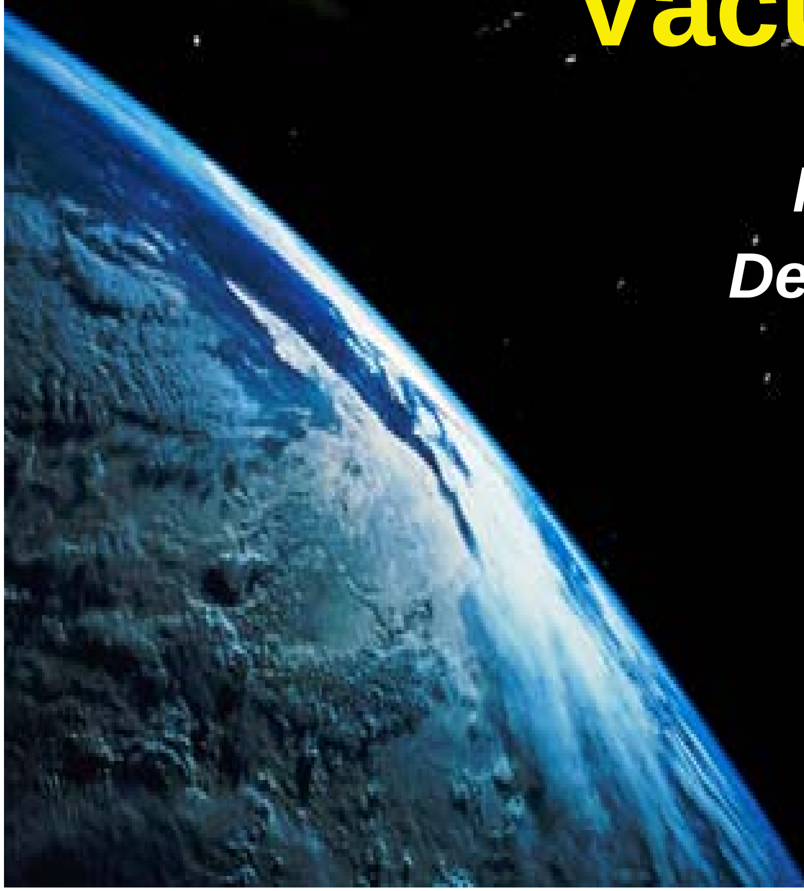
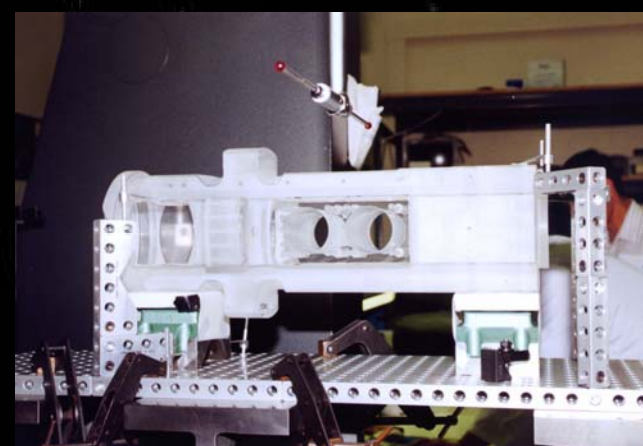
LOCKHEED MARTIN
Advanced Technology Center

Vacuum Optics

Mark Sullivan

December 2, 2006





Outline

- System design approach
- Specific steps to build successful vacuum optics
- ASTM E 1559 outgassing test
- Resources & references

How to design for Vacuum Compatibility

- **Obtain system outgassing requirements from System Engineering**
  - **Allowable Partial Pressures for water and hydrocarbons**
    - P_{H_20} , mbar
    - $P_{C_xH_y}$, mbar (AMU > 44)
  - **Effective Pumping Speeds for the system**
    - S_{eff}, liters/sec
- **Calculate allowable outgassing rates, Q, for the system**
  - **Q = P x S, mbar-l/s** ***or pg/s (via PV = nRT)***
  - $Q_{H_20} = P_{H_20} \times S_{eff}$
  - $Q_{C_xH_y} = P_{C_xH_y} \times S_{eff}$

How to design for Vacuum Compatibility 2

- Use outgassing database to construct spreadsheet that estimates outgassing rates (q, pg/cm^2-s) for the system based on material and surface area
  - $Q_{H_2O} = q_{H_2O} \times A$
  - $Q_{C_xH_y} = q_{C_xH_y} \times A$
- Verify with component and sub-assy outgassing tests
  - Place components/sub-assys in effusion cell
  - Measure q or Q per ASTM E 1995

This never happens!!

So how should we prepare our opto-mechanical systems for high vacuum applications?

- **Material Review**
- **Design Review**
- **Outgassing Tests**
- **High Vacuum Fabrication Procedures**
- **High Vacuum Cleaning Procedures**
- **Clean Assembly Procedures**
- **Conditioning & Verification of Systems**
- **Clean Packaging**

Missing any one of these can ruin all other beautiful, meticulous work!

Material Review

- Detailed review of Bills of Materials (BOMs) for all high vacuum (HV) opto-mechanical assemblies
  - Not allowed
    - Many plastics
    - Unverified adhesives
    - Conventional labels
    - Anodization
    - Carbon steel
    - Brass, Zinc, Cadmium

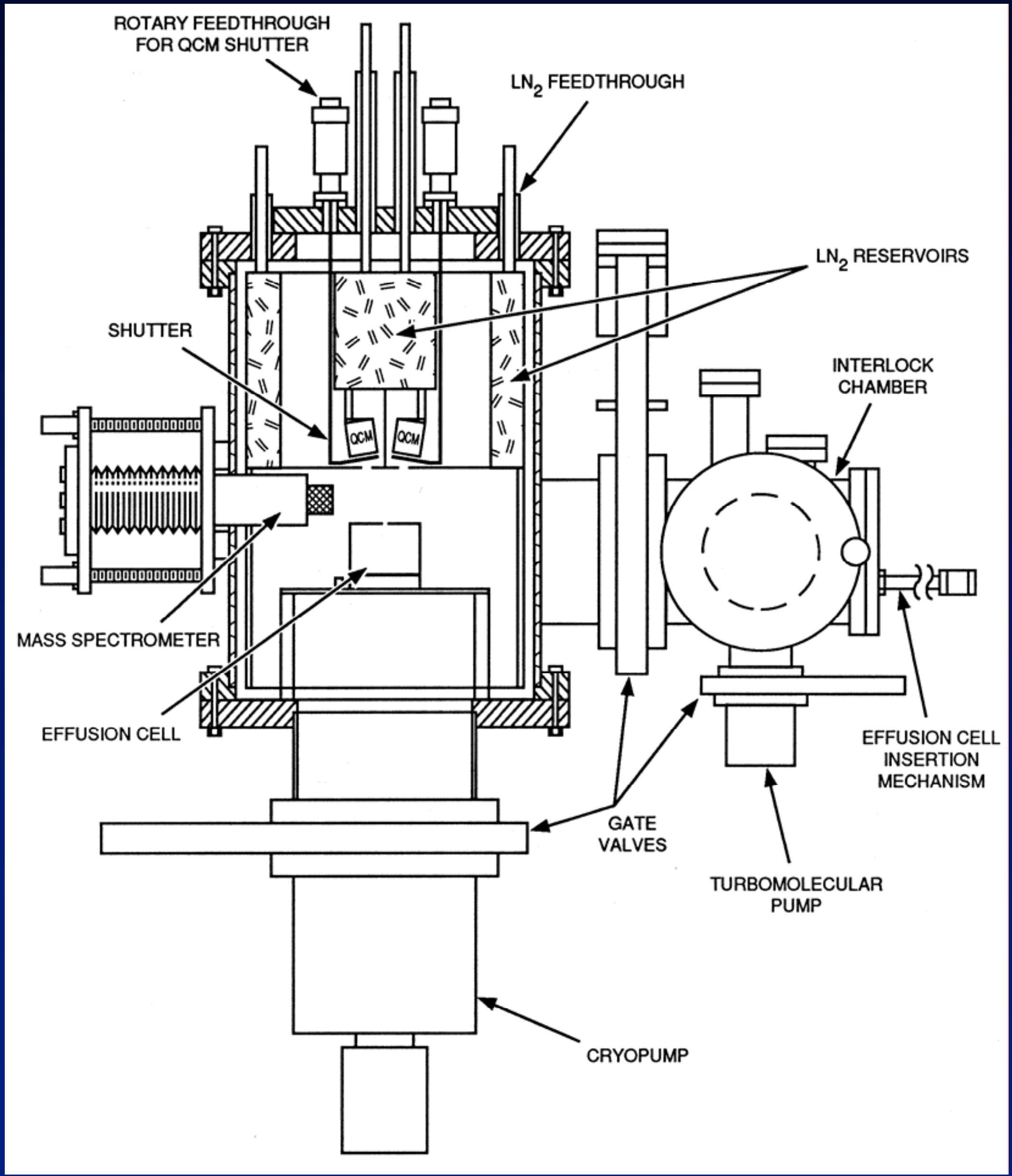
Design Review

- Compare specified materials with those evaluated by NASA Goddard Space Flight Center (GSFC) per ASTM E 595, ***Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment*** (http://outgassing.nasa.gov)
- Assure all part & assembly volumes have leak paths (no trapped volumes)
- Specify approved, dry-film lubricants (e.g., MoS_2, WS_2, WC/C) where galling is a concern

Outgassing Tests

- Perform outgassing tests on candidate materials and components per ASTM E 1559, *Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials*
  - 10^{-7} to 10^{-10} torr, 30°C, 24 hr
- Results provide quantitative & qualitative data
  - Quantitative: amounts outgassed normalized with respect to sample size
  - Qualitative: identification of outgassed species
- Outgassing test apparatus
  - Ultra-High Vacuum (UHV) Pumps (cryogenic, turbo, dry mechanical)
  - Quartz Crystal Microbalances (QCMs)
  - Mass Spectrometer

Outgassing Test Apparatus



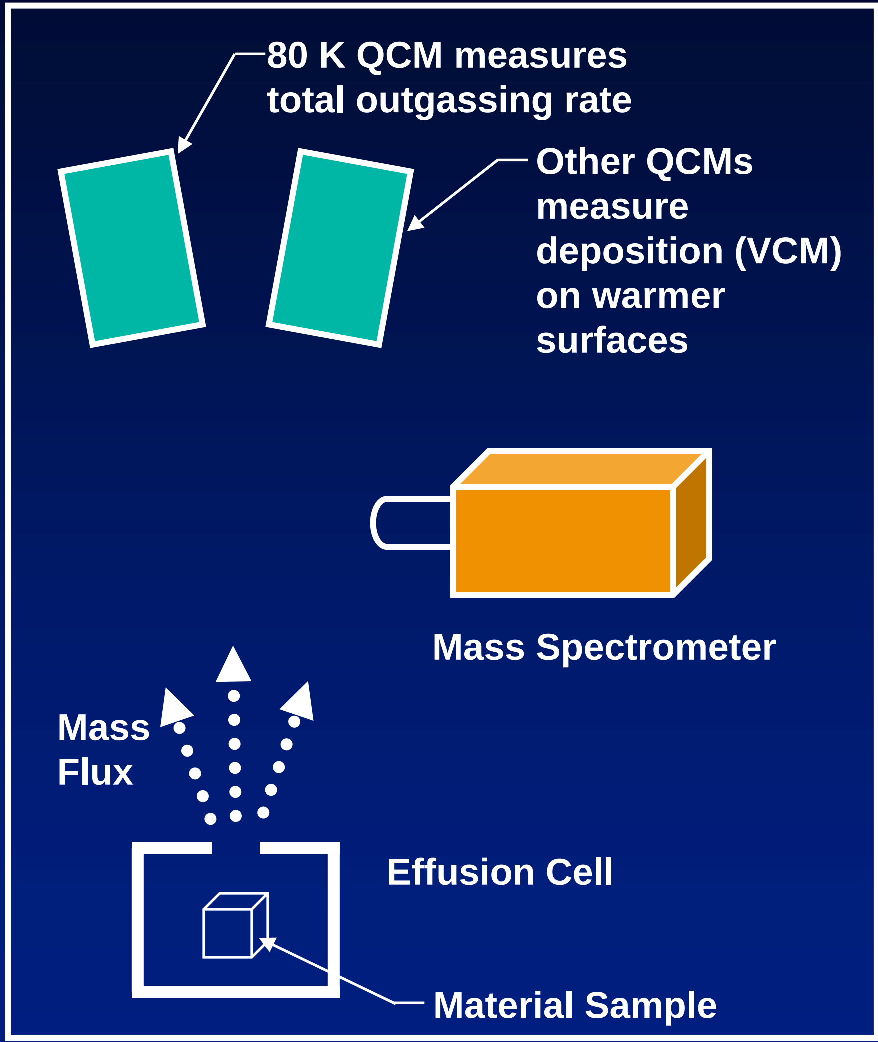
Outgassing Chamber

Outgassing Terms & Definitions

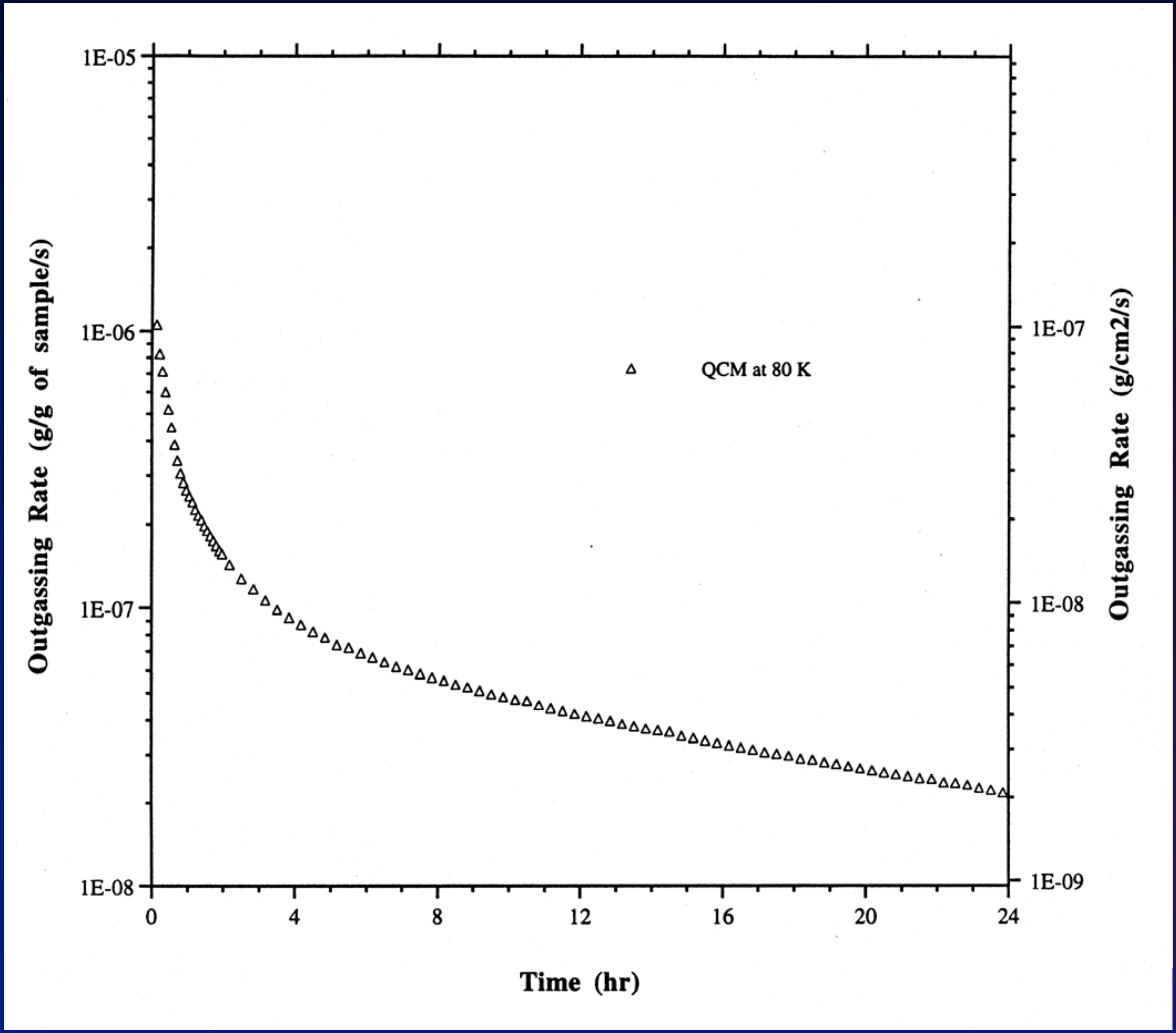
- **Outgassing - the evolution of gas from a material, usually in a vacuum**
- **Total Mass Loss (TML) - total material outgassed from a test specimen, g/g, g/cm^2, or g/assembly**
- **Volatile Condensable Material (VCM) - the material that outgasses from a test specimen and condenses on a collector surface at a specified temperature, g/g, g/cm^2, or g/assembly**
- **Effusion Cell - a container, placed in a vacuum, in which a sample of material can be placed and heated to some specified temperature**
- **Quartz Crystal Microbalance (QCM) - a device for measuring small quantities of mass using the properties of a quartz crystal oscillator**
  - **QCM resolution: <1 ng/cm^2 (n.b., 1 ng/cm^2 of H_20 = 0.01nm thickness)**
- **Outgassing Rate - the net rate of mass loss from a material sample due to outgassing per unit mass or surface area, g/g-s or g/cm^2-s**

ASTM E 1559 Outgassing Test

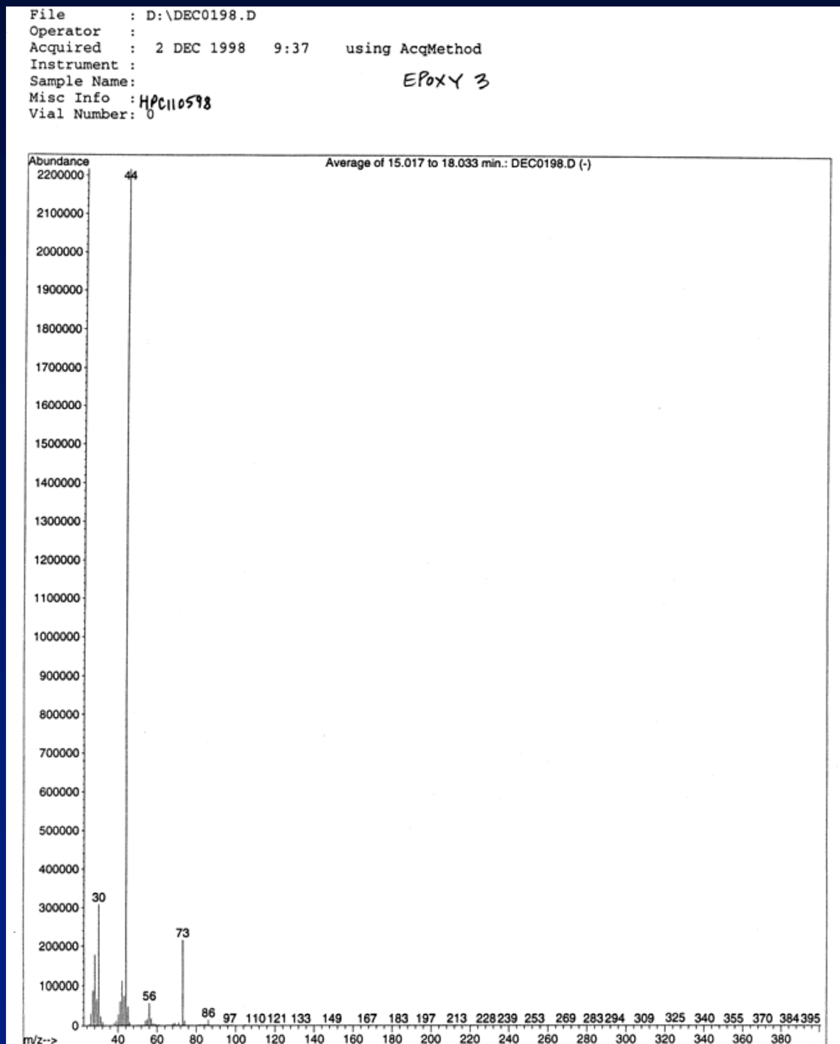
- TML & VCMs are measured
- Outgassing rates are measured
- Sample temperature range 25–150°C
- Mass Spectrometer scans mass flux spectrum 2–1000 amu
- QCMs are heated to analyze the collected deposit
- Measurements are independent of specific chamber
- Pass criteria independent of sample size (i.e., data is normalized)
  – Material samples, parts, & assemblies can be equivalently tested

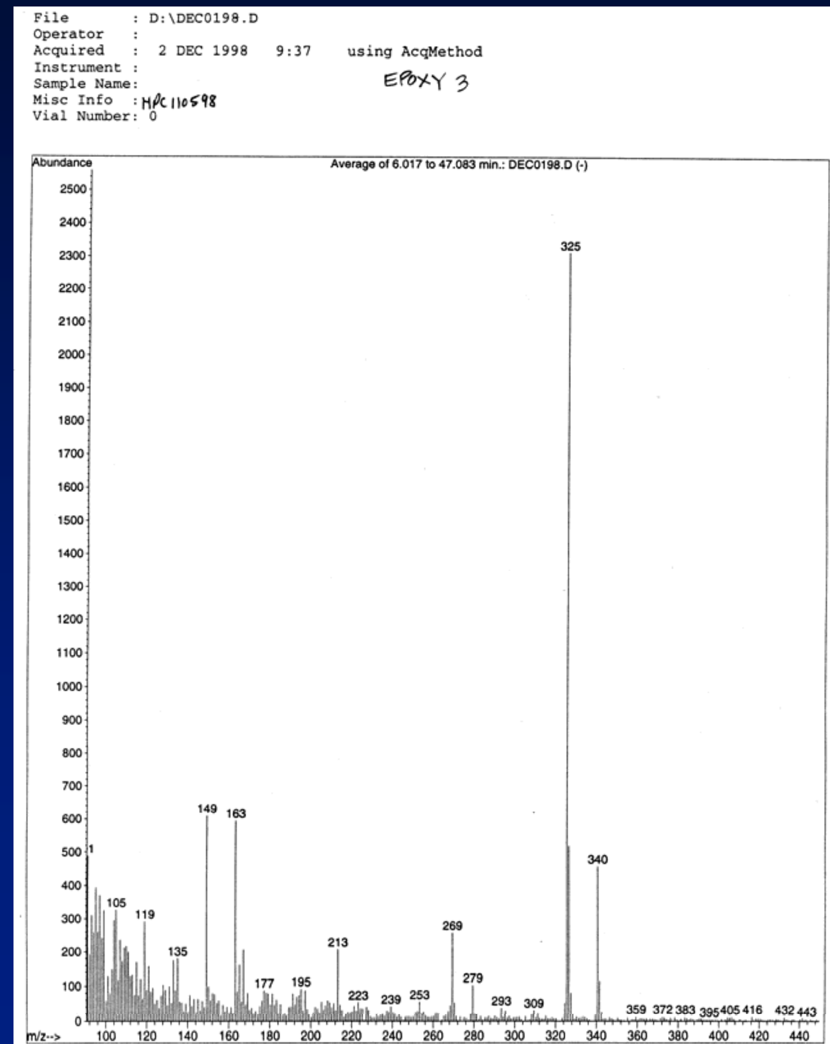


Outgassing Rate vs. Time



Mass Spectra for Outgassing Flux





Vacuum Optics Pop Quiz #1

- Which of the following has the largest effect of outgassing rate, q?
  - A) Vacuum Level
  - B) Surface Area
  - C) Temperature
  - D) The system Lead saying, “This thing’s gotta be real clean!”

C) Temperature

Outgassing rates increase 2 – 3x for a 10 °C temperature increase (see the Arrhenius Equation)

High Vacuum Fabrication Procedures

- Use only approved cutting fluids & lubricants
  - No cutting fluids or lubricants with silicones or sulfur
- High-quality surface finish (R_a<0.4 μm)
- Threads are cut (no rolled threads)
- All parts deburred
  - Edges chamfered, radiused, or manually deburred
  - No bead blasting, buffing, sanding, vibratory deburring, or tumble deburring
- ⇒ Provide less adsorption sites for molecular contamination

High Vacuum Cleaning Procedures

- Multi-step operations suited to specific part materials & geometries
- Complete process documentation (“Traveler”)
- Clean bagging
  - Individually wrapped in clean, UHV aluminum foil
  - Parts & assemblies double-bagged in low-outgassing polyethylene bags
- All parts tagged with part numbers
  - Scribed, laser engraved, etched
- At least two local vendors available (Pentagon Technologies, TMPI; both in Hayward)

Clean Assembly Procedures

- Use clean room facilities
  - Laminar flow benches generally improve cleanliness by 10x
- Use only HV-clean parts
  - Don’t mix & match (e.g., fasteners)
- Use clean assembly procedures for all HV assemblies
- Use clean alignment fixtures and <u>tools</u>
- Make use of CO_2 cleaning for parts and finished assemblies

Thermal/Vacuum Conditioning

- Thermal/Vac Conditioning
  - Large (clean) vacuum chamber capable of pumping on assemblies at <10^{-5} torr for days at various temperatures
    - Reduces remaining amounts of superficial contaminants
- High Vacuum Verification
  - QCMs measure quantities of any remaining volatiles
  - Mass spectrometer identifies volatiles
    - Typically expect only low levels of H_2, H_2O, N_2, CO, O_2, & CO_2

Clean Packaging

- Assemblies double-wrapped in clean, UHV aluminum foil
- Assemblies double-bagged in low-outgassing polyethylene bags
- Packaged assemblies tagged with part numbers
- Clean-bagged assemblies packed in standard, foam-lined containers for shipping

Outgassing & Contamination Resources

- NASA Outgassing Data for Selecting Spacecraft Materials
  - ASTM E 595 database
  - http://outgassing.nasa.gov/
- NASA Space Environment and Effects (SEE) Program
  - ASTM E 1559 database
  - http://see.msfc.nasa.gov/nec/db_contam.htm
- American Vacuum Society (AVS)
  - http://www.avs.org/
- Arrhenius Equation relates the effect of temperature on reaction rates: $K = A^*\exp^{(-E_a/R^*T)}$
  - http://www.cogs.susx.ac.uk/users/adrianth/ecal97/node3.html

References

- H. G. Tompkins, *The Fundamentals of Vacuum Technology*, AVS, 1997.
- M. H. Hablanian, *High-Vacuum Technology, A Practical Guide*, 2nd Edition, Marcel Dekker, 1997.
- A. C. Tribble, *Fundamentals of Contamination Control*, SPIE, 2000.
- "Product and Vacuum Technology Reference Book," Leybold Inficon, Inc., 1991.
- M. J. Drinkwine, D. Lichtman, Partial Pressure Analyzers and Analysis, AVS, 2000.