Jabil Guidelines for Manufacturing High Vacuum Chamber

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Abstract

Manufacturing vacuum chambers requires fabrication that ensures leak-free performance under demanding conditions. Producing a very high vacuum chamber ($1x10^{-6}$ to $1x10^{-8}$ torr) is one of the most challenging areas in the design and manufacturing of instruments such as Mass Spectrometers (MS). The goal of this paper is to introduce the basic guidelines for manufacturing a rectangular chamber that will achieve very high vacuum levels without compromising cost or required performance by explaining the various manufacturing, cleaning and quality assurance processes (feel free to re-word this, I was just looking at adding some additional details in the abstract to show a more comprehensive overview of the paper).

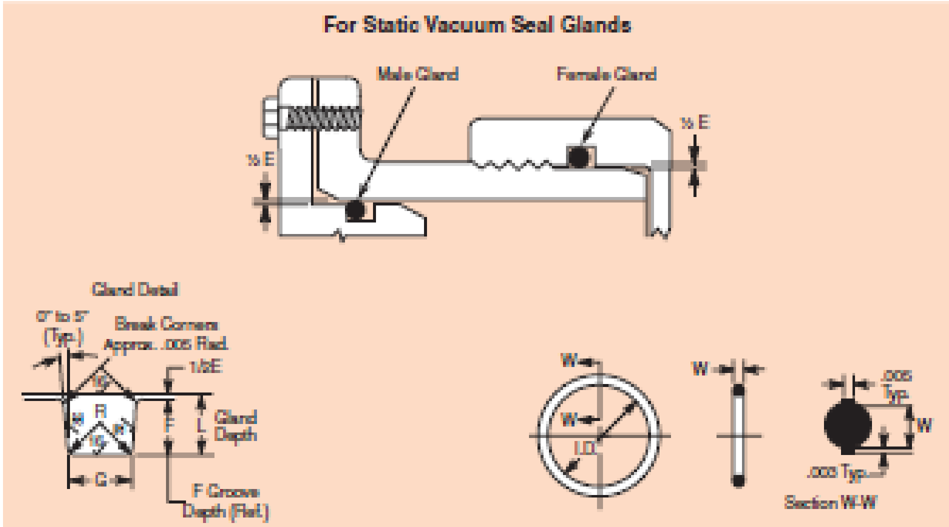
Introduction

There are several aspects that must be taken into account while manufacturing high vacuum chambers, among them are the following: mechanical seals to ensure that the chamber's vacuum is kept intact (i.e. welding of flanges, surface finish of sealing surfaces, etc.), material compatibility (outgassing, chemical reactions, etc.), cost/performance, cleaning process (ultrasound baths with various solvents), and quality assurance (leak testing, contaminates control, etc.). Jabil has extensive experiences and knowledge with manufacturing process of very high vacuum systems for medical and research institutions. These experiences position Jabil to be one of the top manufacturers of high quality vacuum instrumentations such as mass spectrometers. The focus of this paper will be on common manufacturing, cleaning, and quality assurance processes for chambers in the very high vacuum (VHV) with a range of $1 X 10^{-6}$ to $1 X 10^{-8}$ torr.

Manufacturing Process

There are many ways to manufacture rectangular chambers, some of them are machining from a metal billet, welding of walls together (most commonly used in making large chambers), and in higher quantities - extrusions or castings. In mass spectrometry, the most common way of construction are "Hog-outs"; basically by removing material from a billet of aluminum or stainless steel. Features such as high tolerance features for mounting flanges and surface finish specifications for sealing surfaces must be achieved in order to reach the specified vacuum levels. In addition, the correct chemicals and processes must be utilized in order to prevent outgassing or water vapor retention.

- **Materials –** The two most common materials used to construct Mass Spectrometer chambers are aluminum and stainless steel (SS) 304L or 316L. Due to its cost, weight, ease of machinability, and lower hydrogen content, aluminum is the material of choice when manufacturing very high vacuum chambers. Some of the drawbacks are: it can't be baked thoroughly and is not as easy to weld as SS. So it is not recommended for ultrahigh vacuum.
- **Machining –** There are many ways of creating VHV chambers including casting, welding or extrusions, but the most popular way is machining hog-outs, or coring out the chamber's cavity. Due to its cost and weight, most of these chambers are made out of Aluminum.
  - Main Chamber – Standard edge tolerances are as follows:
    - Edges (HV region) chamfer – 1mm
    - Deburr (HV region) – Radius: .762mm to 1.27mm
  - Coolant – Water cooling (oil-less & Sulfur free) is the most common coolant used in machining chambers. The lubricants used must be at extremely low vapor pressure and preferably applied at constant flow without interruptions. Features that require coolant should be machined in the early stages. The machinist must take into account the coolant path, pressure, temperature and heat dissipating capacity when determining the water rates. This is done to minimize coolant residue on the part's surfaces and crevices, preventing outgassing.
  - Tolerances – Standard tolerances are as follow:
    - General features : ±.127mm
    - Most Critical features (i.e. flanges, sealing features) : ± .050mm
    - Tightest tolerance: ± .025mm
    - Angles: ±1/2°
  - O-ring groove
    - Size & tolerances
      - Groove depth: +.152mm/-.000
      - Groove OD: +.000/-.152
      - Groove width: +.254mm/-.000



Design Chart Static Vacuum Seal Glands

O-Ring Size AS568A-	W Cross-Section Nominal	W Cross-Section Actual	L Gland Depth	Squeeze Actual	Squeeze %	E Diametral Clearance	G Groove Width	R Groove Radius	Max.* Eccentricity
004 through 050	1/16	.070 ±.003	.050 to .052	.015 to .023	22 to 32	.002 to .005	.093 to .098	.005 to .015	.002
102 through 178	3/32	.103 ±.003	.081 to .083	.017 to .025	17 to 24	.002 to .005	.140 to .145	.005 to .015	.002
201 through 284	1/8	.139 ±.004	.111 to .113	.022 to .032	16 to 23	.003 to .006	.187 to .192	.010 to .025	.003
309 through 395	3/16	.210 ±.005	.170 to .173	.032 to .045	15 to 21	.003 to .006	.281 to .286	.020 to .035	.004
425 through 475	1/4	.275 ±.006	.226 to .229	.040 to .055	15 to 20	.004 to .007	.375 to .380	.020 to .035	.005

*Total indicator reading between groove and adjacent bearing surface.

Figure 1 Design Chart for Static Vacuum Seal Glands

Surface Finish of Vacuum Gland				
	Surface Roughness of Vacuum Gland Load Area t_p > 50%			
	A Contact Area		B Gland Flanks	
	R_a	R_{max}	R_a	R_{max}
Vacuum	0.8	3.2	1.6	6.3
to 10^{8} Torr	0.4	1.6	1.6	6.3
to 10^{11} Torr	0.10	0.40	1.6	6.3

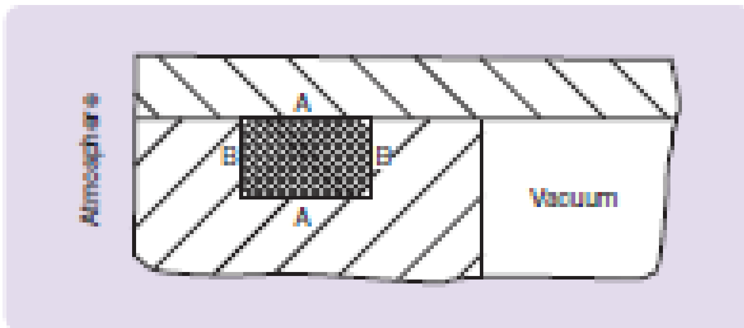


Figure 2- Parker guide "Surface Finish of Vacuum O-ring Gland

- **Vacuum Flanges –** These flanges are used to attach components that are assembled to the chamber and can't be permanently fixed to it. These parts could occasionally be serviced or replaced and can't be welded due to heat sensitivity. The most common are valves, pumps and gauges. In many cases, the flange's features (i.e. knife edge) are machined on the chamber or covers. In most cases though, one of the mating flanges is welded onto the chamber.

  - ConFlat (CF) – This type of seal was originally developed and trademarked by Varian, Inc in the 1960's. It creates a metal seal between 2 surfaces by squeezing a soft metal gasket between 2 knife edge features in the (often) stainless steel mating surfaces. This provides a extremely leak-tight, metal to metal seal rated to 10^{-13} torr. This type of flange is sexless and operates within the temperature range -196°C to 450°C.

  - Quick Release Flange (KF, QF, NW or DN) – Designed to be quick release flanges. The basic design squeezes a centering ring containing an elastomeric o-ring between two chamfered flanges. The flanges and centering ring are held in place by a circumferential clamp tightened by a fastener (i.e. wing-nut or over-center level). This type of flange is rated to a minimum of 10^{-8} torr and 0°C to 180°C depending on the elastometer chosen.

  - ISO Flange (LF, LFB or MF) – Just like the quick release flange, the ISO flange are joined by a centering ring and an elastomeric o-ring. Instead of the circumferential clamp, the flanges are secured by bolts (ISO-F or ISO LFB) or several small clamps (ISO-K or ISO-LF) along the flange's circumference. These flanges are larger than quick release flanges with nominal tube diameters between

63 and 500mm. This type of flange is rated to a minimum of 10^{-8} torr and 0°C to 180° C depending on the elastometer chosen.

- **Vacuum Fittings**
  - VCR – Fittings with metal seals made out of 316L stainless steel. They are often used in ultra high vacuum applications due to the ability to seal down to 4 X 10^{-11} std cm3/s without virtual leaks.
  - VCO – Fittings with FKM (viton) seals made out of 316L stainless steel. They are often used in high vacuum applications. The VCO face seal fitting design has been helium leak tested to a maximum leak rate of 4 X 10^{-9} std cm3/s.

- **Welding**
  - Inert gas (TIG welding) – As most of the high vacuum chambers are made out of either Aluminum or Stainless Steel, one of the vast majority preferred welding methods is the Tungsten Inert Gas (TIG) welding / Gas Tungsten Arc Welding (GTAW). This method is commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys. In TIG welding/GTAW, a non-consumable tungsten electrode heats the welding metal and the inner shielding gas (most commonly Argon or Helium) protects the weld puddle from airborne contaminants. TIG welding/GTAW produces clean, high quality and precise welds.
    - High purity Argon, Helium, Argon-Helium, Argon-Hydrogen

      - In TIG welding, shielding gases are necessary to protect the welding area from atmospheric gases such as nitrogen or oxygen that can cause fusion defects, porosity, and weld metal embrittlement if they come in contact with the electrode, the arc, or the welding metal. The gas also functions to transfer heat from the tungsten electrode to the metal, and it helps to initiate and maintain a stable arc.

      - Selection of a shielding gas depends on several factors as follows:

        I) type of material being welded
        II) joint design desired
        III) desired final weld appearance

      - Argon is the most commonly used shielding gas as it helps prevent defects due to a varying arc length. When used with alternating current, the use of argon gas results in high weld quality and good appearance.

      - Other than Argon, another commonly used shielding gas is helium. Helium is most often used to increase the weld penetration in a joint, to increase the welding speed, and to weld metals with high heat conductivity, such as copper and aluminum. A significant disadvantage or drawback is the difficulty of striking an arc with helium gas and the decreased weld quality due to a varying arc length.

      - Argon-Helium mixtures are also occasionally utilized in TIG welding/GTAW since they can potentially increase control of the heat input while maintaining the benefits of using argon. Normally, the mixtures are made up of primarily Helium (often approximately 75% or higher) with a balance of Argon. These mixtures increase the speed and also the quality of the AC welding of aluminum. This also eases the effort to strike an arc.

- Another shielding gas mixture is the Argon-Hydrogen. It is used in the mechanized welding of light gauge stainless steel, but because hydrogen can cause porosity, its uses are limited.

- Avoiding artificial (virtual) leaks – This type of leak is created when gas gets trapped between the inner (vacuum side) and outer (atmosphere side) continuous weld. They are not detectable during the helium test and make it really difficult for the chamber to pump down (often impossible). The best way to prevent them is to weld continuously on the vacuum side and intermittently on the atmosphere side.

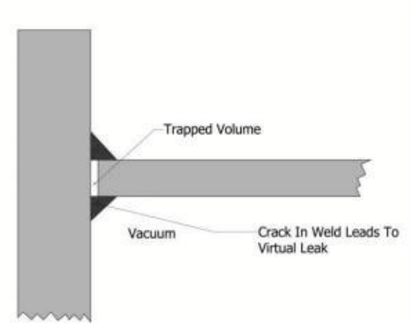


Figure 3 - Example of virtual leak due to welding

- Using proper weld symbols - Welding symbols, when properly applied to drawings, consistently and correctly interpreted; offer a potentially convenient way of controlling the welding of a particular joint, which eventually will led to the development of a standard for these activities. In order to minimize sources of virtual leaks, external welds are only used when required for structural reinforcement and are limited to configurations such as stitch, skip, span, or spot weld.
- TIG welding is best performed in a clean room under controlled relative humidity (< 40%).
- Proper fixturing may be required to avoid distortion during welding.
- Typical TIG welding parameters are:

Welding current	: 120-150 Amps
Filter Wire	: ER 316L (dia. 2.5 mm and 3.15 mm)
Shielding gas	: 99.999% (Pure Argon-Typically used)
Shielding gas flow rate	: 8 L/min
Relative humidity	: 35-40% @ 22-25^{0}C

- Nonfiller metal (ok as long as it is the same grade/quality as native material)
- Internal fusion weld (welding on the "inside" of all weld joints that are not square/buttweld.) solved by the use of correct weld symbols
  - Occasional external weld
- Welding joint design (as per Miller's welding tips):
  - Butt welds

- When welding a butt joint, the weld pool is centered on the adjoining edges. When finishing, the heat (amperage) is decreased to aid in filling the crater.

- Lap joint

  -For a lap weld, the weld pool is formed so that the edge of the overlapping piece and the flat surface of the second piece flow together. Since the edge will melt faster, the filler rod is dipped next to the edge and make sure that there are enough filler metal to complete the joint.

- T-joint

  -When welding a T-joint, both the edge and the flat surface are to be joined together, and the edge will melt faster. The torch is angled to direct more heat to the flat surface and the electrode is extended beyond the cup to hold a shorter arc. The filler rod is deposited where the edge is melting.

- Corner joint

  -Both edges of the adjoining pieces should be melted and the weld pool should be kept on the joint centerline for a corner joint. A convex bead is necessary for this joint, thus a sufficient amount of filler metal is needed.

Cleaning Process/Surface Treatment

Most of the components and tools used in the construction of the vacuum system have to be cleaned beforehand. Cleaning process is done to minimizes outgassing and contamination from environmental effects. Water vapor is the primary contaminant/gas in a vacuum system. In addition to water vapor, other chemicals, oils, lubricants, and even residue from fingerprints will also limit vacuum performance. Latex gloves were worn throughout to eliminate the possibility of stray fingerprints inside the chamber. Vacuum baking of the vacuum chamber might be required if vacuum levels need to be below 10^{-6} torr. Factors that needed to be considered when choosing the correct cleaning process are as follows:

I) The level of vacuum required (High, Ulltra High etc.)
II) Special performance requirement (eg. low desorption)
III) Presence of particular contaminant whose partial pressure should be minimized (eg. hydrocarbons)
IV) The type of materials that the items are made from
V) Item construction method
VI) Cost and safety

Cleaning processes available are:

- **Solvents**
  1. Acetone – aggressive solvent that works for a range of contaminates but may leave residue
  2. Alcohols – Do not dissolve as many substances, but evaporate without leaving residue
  3. Methanol – Most aggressive and quickest to evaporate. Good for cleaning visible dirt

4. Isopropyl – Gentlest and safest to use. It evaporates more slowly, so it is great for ultrasound
5. Ethanol – Is not as aggressive as Methanol or as gentle as Isopropyl

- **Ultrasound washing with acetone**
    1. Ultrasound the parts for 15 minutes in acetone – Place the parts in a solid clean receptacle and pour acetone to completely submerge all parts. While wearing gloves, remove the parts from the acetone bath and place them on an oil-less clean foil. DO NOT REUSE THE ACETONE.
    2. Rinse the parts with isopropanol – To eliminate any residue from acetone
        a. Hold the part by an external surface and spray with isopropanol. Let it dry in air. OR
        b. Hold the part by an external surface and blast it with Nitrogen
    3. Bake the parts in a vacuum oven
- **Ultrasound washing rinsed with decon90**
    1. The items were cleaned for 30 minutes in a 5% solution of decon90 in an ultrasonic cleaner.
    2. After draining, residual decon90 was removed by rinsing in tap water for 10 minutes.
    3. The items were then cleaned with distilled water in an ultrasonic cleaner for a further 60 minutes
    4. A heat gun was used to remove water from the components and then the components were wrapped in foil until ready for use.
- **Chemical Cleaning – Stainless Steel** as per R.J. Reid (CLRC Daresbury Laboratory, Warrington WA 4 4AD, UK) in his white paper titled "Cleaning for vacuum service"
    1. Remove all debris such as swarf by physical means such as blowing out with a high-pressure air line, observing normal safety precautions. Remove gross contamination by washing out, swabbing or rinsing with any general purpose solvent. **Scrubbing, wire brushing, grinding, filing or other mechanically abrasive methods may not be used**.
    2. Wash in high pressure hot water (approx. 80°C) jet, using a simple mild alkaline detergent. Switch off detergent and continue to rinse thoroughly with water until all visible traces of detergent have been eliminated.
    3. If necessary, remove any scaling or deposited surface films by stripping with alumina or glass beads in water jet in a slurry blaster.
    4. Wash down with high pressure hot water (approx. 80°C) jet, with no detergent, ensuring that any residual beards are washed away. Pay particular attention to any trapped areas or crevices.
    5. Dry using an air blower with clean dry air, hot if possible.
    6. Immerse completely in an ultrasonically agitated bath of clean hot stabilized trichloroethylene for at least 15 minutes, or until the item has reached the temperature of the bath, whichever is longer.
    7. Vapor wash in trichloroethylene vapor for at least 15 minutes, or until the item has reached the temperature of the hot vapor, whichever is longer.
    8. Ensure that all solvent residues have been drained off, paying particular attention to any trapped areas, blind holes, etc.

9. Wash down with high pressure hot (approx. 80°C) water jet, using clean DI water. Detergent MUST NOT be used at this stage.
10. Immerse in a bath of hot (60°C) alkaline degreaser (P3 Almeco™ P36) with ultrasonic agitation for 5 minutes. After removal from the bath carry out the next step of the procedure immediately.
11. Wash down with a high pressure hot (approx. 80°C) water jet, using clean DI water. Detergent MUST NOT be used at this stage. Ensure that any particulate deposits from the alkaline bath are washed away.
12. Dry using an air blower with clean dry air, hot if possible.
13. Allow to cool in a dry, dust free area. Inspect the item for signs of contamination, faulty cleaning or damage.
14. NOTE: High Vacuum Chamber applications will have various vacuum baking processes to further de-contaminate the chamber components. The following are guidelines only :
    - Vacuum bake to 250°C for 24 hours using an oil free pumping system.
    - Reduce the temperature to 200°C and carry out an internal glow discharge using a helium/10% oxygen gas mix.
    - Raise the temperature to 250°C for a further 24 hours then cool to room temperature.

- **Chemical Cleaning – Aluminum (CERN specification)**
    1. Spray with high pressure jets at 60°C with 2% solution of Almeco 29™ (an alkaline detergent)
    2. Repeat with a 2% solution of Amklene D Forte™.
    3. Rinse thoroughly with a jet of hot DI water.
    4. Dry with hot air at 80°C
- **Chemical Cleaning – Aluminum** as per R.J. Reid (CLRC Daresbury Laboratory, Warrington WA 4 4AD, UK) in his white paper titled "Cleaning for vacuum service"
    1. Immerse in Sodium Hydroxide (45gm-1 of solution) at 45°C for 1 to 2 minutes.
    2. Rinse in hot DI water.
    3. Immerse in an acid bath containing Nitric acid (50%v/v) and Hydrofluoric acid (3%v/v).
    4. Rinse in hot DI water.
    5. Dry in warm air.
- **Typical Surface Treatments:**
    - Bead blasting
    - Ultrasonic cleaning
    - Electro-polishing
    - Air baking
    - Chemical baking
    - Glow discharge

Quality Assurance Process

Cleanliness has to be maintained to prevent recontamination until assembly. Following flange assembly and surface finishing, a completed vacuum chamber is usually helium (He) leak tested. It is important to perform regular inspection/maintenance to ensure no defects or wear has occurred and that the vacuum chamber is at its optimum performance. Vacuum chamber manufacturers should be ISO 9001:2000 certified.

- **Helium leak detection**
    - A helium mass spectrometer is an instrument commonly used to detect and locate small leaks. It typically uses a vacuum chamber in which a sealed container filled with helium is placed. Helium leaks out of the container, and the rate of the leak is detected by a mass spectrometer.
    - Helium is used as a tracer because it penetrates small leaks rapidly. Additionally, Helium also has the property of being non-toxic, chemically inert, inexpensive to produce and present in the atmosphere only in minute quantities (5 ppm). Typically, a helium leak detector will be used to measure leaks in the range of 10^{-5} to 10^{-12} $Pa.m^3.s^{-1}$.
    - Vacuum chamber must be He leak tested to <1 x 10^{-9} Torr.1/sec. where pressure applications may be involved in the final chamber use.
    - He leak enable real leak, virtual leak, permeation etc to be distinguished.
- **Contamination**
    - Chamber has to be regularly cleaned with right cleaning process to keep it running at optimum performance. A dirty or contaminated chamber will affect the vacuum process. Chamber can be cleaned using detergent and rinse with DI water, followed by wiping using methanol or other mild solvents.
- **Scratched surfaces**
    - Prevent occurrence of scratched surface by using protecting seal surface materials (eg. aluminum foil, plastic covers etc).
- **Bad welded joints**
    - To examine presence of bad welded joints, every weld is inspected and leak checked with He mass spectrometer to ensure leak rates of 1 x 10^{-9} Torr.1/sec or less.
- **Coordinate Measuring Machine (CMM)**
    - To confirm dimensional check and to aid mechanical inspection.
    - CMM inspection report could usually be provided to customer upon request.
- **Certificate of Compliance (COC)**
    - Ensure all raw material received from the supplier are accompanied by COC.

Packaging and Shipping Process

Different size chambers have different requirements for packaging and shipping (eg. depending on how much protection is needed, how it will be shipped etc.). Vacuum chambers and other large components are usually packaged appropriately according to packaging and shipping guidelines for truck, ship or airfreight to customer's location unless specified otherwise.

- **Protect seal surfaces**
    - Flanges are oftentimes covered with aluminum foil to prevent internal contamination and also scratching of the flange faces.
    - Protective plastic covers are sometimes placed over the foil for additional protection.
    - Chamber is wrapped in 4-mil plastic and placed in a wooden crate.
    - Foam is injected into plastics "pillows" which expand to fill the voids in the crate, suspending the chamber inside.
    - Depending on customer specifications for the vacuum chamber systems, after qualification, the chambers can be disassembled or purged with nitrogen gas, clean room packaged and shipped.
    - Alternatively, there are also some chambers that have been packaged and shipped under vacuum.

Conclusion

This paper has summarized briefly on guidelines for manufacturing, cleaning, and quality assurance processes of a very high vacuum chamber machined components and has indicated what factors are of importance for consideration to be used in particular processes. The paper touched on various manufacturing processes such as hog-outs, machining tolerances, vacuum flanges/fittings, and welding of attachments to the very-high vacuum chamber. It has also provided insights to how one can ensure that the vacuum system is indeed in its optimum performance. And finally, this paper has provided insights on quality assurance of the vacuum chamber and proper packaging/shipping of the vacuum system.

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