U.S. AIR FORCE

USSF

AFRL

Designing the 'Best' Combustion (For Rockets)

Malissa Lightfoot

Air Force Research Laboratory, Edwards AFB, Ca

Outline

- Who I am and how I got here
- ‘Best’ Combustion
  - What that means for rockets
  - An approach assessment of options
  - Example—new injector concept
- Brief commercial
  - Gov’t labs

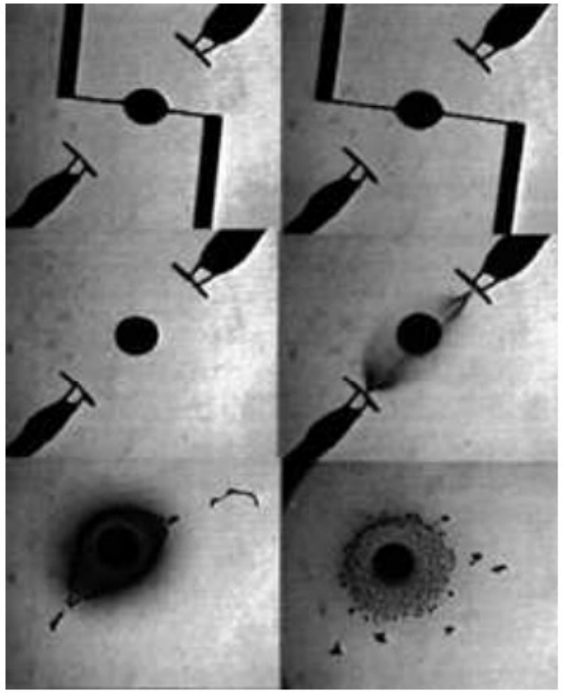
Introduction

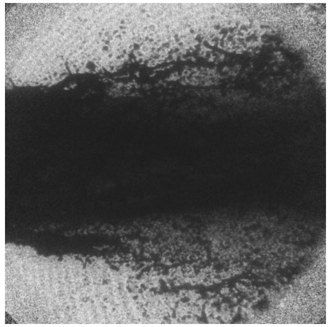
The Now

- I am the Technical Advisor for the Combustion Devices branch of AFRL's Rocket Propulsion Division
  - Even though I work for AFRL, I am a civilian in the US Space Force
- Combustion Devices branch is in charge of the basic and applied research in liquid rocket engine combustion devices
- My role as technical advisor is to oversee the portfolio of the branch
  - Ensuring work is impactful to Dept of the Air Force needs
  - Helping manage priorities (needs always outweigh resources)
  - Enabling transitions to the companies building and launching vehicles
  - Helping develop next generation of researchers
- I am also a researcher: I have my own fundamental research task in near-critical thermodynamics and I support several applied topics

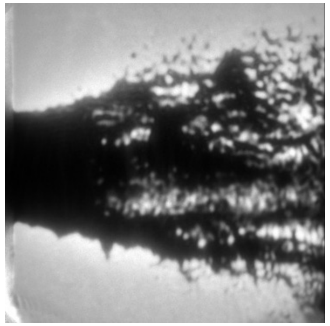
Droplet and Spray Combustion

- **Much of my research has been related to droplet and spray combustion**

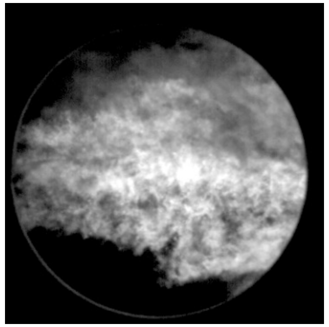




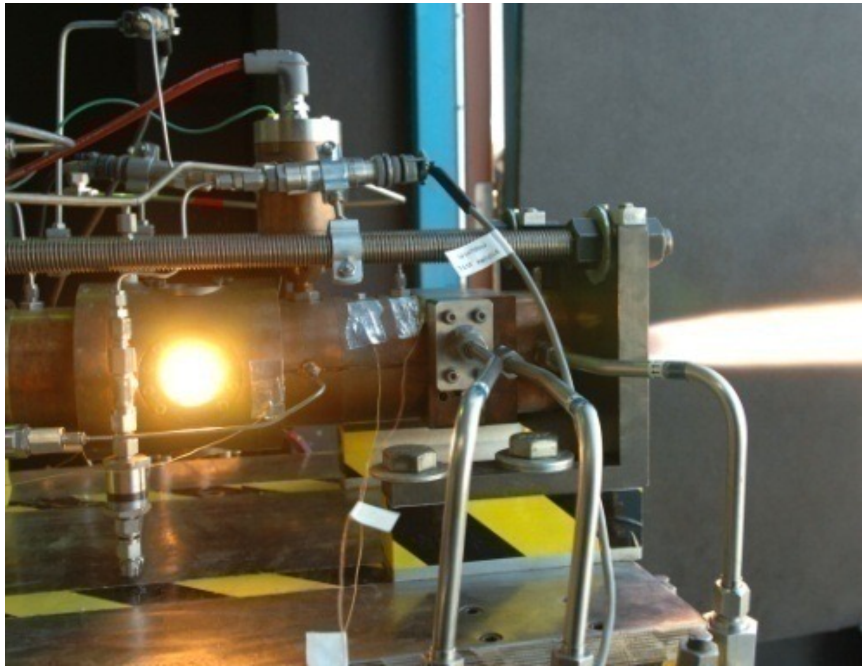
Cold-flow Shadowgraphy



Cold-flow Ballistic Imaging



High-speed Flame Image



‘Best’ Combustion (for Rockets)

Rocket Basics

- There are at least 2 combustion chambers in a launch vehicle
  - Mostly we think of the main chamber where the fire comes out
  - But for launch vehicles there is a chamber that produces work to drive the turbomachinery and feed this main chamber

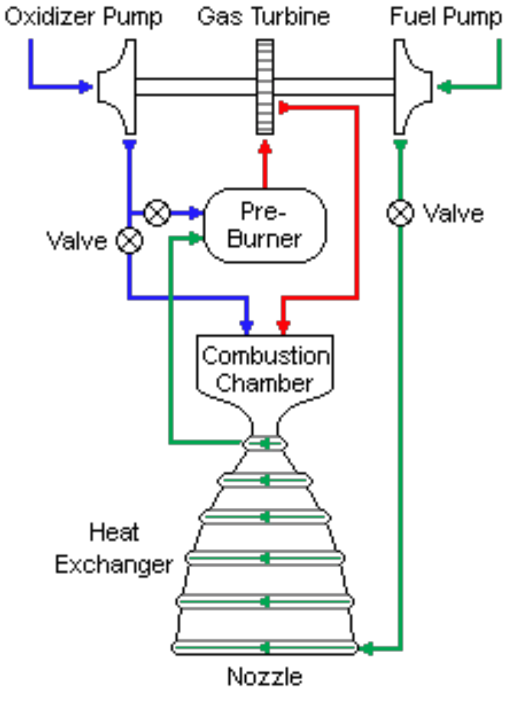


Fig. 1.9 - STAGED COMBUSTION

- Fuel is used to cool the nozzle and chamber

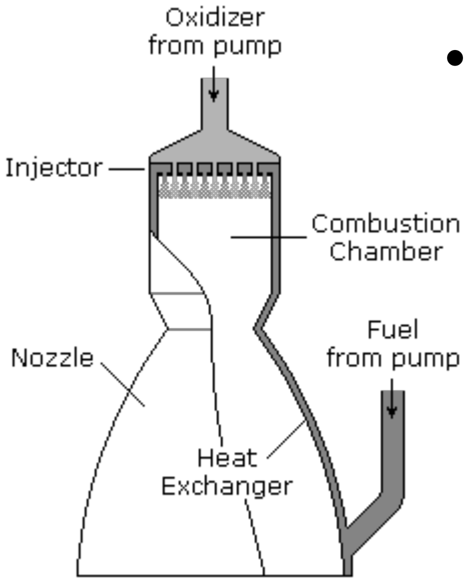
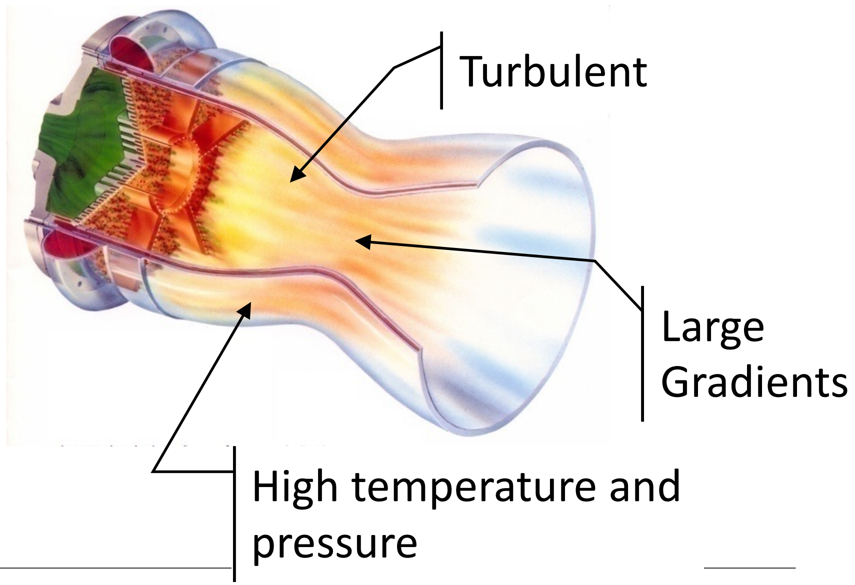


Fig. 1.12 - REGENERATIVE COOLING

http://www.braeunig.us/space/propuls.htm#engine

- Chamber has many challenges



Combustion Chambers

- **Rockets are all about minimizing the weight of the engine to maximize the payload that can be launched**
- **Combustion chamber size is set by how quickly can we mix and react the propellants**
  - **So, from a standpoint where all we care about is this combustion aspect 'best' is**
    - **Mixing time scales are minimized**
    - **Flame zones are compact**
- **This is a real-world device, though, so it has practical limitations**
- **It's also part of a system, so there are constraints related to the system**

Practical Combustion Challenge 1: Heat Flux

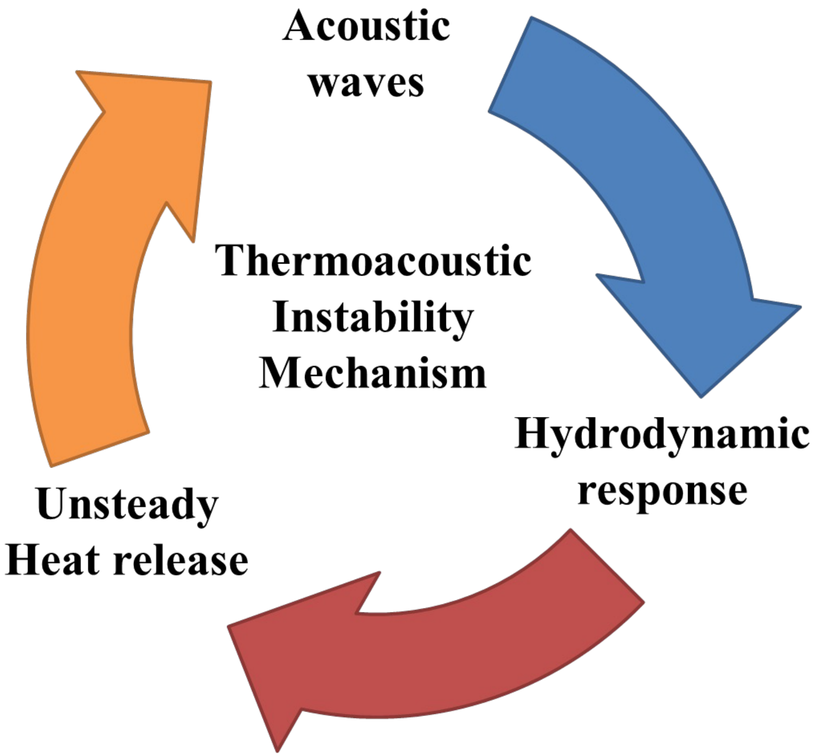
- **Flame temperature for Ox-Kerosene is >3700K at atmospheric pressure**
  - **Rough rule of thumb, for every 500 psi of pressure, it increases 50K**

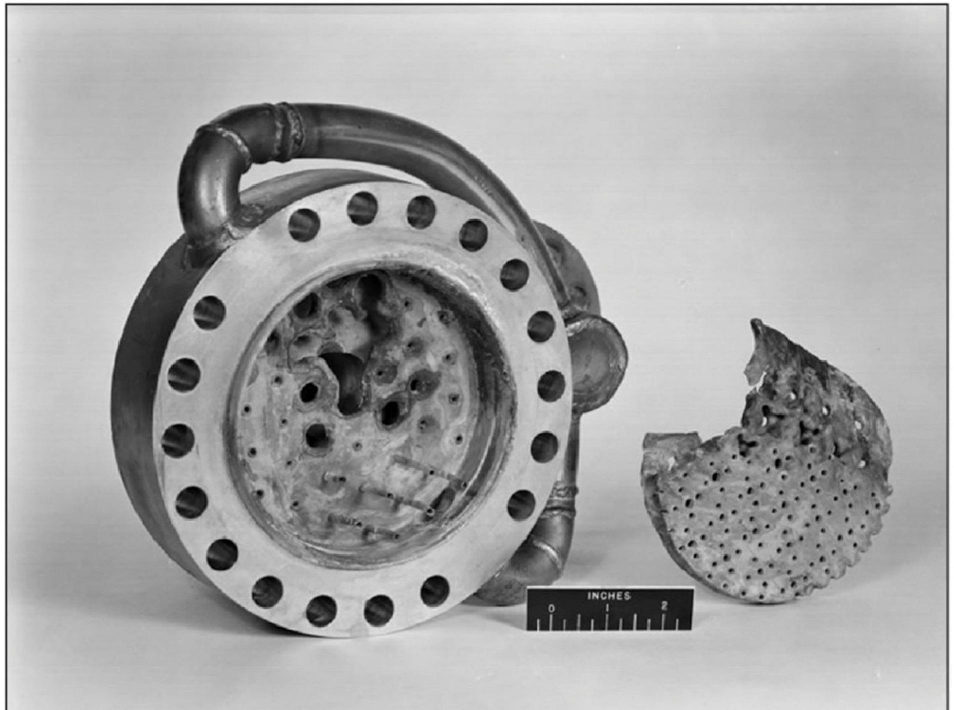
Metal	Approx Melt T	Thermal Conductivity
Copper	1350 K	400 W/m.K
Stainless Steel	1700 K	15 W/m.K
Inconel	1675 K	6 W/m.K

- **Weigh options for preventing wall failure**
  - **Cool with propellant—now heat capacity matters tremendously**
  - **Shape the combustion zone away from walls—can we reliably do this**
  - **Protect walls with propellant film—lose efficiency because film doesn't contribute by burning**

Practical Combustion Challenge 2: Instabilities

- **The more compact (and symmetric) the combustion zone the more prone to system instabilities**
  - **This has not been definitively proven, but is an excepted**





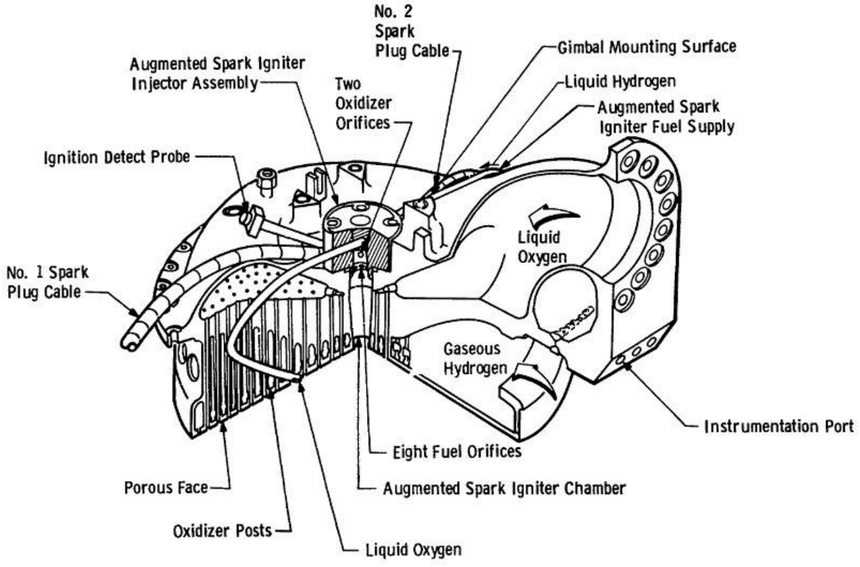
Rocket Engine Test Facility (NASA, 1957)

Practical Combustion Challenge 2: Instabilities

- **Mitigating is a challenge because of a lack of understanding of high-pressure flame dynamics, esp when coupled with feed systems**
  - **Even knowing speed of sound is difficult in these environments**
    - **Temperature and species are nonuniform**
    - **Thermodynamics of these conditions not well explored for these mixtures**
- **Weigh options for preventing failure due to instability**
  - **Add mechanical means of damping (cavities/baffles)—can be heavy**
  - **Spread out combustion zone—increase length of engine**
  - **Think outside the box and embrace instabilities (pressure gain combustion)—unproven**

System's Limitations

- **Carry fuel and oxidizer with so volume and weight matter—energy density of propellants**
- **Ignitability**
  - **How will it be accomplished**
  - **Is there an ignitable zone**
  - **Will propellants burn at low pressures (more a solid propellant problem)**
- **Need to change conditions mid flight while maintaining performance**



Details of the Augmented Spark Igniter Assembly and Main Chamber Injector

http://heroicrelics.org/info/j-2/augmented-spark-igniter.html

https://en.wikipedia.org/wiki/Delta_IV_Heavy

So, What is 'Best'

- **Cannot maximally meet all demands simultaneously**
- **How do we balance, then?**
  1) **Know your requirements—what do you need to accomplish**
  2) **Know your options**
  3) **Quantify those options and weed out unlikely ideas**
     - **Rough comparisons are generally enough at this point**
  4) **Measure relative performance between candidates**
     - **Need to determine what metric(s) is important, fidelity needed, and feasibility of obtaining**
  5) **Arrive at usable answer, and determine which candidate is 'best'**
  6) **Optimize**
     - **Currently, this is too expensive for rocket engines to be practical**

So, What is ‘Best’

- **Cannot maximally meet all demands simultaneously**
- **How do we balance, then?**
  1) **Know your requirements—what do you need to accomplish**
  2) **Know your options**
  3) **Quantify those options and weed out unlikely ideas**
     - **Rough comparisons are generally enough at this point**
  4) **Measure relative performance between candidates**
     - **Need to determine what metric(s) is important, fidelity needed, and feasibility of obtaining**
  5) **Arrive at usable answer, and determine which candidate is ‘best’**
  6) **Optimize**
     - **Currently, this is too expensive for rocket engines to be practical**

Quantifying—Approximations and Comparisons

- **Start with scale modeling—dimensionless numbers**
  - **What is known about fundamental behaviors and scales?**
  - **How do approaches compare with each other?**
- **A solid foundation will enable development of a level of intuition**
  - **Valuable for knowing what concerns to raise**
  - **But, remember to be skeptical of ‘gut feelings’ and back them up with numbers**
- **Use these approximation and comparisons for down selecting to a few candidates to spend more resources on**
- **Gives you a jump start on the next step, identifying key parameters**

Candle plume transitions from laminar to turbulent
(from https://en.wikipedia.org/wiki/Reynolds_number)

So, What is 'Best'

- Cannot maximally meet all demands simultaneously
- How do we balance, then?
  1) Know your requirements—what do you need to accomplish
  2) Know your options
  3) Quantify those options and weed out unlikely ideas
     - Rough comparisons are generally enough at this point
  4) Measure relative performance between candidates
     - Need to determine what metric(s) is important, fidelity needed, and feasibility of obtaining
  5) Arrive at usable answer, and determine which candidate is 'best'
  6) Optimize
     - Currently, this is too expensive for rocket engines to be practical

Compare Candidates

- **Identify comparators of interest**
  - **Requirements provide many of these—what do you have to ensure you meet**
  - **Others come from initial assessments—options vary in specific way which (sometimes) should be probed**
- **Determine the fidelity you need for the metrics**
  - **If you have an equation for a system-level requirement, this can be relatively straightforward (e.g., $efficiency = \frac{P_c A_t}{\dot{m}_{total}} / c^*_{ideal}$)**
  - **Can end up being trial-and-error—change x by 5% and see if requirement metric is observably impacted**
    - **Experience is a good tool here, but takes time to develop**
    - **Modeling UQ and/or sensitivity analysis can be helpful**

Compare Candidates—Fidelity Needed

- **Uncertainty is foundational to drawing conclusions**
  - **Necessary for both experimental and simulation results**
- **System-level parameters rely on equations, Monte Carlo analysis, or sensitivity/UQ approaches from numerics**
- **Individual measurements have many contributions to uncertainty**
- **UNCERTAINTY IS NOT STANDARD DEVIATION**
  - **Standard deviation is only one contributor; for measurements it accounts for the noise in your system**
  - **Repeatability, temperature drift, instrumentation limitations, resolution, etc also need to be considered**
- **Know your system / model and be attentive to changes that introduce more uncertainty**
  - **Insidious problem—reasonable data that corrupted by an unintended change**

Compare Candidates—CAN the Measurements by Made

- **Practically, is there access to the types of data necessary?**
  - **E.g., experimentally, thrust is easily measured but temperature of the flame is not, while a simulation gets temperature everywhere but thrust is more derived**
- **Can the necessary uncertainty be achieved?**
- **Can I afford to acquire this data at the uncertainty needed?**
- **Are the number / types of tests required affordable?**

- **If the answer to any of these questions is ‘no’, what can be done**
  - **Combination of experiments and simulations**
  - **Move to smaller scales—are you still capturing all the physics**
  - **Extrapolate behavior from simpler system**
  - **Relate to similar systems and draw conclusions from them (educated guess)**

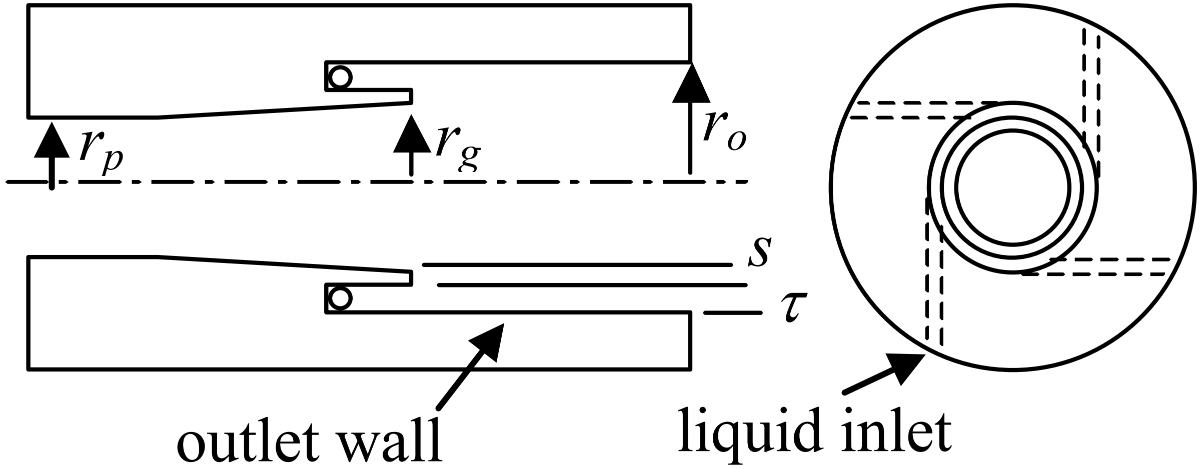
So, What is ‘Best’

- Cannot maximally meet all demands simultaneously
- How do we balance, then?
  1) Know your requirements—what do you need to accomplish
  2) Know your options
  3) Quantify those options and weed out unlikely ideas
     - Rough comparisons are generally enough at this point
  4) Measure relative performance between candidates
     - Need to determine what metric(s) is important, fidelity needed, and feasibility of obtaining
  5) Arrive at usable answer, and determine which candidate is ‘best’
  6) Optimize
     - Currently, this is too expensive for rocket engines to be practical

Example—A New Injector

General Idea

- **Different type of injector that should improve performance, but there isn't much design/any information available**
  - **Injector is of interest in oxygen-rich cycles using hydrocarbon fuels, and is similar to what is used on Russian-built kerosene engines**



- **Swirling liquid is introduced along the wall creating an annular sheet**
- **Sheet is sheared and atomized by a high-velocity annular gas flow (unswirled)**

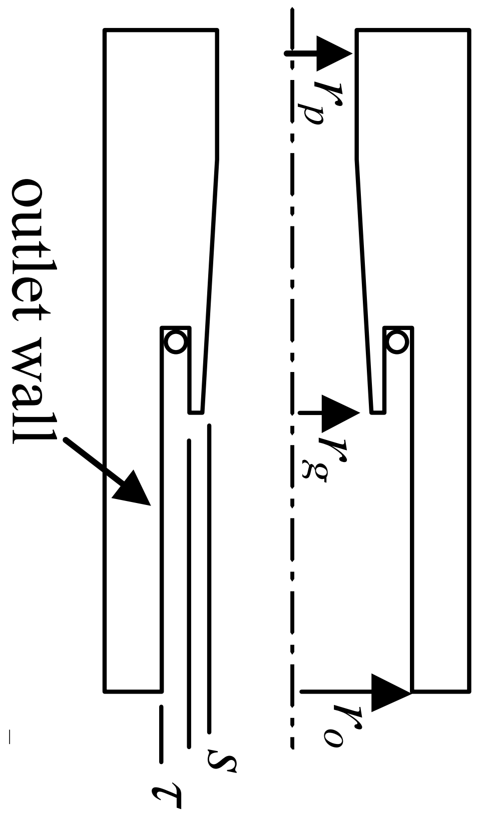
System Requirements

- Performance improvement over traditional approaches—enable a shorter, lighter engine
- Similar wall conditions (heat flux) to a traditional engine
- Stable operation and similar stability envelope
  - For the sake of time, we'll skip most of this today
- Engine operational envelope is already set and must work within it
  - Flow rates of the propellants are specified
  - Operating pressures are also given
  - There is a need to throttle, so a range of these are provided instead of a single point
  - Needs to fit within the footprint of the traditional injector

Distribution Statement A: Approved for Public Release. Distribution is unlimited. PA# AFRL-2023-3756

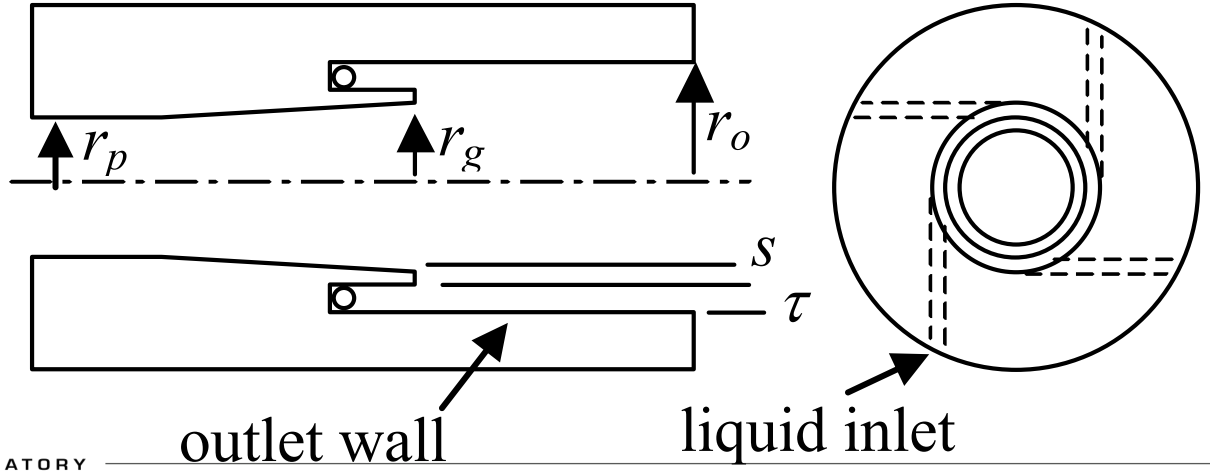
Requirements from the Injector

- **Operational envelop is set, but many geometric parameters of the injector can be tweaked**
- **How do system requirements flow down to the injector?**
  - **Performance relates to flame/reaction-zone which is, in turn, related to the atomization efficacy**
  - **Stability relates to items like shedding from the lip (and many other things)**
  - **Wall heat transfer is related to angle of spray/flame**
- **Also, I see a potential problem**
  - **Atomizing in the injector cup will be great for performance and stability, but if the flame is there it could melt the injector**



Quantifying ‘Goodness’—Performance

- **Since performance is ultimately related to atomization, what nondimensional number describes it**
  - **Lots of atomization regimes, but textbook suggest momentum flux ratio**
    - $\frac{\rho_g}{\rho_\ell}\frac{v_g^2}{v_\ell^2} = \frac{\dot{m}_g}{\dot{m}_\ell}\frac{\rho_\ell}{\rho_g}\frac{r_o^2 - r_g^2}{r_p^2}$
    - r_o **is limited set by footprint constraint, and** r_g **is limited by stability constraint**
  - **Higher momentum flux leads to better atomization, so is preferred**



Quantifying ‘Goodness’—Wall Heat Transfer

- Flame zone is controlled by the spray, so we want to constrain the spray angle
- Spray angle is controlled by the swirl in the liquid, but the gas has a huge impact on this
  - Momentum transfer caused but surface effect needing to impact volume while volume is decreasing due to atomization
  - Puts constraints on film thickness, which could over prescribe the problem when combined with the momentum flux requirements
    - So, take on the risk that this won’t be met but can be mitigated with other solutions

No Gas Flow

With Gas Flow

Quantifying ‘Goodness’—Melting the Injector

- **Maintaining a liquid film in the cup should protect it from the flame**
- **Film thickness at end of cup is again related to atomization**
  - **Mass flux being atomized times surface area of film (where atomization is occurring) divided by mass flow of liquid**
  - **Make assumption of conic variation to get surface area (through volume conservation)—get a relation for axial velocity and cup length**
- **Two big challenges**
  - **Not clear how to even estimate the mass flux being atomized**
  - **What volume of film do we want at the end of the injector? What value of the ratio do we want?**
    - **Could ignore transient and calculate, but that gives too large a value**
    - **Can’t have cup length zero—atomization different if not confined and stability degraded if flame doesn’t anchor in cup**

Quantifying Sum Up

- **Momentum flux should be large (within constraints of stability and the engine system)**
- **Length of the film is important, but difficult to quantify relative impact**
  - **Shorter cup length preferred for both weight and to ensure thermal protection for injector**
  - **Known this will impact performance—don't move to regime where most atomization is outside injector or flame doesn't anchor**
- **Important parameters to measure**
  - **Performance, since that is main system parameter**
  - **Film length since it's important and difficult to assess otherwise**

How Can These be Measured?

- **Performance:**
  - **Experimentally by shortening the combustion chamber, the fall off of performance provides information on the length of the combustion zone**
  - **Simulations are able to provide quantities that are traceable such as flame length and chamber pressure, but getting thrust is difficult**
- **Film Length**
  - **Optical and mechanical methods exist for measuring film thickness**
  - **Simulations capturing atomization in high pressure, high shear environments do exist but are generally academic codes right now**

Feasibility and Affordability

- **There are problems!**
- **Changing the length of a full-size engine will require a lot of hardware (expensive) and a lot of testing (expensive and slow)**
- **Modeling a full engine with the fidelity needed is impractical at best (due to expense)**
- **There isn't optical access to the injector and it's not clear how that could be achieved in an engine**
- **Mechanical methods to measure film thickness are not thermally robust, and alterations to make them so are unlikely**
- **Primary atomization models continue to evolve, so validation of the problem (at a minimum) would be necessary**

Overcoming These Problems

- **Many of these problems are related to having multiple injectors—consider a single injector**
  - **That captures all the atomization physics**
  - **It does not capture the interaction between elements which does change the performance some (but should be similar between injector)**
  - **This is still a bit expensive, but modeling enters the realm of feasible**
  - **Doesn't solve the film length measurement issues**
- **Remove combustion from the problem**
  - **Much of are initial exploration showed atomization underpins behaviors, so the first-order physics is being captured without combustion**
  - **Lose evaporation and heat transfer aspects, though**
  - **Much less expensive in time and money, and I can measure the film**

Cold Flow Thoughts Expanded

- Cold flow allow measurement of film thickness and length, and it is related to performance because it's a measure of atomization
- Need to ensure conditions match the real engine
  - Nondimensional parameters—momentum flux again
  - Also check to ensure Re is turbulent
- Because this scales with momentum flux ratio, experiments can be run at atmospheric conditions
  - Great for reducing time and cost even more
- But, what if we're off in our assumptions and definitions?
  - Some literature suggests at high pressures the important ratio is density ratio. Others velocity ratio.
  - Perform experiments at elevated pressure to match these (requires specialized equipment) or model with anchoring to above data

Suggested Approach

- **Develop several injector geometries that sweep momentum flux ratio and cup length**
- **Utilize cold flow to down select to two or three injectors**
- **Perform combustion tests at relevant pressures but using only a single injector**
- **Modeling would be great to bring in here, too**
  - **It provides more data than can be extracted from the experiment**
  - **Except in this outline, I didn't really make a case that I needed much if any of that—so, maybe this only makes sense if it is the more affordable choice while maintaining the fidelity of result we need**
- **Speaking of fidelity, we didn't talk about whether we had acceptable uncertainty in our measurements…**

Uncertainty (in the combustion chamber)

- **Performance changes within a few % are impactful to vehicle performance, so need to reduce uncertainty to that level**
- **For engine length investigations outlined above, the performance metric is c* efficiency,** $\eta_{c*} = \frac{P_c A_t}{\dot{m}_{total}} / c^*_{ideal}$
- **Within this mass flow, uncertainty depends on how it's metered; we use critical orifices**
  - **That requires uncertainties in measuring the pressure, temperature, and some fuel properties to be known**
- **Fuel properties are actually a challenge—we use kerosene as a fuel, and this is a mixture with wide specifications, so each batch is different**
  - **Measure the exact fuel being used and calibrate with the fuel**
  - **This is extra time and expense, but an analysis of the uncertainty shows it's required to meet the few % number**

Optimization

- At the end of this, we'll get an answer of which injector is 'best'
  - But, we only chose a few geometries to examine, so it may not be 'optimal'
- In these complex systems, optimization cannot be done by brute force, it's not affordable (design of experiments space is HUGE)
- Requires affordable models that maintain a fidelity of a few % in overall engine performance
  - Currently, these do not exist
  - No small task to get there: need capture atomization, combustion, heat transfer, and turbulence interactions (and these are all coupled)
  - It's a great goal

Some Points I hope I Conveyed Today

- **A majority of this is uncovering stumbling blocks and overcoming them**
  - **Anticipate them early—they're easier to surmount before you've started testing or simulating**
  - **Don't get discourage: if it was easy, it would have been done already, and you wouldn't be researching it.**
- **Affordability is also extremely important**
  - **Is what you will get worth the investment?**
  - **Can you find a cheaper way to answer the question? (with what limitations)**
- **Fundamentals are important**
  - **Scaling and nondimensional parameters**
  - **Meeting needs other ways by capturing the physics in a different way**
- **Uncertainty. Don't fool yourself into thinking you have an answer when you only have a possibility.**

Commercial Break

Option(s) Outside of Academia—Gov't Labs

- **As I said at the beginning, I was not initially interested in a PhD because I didn't know the options outside of academia**
- **There are a multitude of government and national labs across the US**
  - **The staff in these labs is more heavily weighted to PhDs than industry**
  - **Range of focus areas, but there is a mandate to solve specific problems or advance specific areas for national benefit**
  - **Army, Navy, and Air Force have research laboratories which do applied work with divisions focused specifically on fundamental research**
- **Unique opportunities at these labs**
  - **Work across academia and industry, and fill the gap between**
  - **Build from fundamental research to a demonstration using those concepts to meet a need**