AA 284a
Advanced Rocket Propulsion

Lecture 16
Rocket Testing

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Rocket Testing

- The physical and chemical phenomena that take place in a rocket system is very complex and comprehensive models to reliably design a new system or predict the performance of a new design do NOT exist.
- This requires an extensive testing effort in the development process
- Testing should be conducted in conjunction with a comprehensive modeling/simulation activity.
- The performance parameters that are of interest for a rocket system are
  - c* and Isp efficiencies
  - Regression rates for solid and hybrid rockets
  - Stability character (See Lecture 14)
  - Injector performance (See Lecture 12)
  - Nozzle erosion rates (for ablative nozzles)
  - Nozzle cooling system performance (for cooled nozzles)

Rocket Testing – Efficiency Estimation

- Determination of the efficiencies from motor/engine test data
- c* efficiency can be calculated using the following set of equations (chamber pressure integral method) – derived from c* equation

$$c^*_{act} = \frac{C_d \bar{A}_n \int_0^{t_b} P_c dt}{(\Delta M_{ox} + \Delta M_f + \Delta M_{in})} \qquad \eta_c = \frac{c^*_{act}}{c^*_{theo}} \qquad O/F = \Delta M_{ox} / \Delta M_f$$

- Note that the theoretical c* can be calculated using the average chamber pressure, and average oxidizer to fuel ratio
  - One must assume frozen or shifting equilibrium in this calculation
  - This assumption would change the numerical value of the efficiency
  - Frozen equilibrium assumption results in higher than actual efficiencies
  - Shifting equilibrium assumption results in lower than actual efficiencies
- Discharge coefficient of the nozzle can be obtained from cold gas flow test
- Nozzle area is the average value for the test

Rocket Testing - Efficiency Estimation

- Isp efficiency can be calculated using the following set of equations (thrust integral method)

$$\left(I_{sp}\right)_{act} = \frac{\int_{0}^{t_b} T\,dt}{g_o\left(\Delta M_{ox} + \Delta M_f + \Delta M_{in}\right)} \qquad \eta_{Isp} = \frac{\left(Isp\right)_{act}}{\left(Isp\right)_{theo}}$$

- Note that the theoretical Isp can be calculated using the average chamber pressure, average oxidizer to fuel ratio and the nozzle area ratio
    - One must assume frozen or shifting equilibrium in this calculation
    - This assumption would change the numerical value of the efficiency
    - Frozen equilibrium assumption results in higher than actual efficiencies
    - Shifting equilibrium assumption results in lower than actual efficiencies

Rocket Testing – Regression Rate Estimation

- For hybrid or solid rockets with circular ports
- Space time averaged regression rate can be estimated using the following equations

$$\bar{\dot{r}} = \frac{d_f - d_i}{2 \; t_b} \qquad\qquad d_f = \left[d_i^2 + \frac{4 \Delta M_f}{\pi \rho_f L_g} \right]^{1/2}$$

- Estimating the final diameter from the fuel mass loss results in final diameters that are more accurate than the directly measured values.
- Burn time can be defined as the action time
  - From the moment that 50% of the full pressure is achieved
  - To the moment that 50% of the full pressure is lost
- Selection of burn time is critical for accurate measurement
  - For short tests the transients dominate
  - For long tests the flux variation is too large (for hybrids)

Rocket Testing – Oxidizer Mass Flux

- In a hybrid rocket oxidizer mass flux has to be estimated
- First a flow rate measurement required
  - Average from a direct measurement of the flow rate (i.e. turbine flow meter)
  - Or from oxidizer tank weight measurement

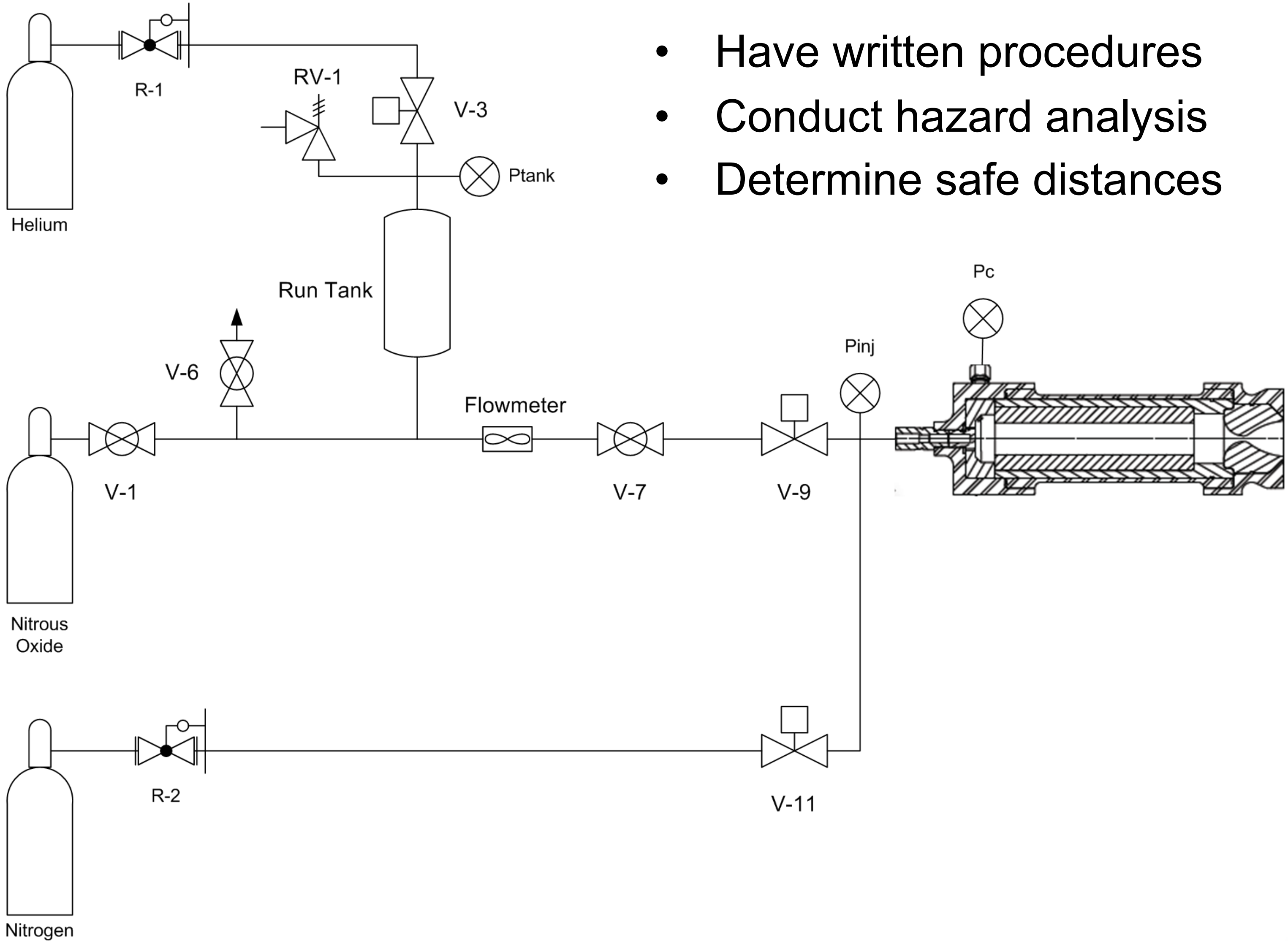
$$\overline{\dot{m}}_{ox} = \frac{\Delta M_{ox}}{t_b}$$

- Three methods of defining average flux is possible (always specify the method used in the calculation)
- The most accurate one is based on average diameter

$$\overline{G}_{ox} = \frac{16\ \overline{\dot{m}}_{ox}}{\pi (d_i + df)^2}$$

- Each motor test generates a regression rate oxidizer mass flux pair. At least 10-15 tests should be used to establish the regression rate law for a propellant combination. Length and pressure effects should also be evaluated by additional testing.

Rocket Testing – P&ID Diagram for a Hybrid Rocket



- Have written procedures
- Conduct hazard analysis
- Determine safe distances

Rocket Testing – Measured Quantities

- Thrust Force:
  - Use a set of load cells to measure forces in the axial and lateral directions
  - Always conduct an *in situ* calibration by applying a known force to the fully assembled configuration and measuring the voltage output.
  - Note that the effect of oxidizer flow into the motor on the thrust measurement accuracy in a gaseous system is significant
  - For most liquid oxidizer systems 1-2% accuracy is achievable
- Pressures:
  - Combustion chamber (multiple locations, pre and post combustion chambers)
  - Injector upstream
  - Oxidizer tank
  - Use two kinds of transducers simultaneously
    - Fast responding for dynamic measurements (i.e. Kistler). Major DC shift
    - Slow responding with high DC accuracy (i.e. GEM). Poor dynamic response
  - Better than 1% accuracy is easily achievable

Rocket Testing – Measured Quantities

- Oxidizer (and liquid fuel) Flow Rate:
  - This is one of the most difficult measurements (>5% accuracy is common)
  - The following techniques can be used for this purpose
    - Tank weight (gas or liquid) Change in the tank weight
      - Easiest method to directly measure mass flow rate
      - Generally not very accurate or reliable due to zero shift during testing.
      - No transient measurements
    - Turbine flow meter. (gas or liquid) Turbine spinning in a pipe
      - This is a volumetric flow measurement.
      - Inaccuracies due to the estimation of the density
      - Can not be used in a two phase flow situation
      - Fast response
    - Venturi flow meter (gas or liquid); Pressure change in a venturi
      - Small range of flow rates
      - Inaccuracies due to the estimation of the density
      - Can not be used in a two phase flow situation
    - Coriolis Flow meter (gas or liquid) Coriolis force acting on a looping pipe
      - Very accurate. Direct mass flow rate measurement
      - Quite expensive
      - Generally slow response

Rocket Testing – Measured Quantities

- Temperatures:
  - Measure temperatures in
    - Feed lines
    - Injector upstream
    - Inside the combustion chamber (very difficult)
    - Outside wall of the chamber or nozzle
  - Use thermocouples (2-3 C accuracy). Make sure to use the TC types with the correct temperature range
    - LOX lines (90-120 K)
    - Chamber: (2000-3000 K)
  - Most TC's are very slow in responding to changes in temperature
- Port Diameter:
  - Inside micrometers, T-scopes (accurate to 0.002"-0.005")
  - Laser systems
- Fuel Mass
  - Scales (before and after test)
  - This could be a highly accurate measurement

Rocket Testing – Measured Quantities

- High Speed Video of the plume and motor/engine:
  - Video recording at speeds of 1000 frames per second is very useful
  - Plume events can be used to construct the failures or anomalous behavior.
- Filtering:
  - Use analog filters for anti-aliasing purposes
  - Cut off frequency selected to resolve up to the 3rd – 4th longitudinal mode for a hybrid. For liquids sampling rate should be much faster (radial and tangential modes)
- Data Acquisition:
  - Sampling rate should be selected at least 4 times the maximum frequency of interest
  - A 16 bid DAQ board have reasonable resolution for most systems.