A Review of Real-Time Radiography as a Solid Propellant Burn Rate Measurement Technique

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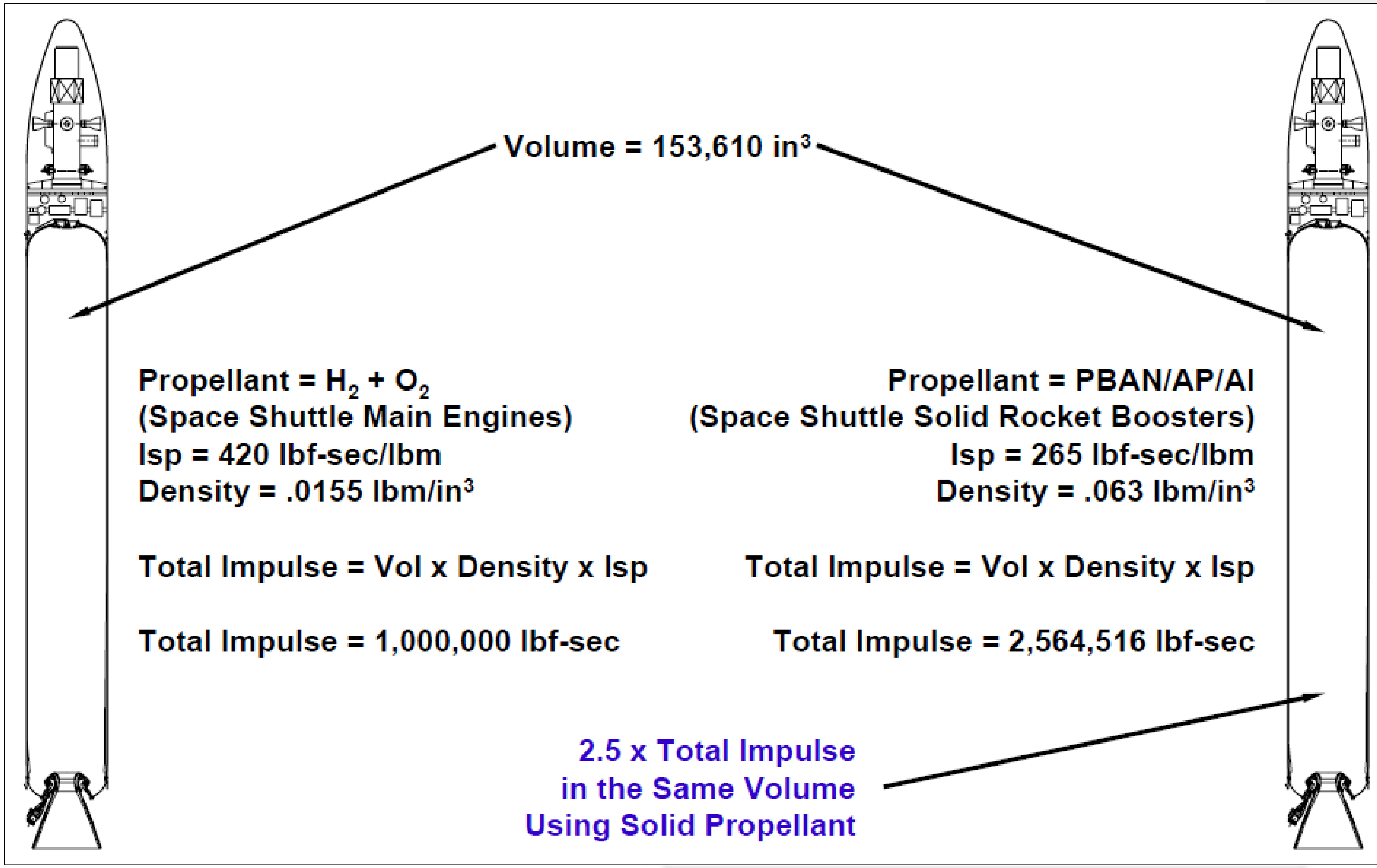
Overview

- Interest in solid propulsion
  - Resurgence
  - Imperative

Solid Propellant



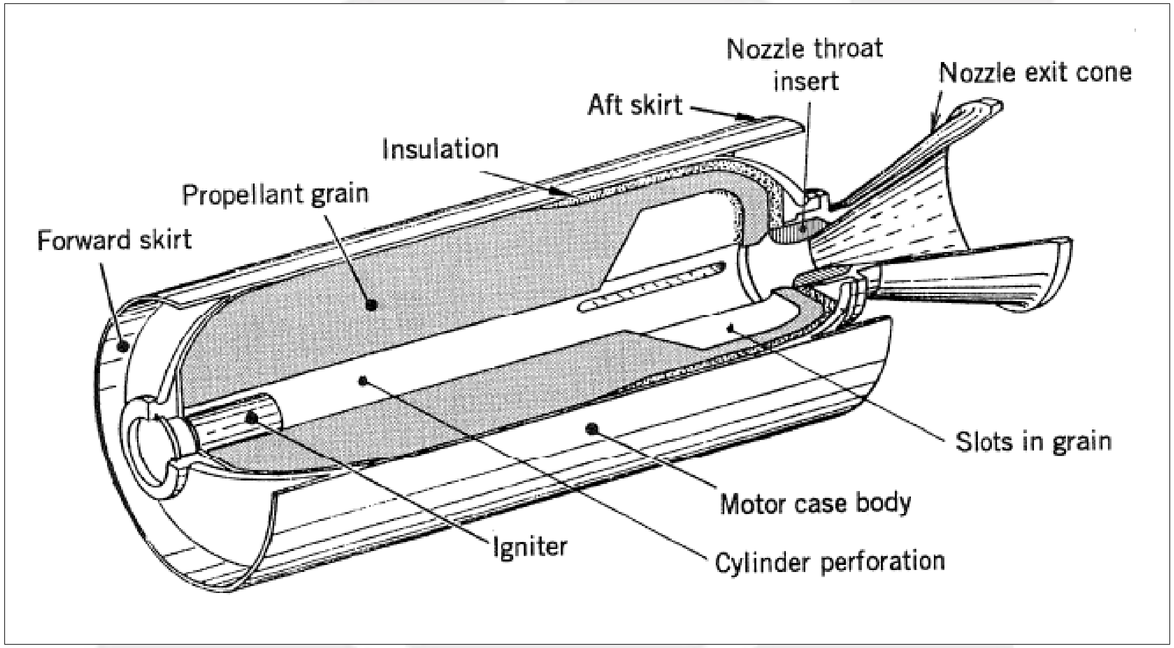
Thrust | Storage | Cost

Solid Propellant

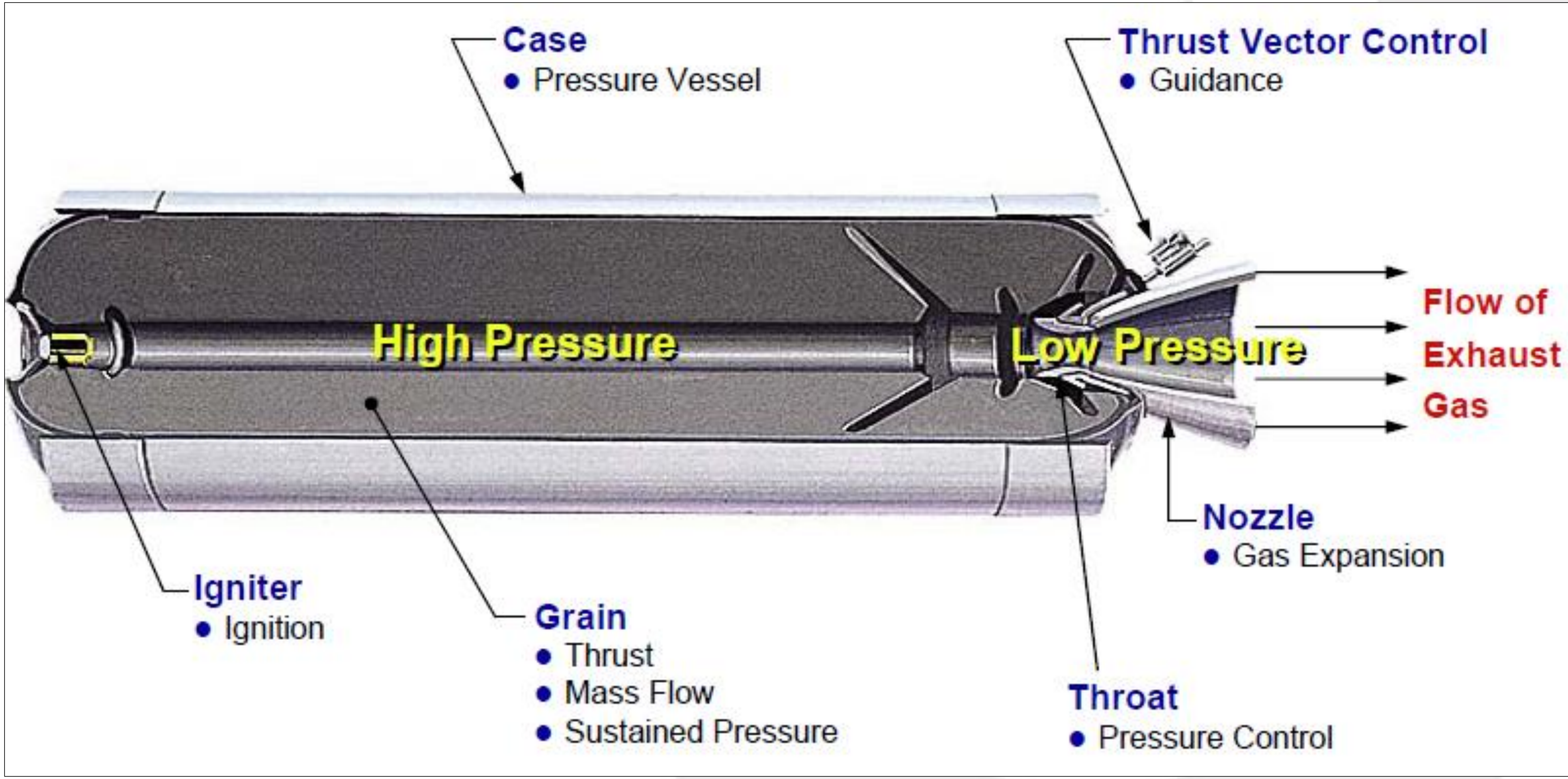
- Types
  - Homogenous
    - Single Base
    - Double Base
  - Composite
    - Heterogeneous propellants
      - Homogenous solid particles (oxidizer)
      - Polymeric binder (fuel)
- Burning Rate Dependence
  - Composition
  - Pressure
  - Temperature
  - Velocity of gas flow
  - Motor motion

Solid Rocket Motor

- Major Components
  - Case
    - – Pressure Vessel
  - Propellant
    - – Energy Provider
  - Nozzle
    - – Energy Converter



How Solid Motor Works

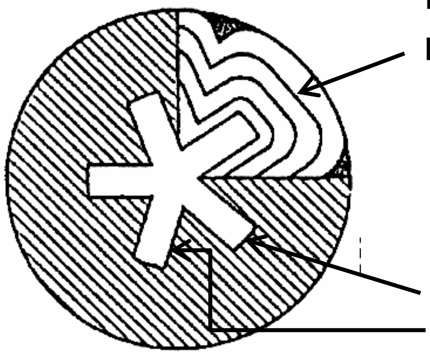


Propellant burns, increasing chamber pressure

Pressure differences causes hot gases to accelerate and exit through nozzle, resulting in thrust

Solid Propellant

- Thrust -> Mass Flow
- Mass flow -> Exposed Burning Surface
- Burn Area -> Propellant Grain Design



- Propellant Burns radially outwards from port to casing
- Regression is normal to surface

Throttle By Design

Significance of Burning Rate

- Motor operation and performance
  - Propellant combustion characteristics
  - Burn Rate $$r = a_0 \exp\left[\sigma_p \left(T_b - T_{b,0}\right)\right] P^n$$
  - Burn Surface
  - Grain Geometry
- Most important factor in internal ballistics
  - Chamber Pressure -> Thrust -> Performance

Understanding burning rate behavior under all operating conditions and design limits ensures successful rocket motor design

Types of Measurement Techniques

- Three broad categories
  - Strand Burners
  - Sub-scale (Ballistic Evaluation Motors)
  - Full-scale
- Non-Intrusive Techniques
  - Instantaneous measurements

Overview Non-Intrusive Methods

- Ultrasound
  - Measurement uncertainty
    - 1-5% for propellant applications [2]
    - 5-10% for propellant transients [2]
- Microwave
  - Accurate
    - burning rate shows a standard deviation between 0.3-1.3% [2]
  - Costly
  - Personnel Training
- X-Ray
  - Burning Rate Resolution
    - At best 3-5% [2]
  - Relatively expensive
  - Labor intensive data interpretation
  - Tested with wide variety of configurations
  - Applicable to any burning apparatus
    - Recommended for full-scale motors [1]

X-Ray Radioscopy

- Wavelength range: 0.01 to 10 nanometers [10]
- Frequencies range: 3×10^{16} Hz to 3×10^{19} Hz [10]
- Typical energies range: 100 eV to 100 keV [10]
  - Higher energy: 6–20 MeV (Hard X-rays)
    - Traverse relatively thick objects without being much absorbed or scattered [10]
- Two-Dimensional Radiographic intensity to predict motor port diameter
- Blurred nature of radiography

Review of Past and Contemporary Research

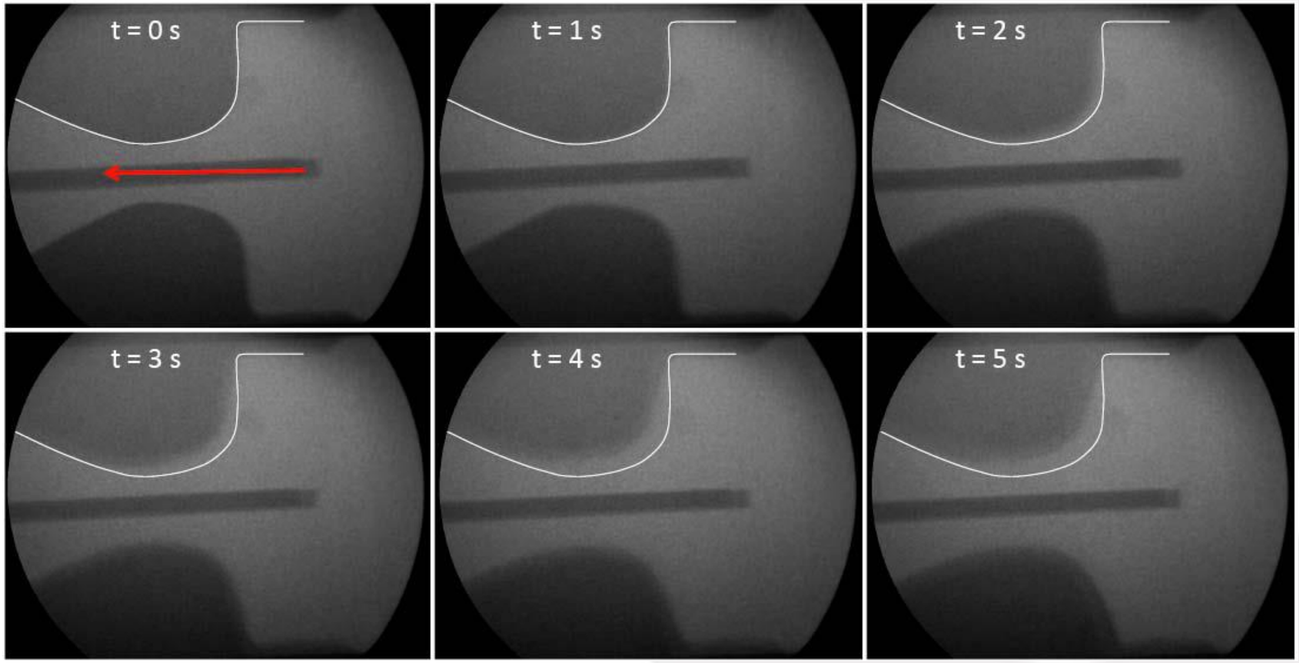
- Sequential flash radiograph [Monk;Markland 4,5]
  - measure grain geometry at several intervals during solid propellant regression
  - Poor accuracy [6]
    - – blurred nature of radiography
      - » Location of precise propellant surface
    - – Operator subjectivity implies inconsistent results

Review of Past and Contemporary Research

- X-Ray RTR To Analyze Nozzle Erosion [Cortopassi 15]
  - Important system components
    - – X-ray source: 320 KV, 10mA
    - – Focal spots: Large (5.5 mm), Small (3.0 mm)
    - – X-ray image intensifier
      - » lead-lined cesium iodide
    - – Image acquisition system
      - » 1,000 x 1,000 pixel resolution

Review of Past and Contemporary Research

- X-Ray RTR To Analyze Nozzle Erosion [Cortopassi 15]



Source: [15]

Review of Past and Contemporary Research

- Computer aided enhancement [Walker 18,19]
  - Improved image processing and analysis
    - Define propellant surface
    - Specify most probable location (averaged)
- Improved radiographic performance [Tosti 16]
  - Improved Image acquisition system (CCD Camera)
    - High frame rate, High sensitivity (min 10^{-3} lux), Variable Gain (adjust to variable propellant thickness)
  - Noise level increased for 15 Mev X-Ray source, compared to 9 MeV
    - Frame integration
    - Gain adjustment

- Improved radiographic performance [Tosti 16] (contd.)
  - Relevant reported results
    - Improved radiographic performance
    - Shorter image requisition time (50% less)
    - Lower camera dose

1 mm de-bonding between thermal protection and propellant

Old system

New system

Review of Past and Contemporary Research

- Solving film-film variation and imprecise surface location [7,8,11,12]
  - New Procedure
    - X-ray beam intensity modulation
    - Multiple exposure images
    - Reduces error with change of diameter
      - Diameter change measured directly from radiography
      - Eliminated film-to-film variation
  - Spatially resolved measurement
    - Combine temporal continuous indirect method and direct time mean method
    - Detailed modeling of the flash x-ray process and digitized film-density data employed
    - Approximately 3% error in propellant burning rate reported

Review of Past and Contemporary Research

- Improving quality of x-ray images [Allen 13]
  - Sequence of Images (every 17 seconds) obtained during motor transients
  - Used cooled-CCD camera
  - Classification of noise
    - Electronic gain reduced well depth (x18)
    - Optimized accuracy
      - » Signal-noise ratio minimized
  - Improvement in hardware and image acquisition software analyzed
    - Total cycle time 6 secs – for required exposure of 4 secs
    - Acquisition speed limited by exposure time required
      - » Using Present X-ray linac sources, 1-2 secs

Proposed Future Research Directions

- Imaging system
  - Image Acquisition
    - Use of High speed, High se
  - Image processing
    - Precise and Accurate edge detection
    - Better Imaging system
- X-Ray source
  - Depends on available machine

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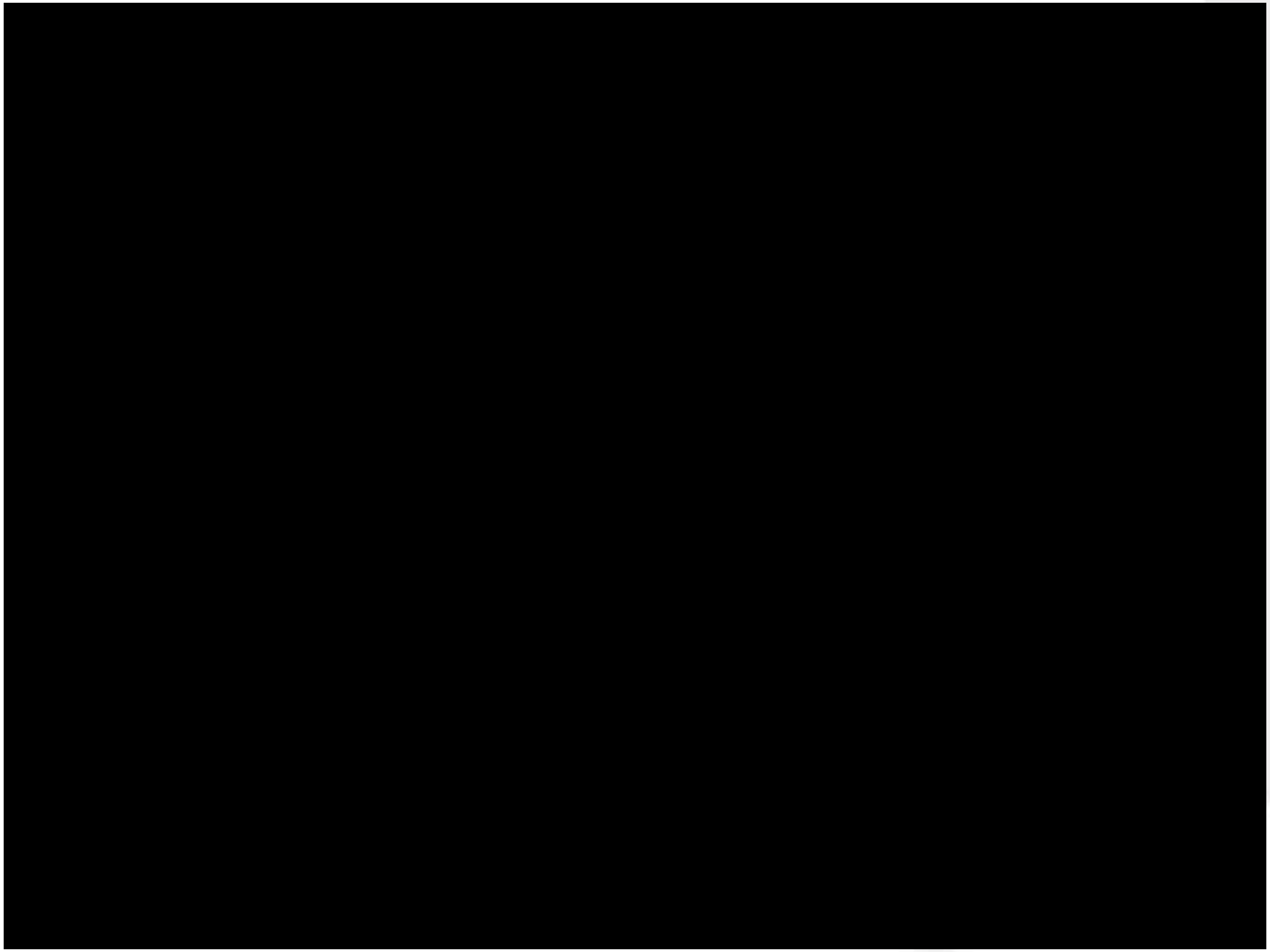
[19] Walker, R.Y., Weller, L., and Frix, W.M., “X-Ray Measurement of Solid Rocket Motor (SRM) Surfaces,” Arnold Engineering Development Center Report. AEDC-TRM-82-E60, December 1982.

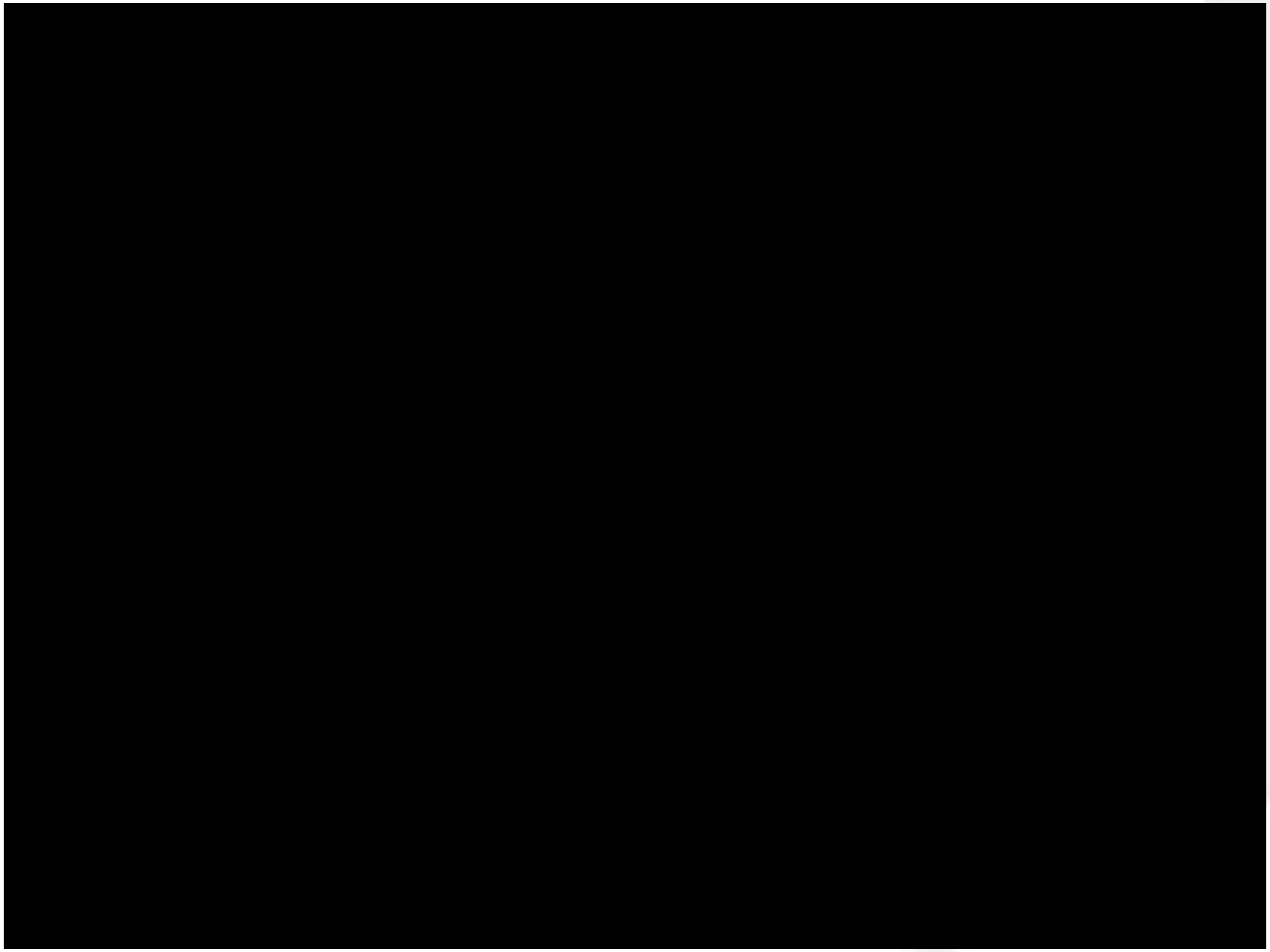
Thank you for your attention!

QUESTIONS? COMMENTS?

G138 Test with Plastic Nozzle

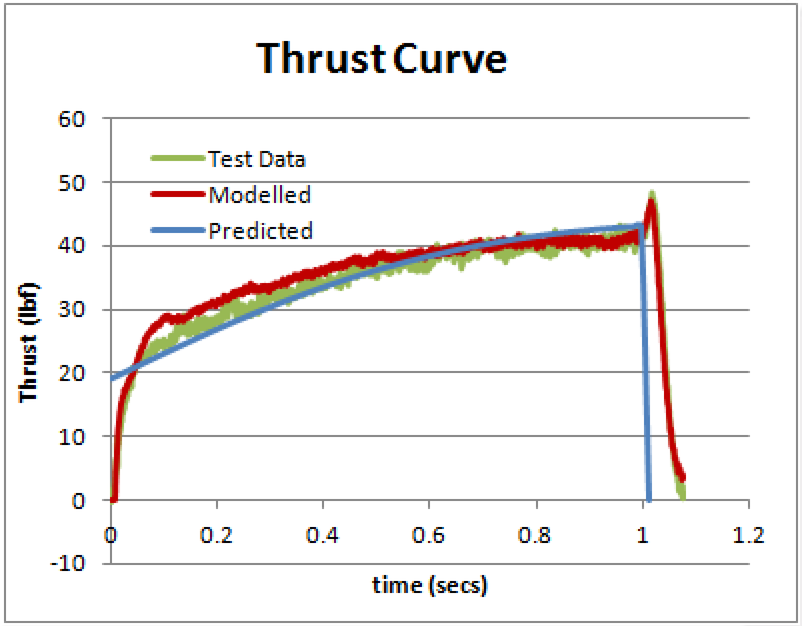


G138 Test with Copper Nozzle



G138 Test - Results

Plastic Nozzle



Copper Nozzle