Engine Systems, Control & Integration

Washington State University

Engine Design Overview

- Propellant Budget
- Engine Controls
- Engine System Calibration
- System Integration
- Engine Optimization
- Performance of Rocket Propulsion Systems
- Timeline

Propellant Budget

Propellant Budget

- Sum of total propellant usage and losses in an engine

TABLE 11–1. Example of a Propellant Budget for a Spacecraft Propulsion System with a Pressurized Monopropellant Feed System

Budget Element	Typical Value
1. Main thrust chamber (increasing the velocity of stage or vehicle)	85–95% (determined from mission analysis and system engineering)
2. Flight control function (for reaction control thrusters and flight stability)	5–10% (determined by control requirements)
3. Residual propellant (trapped in valves, lines, tanks, etc.)	0.5–2% of total load
4. Loading uncertainty	0.5% of total load
5. Allowance for off-nominal performance	0.5–1.0% of total load
6. Allowance for off-nominal operations	0.25–1.0% of total load
7. Mission margin (reserve for first two items above)	3–5% of items 1 and 2
8. Contingency	1–5% of total load

Propellant Budget

- Propellant to complete mission
- Gas Generator Cycle
- Thrust Vectoring Control
- Heating of Cryogenic Propellant Tanks
- In Flight Maneuvers
- Residual Propellant
- Loading Uncertainty
- Off-nominal Rocket Performance
- Operational Factors
- Evaporation and/or Cooling due to Cryogenic Propellant
- Overall Contingency

Propellant Budget

- Propellant to complete mission
- ~~Gas Generator Cycle~~
- ~~Thrust Vectoring Control~~
- ~~Heating of Cryogenic Propellant Tanks~~
- ~~In Flight Maneuvers~~
- Residual Propellant
- Loading Uncertainty
- Off-nominal Rocket Performance
- Operational Factors
- ~~Evaporation and/or Cooling due to Cryogenic Propellant~~
- Overall Contingency

Propellant Budget

- Propellant to complete mission
  - Typically 85-95% of Total Propellant
  - Will be calculated after completion of testing
  - Altered By:
    - Barometric Pressure
    - Wind Conditions

Propellant Budget

- Residual Propellant
  - Unused Propellant at the End of the Burn
  - Typically .5-2% of Total Propellant
  - Alters:
    - Final Mass
    - Velocity
  - Will Find Accurate Data During Testing

Propellant Budget

- Loading Uncertainty
  - Variation in propellant density or liquid level in tank
  - Typically .25-.75% of total propellant
  - Alters:
    - Flow of Propellant
    - Duration of Propellant Flow
    - Thrust Numbers
  - Vacuum Casting of Solid will Lessen Variation

Propellant Budget

- Off-nominal Rocket Performance
  - Manufacturing Discrepancies
  - Typically 0-2% of Total Propellant
  - Alters:
    - Regression Rate
    - Flow Rates
    - Thrust Values
  - Using the Same Rocket Parts for Every Launch

Propellant Budget

- Operational Factors
  - How accurate valves, flow, tubing is
  - Typically .1-1% of Total Propellant
  - Alters:
    - Everything
  - Purchase High Quality Components

Propellant Budget

- Overall Contingency
  - Extra Fuel to account for unaccountable data
  - Typically 1-5% of Total Fuel
  - After testing and data collection, add or subtract some fuel to achieve desired flight

Propellant Budget

- Important Take-Away:

  - There are many things to consider about your rocket fuel consumption before finalizing your fuel amount

Engine Controls

Engine Controls

- Prior to starting:
  - Check that systems work
  - Fill the tanks
  - Bleed liquid lines
  - Pressurize tanks

Engine Controls

- Starting-Preliminary Operation:
  - Provide start electric signal
  - Start ignition system
  - Open valves
  - Double check the systems

Delta II

Engine Controls

- Starting-Transition to full thrust:
  - Allow propellant to increase to full-rated values
  - Be sure that principal valves fully open
  - Activate systems for thrust control

Soyuz

Engine Controls

- Stopping:
  - Signal to stop
  - Key valves close in sequence

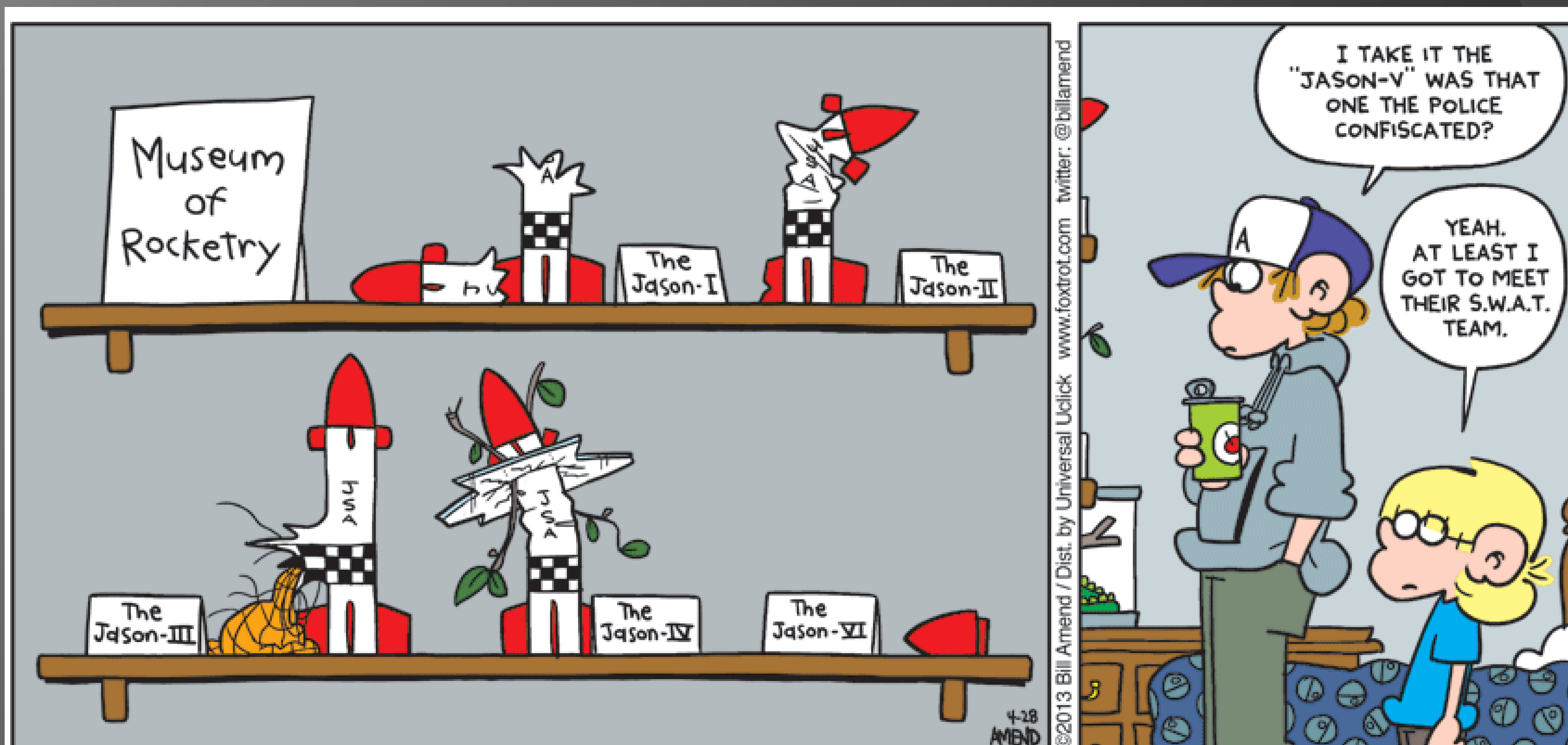
Engine Controls

- Benefits of electronic control systems:
  - Lighter
  - Cheaper
  - Easier
  - More accurate
  - Feedback for learning

Engine Controls

- Our control system needs to be:
  - Shockproof
  - Heat resistant
  - Flame retardant
  - Moisture resistant

Engine System Calibration



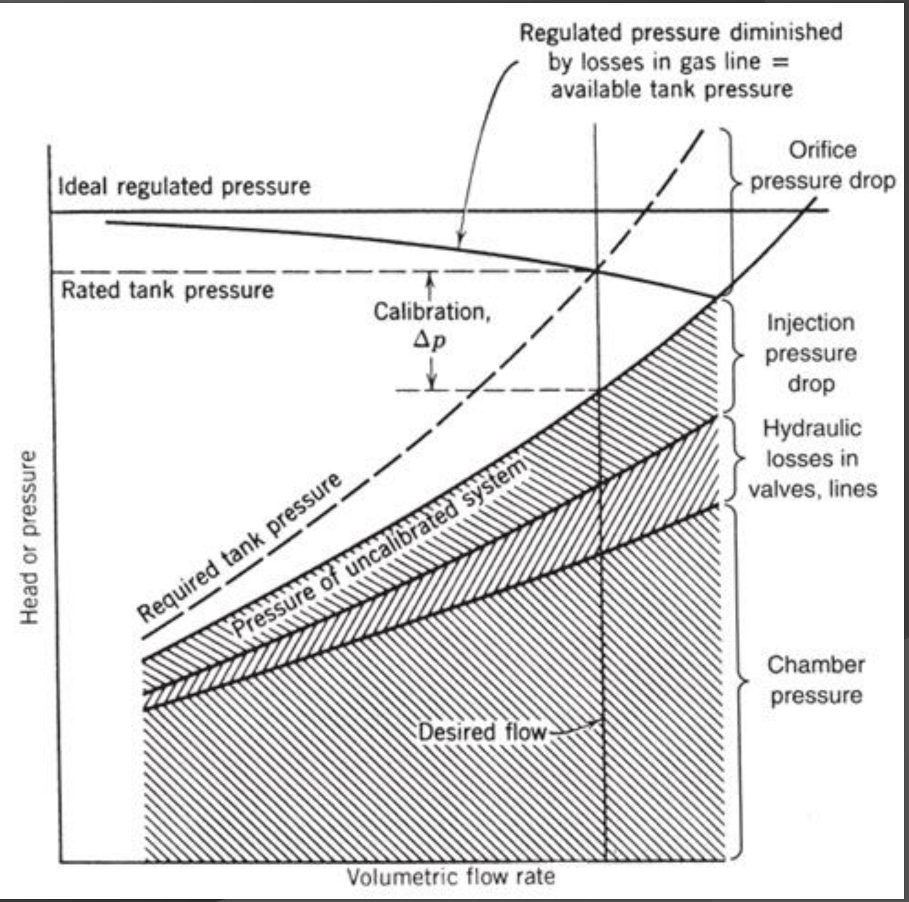
Engine System Calibration

- Corrects engine system for nominal performance
- Testing: actual engine v. ideal engine
  - i.e. hydraulic/pneumatics (valves, pipes, etc.)
  - hot fired components (thrust chamber, turbines, etc.)
  - cryogenic propellants (pumps, valves, etc.)
  - Automated or Manual
- Pressure balance the system
- Health Monitoring System (HMI)

Engine System Calibration

Pressure balance the system

- $P_{engine} = P_{drop} + P_{chamber}$
- Intended flow and mixture ratio
- Orifice plate
- Example 11-2
  - Actual v. intended chamber conditions
  - Deviations in mixture ratio, thrust and specific impulse.
  - Tank pressure
  - Orifice dimensions



Rocket Propulsion systems

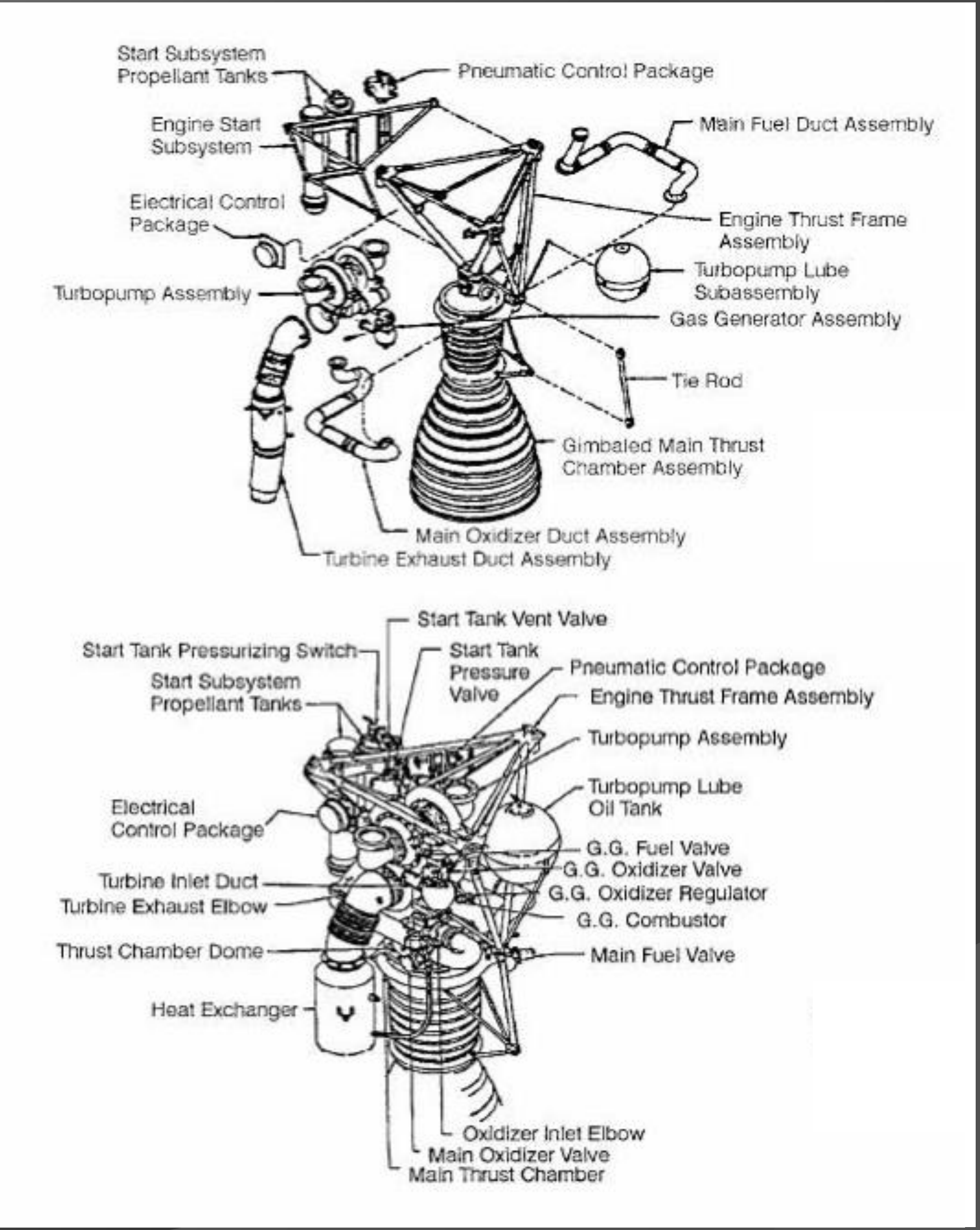
Engine System Calibration

http://www.nasa.gov/images/content/453915main_2010-3355_full.jpg

Health Monitoring System

1. Monitor behaviour
   a. analyzes actual v. intended
   b. Outputs calibrations
2. Anticipates failure
   a. protects equipment
3. Lift-Off monitors
   a. booster engines and launch vehicle
   b. predicts “health”
   c. (dis)allows launch.

System Integration and Engine Optimization



D.K. Huzel *Modern Engineering Design of Liquid Propellant Rocket Engines Vol.147 of Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 1992*

Engine Optimization

- Optimization Studies
  - Thrust
  - Chamber Pressure
  - Mixture ratios
  - Nozzle area ratio
  - Chamber to throat area ratio
  - Engine Volume

- Vehicle Parameters
  - Payload
  - Vehicle Velocity Increment
  - Range
  - Propellant Mass Fraction

System Integration

- Optimization Parameters
  - Performance
  - Reliability
  - Cost
- Limitations
  - Heat emissions
  - Noise
  - Vibrations
- Interfaces
  - Connections
  - Wires
  - Pipelines

Performance of Rocket Systems

- Performance Characteristics
  - Whole is equal to sum of parts

$$(I_s)_{oa} = \frac{\sum F}{\sum \dot{w}} = \frac{\sum F}{g_0 \sum \dot{m}} \quad (11\text{–}1)$$

$$\dot{w}_{oa} = \sum \dot{w} \quad \text{or} \quad \dot{m}_{oa} = \sum \dot{m} \quad (11\text{–}2)$$

$$r_{oa} \approx \frac{\sum \dot{w}_o}{\sum \dot{w}_f} = \frac{\sum \dot{m}_o}{\sum \dot{m}_f} \quad (11\text{–}3)$$

Sutton, George Paul., and Oscar Biblarz. *Rocket Propulsion Elements*. New York: John Wiley & Sons, 2001. Pages 402

Performance of Rocket Systems

- Preliminary Data from RPA with HTPB/Paraffin Sim.
  - Inputs
    - Fuel: HTPB 70% Paraffin 30%
    - Oxidizer: Nitrous Oxide
    - Chamber Pressure 550
    - Pressure at 5000 ft = 84.3 kPa
    - Conical Nozzle with Half Angle of 20 degrees
  - Outputs
    - Thrust Coefficient: 1.526
    - Burn Time: 10 sec
    - Mixing Ratio: 7.739
    - Specific Impulse: 245 s

Engine Design Conclusion

- Preliminary Design
  - 3.75 inch fuel grain
    - Fuel TBD
  - Oxidizer: N2O
    - Available from Chem Stores
  - Oxidizer Tank
    - Create from 6061 Aluminum Tube Stock 4” Diameter, .125” Thick
    - Bulk Heads Machined from 6061 Aluminum
  - Combustion Chamber
    - 6061 Al Stock or
    - 3D Printed from Aerojet
- Injector
  - Shower Head Design
- Nozzle
  - 3D Printed from Aerojet
  - Graphite Machined
- Valves
  - TBD
- Electronics
  - TBD

Engine Design Conclusion

- To Do
  - Propellant Budget
  - Finalize EES Code
  - Create Simulations on all propellant options
  - Finalize Engine Design
  - Finalize Test Stand Design
  - Finalize Test Plan Procedures
- Safety Tests and Approval
- Procure Propellant Casting Chemicals and Equipment
- Cast Propellants
- Test Propellants
- Order Components
- Machine Components

… and then BUILD!

Timeline

Hybrid Rocket

Period Highlight: 1 | Plan

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Finalize Test Design	1	5	0	0	0%
Finalize Test Plan	5	12	0	0	0%
Order Propellant Equipment	1	3	0	0	0%
Finalize EES Code	2	12	0	0	0%
Budget Propellant	1	5	0	0	0%
Create Simulations on all propella	5	20	0	0	0%
Finalize Engine Design	1	11		0	0%
Safety Tests and Approval	23	30	0	0	0%
Cast Propellants	23	30	0	0	0%
Test Propellants	32	39	0	0	0%
Order Components	23	30	0	0	0%
Machine Components	23	30	0	0	0%
BUILD	32	60	0	0	0%