So you want to design a pintle injector

an introduction and guidelines

(and way more details on how I designed an injector than you probably ever need, all in the the context of Herald's development)

By Max Oberg

Warning: Units are everywhere. I may be referring to kg in one section, and lbs in the next. I wish it wasn't this way but someone decided to ignore the French in the 1800s and now it's out of my hands. Screw you 1950s paper on annular orifice discharge coefficients specifically. (And for future reference, Herald is an engine developed by the Parsec team at Caltech)

Nomenclature

$\dot{m}$ = mass flow rate ρ = density u = velocity C_d = Discharge Coefficient $\dot{V}$ = volumetric flow rate A = area ΔP = pressure difference/stiffness N = number of central pintle shaft orifices d = diameter BF = Blockage Factor *(1950s paper terms below)* G = mass flow rate through an orifice, $\dot{m}$/area μ = fluid absolute viscosity C_C = coefficient of stream contraction in an orifice F = fraction of maximum pressure recovery due to stream expansion from the vena contracta to full annulus area actually recovered in an orifice f_p = friction factor for flow between parallel plates of infinite width Z = concentric annular length-to-width ratio L = orifice thickness/length	*Subscripts* exp = expected ideal = value dealing with ideal flow fuel = value dealing with fuel characteristics ox = value dealing with oxidizer characteristics p = dealing with pintle shaft oa = outer annular orifice

Introduction

Every rocket engine will typically have a few preset parameters before you approach the design of an injector, fuel/oxidizer choice, mixture ratio and mass flow rates of your propellants, and the chamber pressure of your engine.

Before we use these values however, some aspects of fluids need to be discussed. Injectors on a fundamental level are plates of metal with holes in them. One of the only questions that needs to be asked is how big to make said holes. With a certain set mass flow rate, density, and injection velocity, one can calculate an ideal area for which the hole (or orifice) should be ideally sized. This can be seen below.

$$Area = \frac{\dot{m}}{(\rho * v)} \quad (1)$$

However, when fluid flows through an orifice, effects of boundary conditions around the flow, as well as entry/exit conditions into/out-of the hole, causes the ideal mass flow rate to not accurately reflect reality. This results in a lower mass flow rate through the orifice than originally calculated. We account for the difference between the ideal flow and the actual flow as the **discharge coefficient**.

The discharge coefficient is the ratio of expected flow over ideal flow. For circular orifices, the equation is shown below in equation 2.

$$C_d = \frac{\dot{m}}{\rho \dot{V}} = \frac{\dot{m}}{\rho A u} = \frac{\dot{m}}{\rho A \sqrt{\frac{2\Delta P}{\rho}}} = \frac{\dot{m}}{A\sqrt{2\rho\Delta P}}$$

$$C_d = \frac{Q_{exp}}{Q_{ideal}}$$

(from wikipedia)^ (2)

A few assumptions must now be made to make forward progress using equation 2. In order to find A, an assumption for Cd, and an ideal ΔP value, must be used. A Cd value for a circular orifice can be assumed to be around .61 from previous experimental experience. The ΔP value is more complex however.

ΔP is more typically called the **stiffness** when dealing with injectors. The stiffness is the difference in pressure across the injector. More specifically, it is the difference between the combustion chamber pressure and the pressure in the main manifold on the injector (on the other side of the injection orifice). Typically this value is roughly around 20% for rocket injectors. One of the primary reasons you want your injector to have a certain amount of stiffness is to avoid any backflow. This occurs when the flow reverses across the injector. Combustion gasses potentially turning your injector manifold into a new combustion chamber is, to say the least, not great!

Additionally, if the stiffness is sufficiently low, a pressure wave could momentarily reverse the flow in the injector orifices, causing an interruption to any propellant injection, and an interruption to combustion. This is a phenomenon known as “chugging”. Further complications to the stiffness requirement arise from throttling requirements.

When an engine is designed to throttle, the mass flow rate is the variable that we are changing. This can be by two different methods. The first is by varying the mass flow rate at a valve along the propellant feed lines. A few rules of thumb for fixed area throttling is that mass flow rate varies linearly with thrust, and pressure drop (ΔP) changes as the square of flow rate. For example, a 50% reduction in thrust results in a drop from an example 200 psi ΔP to 50 psi ΔP.

For the fixed injector version of Herald, the engine is designed to throttle to 40% of its maximum thrust. As such, with an initial stiffness of 30% at maximum thrust, the stiffness at minimum thrust will be 12%. Since the 40% goal is only an ideal test stand target, and not a planned nominal operational range in flight, running at this low stiffness is a risk we will discover more about once we have hot fired Herald.

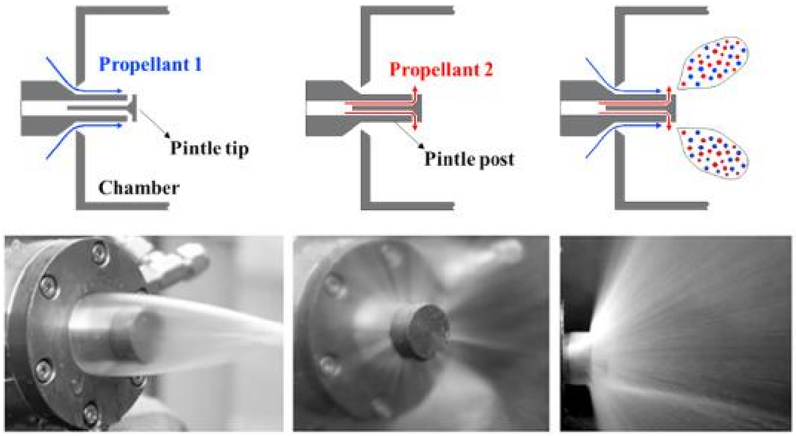
The second method to throttle an engine is by varying the injection area to effectively change the mass flow rate at the point of injection. This makes a more complex engine and injector, however, the throttle response of the engine is much quicker, reducing the input lag compared to a design that uses propellant line throttling. A specific version of a pintle injector is typical of this method, however, this will be further expounded on in the future after the pintle injector has been described below, and my own senior thesis is complete.

Pintle Injector

According to all known laws of rocket science, the pintle injector is hands down the best injector and absolutely nobody else disagrees. We will be ignoring all claims otherwise and proceed with said pintle injector description now.

The pintle injector was first developed at JPL in the midst of the rocket renaissance in the 1950s. The design would then get much further developed by TRW over the next 30 years until it was acquired by Northrup in 2002. Perhaps the most famous use of the pintle injector was on the Lunar Module Descent Engine (LMDE) and on Space X's Merlin engines.

The pintle functions with two main parts, a manifold body, and a pintle shaft. Propellant 1 will be injected via an annular gap around the outside of the central pintle shaft. This will create a circular sheet (typically.However, there are different versions of pintle injectors that could have separate channels all around the pintle shaft instead) of propellant injected directly towards the throat of the engine. Propellant 2 will then be injected at (typically) 90 degrees to propellant A's sheet out of the central pintle shaft. The two propellants will then impinge and mix. An example is shown below in Figure 1.



(a) Outer Flow Only (b) Inner Flow Only (c) Combined Flows

Figure 1: Pintle Diagram

As much as the pintle is always the best injector, it might need some further justification. The pintle injector was chosen for the Herald engine for a few different reasons. The first is ease and simplification of manufacturing. Avoiding the drilling of holes at unique angles in an injector face to impinge on each other (in a like impinging design), or drilling a lot of holes (for a shower head injector) was ideal. Furthermore, creating a single injector body, then varying the width of the central pintle shaft to control Propellant 1 injection area allows a fundamental flexibility in the design. This allows any future iterations to our design to be much simpler and cheaper to iterate by simply creating a new pintle shaft, assuming there isn't a fundamental issue with the initial manifold body.

A slightly lesser reason, but worth mentioning, is the combustion stability of pintle injectors. At the size of Herald (3-4ish in in diam), this isn't too applicable as combustion instabilities generated from other injector designs likely won't affect this small of engine types. However, in larger engines it is very much a concern. In the F-1 rocket engine (which powered the Saturn V), baffles were added into the injector plate to avoid just such instabilities. These can be seen below in Figure 2.

Figure 2: F1 injector plate

It should be mentioned that the pintle was also chosen due to some previous experience with the pintle injector in the club from its previous use in our Valkyrie engine. It was also highly recommended by alumni and advisors of the club.

So far in this, whatever this is, I have only made mention of propellant 1 and propellant 2. This is because pintles can be designed to have either the oxidizer or fuel as its central propellant. There are pros and cons to both.

Because Herald is a regeneratively cooled engine, Jet-A flows into the injector manifold from all directions. As such, creating a manifold that directs this flow down the central shaft and allows a separate lox feed system to be injected around the pintle shaft adds undue complexity to our design. Instead, a lox centered design was chosen.

However, there are a few drawbacks to a lox centered design. If the momentum ratio of the fuel and oxidizer streams is off, the oxidizer stream could break through and directly impinge on the walls of the combustion chamber. This could lead to localized hot spots and eventually engine failure. Herald's injector will be going through extensive flow testing to confirm the injection pattern characteristics and to avoid this situation as much as possible. Additionally, with lox flowing down the central shaft at a temperature of around 117K, and Jet-A's freezing point of around 226K, there is a risk of Jet-A freezing before being injected.

Nitty Gritty

So, now you understand the basics of the pintle, and how the discharge coefficient works, but how does this affect our pintle design? It should be noted, this section starts to get into rules of thumb, and values that sometimes aren't very heavily justified. Often this is general advice given to people from TRW engineers who tested this privately back in the day.

The first detail of note is the momentum ratio. As alluded to in the introduction, the momentum ratio heavily affects the amount of area of propellant injection. NASA and TRW's experience with pintle injectors indicates that a momentum ratio near 1/1 is best for mixing. That is, the two impinging streams of propellant should impinge at a 45 degree angle.

$$\frac{(\dot{m}_{fuel} u_{fuel})}{(\dot{m}_{ox} u_{ox})} = 1 \qquad (3)$$

The next value of note is the **blockage factor**. The blockage factor is the total hole length in the circumferential length over the circumference of the pintle shaft. The equation for a number (N) of circular holes (of diameter d_{ox}) is shown below in equation 4.

$$\frac{Nd_{ox}}{\pi d_p} = BF \quad (4)$$

As the blockage factor decreases, mixing from direct collisional mixing decreases, and interfacial (or shear) mixing increases. It is specifically mentioned in a Penn State study on pintle injectors that TRW has a history working with injectors with BFs between .3 and .7.

Blockage factors will vary between different designs of pintle injectors based on the setup of the pintle shaft. If a pintle shaft is created in the vein of Figure 1's pintle, then the blockage factor will be very high if not 1. However, in designing Herald's injector, we tried to keep the complexity of our system low by keeping it to a single element. An example of this can be seen in the diagram cutaways located at the end of the paper.

When it comes to the number of holes made in the pintle shaft, a rough estimate of 20-36 slots is what has been found to work well (also from the same Penn State study based off of TRW engineer advice). However, (heavily biased author's opinions that might be totally off) trying to maximize collisional mixing, maximize BF, and keeping in mind material properties so the injection orifices hold up to the forces within the combustion chamber should be balanced out to whatever is optimal and maximizes the above values. Mixing can be tested via flow tests with prototypes before any hot fires.

The ratio of the diameter of the chamber to the diameter of the pintle is known as the diameter ratio. This ratio is typically around 3-5 (also sourced from the Penn state study).

Furthermore the **skip ratio** is the length from the injector face to the perpendicular injection point (the lox injection holes in Herald's design) over the diameter of the pintle shaft. This essentially dictates how far into the chamber the pintle shaft reaches. This value should also be around 1. This fact was revealed to me in a dream as I can not locate the source for it.

The dynamics of pintle injectors cause the circulation zones indicated in figure 4 below.

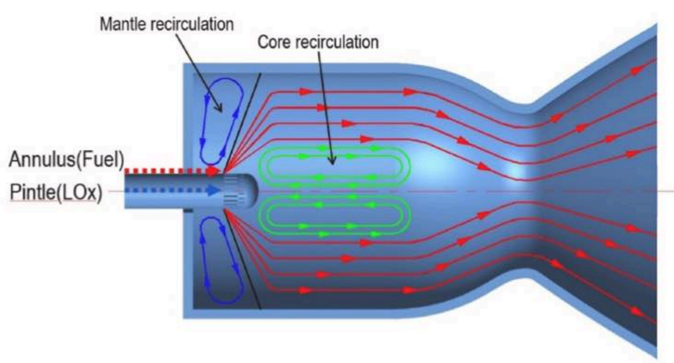


Figure 4: Recirculation in pintle shaft combustion

Now, I bring this up for two reasons, the circulation zones indicated above could add to the pintle's stability mentioned earlier in this article. It could also create complex thermal loads on the pintle tip. There have been some studies done on trying to better cool the pintle tip, which could be a weak point of the pintle design. In designing Herald, a single small extra hole was added on the bottom of the pintle shaft that will have lox flowing through it in an attempt to better cool the tip. Some designs to increase cooling add extra structure on the internal tip to create better circulation as seen in Figure 5.

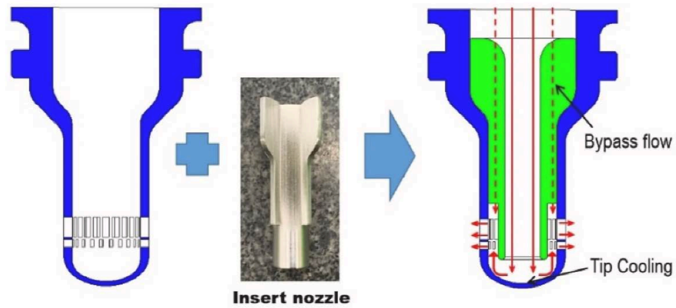


Figure 5: Example pintle

Now, the one part of this I have not mentioned yet is the size of the annular injection orifice (the fuel injection orifice in Herald's application). This opens a slight can of worms. The discharge coefficient mentioned earlier in this article specifically applies to circular holes only. So how does this equation change for annular orifices? The answer? Not nicely.

There does not appear to be a nice equation as for circular orifices. Some of the most recent work done for those orifices specifically can be found in papers from the 1950s. The most recent I found was from 1989. The 1950 paper's annular tests seem most similar to pintle annular orifices in terms of sizing and pressure environments. Now, before I go into too much detail here, the end result for the sizing of the annular orifice doesn't change much from an ideal flow area calculation mentioned in the introduction (by only about 2 mm^2 for herald specifically). But dammit I did way too much work to get info from this paper to leave it unmentioned.

The Nitty Nitty Gritty

The Herald specifics

(and potentially skippable depending on the audience here)

(and I'm really sorry about the units)

Herald was designed with the following stats:

Maximum Thrust	610 lbf
Fuel	Jet A
Oxidizer	Liquid Oxygen
Fuel Mass Flow Rate	.4801 kg/s
Oxidizer Mass Flow Rate	.75499 kg/s
Total Mass Flow Rate	1.16309 kg/s
Minimum Throttle	40% (244 lbf)
Chamber Pressure	300 Psi
Stiffness at Max Thrust	30% (90 Psi)
Blockage Factor	.58

Diameter Ratio	5.05

For Caltech readers: Most if not all calculations done in this section are in the Matlab code. I am simply walking through each calculation I have coded there, and any justification for decisions I made along the way.

The first calculations done were around the lox shaft hole sizing. A number of 28 orifice holes was arrived at (some napkin calculations were done looking at the amount of material that would be between two holes on the inside diameter. A minimum of 1 mm of material between holes was set. This was chosen partially in case we did end up wanting to 3D print this part, and keeping parts of at least 1 mm thickness seemed smart at the time).

Dividing the mass flow rate by the number of channels to get a per orifice ṁ, and then using the discharge coefficient equation, the area/diam of each lox channel was found to be $1.1857mm^2/1.2287mm$. The same stiffness (or ΔP) was used for both fuel and oxidizer orifices. This isn't strictly necessary, however, it means that any “funky” combustion behavior will affect fuel and oxidizer injection equally (theoretically). It also simply worked out well for some rough goals of injection velocities so, we'll take the wins we can here.

The injection velocity was then found using the equation shown below.

$$\frac{\dot{m}_{ox}}{\rho_{ox} A} = u_{ox} \tag{5}$$

This value turns out to be around 20.31 m/s. This should be a good injection velocity (I've seen sources cite ranges of 20-50 m/s as somewhat typical injection velocities. Keep in mind, there is a balance of injection velocity, and chamber length occurring here. If the propellant does not have enough time to fully burn before its velocity carries it out of the chamber, you've got a pickle (and an underperforming engine). If you inject too slowly however, you're leaving potential performance on the table).

So now that we have a ṁ and u for our oxidizer, and an ṁ for our fuel, we can use the momentum ratio to figure out the needed injection velocity of our fuel (remember we are shooting for a momentum ratio of 1). This leaves us with a needed fuel injection velocity of about 37.57 kg/s of fuel.

Now, later on when finding the correct area of fuel injection, we will need an initial guess. To arrive at a good initial guess, we'll do the ideal calculation for the area from the values we already have. This is shown in equation 6 below. This gives us an area of about $13.41mm^2$.

$$\frac{\dot{m}_{fuel}}{\rho_{fuel} u_{fuel}} = Area \tag{6}$$

Different regimes for annular orifice discharge coefficient calculations are discussed in the paper. The 1950s paper relies heavily on Reynolds number defined as in equation 7 below.

$$Re = \frac{(d_{oa} - d_p)G}{\mu} \tag{7}$$

Using equation 6's estimate for d_{oa}-d_p, finding the value of G for that same area (the mass flow rate through an orifice, ṁ/area), and using .00043 (kg/m/s) as the fluid absolute viscosity, a reynolds number of a little greater than 30,000 was found. So in the case of a heavily turbulent, concentric annular orifice with square edges, regime E from the paper applies. Regime E is below in equation 8. Z is defined by equation 9.

$$\frac{1}{C_d^{\,2}} = \frac{1}{C_c^{\,2}} - [\frac{2}{C_c} \ - 2]F \ + \ 2f_p Z \qquad (8)$$

$$Z \ = \ \frac{2L}{d_{oa} - d_p}$$

(9)

It is expressed in the paper that where F = 0 for Z < 1.15, and $F \ = \ 1 \ - \ e^{-.95(Z\,-\,1.15)}$ for Z > 1.15. Since our Z value is around 4 (assuming a thickness of around 1 mm), the latter is the situation we will implement. Values of C_C and f_p and found from the two figures below respectively.

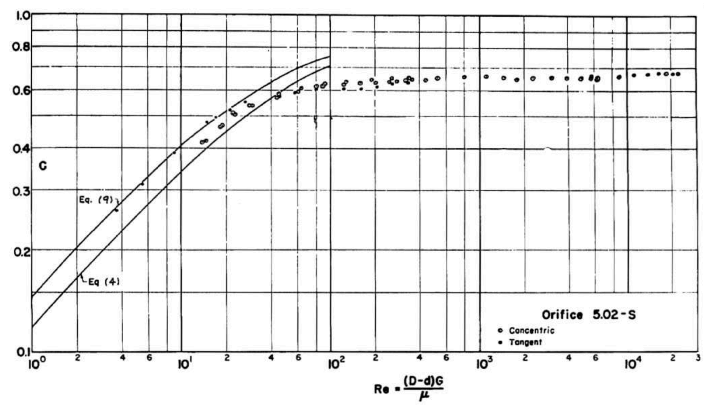


FIG. 5 COEFFICIENTS FOR ORIFICE 5.02-S

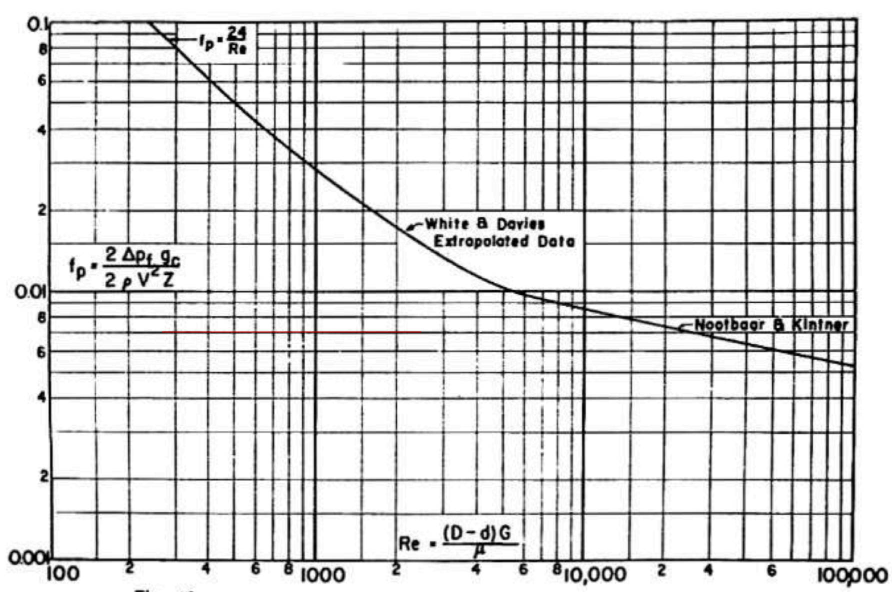
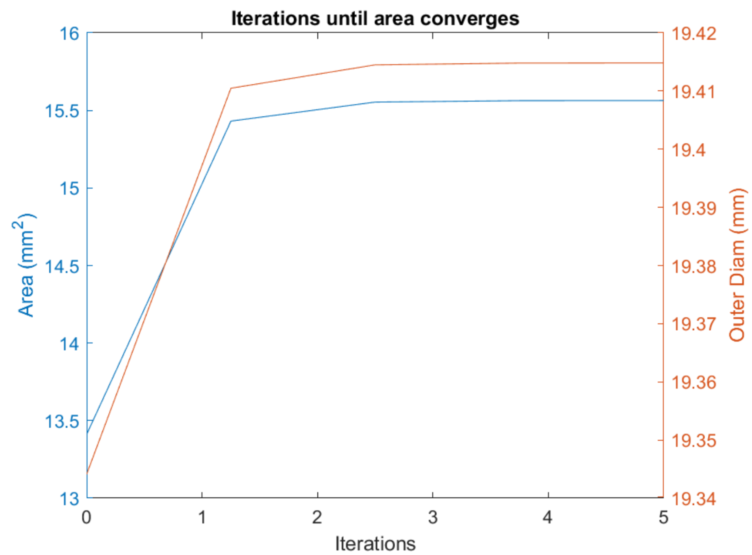


Fig. 10

FIG. 10 FRICTION FACTOR FOR ANNULI OF FINE CLEARANCE AND FOR PARALLEL PLATES

Of note in these figures is that they are both functions of Reynolds number. In order to implement these into my code, I manually picked out values on the graphs for Reynolds numbers of 30,000.

The function I created to size the annulus orifice first calculates the cd value for the ideal/initial sizing estimate. Then, using that cd value, finds a new ideal area. In this process it calculates the Reynolds number for every cd value calculated. If the new values create a Reynolds number lower than 30,000, it will pause and request new C_c and f_p values from the graphs. Otherwise, it runs using the initial values since the change in Reynolds number is not terribly significant. This function runs until the difference between the previous diameter and the new diameter is smaller than .0001 m (arbitrarily chosen). The iterations can be seen in the figure shown below.



The final outer annular diameter is 19.415 mm, with an area of 15.564 mm^2, an increase of .071 mm and 2.154 mm^2 respectively.

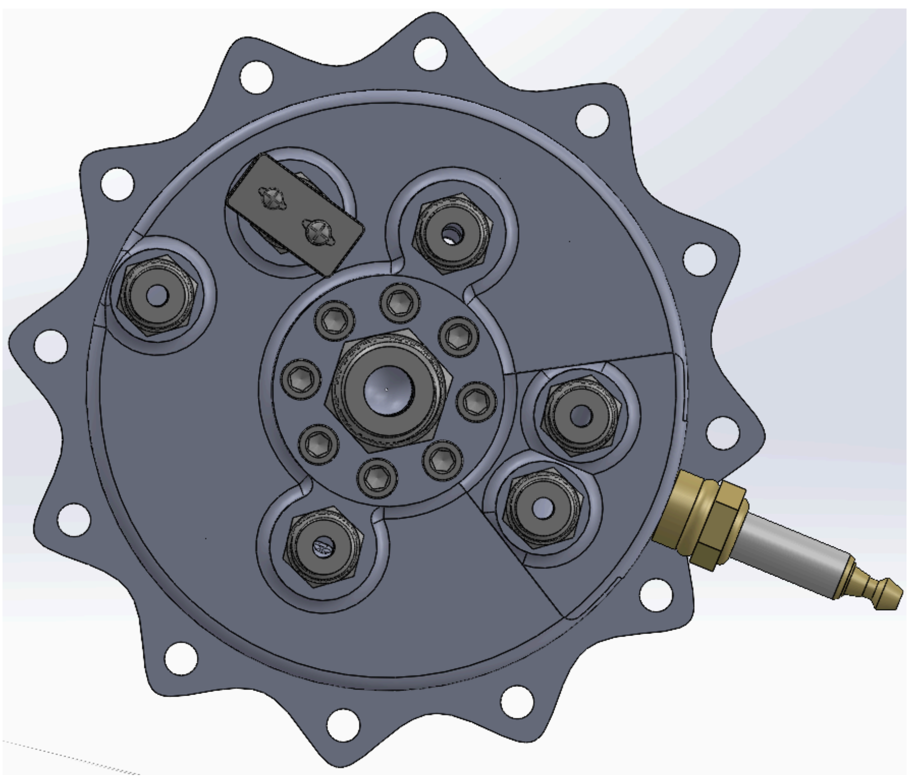
The final aspect that is specific to Herald's developmental injector are extra film cooling components. This was added so that we could be somewhat extra precautious in the first firing and testing of our engine. A separate fuel manifold was added above the main fuel manifold. This allows us to separately feed a fuel line into the film cooling manifold in order to vary it separate from the regenerative cooling fuel routing. We'll be able to slowly turn down the film cooling flow in our tests if it isn't fully needed. The current film cooling setup contains 32 1 mm diam holes that inject around the edge of the injector focused on cooling the walls of the combustion chamber.

The last integral aspect to our developmental injector is sensor ports. We ideally want to record the pressure from the combustion chamber and main fuel manifold as well as the temperature of the main fuel manifold. In our initial design this takes the form of 3 JIC - 4 ports sprinkled around the injector, with an attempt to not put them too close to each other to avoid a concentrated interruption to the flow in the main fuel manifold.

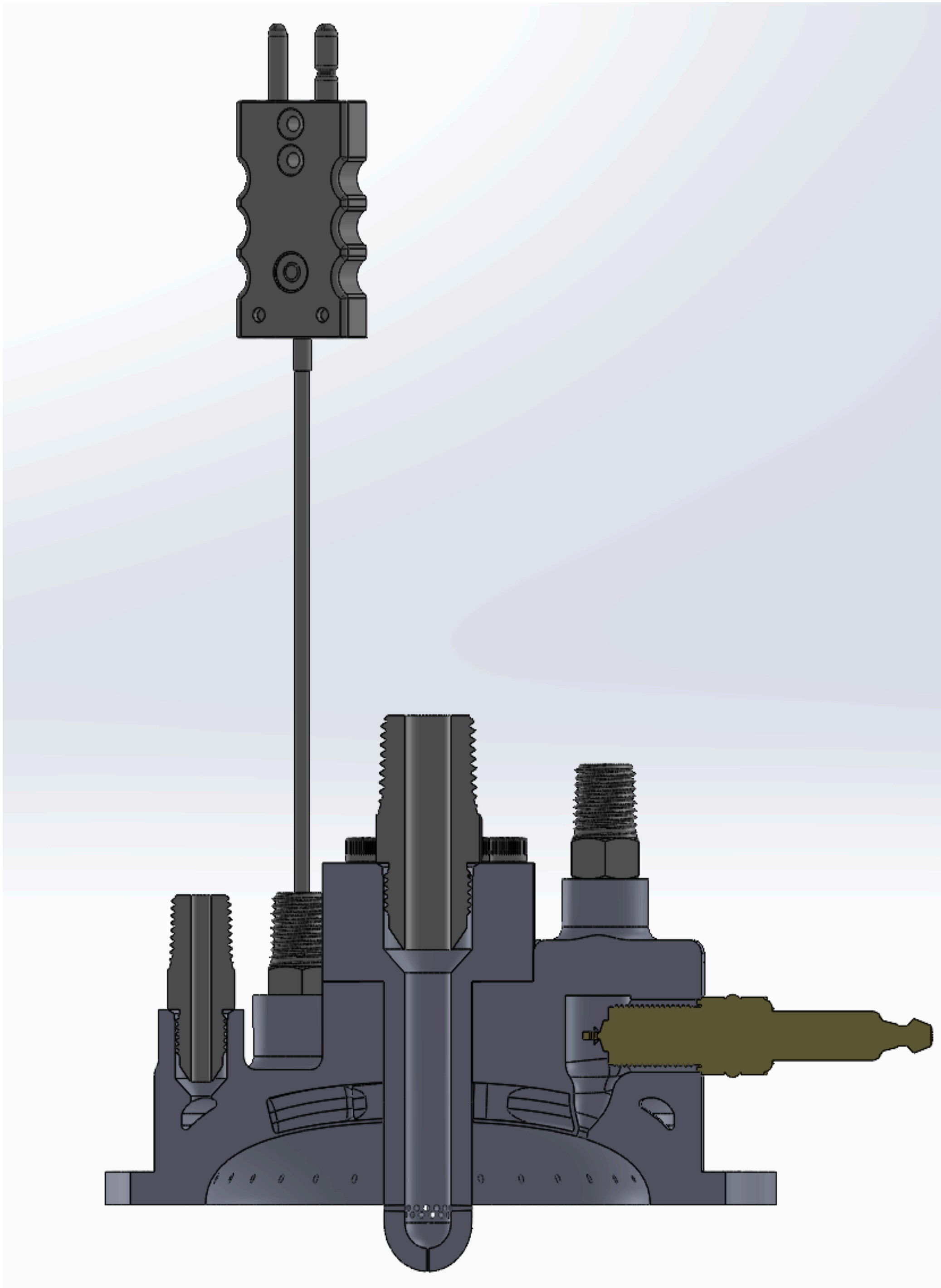
Finally we arrive at the igniter and the decisions made around it. We decided to use a torch igniter for a few reasons. The main reason was due to its simpler reignition remotely. Igniting the engine from our bunker vs replacing a solid propellant igniter every engine fire was ideal. We also wanted the robustness a rapidly re-ignitable engine would give us in designing our self landing vehicle. It also is a feature everyone but the Russians builds into their engine, so figuring out the challenges inherent to the design and creating a working prototype was ideal to us.

The design challenge began when figuring out where to place the igniter. With a chamber diameter of around 3 inches, there is not much space available in the injector face. While we could have put it in the engine wall, we did not want to cause irregular cooling channel behavior in the side wall and figured the fuel manifold in the injector would better adapt to an igniter interrupting its flow. A quick contour was generated using RPA as a guideline for the igniter chamber. The igniter will function by two quarter inch feed lines of lox and Jet-A, with a port for a spark igniter to ignite the propellants. Exact testing will inform us of the usability of our current design.

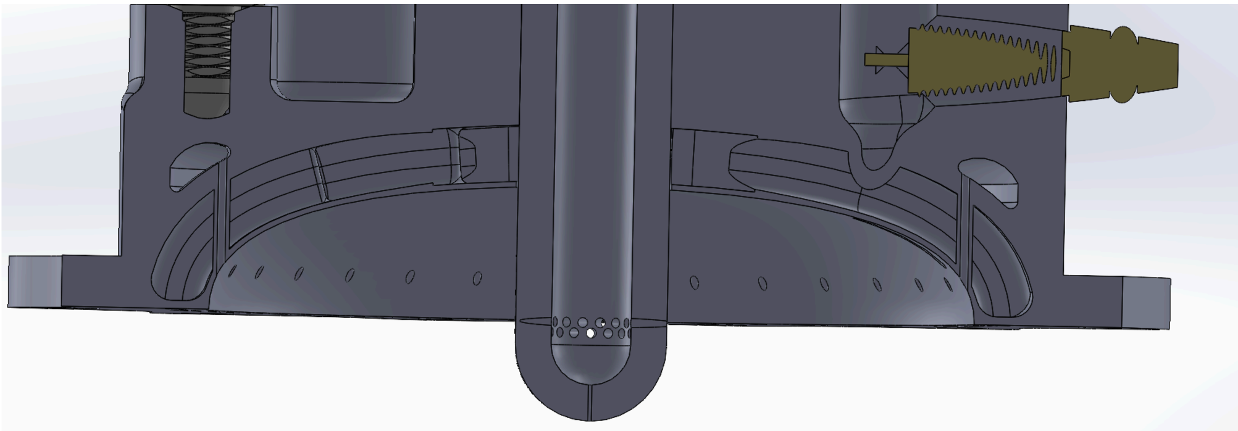
Diagrams/Cutaways/Injector Images



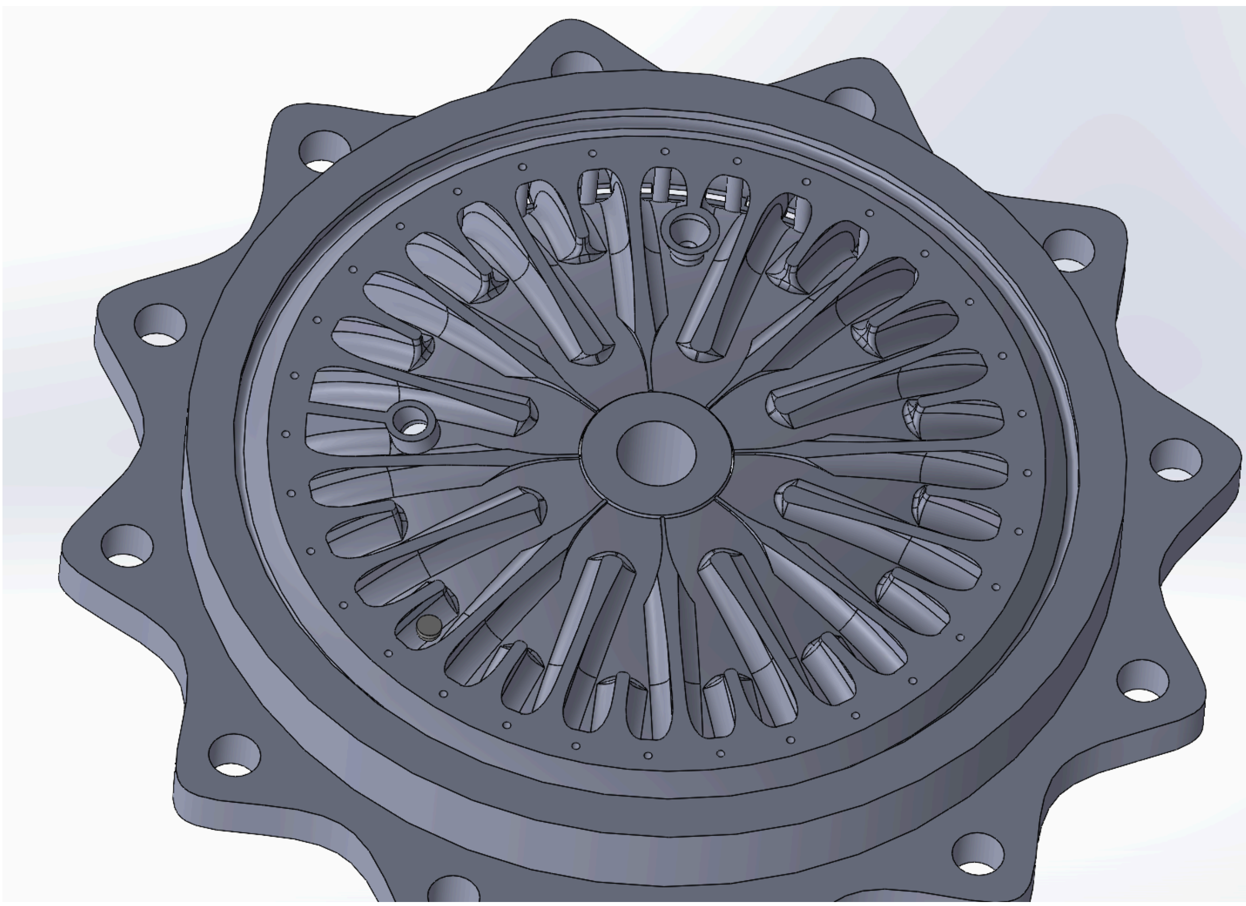
Top Down View



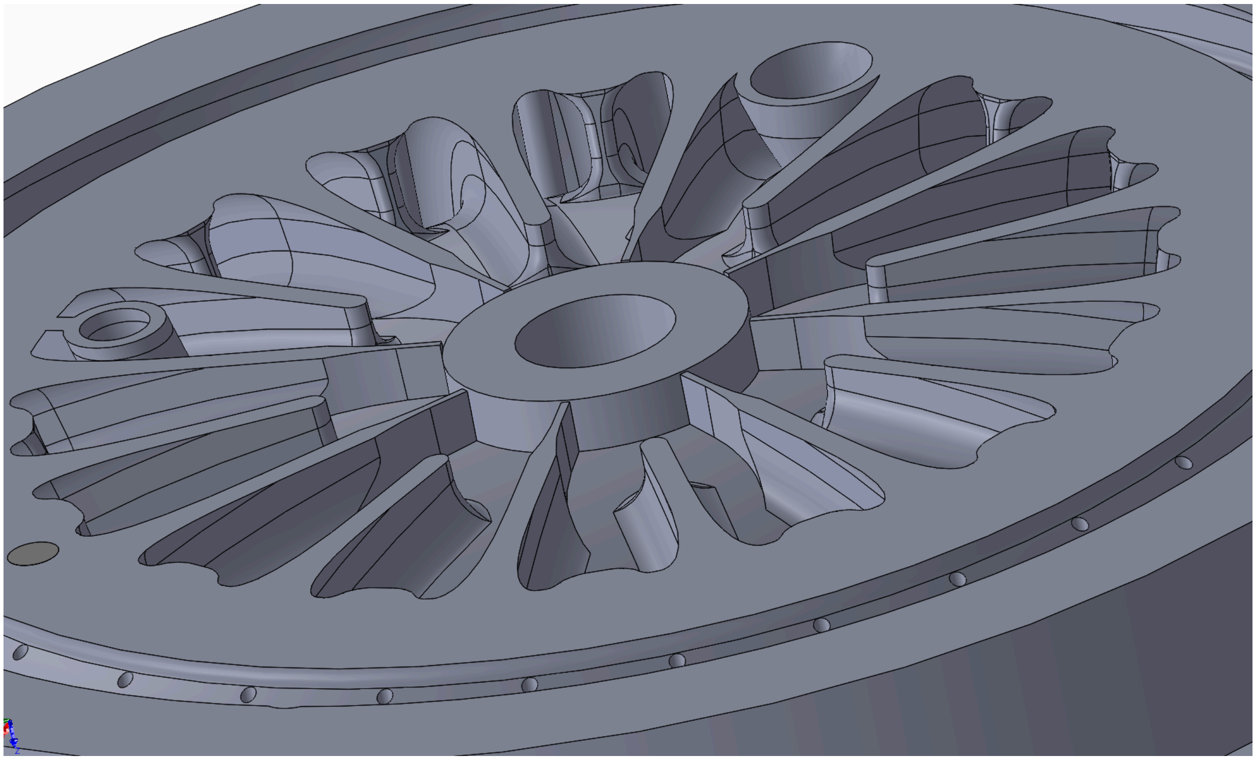
Bi-sected view looking at film cooling fuel manifold feed on the far left, the central pintle shaft in the center, and the igniter with the spark plug on the far right



A cut away to see the film cooling channels feeding into the edge of the injector



Looking down from the top, roughly half of the internal fuel manifold support walls. The hole at the top is the igniter hole. The hole on the left side is the chamber pressure measurement hole. And the small dot in the bottom left of the support area is the tip of the thermocouple for the main fuel manifold.



Slighter closer look at the support structure