UFMF8T-60-M

# Masters Group Capstone Project

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# Race 2 Space

# Hybrid Rocket Engine Component Report: Injector Design




Author: Linus Adzanku

Student number: 21000269

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# Nomenclature

A – cross-sectional area of a single injector orifice that carries the flow.

$C_d$ – discharge coefficient that corrects ideal orifice theory for viscous losses and vena-contracta effects.

$\Delta P$ – pressure drop across an injector element, equal to $P_1 - P_2$.

$P_1$ – total (up-stream) feed-line pressure immediately before the injector plate.

$P_2$ – static pressure in the combustion chamber just downstream of the plate.

Pc – steady combustion-chamber pressure used as the reference for sizing $\Delta P/Pc$.

$\rho$ – liquid-phase density at the injector inlet conditions.

$\dot{m}$ – propellant mass-flow rate through one or more injector elements.

G – mass flux (kg $m^{-2}$ $s^{-1}$) through an orifice; single-phase model $G = Cd \sqrt{(2 \rho \Delta P)}$.

v – jet exit velocity; $v = \dot{m}/(\rho A) = Cd \sqrt{(2 \Delta P/\rho)}$.

L/D – length-to-diameter ratio of an orifice, a key geometric driver of Cd and flashing onset.

$\kappa$ – minor-loss (or cavitation-) coefficient that converts local velocity head to pressure loss.

$P_{sat}$ – saturation pressure of the propellant at the inlet temperature, used in two-phase and cavitation models.

# Introduction

A rocket engine injector is responsible for delivering fuel to the combustion chamber to begin and sustain a stable, efficient combustion process which provides the desired design thrust without endangering the durability of other engine components. As it performs such a critical task, it is consequently one of the most important components in any engine.

A poor design will lead to inefficient engine performance, unnecessary damage to components after use or destruction of the entire engine. Design is highly iterative due to the lack of established, well-tested methods, formulas, and procedures to design the injector.

This report will detail the research done to understand the requirements for a good injector, outline the decisions made and why other options were not chosen, as well as aim to provide a structured approach to designing the injector for a hybrid rocket engine.

## Team Background

To begin, the team needed to gain an initial understanding of what it means to design an injector. Reading “NASA SP-8089” accomplished this primarily a document written to help engineers design better injectors for liquid rocket engines. Many of the fundamentals remain the same regardless of the type of engine, so this document was deemed suitable and has served as the foundation for the design process of the injector.

Further, the team also needed to calculate and establish the operating parameters of the other components, such as the combustion chamber and nozzle (discussed in separate component reports).

# The Basics of Injector Design

The injector in a rocket engine is responsible for delivering the oxidiser to the fuel grain to ensure stable, efficient combustion that provides the required/target thrust without endangering the durability of other engine components.

To design an injector, the entire flow system geometry must be defined. This geometry includes:

1. Total element pattern
2. Individual orifice geometry
3. Flow system upstream of the orifices(manifolding)

The definition of the flow system geometry specifies the various spray distributions such as mass, mixture-ratio and dropsize distributions.

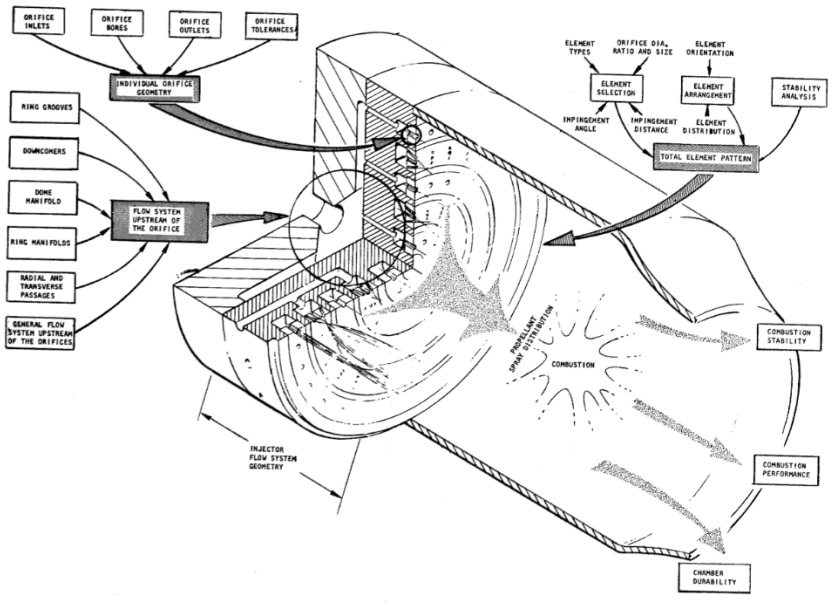



Figure 1. — Relation of injector components to total injector flow system.

*Figure 1 - image of the overall injector geometry (source: NASA)*

## Total Element Pattern

The design of the total element pattern includes:

1. Selection of the injection element
2. Arrangement of the elements
3. Provision for stabilisers such as acoustic absorbers

The total element pattern has a significant impact of the mixing and combustion efficiency of the fuel mixture in the combustion chamber. The propellant mixing and atomisation are controlled by the total element pattern.

Since the mixing and propellant dropsize levels that must be achieved in the combustion chamber are specified using combustion models, those parameters should be used as a starting point for total element pattern designs.

### Element Selection

Selecting an appropriate element type depends on the engine application and the parameters below.

- Propellants
- Condition of propellants (solid, liquid etc.)
- Chamber walls - cooling method.

- Chamber length
- Operating conditions
- Throttling requirements
- System pressure-drop limitations
- Engine life

The team initially decided to use ablative cooling techniques to deal with the elevated temperatures expected because of the combustion process. This means that an element type with good wall compatibility is advantageous as this would make full use of the ablative material to be used.

Due to budgetary limitations however, these ablative techniques were abandoned, further raising the importance of selecting an element type with good compatibility.

### Element Arrangement

Two key factors must be considered when deciding the element arrangement on the injector face.

1. The position of the elements in relation to each other should result in an overall increase in mixing uniformity due to interelement mixing.
2. The orientation of the elements near the chamber wall should provide a combustion chamber that does not affect the durability of the hardware.

Consideration one is important since flow instabilities may arise due to improper arrangement, while consideration two focuses on maintaining combustion efficiency while limiting hardware damage.

The details on what the final arrangement will be as well as investigations into flow behaviour using simulation tools will be discussed later in this report.

## Individual Orifice Geometry

Following the formulation of the total element pattern, the individual orifice geometry can be established.

Theory to predict the individual orifice stream characteristics such as flowrate, stream direction, or stream ‘bushiness’ is not well developed for orifices under the operating conditions and physical constraints of most rocket engine injectors.

NASA’s SP-8089 does however, outline important physical and fluid characteristic variables that must be accounted for in any general theory of this behaviour. They are:

- Orifice bore diameter.

- Bore length-to-diameter ratio (L/D)
- Roughness
- Inlet geometry
- Exit contour.
- Propellant properties
- Orifice pressure drop.
- Back pressure
- Back pressurant
- Propellant cross velocity, which includes the stream flow direction and orifice inlet angle.

Among these variables, the most critical flow-controlling aspects are the orifice inlet geometry, the bore, the exit contour, and the tolerances required for reproducibility.

### Flow System Geometry

The primary purpose of the flow system geometry upstream of the orifices is to produce uniform static-pressure and cross-velocity conditions upstream of the orifice inlets. Poor design can lead to deviations in individual orifice flow such as unpredictable flow characteristics when inlet conditions are known.

This step is deferred until the total-element pattern and individual-orifice geometry are fixed, because these parameters drive the upstream manifold layout.

In addition, there is little information on the methods used to design such a flow system, so the team opted to use an iterative approach, using SolidWorks and ANSYS Fluent to rapidly design and test different geometries.

## Down-Selection Process

There exist various injector design choices each with advantages and disadvantages based on the way in which the injector is to be used. This team started with the aim of designing a concentric swirl injector as we believed it would offer the best mixing and atomisation of the propellant gases once delivered to the combustion chamber.

Because of design complexity, manufacturing limits and budget constraints, the team moved from a swirl injector to a shower-head concept.

Showerhead injectors are the simplest type of injector; they could be as simple as a flat plate with holes drilled into it. Provided the hole diameters fall within established

atomisation limits, the showerhead delivers acceptable performance. Following a discussion with Ranji Gogoi, an external supervisor assigned by the administrators of the Race2Space competition, the team chose to pursue a slightly more complex design – the impinging injector.

An impinging injector works by targeting the stream of gas exiting one orifice of the injector at another. By doing this, the streams collide into one another, spraying outward in a uniform mist, thereby enhancing early-stage atomisation.

## The Swirl Injector

After consulting NASA SP-8089, the team initially identified the concentric tube with swirl as a suitable element type for this injector. This element type has been extensively used in Russian liquid/liquid engines such as the MIRA 150A.

This element provides good mixing, atomisation and a low pressure drop. It is also dependable as Russians almost exclusively used this element type at the time NASA SP-8089 was first written. The disadvantages of this element type are that it can be difficult to fabricate if the annulus gap is very small (< 0.06 inches) and that it tends to become unstable when throttled.

The latter disadvantage is of little concern, as the team aims to produce an engine capable of a maximum thrust of ~1kN for later static fire tests. At such low thrusts, including throttling mechanisms in the engine would introduce unnecessary complexity, so the team would not have done this. In addition, since the goal of a static fire test is to verify ignition, combustion stability and other key performance indicators, the engine is kept at a constant throttle setting or, at full power.

There are multiple types of concentric tube that have been built (see Figure 2), but for simplicity, the team aimed to design a flush face injector with a ribbon swirler. Since ribbon swirlers are easier to manufacture and require fewer parts when compared to tangential swirlers.

A final major disadvantage to this type of injector is just how delicate the swirler element is. As inexperienced rocketeers, the team wanted a design that was dependable and as independent of past experiences to design an injector that was not more fragile than necessary.

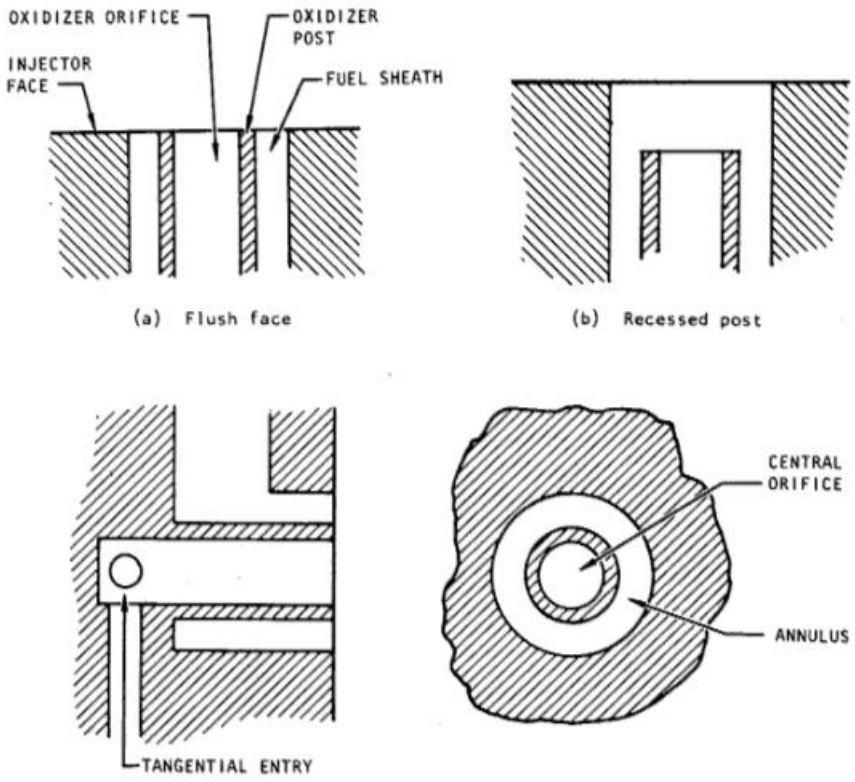



Figure 3. — Three configurations for a concentric-tube element.

*Figure 2 - configurations for a concentric tube element (source: Sutton & Biblarz)*

## The Showerhead Injector

The showerhead injector is simply a flat plate with a number of holes drilled into it. The oxidiser exits the orifice holes, interacts the solid fuel port, 'break up' and vaporise, then burns to promote combustion.

The showerhead injector was considered thanks to its advantages:

- Uniform axial flow: The numerous holes give an almost perfectly uniform entrance profile, providing very even regression around the fuel grain port. This advantage is further heightened in multi-port geometries.
- Simplicity: A single stainless-steel plate is extremely easy to drill in a single shop operation.
- Continuity through disturbance: Orifices are short. This allows for a negligible loss in performance if one orifice is clogged during operation.

The team opted not to pursue this design mainly because it was too simple to design and would not have provided a sufficient challenge. In addition, the shower-head configuration was set aside because, although straightforward to manufacture, it offered no performance margin over the impinging concept and imposed a wider ΔP tolerance that would exacerbate $N_2O$ cavitation risks.

## The Impinging Injector

A like-doublet impinging injector directs two equal oxidiser streams through orifices drilled at opposite, symmetric angles, causing the jets to collide a few orifice diameters in front of the injector face. The impact converts directed momentum into a thin, high-energy liquid sheet; surface tension then fragments the sheet into small droplets that vaporise rapidly, yielding far finer atomisation than the straight axial jets of a shower-head plate. Because only oxidiser is introduced in a hybrid rocket, every fan is chemically identical, and a properly balanced pattern produces a uniform spray curtain across the head end of the grain. Early liquid-engine practice and modern hybrid handbooks alike place the useful impingement half-angle, γ, in the 20–30 ° range, where the sheet is neither too thick to break up nor too wide to wet the face.

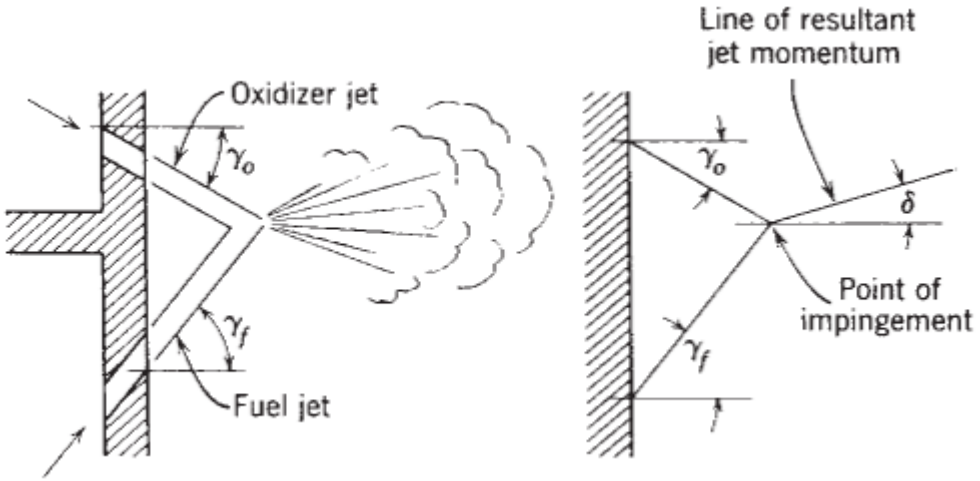



*Figure 3 - unlike doublet impingement (source: Sutton & Biblarz)*

The governing design relation is the momentum triangle. Jet velocity follows the orifice equation $v = C_d\sqrt{2\Delta P/\rho}$ while conservation of momentum for the two streams gives Sutton's Eq. 8-6; when the sine-momentum terms balance, the resultant angle δ vanishes and the sheet travels axially (Eq. 8-7). Newlands recasts the same balance for like-on-like oxidiser pairs, defining the 'β-angle' whose ideal value is again zero. In practical terms, equal areas, equal discharge coefficients and symmetric drilling angles guarantee δ ≈ 0; any mismatch tilts the fan and drives hot gases against one quadrant of the wall.

$$tan\delta = \frac{\dot{m}_o v_o sin\gamma_o - \dot{m}_f v_f sin\gamma_f}{\dot{m}_o v_o cos\gamma_o + \dot{m}_f v_f cos\gamma_f}$$ Sutton's Eq. 8-6

Typical geometry falls out of this momentum framework. Sharp-edged holes 0.5–2 mm in diameter with length-to-diameter ratios of 1–2 give discharge coefficients between 0.65 and 0.80, depending on entrance rounding. A spacing of three to four diameters between neighbouring pairs allows adjacent sheets to overlap smoothly, evening the mixture field downstream. To keep the sheet coherent and the initial Sauter-mean droplet diameter small, designers allocate a pressure drop of 15–25 % of chamber pressure across the injector; this range also drives the element into critical flow, decoupling chamber acoustics from the feed system and improving stability.

## Why Impinging Injectors Are Superior to Showerheads

Compared to shower-head plates, the impinging configuration excels in three areas. First, the stagnation zone at the collision line dissipates kinetic energy directly into surface creation, producing much smaller droplets and therefore a shorter vaporisation length; chambers can be made more compact without sacrificing combustion efficiency. Second, the sheet alternates local rich and lean regions, promoting vigorous entrainment that damps pressure oscillations often seen with purely axial jets. Third, mixture-ratio biasing is straightforward: enlarging the inner-ring orifices shifts oxidiser toward the port core where fuel regression typically lags. Shower-heads, by contrast, rely on slower turbulence-driven mixing and historically needed larger volumes for complete combustion, as the V-2 programme discovered (Karp, 2021).

The performance gain comes at a cost in manufacture and operations. Drilling tolerances tighter than ±0.5 ° in angle and ±25 µm in position are necessary; otherwise, the sheet skews, elevating local heat flux and risking burn-through. Classic deep-hole drilling can meet these tolerances only for modest hole counts; modern practice therefore favours ultrafast-laser drilling or bonded platelet stacks that photochemically etch each orifice and then diffusion-bond the layers into a monolith (Sutton & Biblarz, 2017). Since the momentum balance is fragile, any single-hole blockage breaks the pair and deflects the sheet, so fine upstream filtration is mandatory. Impinging plates also require a higher design ΔP than showerheads, and coarse throttling degrades atomisation as jet velocity falls, narrowing the stable operating envelope (Sutton & Biblarz, 2017).

## Theoretical Limitations

Analytical relations stop at predicting resultant angle and flow area; they say little about droplet statistics, wall impingement or recirculation structures. Modern programmes therefore embed computational fluid dynamics in the sizing loop: a periodic single-doublet model validates the β-angle, swept simulations vary 'γ' and ΔP to visualise breakup length and potential wall wetting, and a transient full-face run confirms

symmetry when all pairs interact. Two-phase CFD studies on hybrid injectors show how differences in the treatment of surface tension or slip velocity can shift predicted vena-contracta behaviour and mass-flow oscillations, underlining the need to cross-check simulations with cold-flow Cd measurements and hot-fire tests (Sutton & Biblarz, 2017).

For this reason, the team opted to design the injector primarily using computational tools, verified performance using analytical methods, and then updated the simulation model to testing any changes and verify new performance. The models used were much simpler than those that would be used in industry however, as vena-contracta was not considered for example. The models are intended to provide a general view of the injector's flow behaviour, not a detailed depiction of its actual operating performance.

### *A note on injector pressure-drop*

Across the classical liquid- and hybrid-rocket literature, injector pressure drop is consistently sized as a fixed fraction of chamber pressure: modern design handbooks recommend keeping ΔP between 15 % and 25 % of $P_C$. Sutton & Biblarz note that values in this band "obtain high injection velocities" and therefore good atomisation and stability, choosing 20 % as a worked-example baseline. Karp, 2021, tightens the lower end, stating that liquid rockets "use an injector pressure drop in the range of 15–20 % of the chamber pressure to ensure stability". Together, these references frame the commonly accepted design window of one-sixth to one-quarter of chamber pressure, with 20 % serving as the go-to starting point.

To distil the research:

- Values a little higher (≈ 25–30%) are chosen when you need extra margin against combustion-coupled pressure oscillations or if you want to guarantee fully turbulent flow through small orifices.
- Going much above ≈ 35% wastes tank pressure (or pump head) and can shorten burn time in blow-down systems without giving a noticeable performance benefit.
- Dropping much below ≈ 15% risks sluggish start-ups, poor atomisation/vaporisation and, in hybrids, feed-system-coupled instabilities.
- 20 % ΔP/Pc is the classic "rule-of-thumb" for bipropellant and hybrid engines that do not employ pumps.

## Design Methodology

As stated before, the team initially designed a showerhead injector before deciding to attempt the more complex, better performing impinging injector, using CFD tools to study the behaviour of the jets exiting the injector.

The results of this process were used as a starting point to design the impinging injector so, a brief explanation of the methodology followed will be outlined below.

## Showerhead Design Methodology

Richard Newlands outlines a systematic method to design a hybrid rocket engine injector. In the book written on the topic, he focuses on a showerhead injector as it is the simplest injector to design and manufacture. For his stated mission, this injector type also offers adequate performance without added operational or manufacturing complexity. Though his injector is a showerhead, he incorporates elements of impingement into its design (see Figure 4), by subtly angling the orifice exits at one another, to benefit from the improved mixing and atomisation offered by the gas jets colliding.

Newlands suggests that orifice diameters should not exceed 1.5mm as atomisation occurs best at diameters ≤ 1.5mm. Smaller orifices offer better atomisation, but due to concerns about manufacturability, operability and budget, the team opted to select a diameter of 1.5mm as this offers the minimum adequate atomisation performance.

A delivery pressure of 44 bar (ΔP = 25 % PC) was selected as an upper-bound value; Karp (2021) and Sutton & Biblarz recommend 15–20 % for hybrid engines, so hot-fire testing will also evaluate 15 % and 20 % drops to balance atomisation against two-phase choking. This delivery pressure was calculated by deciding the pressure drop, then calculating the ideal delivery pressure based on this value and the chamber pressure.

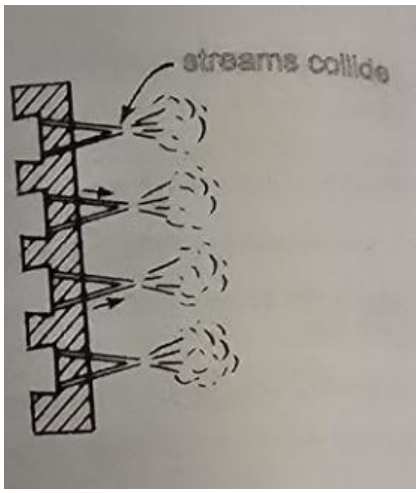



*Figure 4 - Newlands' injector.*

This injector pressure drop was decided on after consulting Karp (15% - 20%), Sutton (15% - 25%) and Newlands' (20% - 25%) recommendations on the ideal injector pressure drop. In addition, the organisers of Race2Space have encouraged participants to aim for higher pressure drops, so the team has attempted to design an injector with a pressure drop on the higher end of the range identified by the three authors.

$$\Delta P = P_{delivery} - P_{chamber}$$

The next step is to calculate the number of orifices needed for adequate burn using the rearranged form of an equation provided by Newlands in the book:

$$N_{orifice} = {m_{prop}} \Big/ {A_{orifice}\sqrt{\frac{2\rho_{ox(l)}\Delta P}{c}}}$$

Where c is 2.0 according to Newlands.

The density of the liquid oxidiser ($\rho_{ox(l)}$) here is 787 kg/m$^3$. This value comes from Appendix 3 of Newlands' book.

### *Orifice exit velocity*

The velocity of the jets leaving the injector can be computed in a few different ways according to Razavi and Niño (2019). This design process only considered the methods outlined below.

#### Single-phase (SPI) velocity

For an incompressible liquid the injector behaves like a thin-plate orifice. Bernoulli's theorem, corrected with a discharge coefficient $C_d$, gives the mass-flux relation below.

$$G_{SPI} = C_d\rho\sqrt{2(P_1 - P_2)}$$

The jet velocity at the orifices can then be calculated using:

$$v_{SPI} = \frac{G_{SPI}}{\rho}$$

Sharp-edged liquid orifices where d ≤ 0.25mm typically have $C_d$=0.60 −0.70. The team uses a $C_d$ value of 0.65.

#### Two-phase (flashing) models.

When the static pressure is driven toward the nitrous-oxide saturation line inside the hole, vapour appears, and the flow can choke. Two well-established analytical mass-flux models are:

- **Homogeneous-Equilibrium Model (HEM)**

$$G_{HEM} = C_d\rho_2\sqrt{2(h_1 - h_2)}$$

- **Dyer non-equilibrium blend** (bridges SPI and HEM)

$$G = \frac{\kappa}{1+\kappa}G_{SPI} + \frac{1}{1+\kappa}G_{HEM} \qquad \kappa = \sqrt{\frac{P_1 - P_2}{P_{sat} - P_2}}$$

The velocity in a two-phase throat follows $v = {G}/{\rho_2}$. Experiments show that critical (choked) flow begins when the backpressure falls below roughly 80% of the local saturation ($P_x/P_{sat}$) pressure (Karp, 2021)

### *Results*

| Table I: Showerhead Injector Data | |
|---|---|
| Injector Pressure Drop (%) | 25 |
| Delivery Pressure(bar) | 44 |
| Number of Orifices | 22.6 |
| Orifice Area($mm^2$) | 1.77 |
| $P_1$: injector feed pressure (bar) | 44 |
| $P_2$: chamber pressure (bar) | 33 |
| $V_{SPI}$ @ 20 ˚C ($m^2$) | 35.2 |
| $V_{SPI}$ @ 25 ˚C ($m^2$) | 35.7 |

### *Pressure drop implications*

At 20 °C, the saturation pressure of $N_2O$ is ≈ 36 bar, so the feed line is “super-charged” ($P_1/P_{sat}$≈ 1.22). The chamber sits just above the saturation line ($P_2/P_{sat}$≈0.92). Because $P_2$ is still above the $0.8P_{sat}$ criterion, the risk of fully choked two-phase flow is modest. Therefore, the single-phase velocity model should describe the jet reasonably well. Nevertheless, the minimum static pressure inside the orifice may dip below $P_{sat}$, creating incipient cavitation pockets that raise turbulence and wall stress.

At 25°C, $P_{sat}$ is ≈ 51 bar, so the liquid is only marginally sub-cooled and $P_2/P_{sat}$≈0.65 which is less than the saturation line on 0.8. The Dyer parameter ‘κ’ therefore becomes large and the blended model tends towards the HEM model, and a choked core can be expected during operation. At this stage, velocities can be expected to climb as high as 110 m/s despite the same chamber pressure drop of 25% in the 20°C case. This occurs because the mixture density drops sharply Razavi and Niño (2019).

During hot fire testing in July, the team will likely choose to perform tests at a lower pressure drop than 25%. This choice will depend on the temperature on the day and the temperature of the nitrous oxide in the tank, this injector drop may be as low as 15% to avoid issues that may cause the engine to fail, such as choked flow.

## Impinging Design Process

### *Geometry*

The orifices were laid out to maximise symmetry while remaining within the maximum diameter of the plate – 120 mm (combustion chamber diameter). Published methods give limited guidance on detailed ring spacing; consequently, the final geometry was iterated empirically (in CFD), guided by the designer's experience.

The technical drawings in Appendix B show all the final measurements and positions of the injector to be built.

One thing to note however, is the angle 'γ' of the orifices relative to the face plate.

Although the accepted impingement half-angle lies between 22° and 30°, the present design employs 45° to clear the torch ignitor. Subsequent CFD indicated acceptable 'sheet' spray integrity; nevertheless, future iterations should reduce this angle or reposition the ignitor to minimise wall-wetting risk.

| **Table II: Final Injector Parameters** | |
|---|---|
| Number of Orifices | 20 |
| Injector Diameter (mm) | 120 |
| Orifice Diameter (mm) | 1.5 |
| Impingement Angle: γ (˚) | 45 |
| Orifice Area ($mm^2$) | 1.77 |
| Injector Pressure Drop (%) | 25 |
| $P_1$: injector feed pressure (bar) | 44 |
| $P_2$: chamber pressure (bar) | 33 |

Needing to maintain symmetry and because impinging injectors inherently improve atomisation, fewer orifices are needed to achieve the same spray quality the team chose to use twenty orifices instead of twenty-three or twenty-four.

### *Worked example (β-angle sensitivity)*

To illustrate how sensitive the spray sheet is, let us assume: Pc = 33 bar and adopt an injector pressure drop ΔP = 0.25 Pc = 8.25 bar.
For a sharp-edged, 1.50 mm orifice the area is $A = \pi d^2/4 = 1.77 \times 10^{-6}\ m^2$.
With Cd = 0.65 and a representative liquid-nitrous density of 750 kg $m^{-3}$, the jet velocity is $v = Cd\sqrt{(2\,\Delta P/\rho)} = 0.65\sqrt{(2 \times 8.25 \times 10^5/750)} \approx 30.5\ m\ s^{-1}$.

The mass flow through each orifice is $\dot{m} = \rho\, v\, A \approx 0.040\ kg\ s^{-1}$, giving a jet momentum $\dot{m}\, v \approx 1.23$ N.

For a like-doublet element the two jets are drilled symmetrically at ±γ (here γ = 27°, in line with the recommended range).
If both orifices are identical the transverse momentum components cancel exactly and

$$\tan \beta = (\dot{m}_1 v_1 \sin \gamma - \dot{m}_2 v_2 \sin \gamma)/(\dot{m}_1 v_1 \cos \gamma + \dot{m}_2 v_2 \cos \gamma) = 0,$$

so the resultant sheet leaves parallel to the injector face (β = 0°), as desired.

A quick tolerance check shows how sensitive the alignment is: a 2 % oversize in one hole (1.53 mm) raises its mass flow by ~4 %, giving tan β ≈ 0.01 and β ≈ 0.6°. That half-degree deflection is already large enough to shift the sheet centre by 5 mm after a 500 mm flight, underscoring the need to hold drilling tolerances within ±20 µm and to measure orifice areas before assembly.

### *Ignitor Placement*

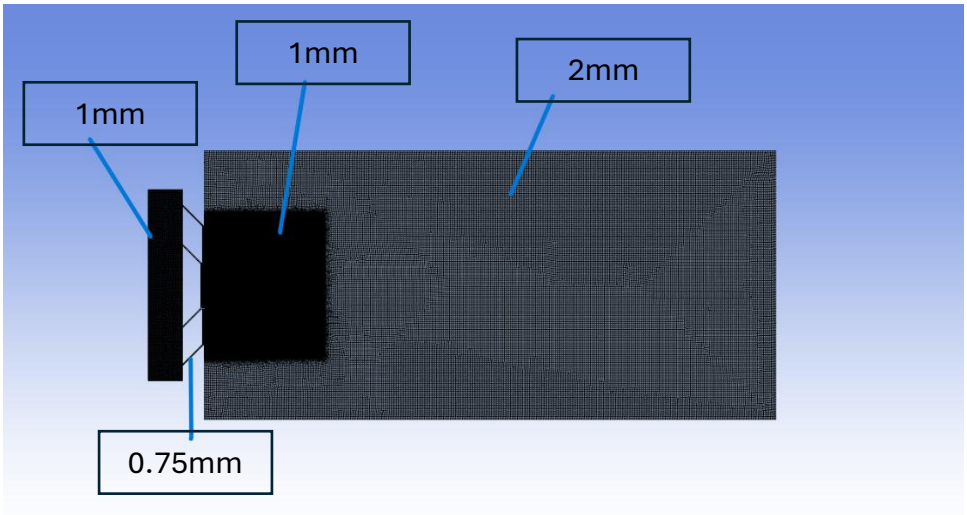
The team has opted not to design an ignition mechanism and will use a torch ignitor provided by Protolaunch – a company affiliated with the Race2Space competition.

Ideally, the ignitor would be placed in a location that allows for the fuel grain to be melted slightly, without intercepting the oxidiser as it coats the fuel grain port.

Three placements were considered for the ignitor: angled through the chamber wall, embedded in the injector body, or protruding from the centre of the face plate. The protruding installation was selected to reduce the avoid potential improper seals on the combustion chamber if it were installed there, and to avoid disrupting the ‘spray’ of the oxidiser onto the fuel grain.

### *Simulation Process*

Three two-dimensional mid-plane section models, representing the top and bottom halves of the injector’s fluid region, were prepared—each corresponding to a one-, two- or three-ring orifice layout envisaged for the manufactured part.



| Table III: ANSYS Fluent Settings | |
|---|---|
| **Parameters** | **Simulation Setting** |
| **Fluid** | Incompressible – $NO_2$ (ANSYS database) |
| **Model** | 2D planar section (mid-plane) |
| **Solver** | Pressure-based; Transient |
| **Models** | Transitional SST SBES |
| **Methods** | Scheme: SIMPLE<br>Gradient: Least Squares Cell Based<br>Pressure: Standard<br>Momentum: Bounded Central Differencing<br>Turbulent Kinetic Energy: Second Order Upwind<br>Specific Dissipation Rate: Second Order Upwind<br>Intermittency: Second Order Upwind<br>Momentum Thickness Re: Second Order Upwind<br>Transient Formulation: First Order Implicit |
| **Residual Convergence criterion** | $10^{-6}$ |
| **Initialisation** | Hybrid Initialisation |
| **Iteration every time step** | 40 |
| **Time Step** | 0.01 s |
| **Number of time steps** | 500 |

*Note – The CFD domain resolves only the fluid region on a mid-plane cross-section; references to "rings" describe the eventual hardware, not additional domains in the CFD.*

## *Simulation Results*

### 1 Ring

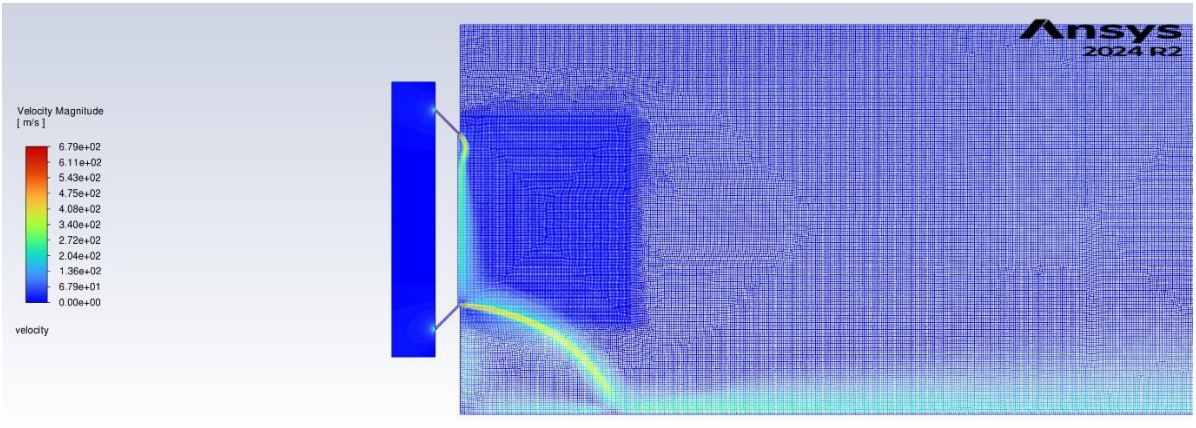



*Figure 5 – end of simulation flow behaviour of a 1 ring injector*

As can be seen in figure 5, the nitrous oxide by the end of the burn no longer collides at the central axis of the injector. It instead flows along the walls of the combustion

chamber. This is not only undesirable, but dangerous as it may damage the combustion chambers walls as the combustion continues.

## 2 Rings

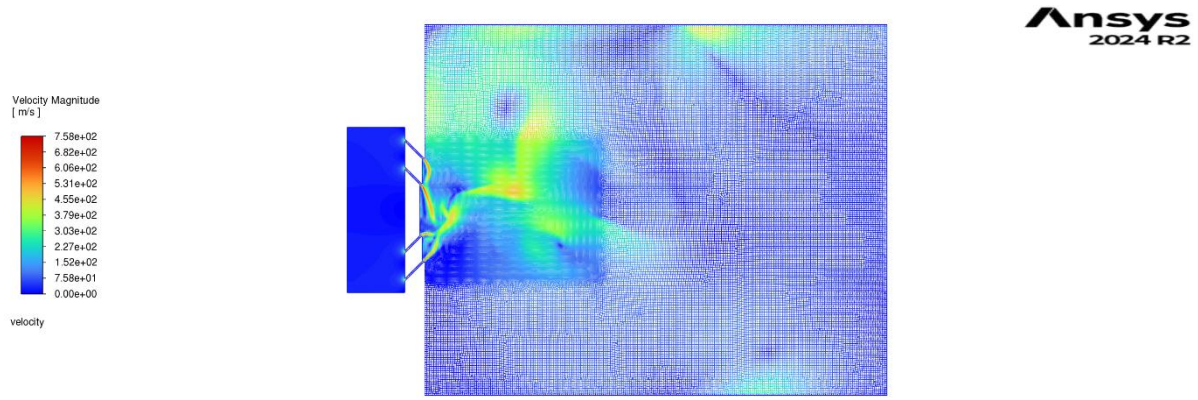



*Figure 6 – end of simulation flow behaviour of a 2 ring injector*

In figure 6, the image shows a relatively steady spray towards the imaginary fuel grain in the imaginary chamber. While some fluid makes contact with simulation model's walls, that gas would be intercepted by the fuel grain during operation before it reached the combustion chambers walls, where it can cause damage and degradation.

## 3 Rings

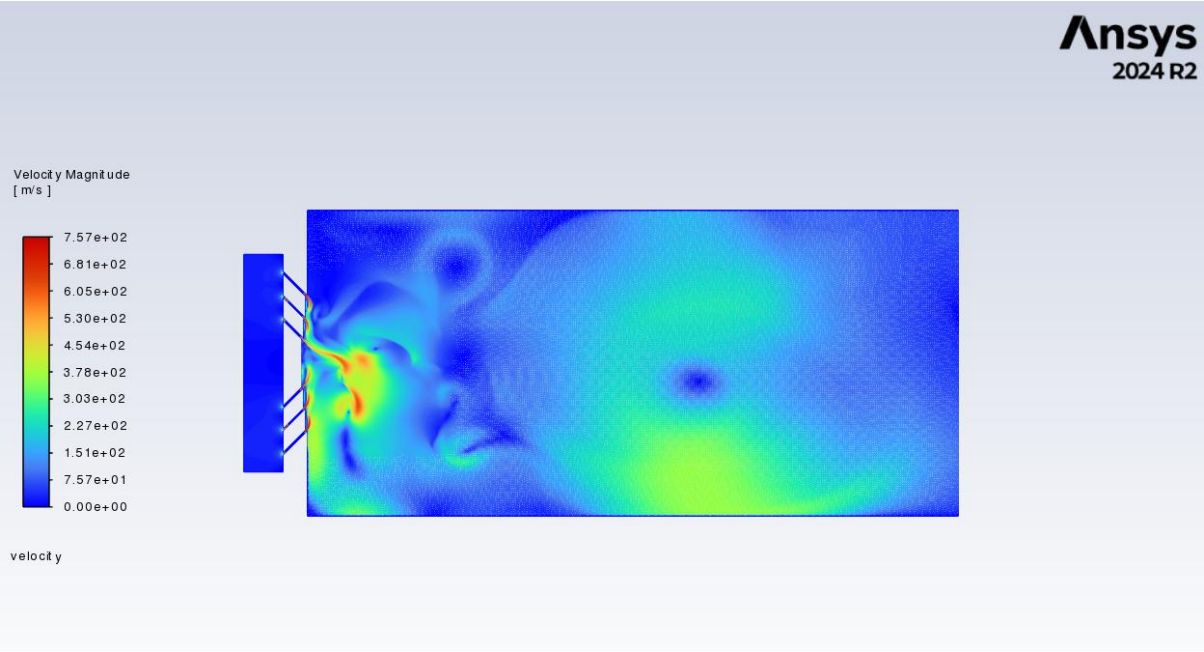



*Figure 7 - end of simulation flow behaviour of a 3 ring injector*

With three rings, the axial flow away from the orifices is the most obvious and stable (see figure 7). Ideally, this arrangement would be manufactured, but as will be discussed below, a different arrangement was selected due manufacturing concerns.

In the Appendix C, there are links to YouTube videos of the simulation as it progresses, to provide a better understanding of the behaviour of this injector.

#### *Final Selection*

The team selected the impinging injector with two rings of orifices instead of the one with three rings despite its better performance for two reasons – manufacturability and performance.

The injector with two rings shows adequate performance for lower manufacturing complexity/cost. Using this design, a machinist would not need to make as many stepped cuts into the base plate, reducing material waste and lowering the risk of a mistake being made. The injector with three rings of orifices, while showing better spray performance does not allow for this. Any slight asymmetry on the part could cause the flow to choke inside one of the orifices, shifting the β angle towards the side with no choked flow.

# Materials and Manufacturing

## Material Selection

Stainless-steel 304 was selected after a brief literature review for the following reasons.

- It is readily available.
- Less expensive than the alternative under consideration (Inconel 718).
- Its performance under the expected operating conditions is documented.

When the design moved to CNC machining, 304 stainless remained the material of choice because its behaviour in similar applications is already well characterised.

## Manufacturing

Additive manufacturing was originally chosen to minimise waste and to produce precise orifice geometry, safeguarding performance.

Budget limitations and the lack of suitable metal-additive facilities prompted a switch to CNC machining.

There are a few considerations and conditions associated with this switch.

1. Additive manufacturing produces the injector as one piece, removing any need to create the internal cavity separately. The result is a monolithic part, eliminating potential oxidiser leaks. Moreover, the printed part needs minimal finishing before meeting performance requirements.
2. CNC machining is subtractive: standard tools remove material from a stainless-steel block. Because CNC tools cannot reach the enclosed internal cavity, the

rear plate will be removed for machining and reattached by a circumferential weld. Although welding introduces a potential leak path, it remains the quickest and least-cost sealing method. See the Appendices A and B for an image of the injector assembly and technical drawings.

# Testing

The team plans to conduct two types of tests on the injector and wider engine: hot, static fire tests, and cold-flow tests.

The hot fire test has been scheduled for 1st July 2025 and is the main priority. Final tweaks and discussions about how to ensure that these tests go well are still under way even as this project begins to wrap up.

On the day, visual data of the engine's performance obtained using cameras will be collected. In addition, more abstract data such as chamber pressure, temperature and thrust will be collected using an array of sensors to be installed on the engine after full assembly.

Cold-flow tests, while extremely useful in detecting leaks and gaining a general idea of the performance of each component remain a secondary priority. These tests have not been conducted by the time of this report's authoring as the parts have yet to be manufactured and delivered in a complete state.

On the day of the hot-fire tests, the team will be given the opportunity to perform these cold-flow tests and will endeavour to do so given no time or other constraints.

# Reflection and Future Steps

The injector work has moved from rough handbook sizing to a practical design that can be machined. The current layout uses two rings of like-doublet holes drilled into a block of stainless steel. A pressure drop of about one-quarter of the chamber pressure (25 %) was chosen because it should give decent mixing while keeping the feed system simple. Machining tolerances are well within what the workshop can hold, so there is confidence the part can be built.

Even so, several gaps remain that need attention before the injector can be signed off for hot-fire tests.

## Where the design now stands

- Geometry and materials – A two-ring plate, made from 304 SS, holds hole diameters under 1.5 mm to encourage fine spray.

- Pressure drop – 25 % of chamber pressure was selected as an easy rule; lower drops (15–20 %) may end up safer once real flow losses are measured.
- Manufacture – CNC machining was chosen after additive printing proved too costly. The body is split for tool access and will be welded back together.

This roadmap is sensible and should produce a working injector. However, the analysis behind it is still lighter than it needs to be.

## Main weaknesses spotted

1. ### Two-phase flow not fully covered
   Liquid nitrous oxide is stored almost exactly on its saturation line, so even a modest pressure drop across the injector makes part of the stream vapourise instantly. This flash boiling produces a frothy two-phase mixture whose density and speed of sound collapse; the flow can therefore "choke" and deliver far less mass than a single-phase Cd estimate would suggest.

   Because flash vaporisation limits the mass flux, sizing the injector with single-phase correlations is unreliable. Replacing those relations with a modern two-phase model s(uch as the Ω-method discussed by Niño & Razavi) will keep predicted mass-flow within about ±5 % of test values.

2. ### Cold-flow testing missing
   Without rig tests the discharge coefficient (Cd) is only guessed. A small orifice test setup can map Cd versus pressure before any fuel is burned.

3. ### CFD detail is too low
   Mesh independence has not been shown, and the current grid cannot capture tiny regions where the jet contracts. A finer grid and a full 360° model, even if run coarsely at first, will prove whether the spray is symmetrical.

4. ### Impingement angle
   The present 45° half-angle breaks the usual 22–30° guideline, chosen only to clear the ignitor. Moving the ignitor slightly or using an off-axis torch would let the angle drop back to a safer range, cutting wall wetting and hot spots. One way to achieve this would be to make the injector plate thicker, so the ignitor is further recessed into the plate, reducing the need to clear it at such extreme half angles.

5. ### Clear pass/fail targets lacking
   At the moment there is no written list of what counts as success. Setting acceptable Cd limits, spray-cone width and maximum wall temperature will make it obvious whether each future test passes.

## Actions for the next design cycle

For the next design cycle, first integrate a modern two-phase mass-flux model so flow predictions remain accurate as the nitrous tank blows down. In parallel, set up a low-cost pressurised rig (using water or compressed air) to measure the injector's discharge coefficient and expose any feed-line oscillations before hot-fire. The computational work needs refinement too. So, carry out a mesh-refinement study, document $y^+$ values and include at least one full-face CFD run to confirm that the spray pattern stays symmetrical. Re-locate the ignitor so the impingement half-angle can return to about 25°, which reduces wall wetting and hot spots. Finally, establish clear pass/fail criteria including but not limited to acceptable Cd range, spray-cone width and maximum wall temperature—so each forthcoming test delivers an unambiguous verdict on the injector's readiness. It must be noted that these pass/fail checks may involve more detailed simulations or more equipment to gather the data necessary to pass/fail the injector's performance under those testing conditions.

### Final Thoughts

With these straightforward upgrades, the injector plan will shift from a promising draft to a design ready for qualification. Future tests will then teach real physics, not fix hidden mistakes, placing the programme on a steady path toward a successful static firing.

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turbine. *International Journal of Numerical Methods for Heat & Fluid Flow* [online]. 31 (2), pp. 655–673. [Accessed 15 March 2025].

# Appendices

## Appendix A – CAD Model

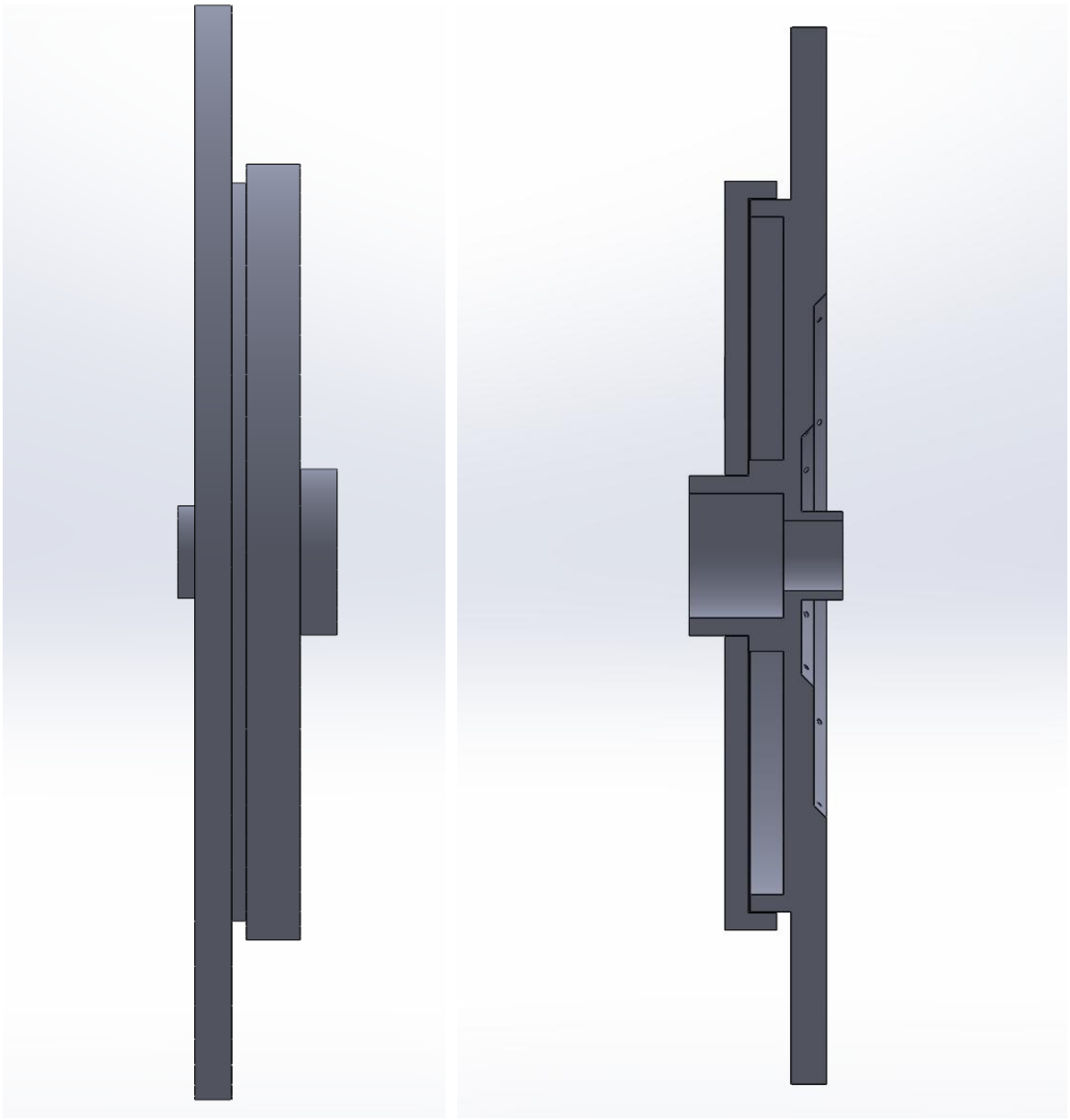


*Figure 8 – section views of Injector*

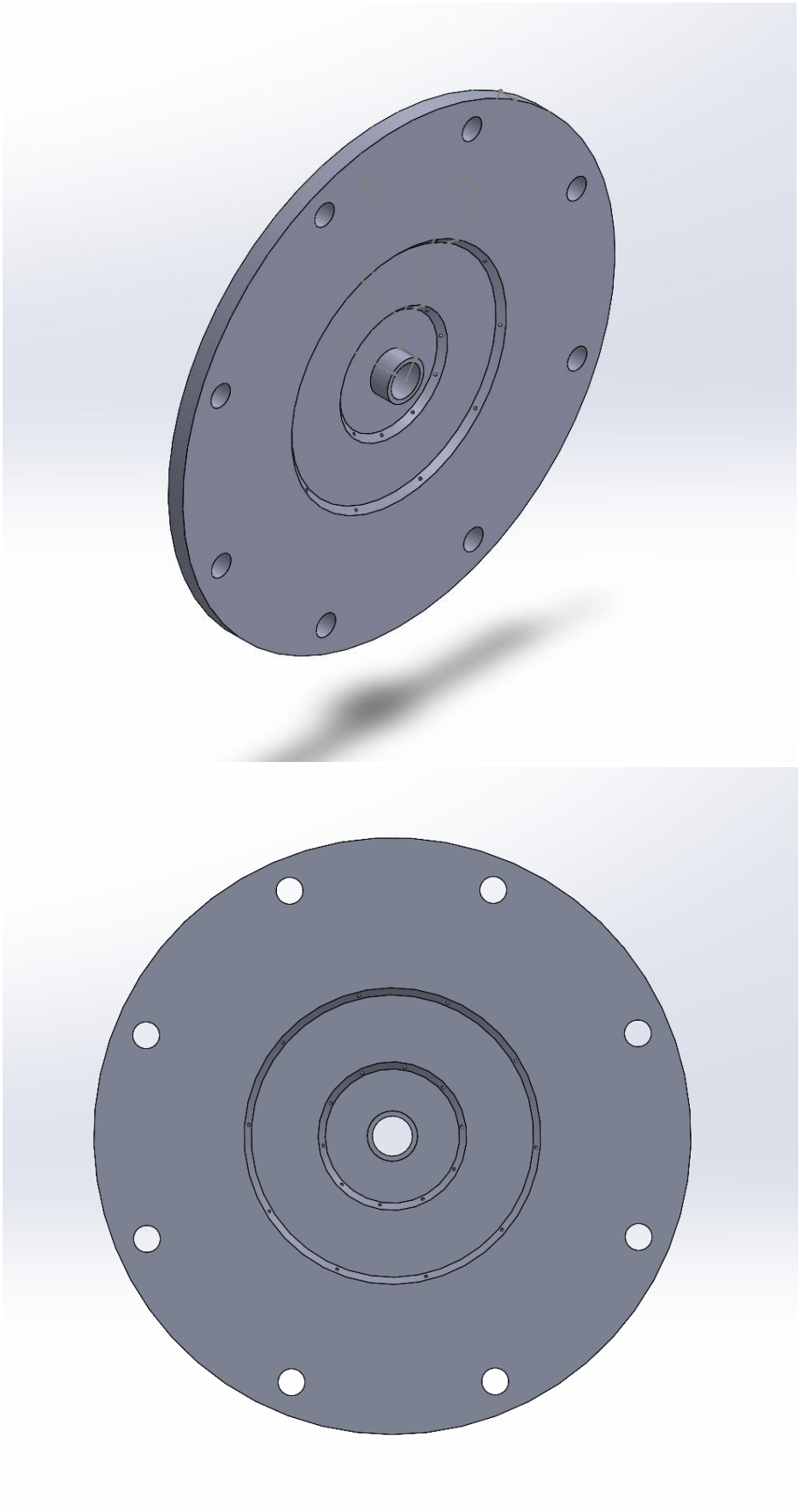
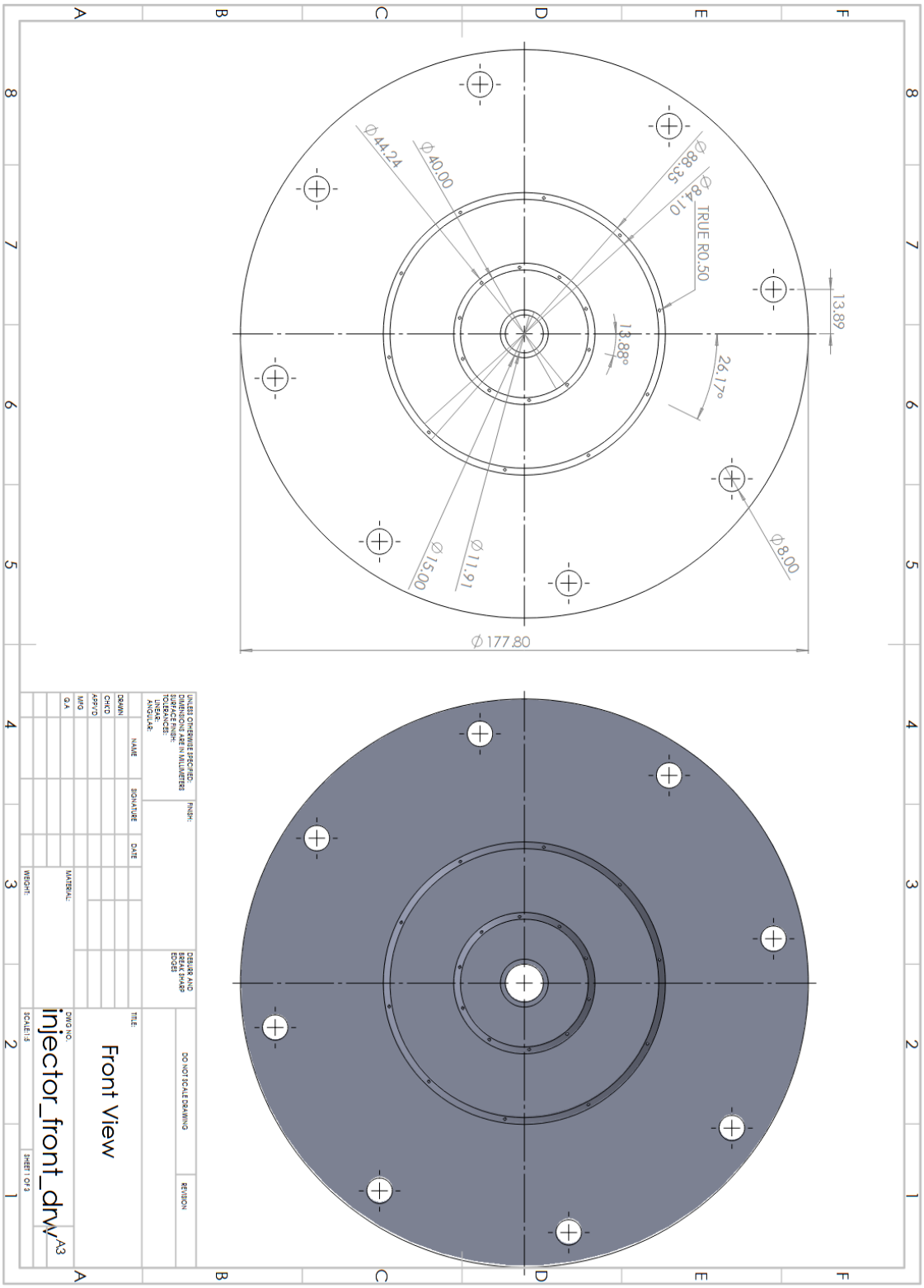
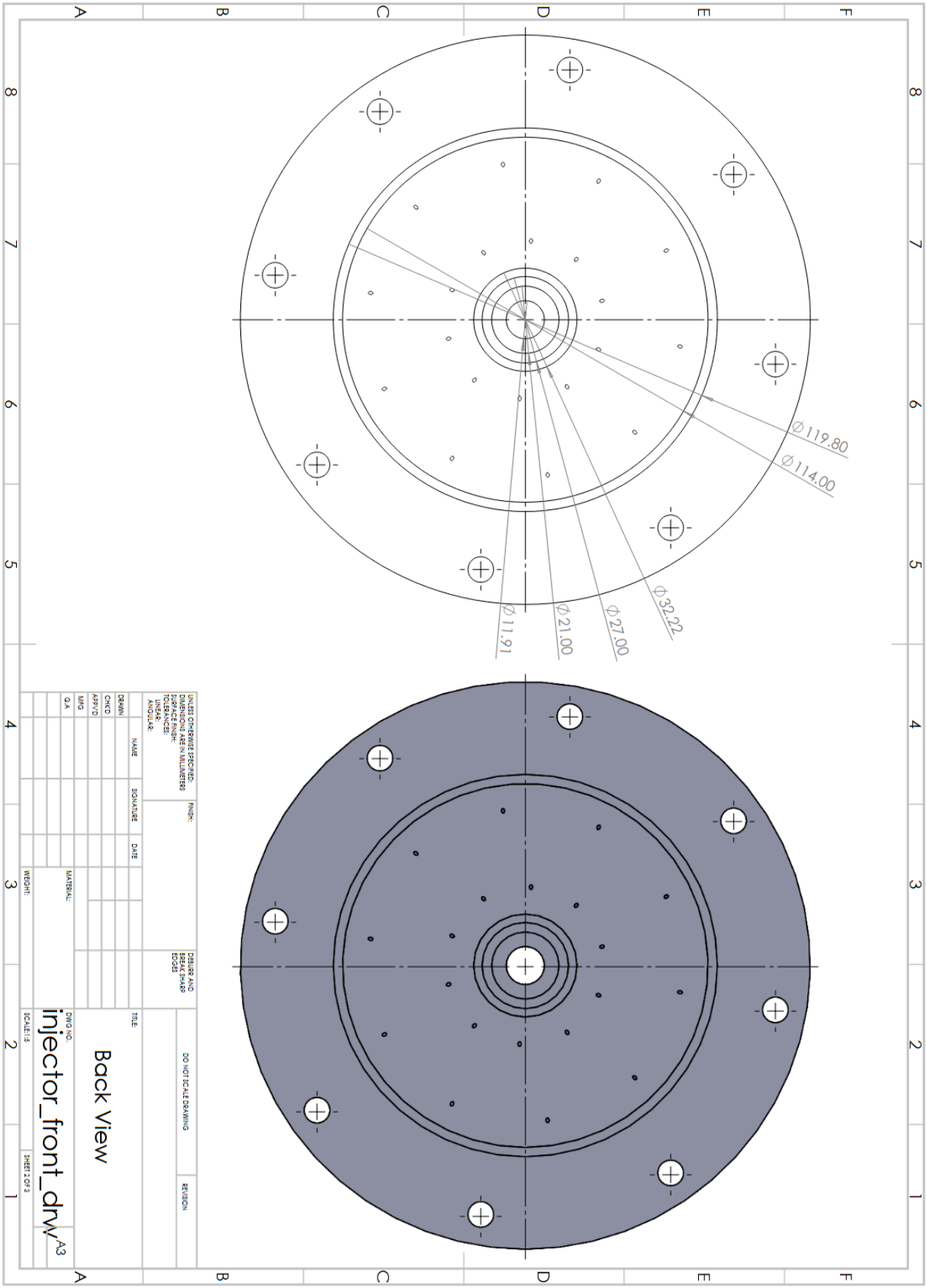


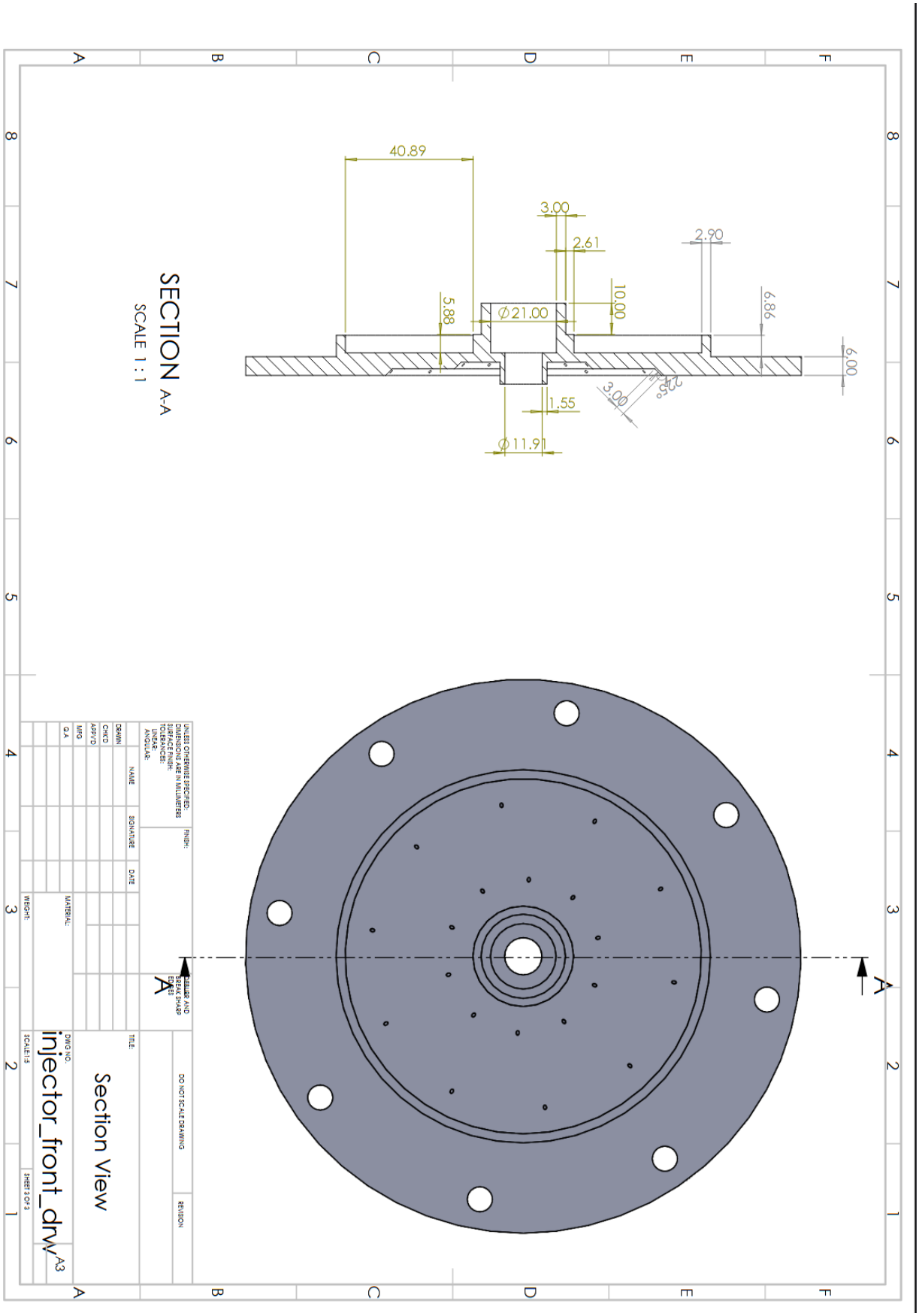
*Figure 9 - isometric and front views of injector*

# Appendix B – Technical Drawings

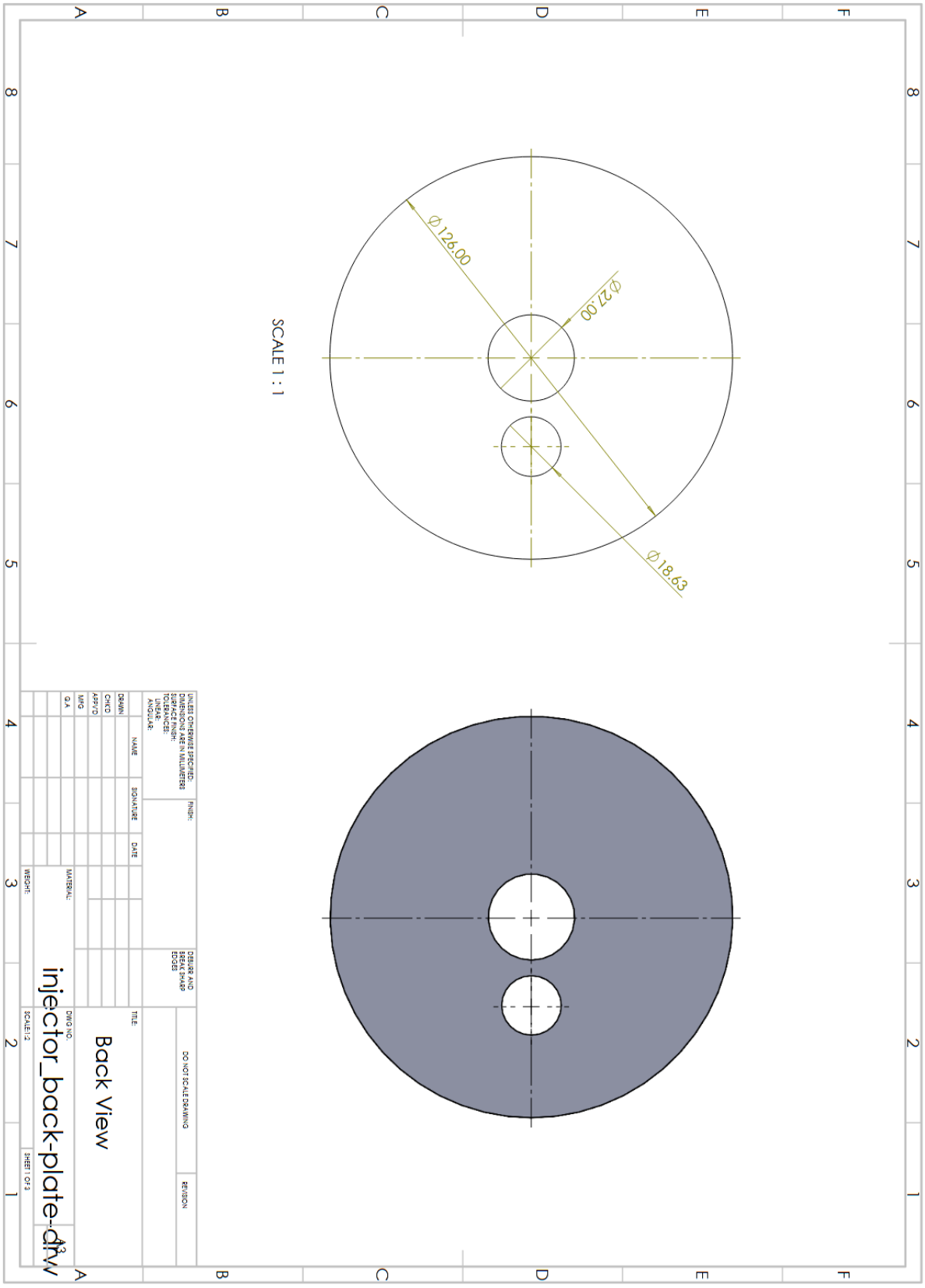
## Front Plate

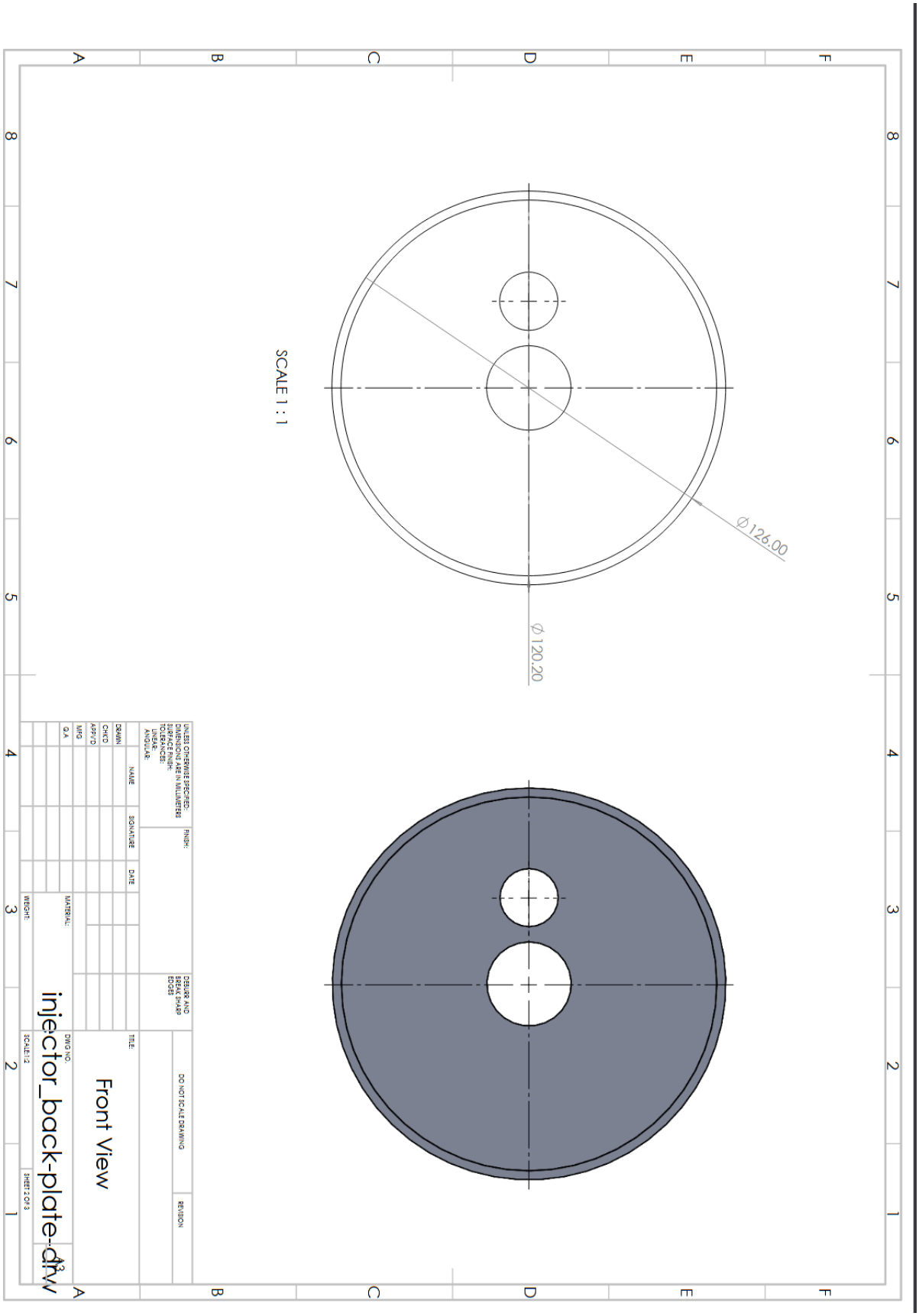


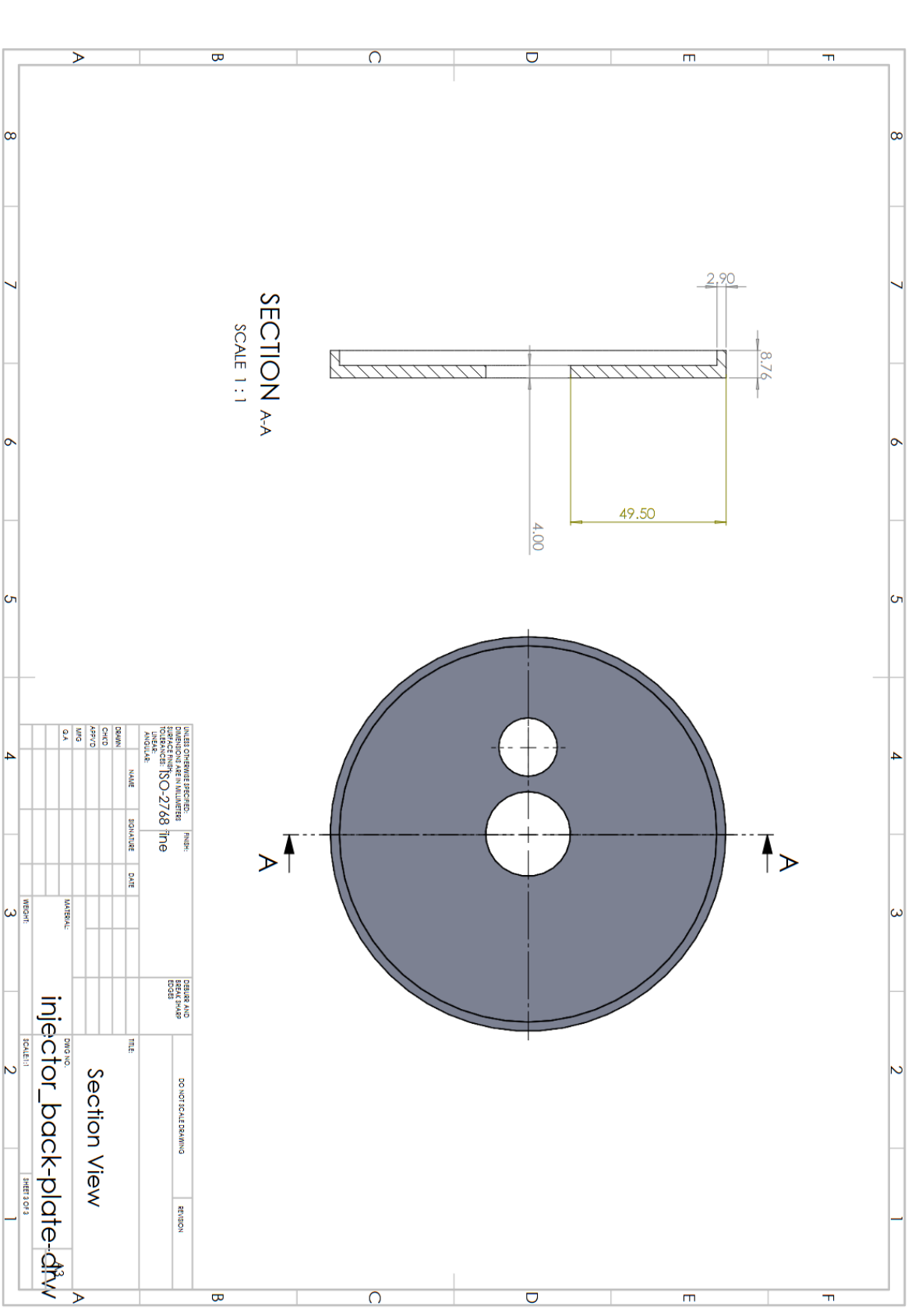

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## Appendix C – YouTube Links

This is a link to a playlist contining the animations generated by ansys fluent during each simulation run:

https://youtube.com/playlist?list=PLPZAsalI_ASofZ93wwFxIOAa9mfjwJ2oj&feature=shared