 hours, and 48 hours, respectively. It was suspected that the samples would lose more mass, due to the achievement of lower internal chamber pressure, at the longer test time intervals.

INTRODUCTION:

This paper reports the total mass loss, or TML (%), of a marshmallow sample under vacuum conditions. The purpose of this experiment was to determine what percentage of the sample's total mass was lost, if any, when pressure within the chamber dropped below atmosphere. It was observed that air significantly contributed to the sample's total mass.

TEST APPARATUS:

Vacuum System.

The vacuum system consists of a main test chamber, Duo-Seal vacuum pump, and a thermocouple gauge control.

The main test chamber is a thick glass cylinder, open at one end, with a stainless steel bottom, having dimensions of 7 cm in height by 45.5 cm in diameter. The chamber is sealed by a 4 cm thick by 51 cm diameter glass lid.

The chamber uses a Duo-Seal vacuum pump, which optimally spins at 300 R.P.M., to evacuate the chamber from atmospheric pressure.

The internal chamber pressure is measured by a thermocouple gauge control.

Additional Equipment.

A Mettler laboratory balance (model No. H15), or analytical balance if available, is necessary for initial and final sample mass measurements. A vernier caliper is required to record pre- and post-test sample dimensions. Metal tongs are used to transport the sample at all times. Kimwipes should be used to prevent any contamination during the experiment.

Hardware Cleaning.

A solvent, such as dichloromethane, is used to clean all stainless steel components.

TEST PROCEDURE:

Sample Preparation.

Prior to weighing a sample, the Mettler balance is cleaned using dichloromethane. The sample is then placed inside the balance, using metal tongs (also solvent cleaned), and its initial mass is recorded. The sample's dimensions are also measured using a clean vernier caliper.

Test Chamber Preparation.

The glass lid is removed from the apparatus and the vacuum chamber is cleaned prior to testing. After all sample preparations are completed, the sample is then transported to the chamber via clean metal tongs. The glass lid is placed and centered over the chamber for a secure fit. The vacuum lines connecting the chamber to the pump are all opened and air is free to be evacuated. The thermocouple gauge is switched on to start reading internal chamber pressure. The vacuum pump is then turned on and an external fan is used to cool the pump from overheating.

TESTING:

Three tests are performed: a 2-hour test, a 24-hour test, and a 48-hour test, respectively – each using a different marshmallow sample and prepared using the previously stated guidelines.

(Note: To analyze what other species outgassed from the sample, rinse the test chamber lid with solvent into a beaker and concentrate the rinse sample to an appropriate volume by blowing it down with dry nitrogen gas. Run the sample using a GC/MS and identify the species by looking at the chromatogram's significant ion peaks.)

DATA PROCESSING:

Final sample dimensions are measured post-test completion, its mass reweighed, and its total mass loss calculated by using the following equation:

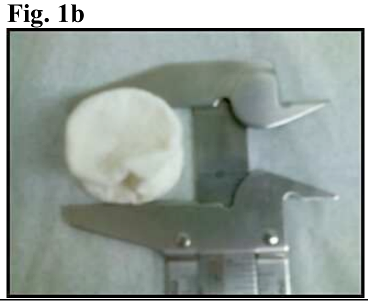
$$\text{TML (\%)} = [\,(m_i - m_f) / m_i]*100 \qquad [1]$$

where m indicates a measured sample mass and the subscripts i and f indicate initial and final sample weighings, respectively.

RESULTS:

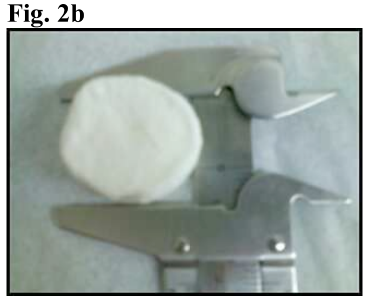
[Table 1]

Test Interval	Initial Mass (g)	Initial Dimensions (cm)	Final Mass (g)	Final Dimensions (cm)	Δ Mass (g)	End Pressure (mTorr)	TML (%)
2-hour	7.101	2.8 high x 3.6 dia.	6.648	2.1 high x 2.2 dia.	0.4530	125	6.374

Sample Picture I (post-vacuum)	**Sample Picture 2 (post-vacuum)**
Fig. 1a 	**Fig. 1b** 

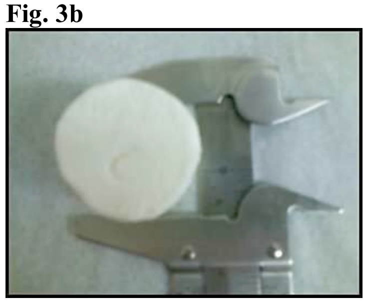
[Table 2]

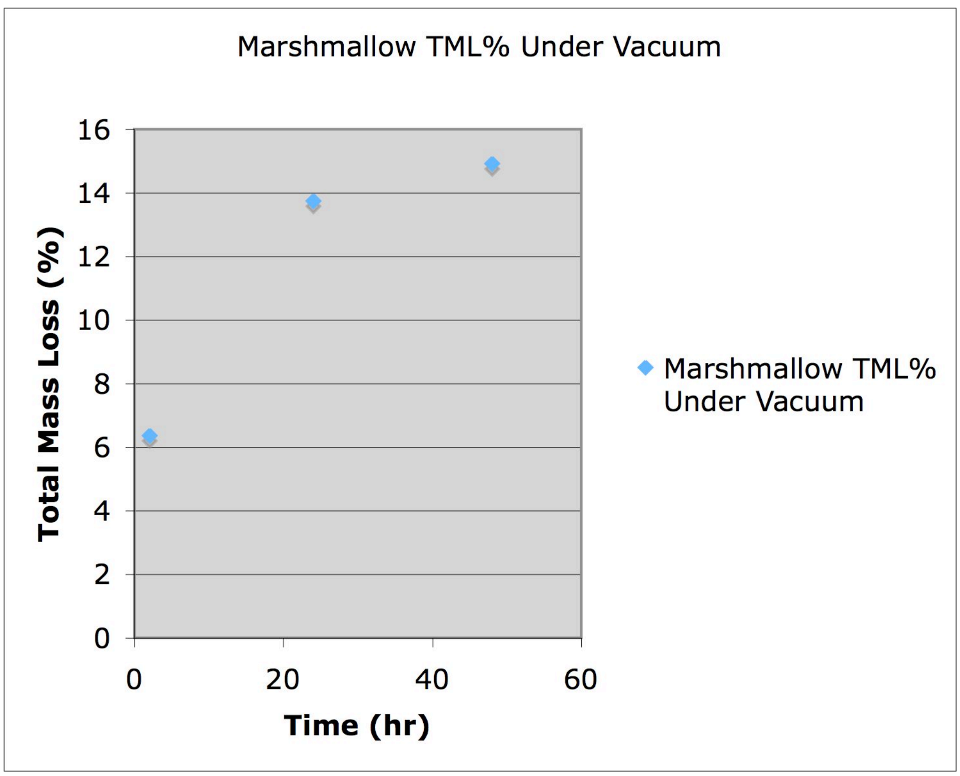
Test Interval	Initial Mass (g)	Initial Dimensions (cm)	Final Mass (g)	Final Dimensions (cm)	Δ Mass (g)	End Pressure (mTorr)	TML (%)
24-hour	6.3787	3.4 high x 3.7 dia.	5.501	3.85 high x 4.1 dia.	0.8770	12	13.75

Sample Picture I (post-vacuum)	**Sample Picture 2 (post-vacuum)**
Fig. 2a 	**Fig. 2b** 

[Table 3]

Test Interval	Initial Mass (g)	Initial Dimensions (cm)	Final Mass (g)	Final Dimensions (cm)	Δ Mass (g)	End Pressure (mTorr)	TML (%)
48-hour	7.261	3.7 high x 3.55 dia.	6.177	4.1 high x 4.0 dia.	1.084	9	14.93

<u>Sample Picture I (post-vacuum)</u>	**<u>Sample Picture 2 (post-vacuum)</u>**
Fig. 3a 	**Fig. 3b** 



[Fig. 4] Total mass loss (%) as a function of time (hr) for marshmallow samples under vacuum conditions

DISCUSSION:

Before the air is evacuated out of the chamber, the marshmallow is still in its normal state; its dimensions neither shrink nor expand. This is because the pressure of air packets within the marshmallow structure is balancing the air pressure still present inside the chamber but outside of the sample. When the vacuum pump is turned on and the air pressure begins to drop within the chamber, less air pressure is pushing in on the marshmallow, but the same pressure within the sample continues to push outwards. Because of this unequal balancing, the marshmallow structure begins to expand. During this time, much of the air within the marshmallow begins to escape. When the vacuum pump is turned off and the chamber is restored back to atmospheric pressure, the force of the air rushing in collapses the marshmallow structure. This is because much of the air inside the structure has dissipated under vacuum conditions and is no longer strong enough to balance the opposing air pressure. [2]

Fig. 1a complies to this collapsing notion. Notice how the structure has been weakened around its midsection due to the effects of vacuum conditions, causing it to cave inwards when the chamber was restored back to atmospheric pressure. However, fig. 2a and 3a show a different phenomenon. Their post-test dimensions (see Table 1) show that they remained in their expanded state, even after the chamber was restored to atmospheric pressure. It is possible that when the marshmallow samples are subjected to vacuum conditions at longer time intervals, their internal structure changes in the process sand becomes more rigid.

In measuring the TML % of each sample, the experiment confirmed that with longer test time intervals at lower internal chamber pressures, more of the sample's total mass was lost.

Fig. 4 shows that the outgassing rate, the time at which it takes for mass to diffuse out of the sample, is leveling off. It can be noted that a further experiment can be conducted for a longer period of time, but a significant amount of mass will not be lost. Note that in Table 1 that the difference in TML % between the 24-hour test and the 48-hour test is approximately one percent. Any longer test time intervals would expect to show fractions of a TML %.

REFERENCES:

1. J.W. Garrett, A.P.M. Glassford, and J.M. Steakley. ASTM E 1559 Method for Measuring Material Outgassing/Deposition Kinetics. 6, (1993).
2. Phun Physics Demonstrations. http://www.phun.physics.virginia.edu/demos/marshmallow.html

APPENDIX

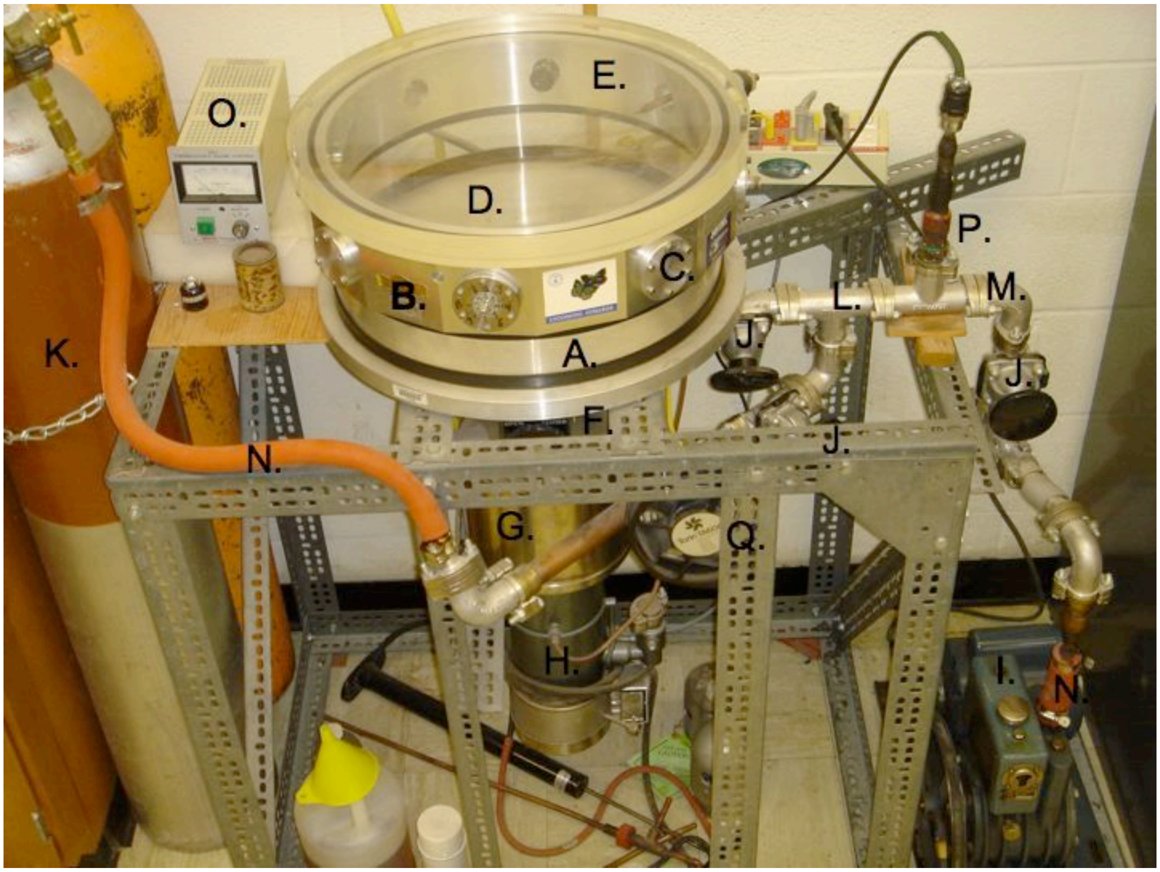
APPENDIX

Table 7: Product Inventory.

Item	Vendor	/N	Item Description	Qty	Unit Cost	Total
1	DV Manufacturing	--	Foreline trap, NW25 Fittings	1	$ 150.00	**$ 150.00**
2	DV Manufacturing	--	SSt Adapter: 2 ¾" O-ring flange to ¼" tubing	1	$ 30.00	**$ 30.00**
3	DV Manufacturing	--	SSt Adapter: 2 ¾" O-ring flange to NW25	1	$ 58.00	**$ 58.00**
4	DV Manufacturing	--	SSt Adapter: 2 ¾" O-ring flange to NW40	1	$ 60.00	**$ 60.00**
5	DV Manufacturing	--	Viton O-rings for 2 ¾" O-ring flanges	8	$ 2.00	**$ 16.00**
6	DV Manufacturing	--	SSt Adapter: 2 ¾" ConFlat to NW25	1	$ 60.00	**$ 60.00**
7	DV Manufacturing	--	SSt bellows, 1-m long, NW25 fittings	1	$ 158.00	**$ 158.00**
8	DV Manufacturing	--	SSt blank, NW25	1	$ 7.50	**$ 7.50**
9	DV Manufacturing	--	SSt blank, NW40	1	$ 11.50	**$ 11.50**
10	DV Manufacturing	--	SSt blank plate, 9.75-in O.D. by 0.5-in thick	1	$ 200.00	**$ 200.00**
11	Nor-Cal Products	2NR-NW-40-25	NW40 to NW25 reducer nipples	1	$ 39.00	**$ 39.00**
12	Nor-Cal Products	NW-40-CP	Clamp, NW40 wing nut assembly	3	$ 8.25	**$ 24.75**
13	Nor-Cal Products	NW-25-CP	Clamp, NW25 wing nut assembly	4	$ 7.00	**$ 28.00**
14	Nor-Cal Products	NW-40-CR-SV	Ring, NW40 centering ring, SSt with Viton O-ring	3	$ 9.50	**$ 28.50**
15	Nor-Cal Products	NW-25-CR-SV	Ring, NW25 centering ring, SSt with Viton O-ring	4	$ 6.50	**$ 26.00**
16	Nor-Cal Products	ILV-1502-CF	Valve, manually operated, in-line, 2 ¾" CF Fitting	1	$ 330.00	**$ 330.00**
17	Swagelok	SS-4BK	Bellows valve, ¼" (for vent)	1	$ 138.70	**$ 138.70**
18	Duniway Stockroom	G-275	2 ¾" ConFlat copper gaskets	4	$ 1.75	**$ 7.00**
19	Duniway Stockroom	SBN-28-212	Bolts, ¼" x 28 with washers and nuts	12	$ 14.00	**$ 168.00**
20	Duniway Stockroom	12-PT-WRENCH	Wrench, ¼" and 5/16" 12 point bolts	1	$ 14.00	**$ 14.00**
21	Duniway Stockroom	--	Wrench, 7/16" combination open/box end	1	$ 5.00	**$ 5.00**
22	Duniway Stockroom	275912-EU	Mini convection module, digital display, Torr	1	$ 530.00	**$ 530.00**
23	Duniway Stockroom	275933	Wall transformer, 120 Vac to 12 Vdc	1	$ 50.00	**$ 50.00**
24	Duniway Stockroom	DC-150	Dow Corning High Vacuum Grease	1	$ 17.00	**$ 17.00**
25	VWR Scientific	63014-714	Tubing, Teflon, ¼" O.D. 3/16" I.D. 4' long	4	$ 4.06	**$ 16.24**
26	Swagelok	SS-400-NFSET	SSt Swagelok fittings, 1'4" nut with ferrules	2	$ 3.22	**$ 6.44**
27	MSC Industrial	505-689	Calipers, 6" dial, 0.001 resolution	1	$ 106.00	**$ 106.00**
					Merchandise Total:	**$ 2,285.63**
					Sales Tax: (8.25%)	**$ 188.65**
					Total:	**$ 2,474.28**

APPENDIX

Original System.



[Fig. 3]: Original System.

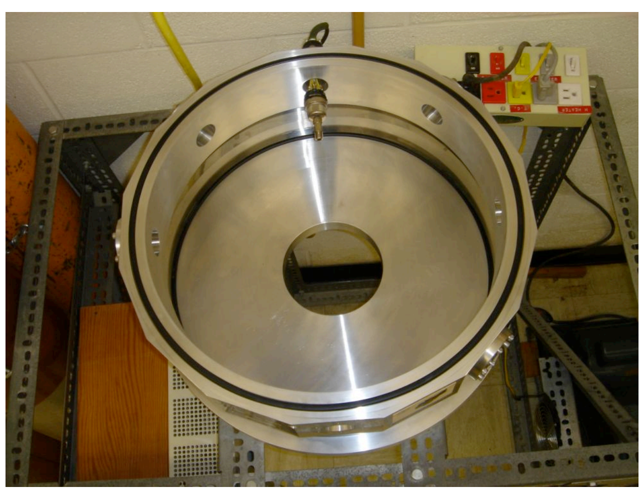
A. Glass cylinder
B. Stainless steel chamber collar
C. Chamber collar "blanks"
D. Stainless steel plate - base
E. Glass lid - top
[A, B, C, D, E make up main test chamber.]

F. SPEEDIVAC Baffle Valve
G. SPEEDIVAC Mercury Vapor Trap
H. SPEEDIVAC Diffusion Pump
I. DUO-SEAL mechanical vacuum pump
J. SPEEDIVAC valves
K. Exhaust cylinder tank
L. SPEEDIVAC vacuum lines
M. SPEEDIVAC wing-nut assemblies
N. Rubber hosing
O. Veeco Thermocouple Gauge Control
P. Veeco Thermocouple Gauge Tube
Q. External fan

Main test chamber.

[Fig. 4a]: Main test chamber.

[Fig. 4b]: Chamber collar, glass cylinder, and stainless steel plate.



[Fig. 4c]: Stainless steel plate with exposed hole.

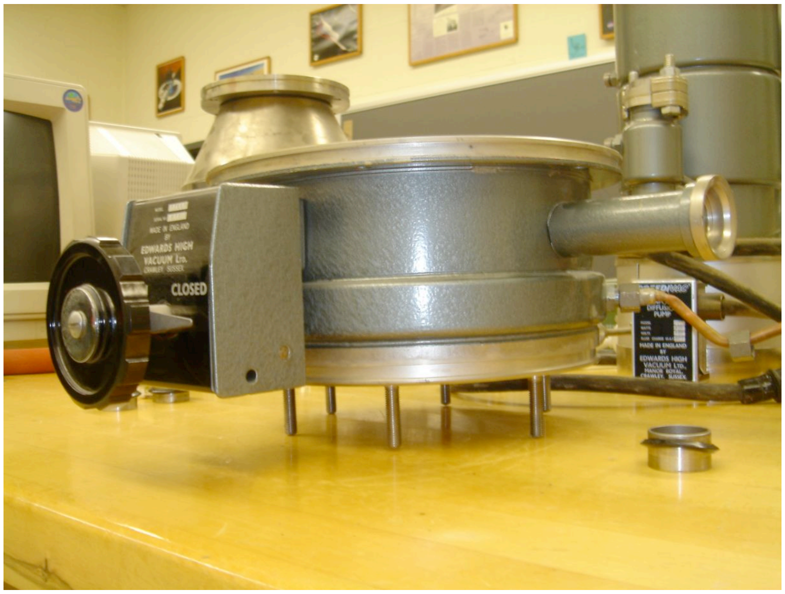
APPENDIX

Unused Components.

[Fig. 5]: Unused components.

APPENDIX

VEECO Baffle Valve.



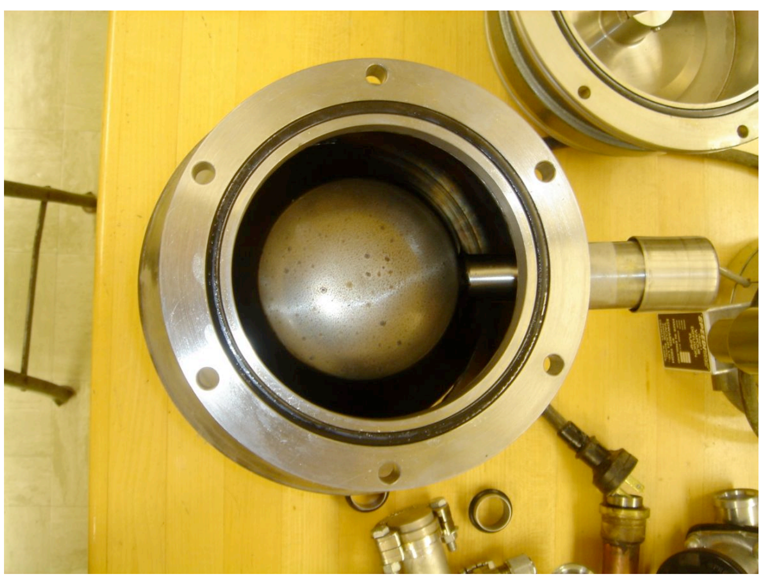
[Fig. 6a]: VEECO Baffle Valve.

[Fig. 6b]: Closed baffle valve to terminate diffusion pumping.

[Fig. 6c]: Open baffle valve to allow diffusion pumping.

SPEEDIVAC Mercury Vapor Trap.

[Fig. 7a]: SPEEDIVAC Mercury Vapor Trap.

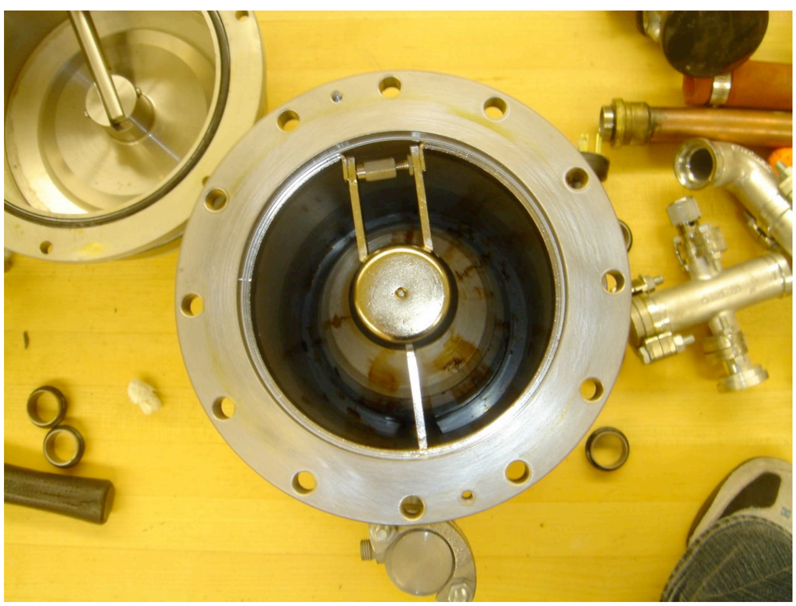


[Fig. 7b]: Vapor trap seen from above.
*Note: Coalesced dirt and rust on inner surface area.

APPENDIX

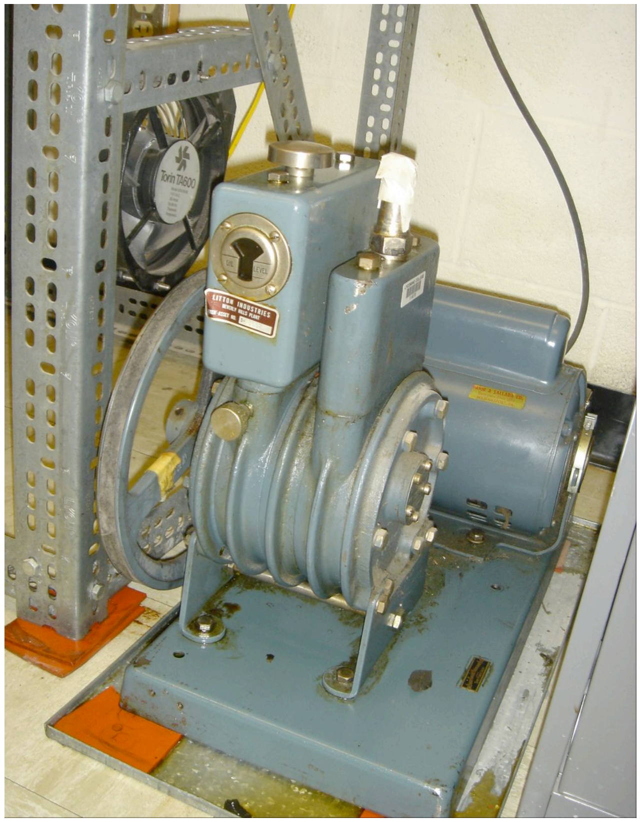
SPEEDIVAC Diffusion Pump.

[Fig. 8a]: SPEEDIVAC Diffusion Pump.



[Fig 8b]: Diffusion pump seen from above.
*Note: Coalesced dirt and rust on inner surface area.

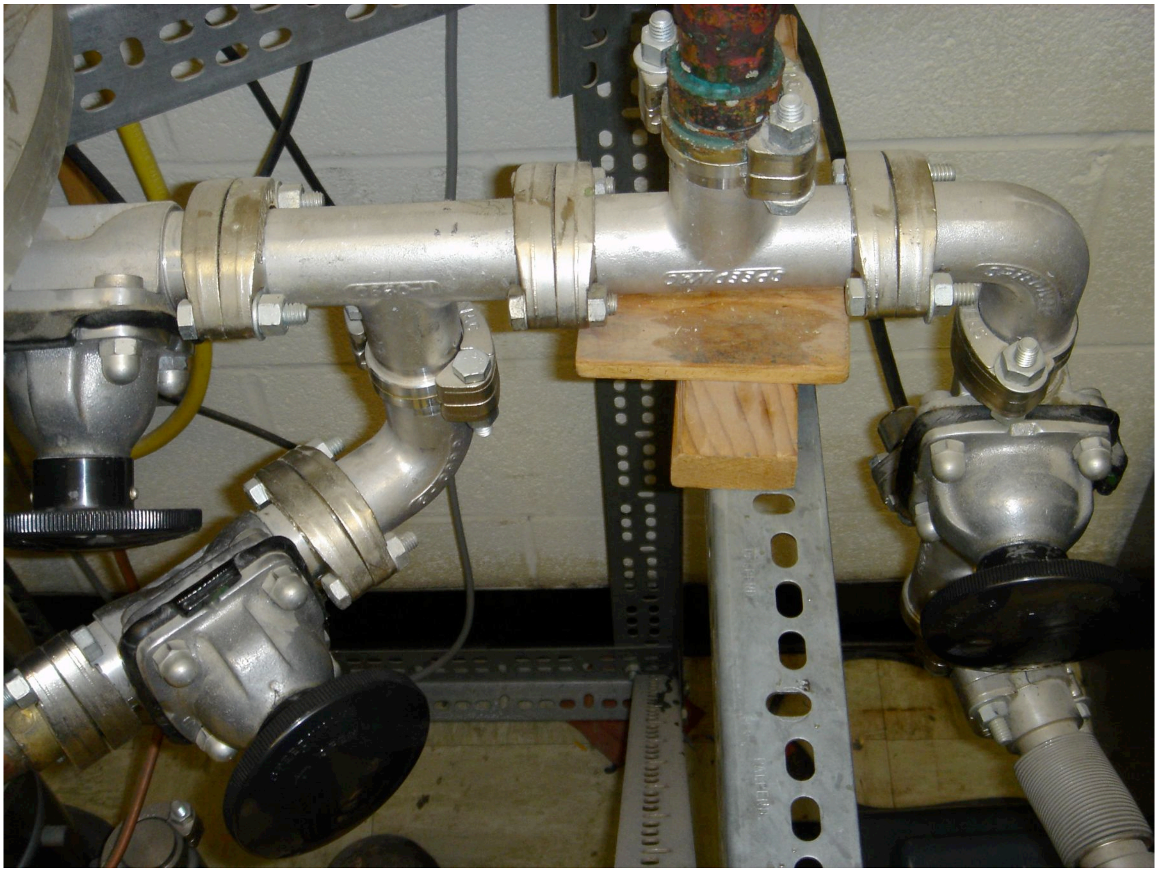
Duo-Seal Vacuum Pump.



[Fig. 9a]: Duo-Seal Vacuum Pump.

[Fig. 9b]: Vacuum pump seen from above.

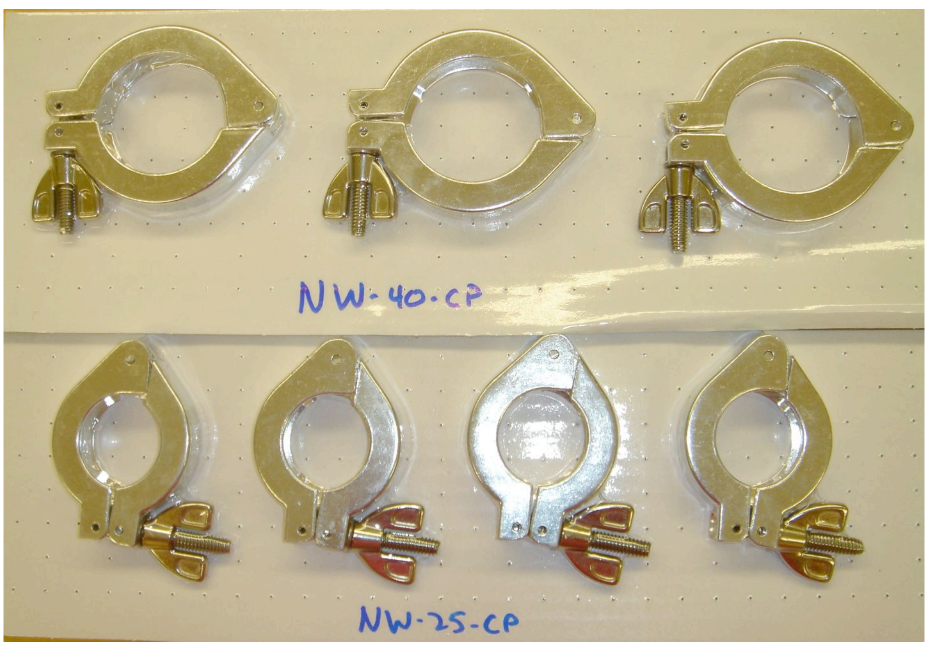
External Components.



[Fig. 10]: SPEEDIVAC flanges, valves, vacuum lines, and thermocouple gauge tube.

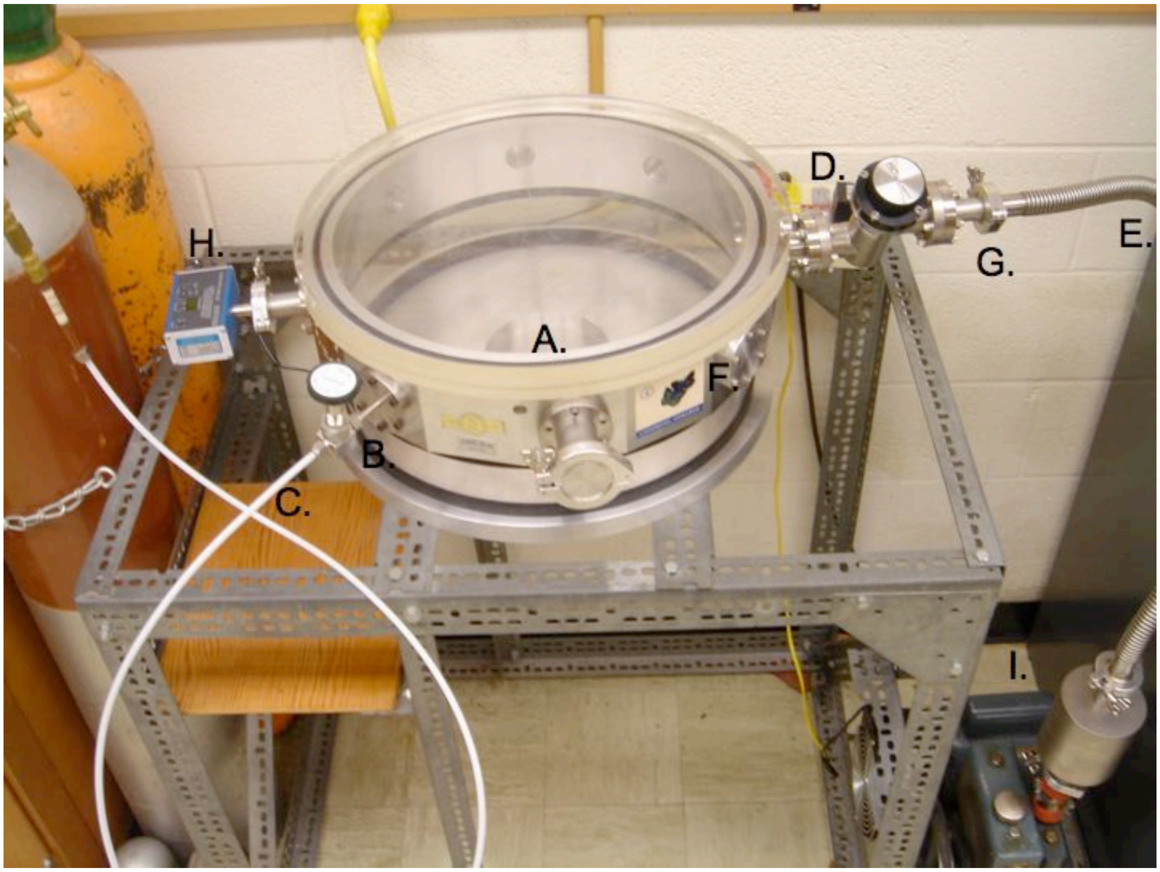
Flanges vs. Wing Nut Assemblies.

[Fig. 11a]: SPEEDIVAC flanges.



[Fig. 11b]: Nor Cal Products wing nut assemblies.

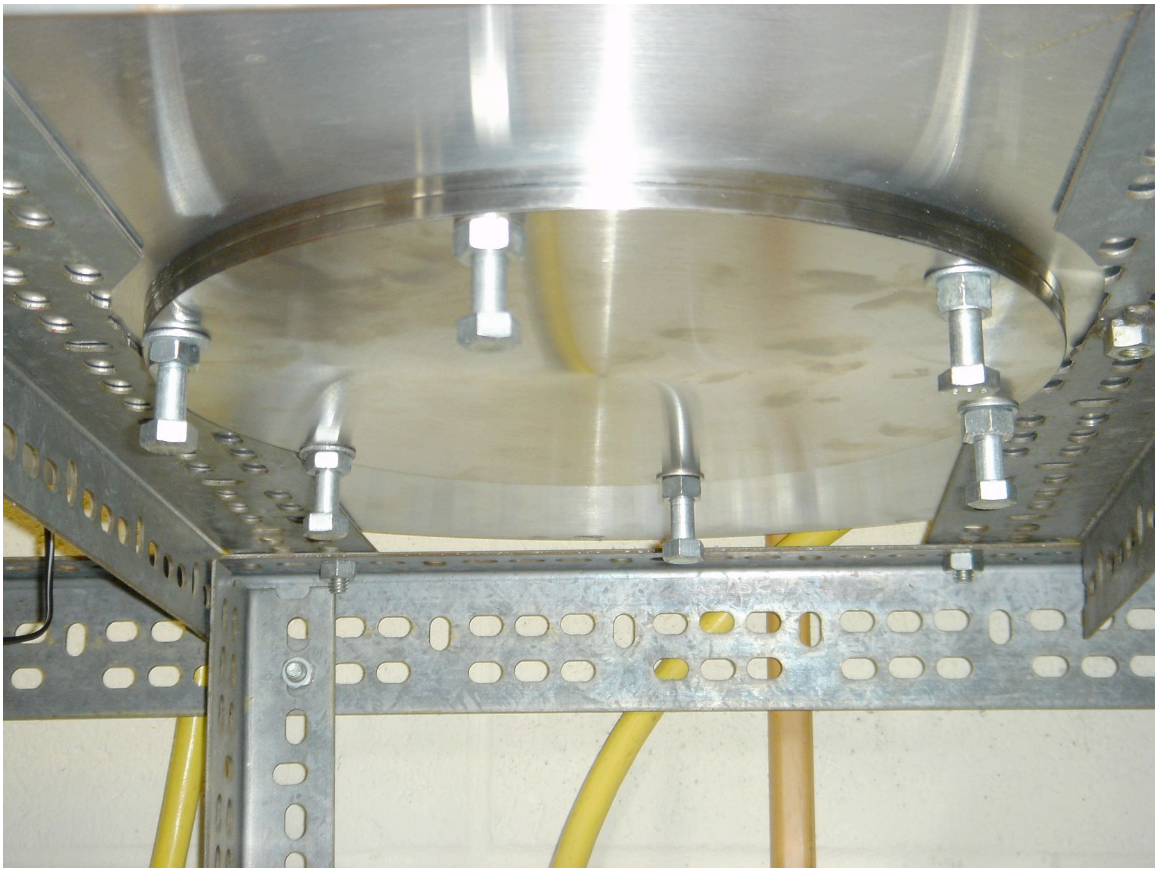
Refurbished System.



[Fig. 12]: Refurbished system.

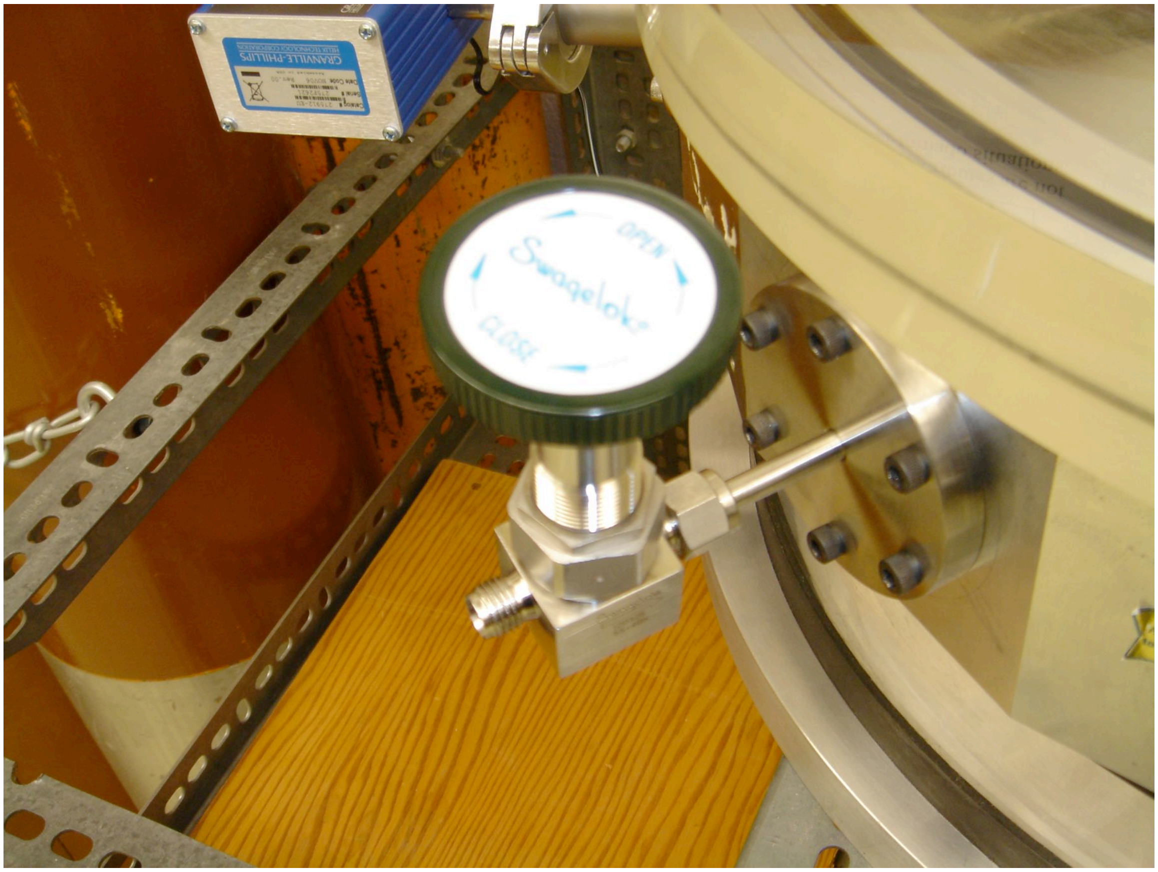
A. Custom stainless steel plate
B. Swagelok bellows valve
C. Teflon tubing
D. Nor-Cal Products valve
E. Stainless steel bellows (1-m long)
F. Chamber collar "blanks"
G. Nor-Cal Products wing nut assemblies
H. Digital thermocouple gauge
I. Foreline trap

Custom Stainless Steel Plate.



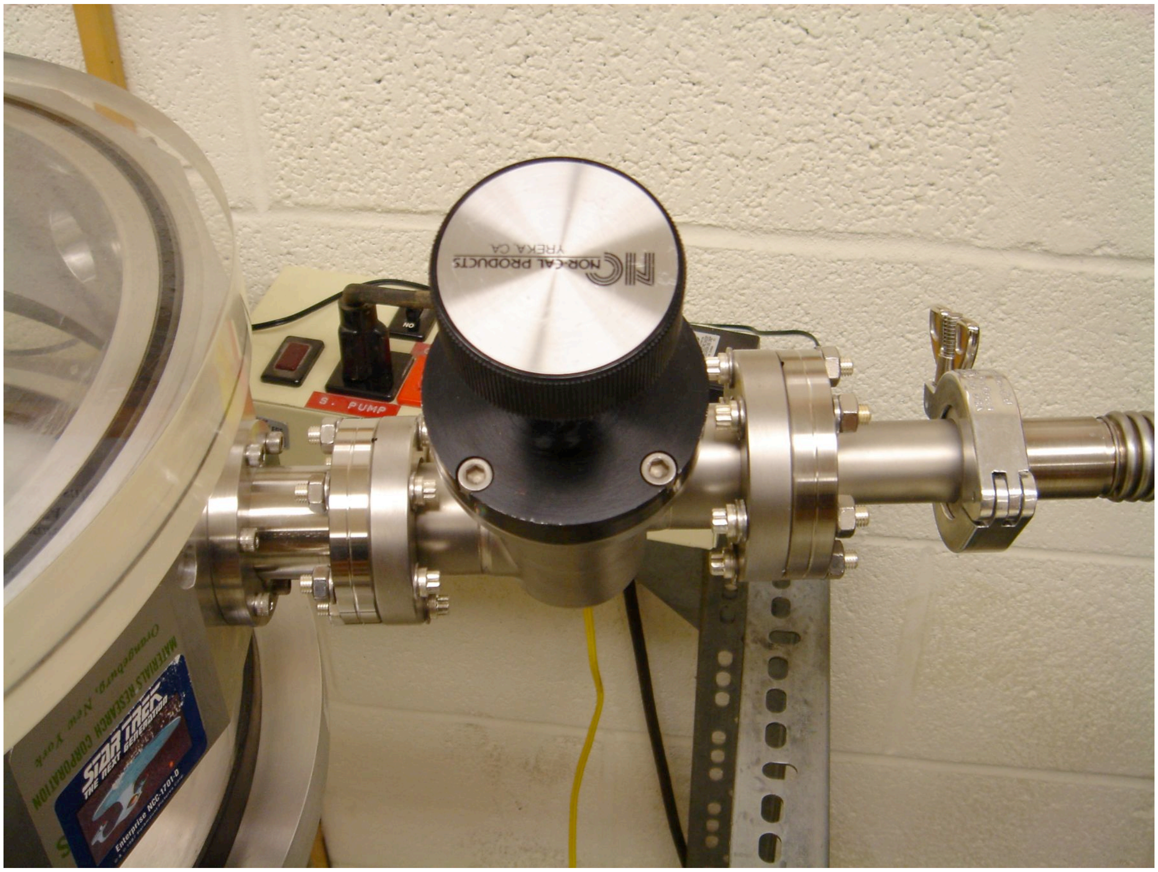
[Fig. 13]: Custom stainless steel plate to cover exposed hole in test chamber.

Swagelok Bellows Valve.



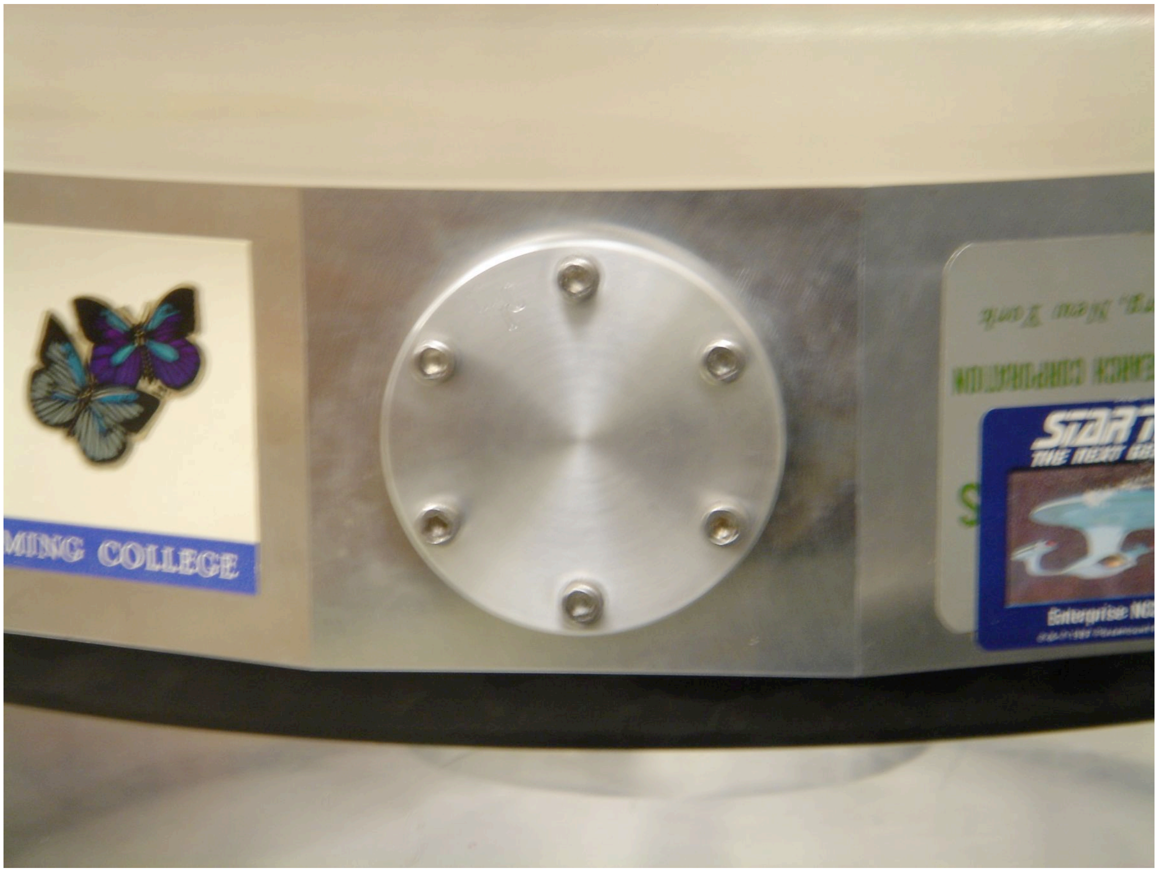
[Fig. 14]: Swagelok bellows valve to vent test chamber back to atmospheric pressure.
(Teflon tubing not pictured.)

Nor-Cal Products Valve.



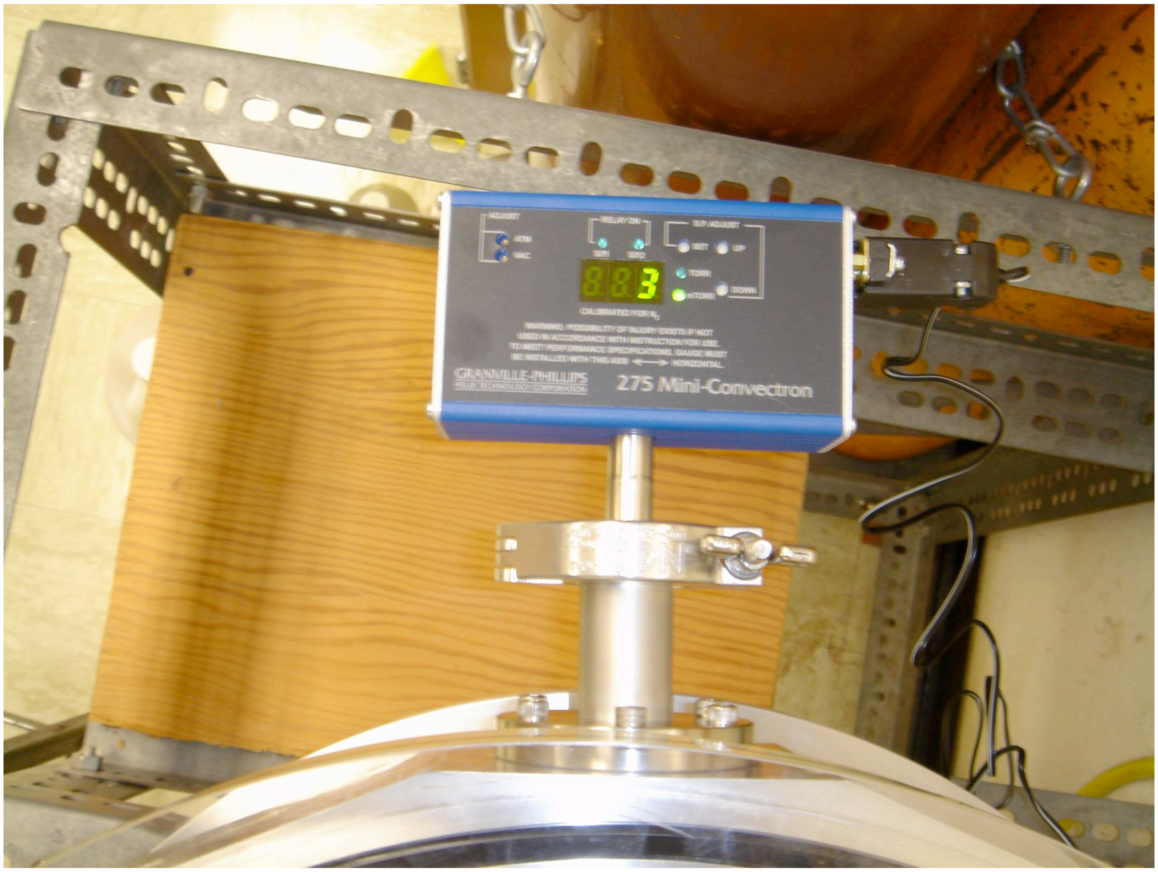
[Fig. 15]: Nor-Cal Products valve and wing nut assembly.

Nor-Cal Products Chamber Collar "Blanks."



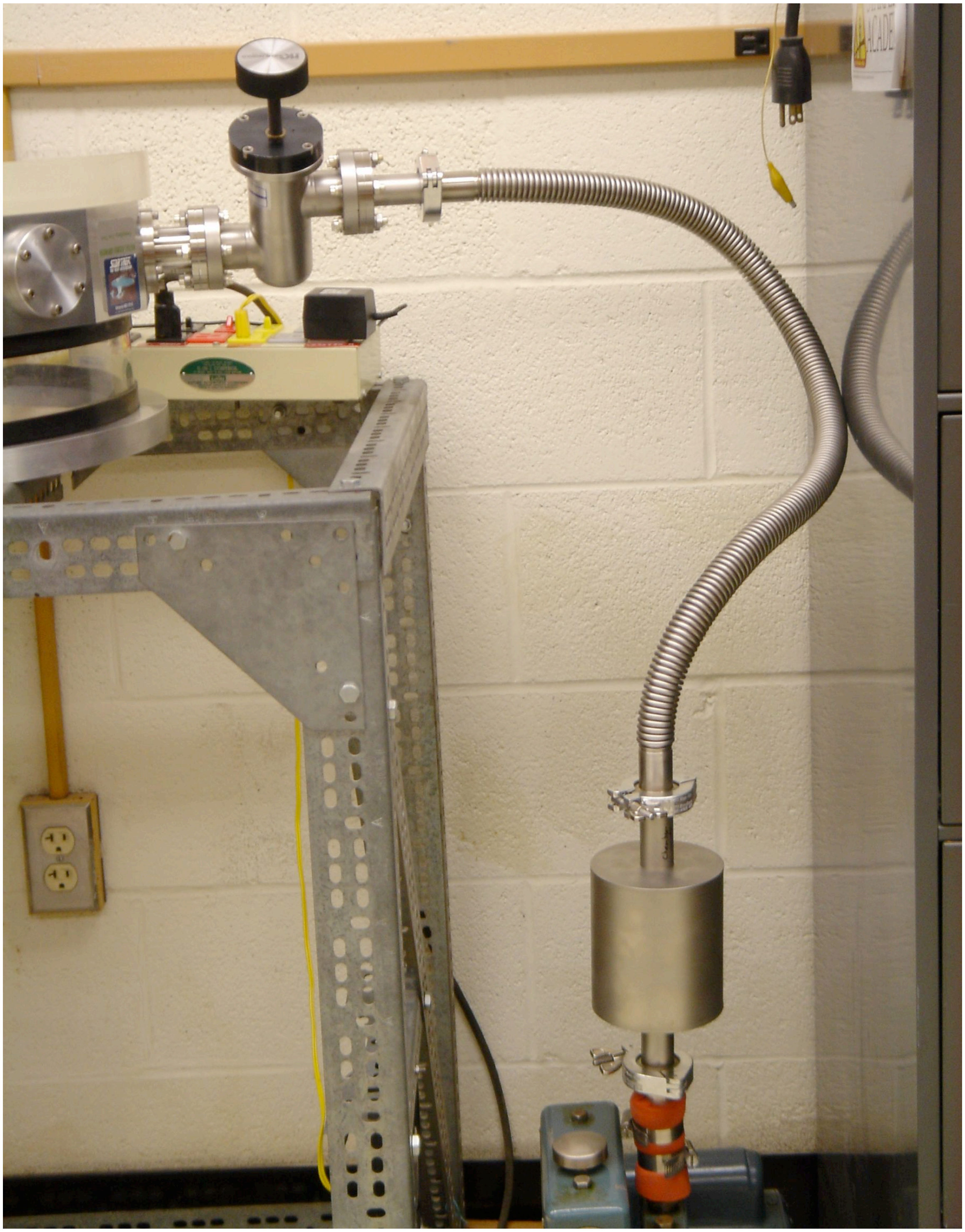
[Fig. 16]: Chamber collar "blank."

Duniway Stockroom Mini Convection Module.



[Fig. 17]: Digital thermocouple gauge bolted directly to chamber collar.

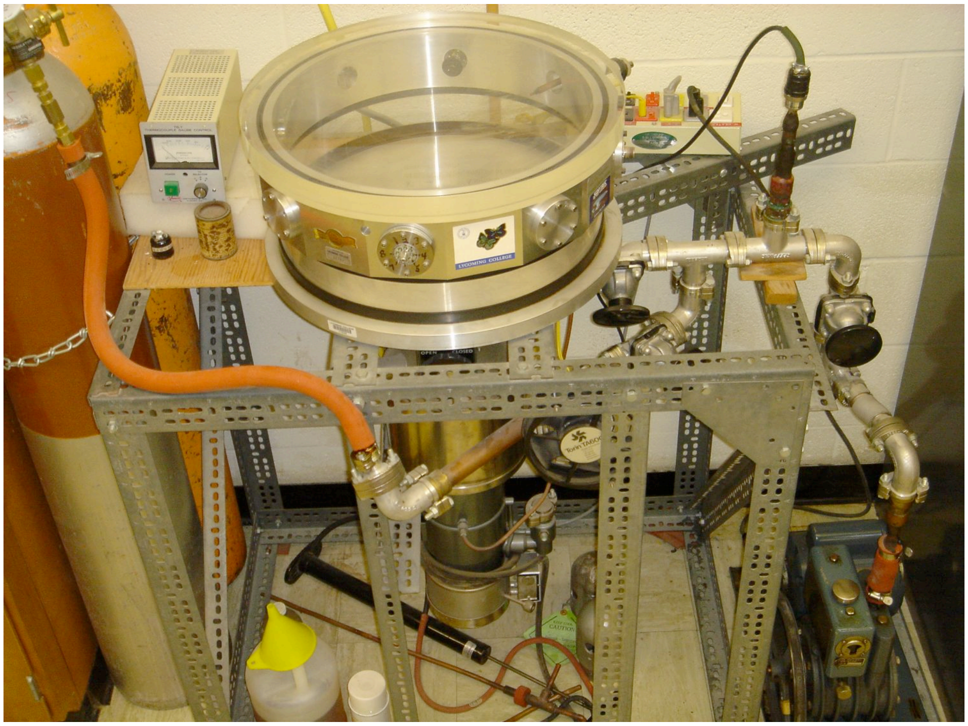
Foreline Trap.



[Fig. 18]: Chamber collar blank, Nor-Cal Products valve and wing nut assemblies, stainless steel bellows, and foreline trap.

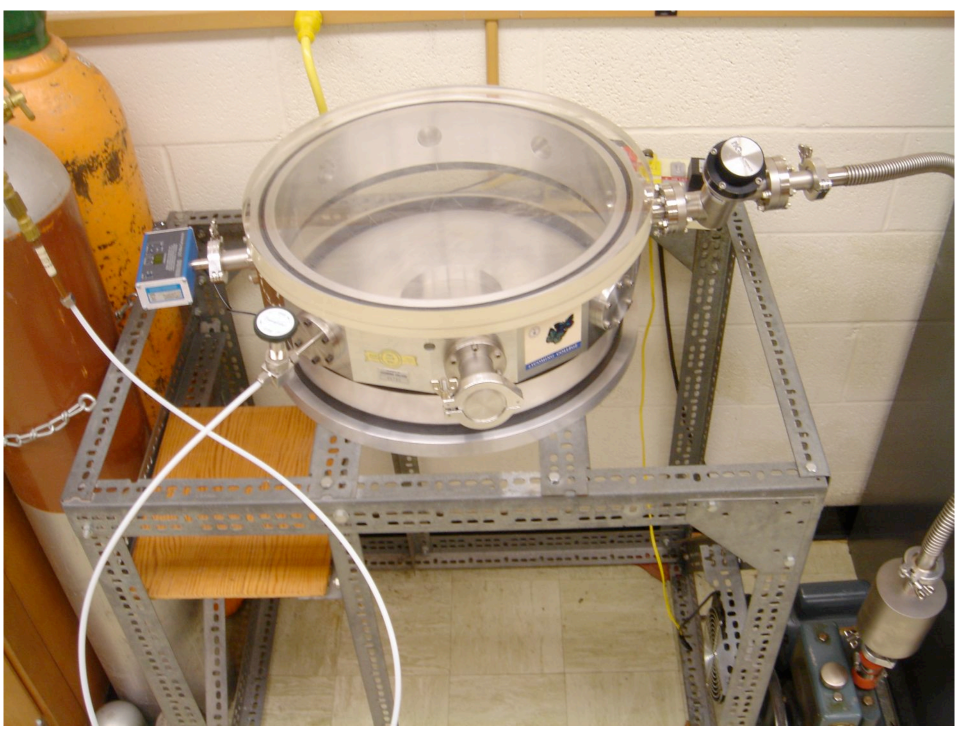
APPENDIX

Before.



[Fig. 19a]: Original System.

After.



[Fig. 19b]: Refurbished System.