Pursuit Heat Exchanger Delta PDR

Justin Le, Elysse Lescarbeau, Fallon McBrien

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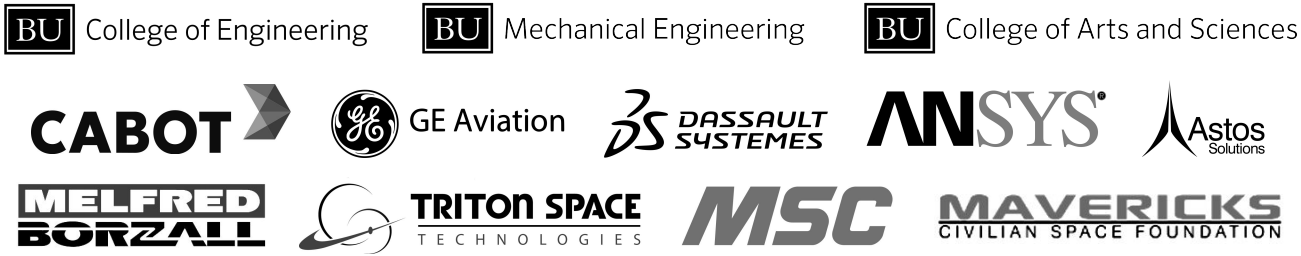


Overview

Goal:

Use high temperature gas from an on board gas generator (GG) to heat up nitrogen (pressurant) in order to reduce the amount of total pressurant gas weight being carried on the rocket. This will be achieved with a decrease in density due to higher temperatures of the heated nitrogen, which allows less pressurant to be used to achieve the same propellant pressurization and displacement. This further reduces mass by decreasing the amount of onboard COPVs required.

Constraints/Requirements:

- Safely transfer heat without damaging any components of Pursuit
  - Max inlet temperature of 1300F (stainless steel at elevated pressure)
  - Max final pressurant tank temperature of 200F (max temperature that COPVs can withstand)
  - Max velocity of 90 ft/s (recommendation by Graham [Heliflow heat exchanger company] design engineer)
- Fit within a 11.5in. diameter and 4-6in. height
  - Height requirement set to ensure HX would not take up too much space in airframe
- Find a feasible design for both manufacturing and cost

Design Inspiration

Design inspired by the Graham Corporation Heliflow Heat Exchanger

- Accommodates for high pressures and temperatures (with the high pressure N2 inside the tubes and the high temperature EG outside)
- Compact design allows for less space to be taken up and smaller mass for shell
- Counterflow design provides highest overall temperature differential which makes more efficient heat transfer and allows for less tubing/mass

Fluid States

Internal Flow N2		
Values		Units
Pressure	789.7	psia
Inlet Temperature	-177.87	F
Outlet Temperature	400	F
Avg. Temp.	111	F

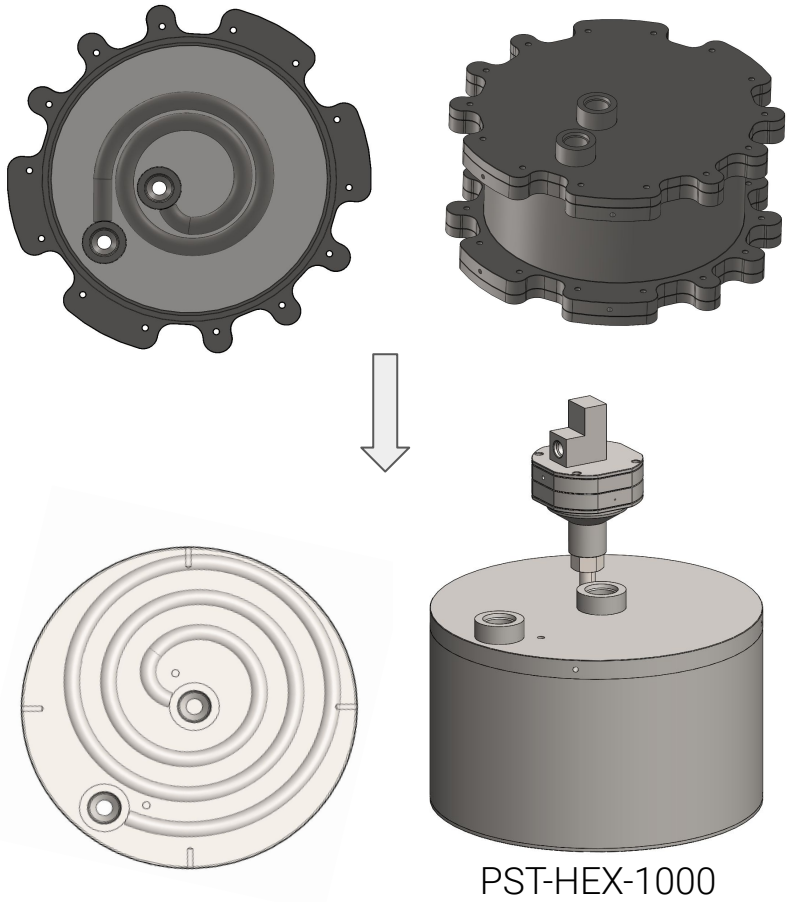
External Flow EG		
Values		Units
Pressure	114.7	psia
Inlet Temperature	1300	F
Outlet Temperature	500	F
Avg. Temp.	900	F

- N2 pressure driven from LD2 requirements
- N2 inlet temperature due to isentropic expansion of gas from COPVs
- Outlet temp is 400F to "overdesign" HX and ensure we can reach the required **200F pressurant outlet temp in the tanks**
  - Will use pre-HX cold gases and a bang bang system to control outlet temperature

- Exhaust gas from gas generator is mixture of nitrous oxide (N2O) and isopropyl alcohol (IPA) at 100 psig/OF ratio of 0.4
  - To keep temperature at 1300F
- Highest possible EG gas inlet temperature for materials used
- Outlet temperature of 500F to keep EG mass flow rate to a similar value as if goal outlet temp was 200F

Design Overview

- Pressure vessel, tubing, and manifolds will be brazed or welded together to prevent use of expensive metal o-rings and reduce mass
  - Change from last design which used o-rings to seal and flanges for fastening
- Inner diameter: 7.9 in (was 7.57 in)
- Outer diameter, shell: 8 in (was 7.67 in)
- Height:
  - Pressure vessel only: 5.1 in (was 6 in)
  - Pressure vessel with manifolds: 5.576 in (was 6.476 in)
- Mass: 16.76 lbs (was 30.66 lbm)
  - 2 manifolds: 1.28 lbm (was 1.53 lbm)
  - Tubing: 5.52 lbm (was 2.24 lbm)
  - Pressure Vessel Shell: 1.6 lbm (was 11.55 lbm)
  - Top cover: 6.93 lbm (was 7.7 lbm)
  - Bottom cover: 1.43 lbm (was 7.64 lbm)
- Total mass including GG: 18.54 lbm
- Exhaust gases will come in the center and flow out, pressurant will come in outside and flow to center (counterflow)
  - Allows use of AISI 1020 steel hollow cylinder for shell (less expensive) as shell will only see 500F
  - Will use 304 SS for top and bottom covers to meet 1300F temperature

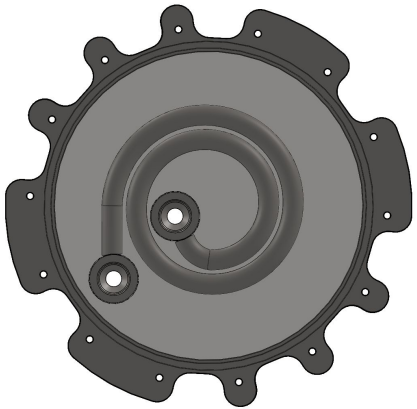


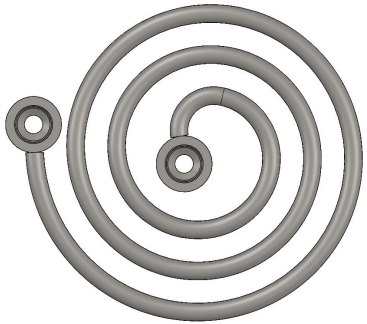
PST-HEX-1000

Tubing

Changes Since PDR

- Correlation used on exhaust gas side is now for a single tube instead of all tubes stacked together
  - Makes inner and outer convection coefficients congruent for final calculation of overall heat transfer coefficient, U
- Considered radiation in calculations
- Increased spacing between tubes to reduce exhaust gas velocity
- Calculated for surface temperature for more accurate determination of thermal expansion
- Decreased size of tubes from 0.5” to 0.375” outer diameter





TUBING:
PST-HEX-0004

TUBING ASSEMBLY:
PST-HEX-1001

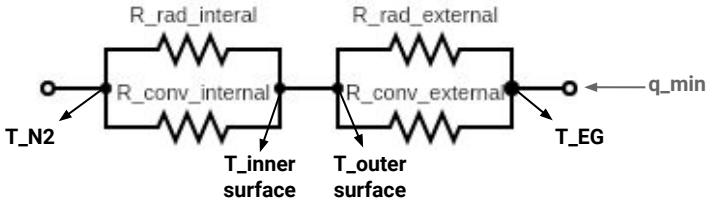
Tubing Size and Material Choice

- Tubing size used is 0.375” outer diameter, 0.035” wall thickness
  - Company manufacturing tubes recommended 0.375” tubing
  - Less than 0.035” wall thickness easily warps when bent
- 304 stainless steel tubing
  - Meets temperature requirements
    - Nominal -425F to 1500F temperature rating

Tubing Calculations & Sizing Methodology Overview

- Find overall heat transfer coefficient, U
  - Neglecting fouling (short usage time span) and conduction (thin walled tubes)
  - Radiation not considered negligible due to extreme temperatures
  - Internal and external convection coefficients found using correlations to determine Nusselt Number
  - Radiation and convection in parallel for both internal and external flow
- After finding U, solve for final required area using Log Mean Temperature Difference for counterflow
- Find inner and outer tubing surface temperature assuming heat flows from external side to internal side (hot to cold)

Thermal Circuit



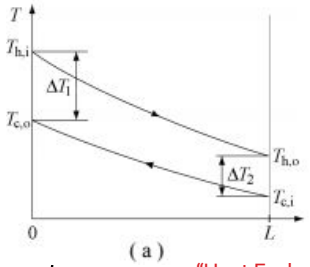
$$\frac{1}{U} = \left(\frac{1}{R_{rad,int}} + \frac{1}{R_{conv,int}}\right)^{-1} + \left(\frac{1}{R_{rad,ext}} + \frac{1}{R_{conv,ext}}\right)^{-1}$$

"Fundamentals of Thermal Resistance"

$$R_{rad} = \frac{1}{\varepsilon\sigma(T_s^2 + T_{surr}^2)*(T_s + T_{surr})} \qquad R_{conv} = \frac{1}{h}$$

$$q_{min} = q_{cold} = q_{hot} = mdot_{N2,per\ tube} C_{pN2,avg}(T_{N2,out} - T_{N2,in})$$

"Heat Exchanger Dimensioning" - p. 35



$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}},$$

$$A = \frac{q}{U \Delta T_m}.$$

"Heat Exchanger Dimensioning" - p. 34-35

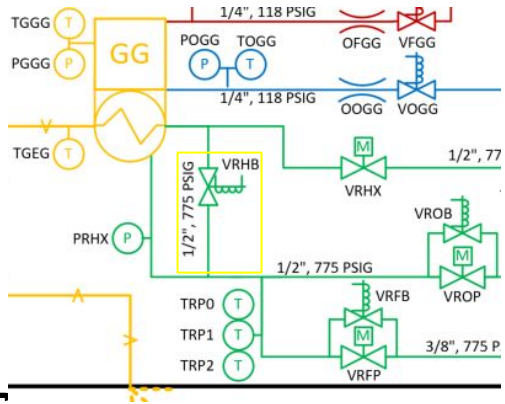
$$T_{inner\ surface} = q_{cold}\left(\frac{1}{R_{rad,int}A_s} + \frac{1}{R_{conv,int}A_s}\right)^{-1} + T_{N2}$$

$$T_{outer\ surface} = T_{EG} - q_{hot}\left(\frac{1}{R_{rad,ext}A_s} + \frac{1}{R_{conv,ext}A_s}\right)^{-1}$$

Fundamentals of Heat & Mass Transfer, 7th Edition, p.136

N2 Mass Flow Rate Split

- Using a bang bang control system and HX bypass line to feed pre-HX cold gases to post-HX heated gases to ensure pressurant gases remain at 200F
- Also helps to account for changes in temperature due to bang bang pressure control system for tank pressurization



Pressurant Mass Flow Rate Split		
Values		Units
Post HX Temp	400	F
Pre HX Temp	-178	F
Total Mass Flow Rate	0.587	lbm/s
Entering HX Fraction	0.654	-
Bypass HX Fraction	0.346	-
Entering HX Mass Flow Rate	0.384	lbm/s
Bypass HX Mass Flow Rate	0.203	lbm/s
Mixed Temp	200	F

Inner Convection Coefficient

- Determined convection coefficient for heat transfer per tube
- Number of tubes a balance of multiple factors:
  - Keeping N2 velocity below 90 ft/s
  - Reducing space required between tubes by increasing cross sectional area where exhaust gas is flowing
  - More tubes -> less tubing length (reduces radial size of HX)
  - Less tubes -> reduces height of HX
- Correlation limitations:
  - Internal flow
  - Fully developed turbulent flow in a smooth tube
    - Note: HX will be running for ~50 seconds and tubes are relatively short
    - Therefore, convection coefficient calculated is a conservative estimate of the heat transfer that will occur
  - $0.5<Pr<3$, $10^4<Re<10^5$
    - Pr = Prandtl Number
    - Re = Reynold's Number
  - Accuracy to -20% to +28%

$$Nu = 0.023 Re^{0.8} \, \mathrm{Pr}^{1/3}$$

"Heat Exchanger Dimensioning"- p. 68

Inner Convection Coefficient (cont.)

Value		Units
N2 Mass Flow Rate	0.384	lbm/s
Number of Tubes	12	-
Mass Flow Rate Per Tube	0.032	lbm/s
Inlet Velocity	5.64	ft/s
Outlet Velocity	26.9	ft/s
Average Velocity	16.3	ft/s
Average Reynolds Number	119,242	-
Prandtl Number	1.08	-
Nusselt Number	272	-
Convection Coefficient	0.05 1115	BTU/s*ft^{2}F W/m^{2}K
Convection Resistance	18.34	s*ft^{2}F/BTU

Outer Convection Coefficient

- To find exhaust gas properties, used available data from CEA and weighted averages of reactants at inlet and outlet temperatures
- Determined convection coefficient for heat transfer per tube
- If a tube is imagined to be uncoiled, can assume convective heat transfer would act as though there is external flow along a flat plate
- Correlation limitations:
  - Flat plate with constant heat flux
  - Turbulent flow: Re > $5x10^5$
  - 0.6<Pr<60
- Spacing between tubes set by limiting velocity to 90 ft/s
  - Cross sectional area is entire space between tubes where exhaust gas is flowing

Value		Units
EG Mass Flow Rate	0.19	lbm/s
Space Between Tubes	0.497	in
Velocity	90.1	ft/s
Reynolds Number	2,510,293	-
Prandtl Number	0.51	-
Nusselt Number	3245	-
Convection Coefficient	0.069 1409	BTU/s*ft^{2}F W/m^{2}K
Convection Resistance	14.5	s*ft^{2}F/BTU

$$Nu_x = 0.0308\, Re_x^{4/5}\, Pr^{1/3}$$

Fundamentals of Heat & Mass Flow, 7th Edition, p.446

Radiation

- Since temperature values are so extreme, radiation could not be assumed to be negligible
- Although radiation coefficient values ended up being fairly small in comparison to the convection values, especially on the internal side, still made the overall sizing and surface temperature calculations more accurate
  - ***NOTE**: Emissivity values are temperature specific for 301 SS (could not find 304 at elevated temperatures, but values at same temperatures for 316 looked consistent so assumed this stays similar across alloys)

	Internal	**External**	
	Value		**Unit**
Emissivity, Stainless Steel* (Thermocera.com Emissivity Tables)	0.299	0.563	-
Radiation Coefficient	0.00034 6.92	0.0019 38.9	BTU/s*ft^{2}F W/m^{2}K
Radiation Resistance	2956	525.2	s*ft^{2}F/BTU

Required Tubing Area

- Length per tube uses average of inner and outer diameter

Heat Exchanger Sizing		
Values		Units
Overall HT Coefficient, U	0.031	BTU/sft^2F
Overall HT Coefficient, U	632.05	W/m^2K
Heat Transfer Rate, Q	7.58	BTU/s
Surface Area, A	0.31	ft^2
Length Per Tube	3.52	ft
Length Per Tube	42.18	in
Total Length	42.18	ft
Total Length	506	in

Tubing Surface Temperature

- Since surface temperature is influenced by radiation and radiation is calculated with surface temperature, used convergence to find final values
- As was to be expected from the thermal circuit, average values of inner and outer tubing temperatures are close to the same

Tubing Surface Temperature: Internal Flow Side		
Values		Units
Heat Transfer Rate (Per Tube)	7.58	btu/s
Surface Area (Per Tube)	0.281	ft^2
Thermal Resistance Due to Convection	18.34	sft^2F/btu
Thermal Resistance Due to Radiation	2956	sft^2F/btu
Inlet Temperature	-178	F
Outlet Temperature	400	F
Average Temperature	111	F
Inlet Inner Tube Temperature	314	F
Outlet Inner Tube Temperature	892	F
Average Inner Tube Temperature	603	F

Tubing Surface Temperature: External Flow Side		
Values		Units
Heat Transfer Rate (Per Tube)	7.58	btu/s
Surface Area (Per Tube)	0.345	ft^2
Thermal Resistance Due to Convection	14.49	sft^2F/btu
Thermal Resistance Due to Radiation	525.2	sft^2F/btu
Inlet Temperature	1300	F
Outlet Temperature	500	F
Average Temperature	900	F
Inlet Outlet Tube Temperature	990	F
Outlet Outer Tube Temperature	190	F
Average Outer Tube Temperature	590	F

Thermal Expansion

Thermal Expansion (Diameter)		
d1 = d0 [(t1-t0) α + 1]		
Linear Expansion Coefficient (α)	6.91E-06	in/inF
Initial Temperature (t0)	70	F
Initial Outer Diameter (d0)	0.375	in
Internal Side		
Extreme Temperature (t1)	892	F
Final Outer Diameter (d1)	3.77E-01	in
Change in Diameter	2.13E-03	in
External Side		
Extreme Temperature (t1)	990	F
Final Outer Diameter (d1)	3.77E-01	in
Change in Diameter	2.38E-03	in

Thermal Expansion (Length)		
L1 = L0 + (L0 α (t1 - t0))		
Linear Expansion Coefficiant (α)	0.00000691	in/inF
Initial Temperatur (t0)	70	F
Initial Length (L0)	42.2	in
Internal Side		
Average Temperature (t1)	603	F
Final Length (L1)	42.3	in
Change in Length	0.2	in
External Side		
Average Temperature (t1)	590	F
Final Length (L1)	42.3	in
Change in Length	0.2	in

Pressure Drop

- Darcy friction factor value assumes surface roughness of tubing of $0.0197*10^{-3}$ ft (Engineering Toolbox)
- Pressure drop is very minimal on both pressurant and exhaust gas sides

Pressure Loss Through Pressurant Tubing		
Values		Units
Darcy Friction Factor	0.021	
Pipe Length	3.52	ft
Average Density of Fluid	6.77	lbm/ft^3
Average Velocity	16.27	ft/s
Tubing Inner Diameter	0.025	ft
Pressure Drop	0.56	psi

Pressure Loss Through Exhaust Gas Channels		
Values		Units
Darcy Friction Factor	0.0108	
Pipe Length	3.52	ft
Density of Fluid	0.12	lbm/ft^3
Velocity	90.08	ft/s
Hydraulic Diameter	0.90	ft
Pressure Drop	0.004	psi

Manufacturing

- In contact with Joel Barrett (jb@bmp.us), COO from Berrien who has offered service for free, and discounted prices if needed in the future
- Can manufacture entire inside assembly of heat exchanger including welding or brazing manifolds to tubing.
- Can test tubing up to 3500 psi
- Gave following recommended restraints for tube coil, leading to the decision to change from ½ in. tubing to ⅜ in. tubing (copper coil guidelines apply to stainless steel as well)
- Company Info:

Berrien Metal Products, Inc.
460 Post Rd, Buchanan, MI 49107
[P] 800.978.5300 x15 [F] 269.695.5300

Standard Copper Coil *Minimum* Outside Dimensions		
Tube OD	**Decimal**	**Min Coil OD**
1/8"	*0.125*	0.85"
3/16"	*0.188*	0.95"
1/4"	*0.250*	1.50"
3/8"	*0.375*	2.75"
1/2"	*0.500*	6.00"
3/4"	*0.750*	8.00"
7/8"	*0.875*	9.00"
1"	*1.000*	10.00"

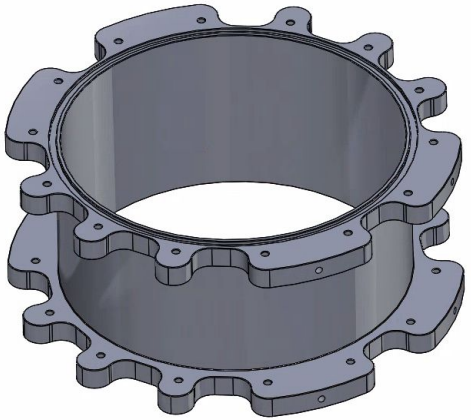
Costs

- Tubing costs:
  - 6 foot straight 304 stainless steel 0.375”/0.035” wall thickness tubing x 8: **$245**
  - Manufacturing & tube bending: **$0.00**

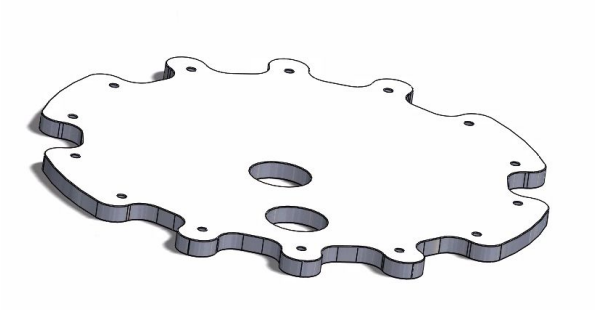
Pressure Vessel

Pressure Vessel: Pre-PDR

- 10” Double Flange w/ 0.5” Thickness
- 7.57” I.D.
- Approx 0.1” Wall Thickness (Overshooting, will go back and do calcs)
- Polymer O-Rings (Face+Gland seals)



BODY (AISI 1020)

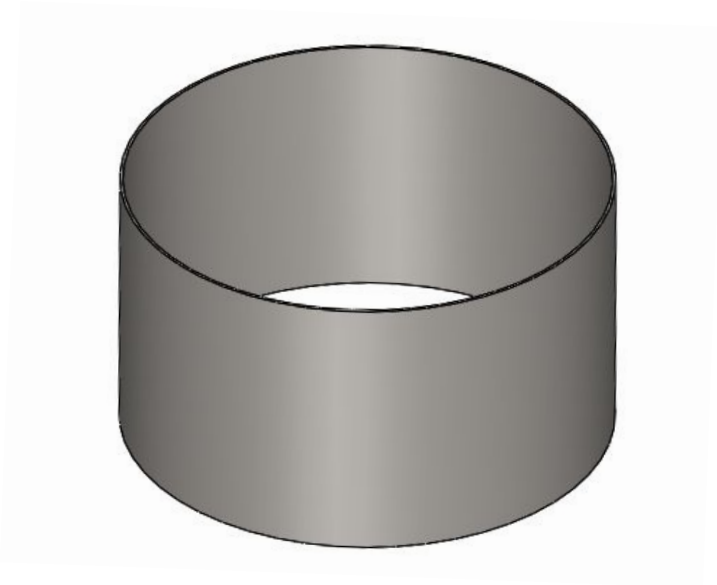


TOP/BOTTOM (304SS)

Pressure Vessel: Post-PDR

Body [PST-HEX-0001]:

- No more O-Rings, everything will be brazed
  - No Flanges
- 8.0” O.D. -- 7.9” I.D.
- 0.05” Wall Thickness
  - Calculated 0.0422” Thickness (Using Von Mises), but 0.05” for manufacturing purposes
  - Margin of 0.25 = 1/4
- 4.5” Height
- AISI 1020



Pressure Vessel: Post-PDR

Top Cover [PST-HEX-0002]:

- 8” Diameter - Gas Inlets and Outlets (0.18”)
  - 0.5” Thickness
- 4 Radial Bolts, Size #8-32, 90° apart
- SS304

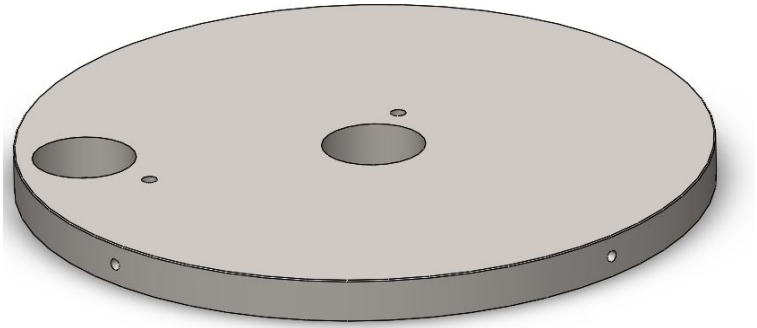
Bottom Cover [PST-HEX-0006]:

- 8” Diameter - Manifold Cover Cutouts (1.19”)
  - 0.1” Thickness

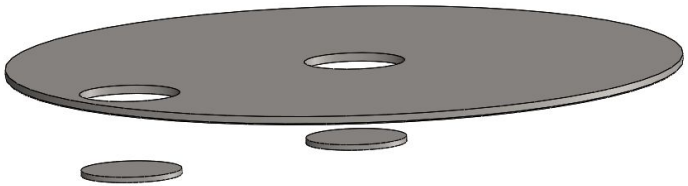
Manifold Covers (1.19”) [PST-HEX-0007]:

  - 0.05” Thickness, to be brazed from bottom
- SS304

TOP



BOTTOM



Pressure Vessel Costs

Top Plate [PST-HEX-0002] 304 Stainless Steel:
https://www.midweststeelsupply.com/store/product.php?product=95&category=55&secondary=81

- ½" x 4" x 4"
- $24.92 + $11.84 Shipping to 02215 = **$36.76**
    - Alternative ½" x 4⅛" x 4⅛" = $26.06 + $11.84 = **$37.90**

Bottom Plate / Sheet [PST-HEX-0006 / 0007]:
https://allmetalsinc.com/ssh105.html

- 12 gauge (0.1084") 4" x 4"
- $11.24 + $15.44 = **$26.74**

Shell / Body [PST-HEX-0001]: **$56**
https://shop.ryerson.com/catalog/search/102122102

Insulation

- Insulation will be a Vermiculite Coated Fiberglass cloth
- Working temperature of up to 1500F
- Can easily be cut/sewn
- According to Newtex (a company that sells this cloth), it is safe to handle without PPE, but gloves are recommended
- Cost: $49.95 (2 yards x 60”)

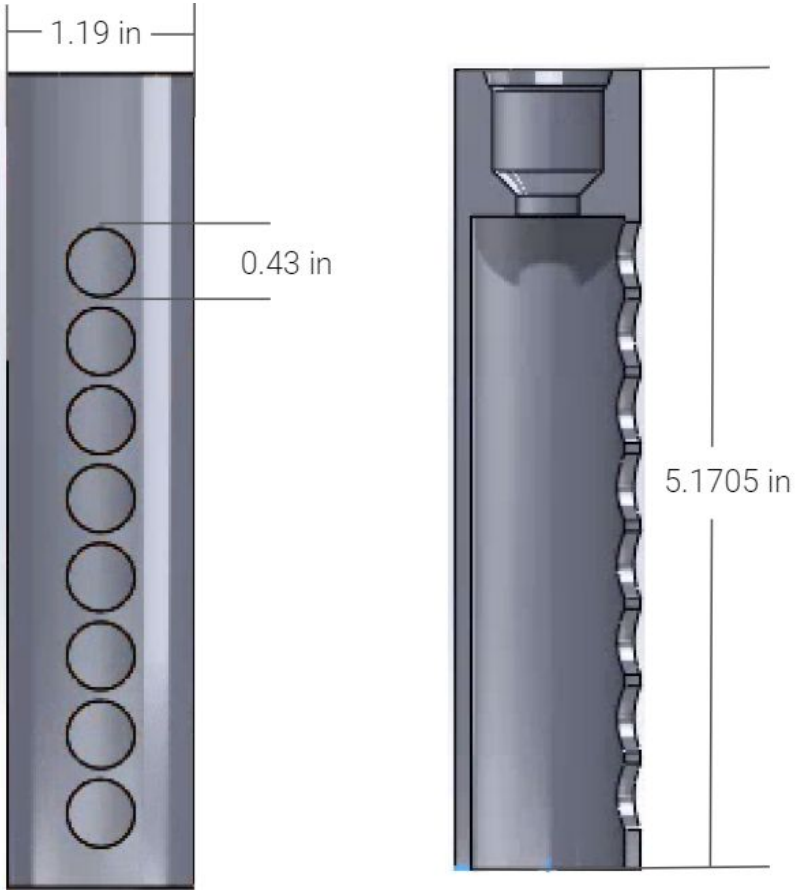
- Can be secured to the pressure vessel using extreme heat JB Weld around the sides (temp. range 0-2400F)
- Cost: $4.79

Temp. Range (F)	**0 Degrees to 2400 Degrees**
Series	**ExtremeHeat**

Manifold

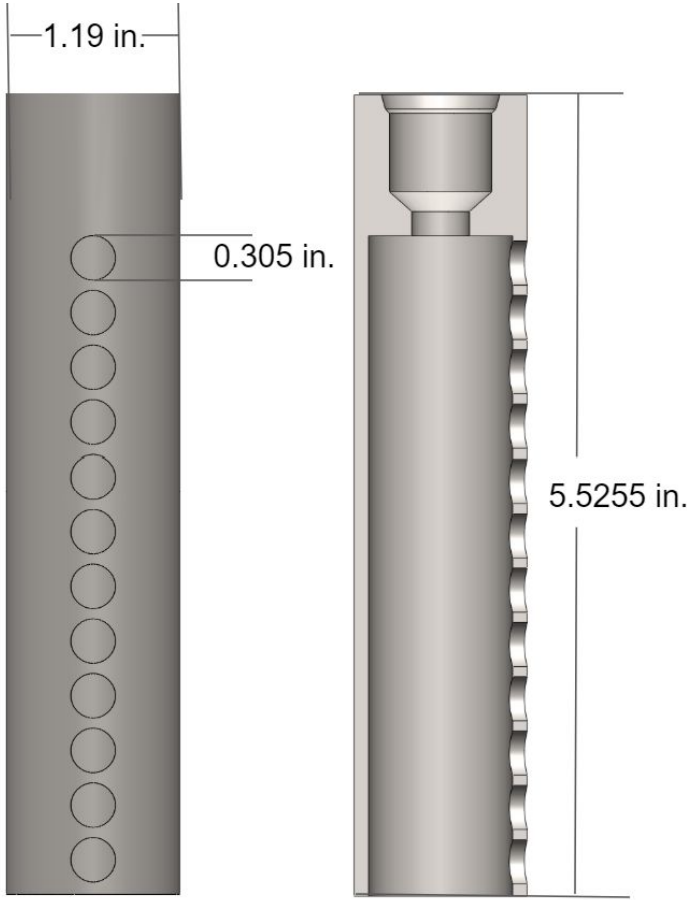
Manifolds: Pre-PDR

- Changes
  - New tubing diameter: ⅜ inch instead of ½ inch
  - 12 tubes instead of 8 tubes
  - Change in length



Manifolds: New Design

- PST-HEX-0003
- New tubing size to accommodate the request of tube coiling company.
- Bottom of the manifold is open, for manufacturability. A cap will be welded or brazed on the bottom.



Manifold Calcs: Minimum Radius

- Chosen radius is 0.5 for the manifolds
- Even with changes in calcs, 0.5 is still well above the minimum radius to maintain a velocity below 90 ft/s.

Minimum Inner Radius Calcs		
r = sqrt[ṁ/(π*ρ*v)]		
Mass Flow Rate (ṁ)	0.384	lbm/s
Maximum Velocity of Fluid (v)	90	ft/s
Inlet Manifold		
Fluid Density (ρ)	11.20	lbm/ft^3
Minimum Radius (r)	0.13	in
Outlet Manifold		
Fluid Density (ρ)	2.34	lbm/ft^3
Minimum Radius (r)	0.29	in
Chosen Inner Radius for Both		
Inner Radius (r)	0.5	in

Manifold Calcs: Wall Thickness

- Wall thickness calcs were redone with new temperatures and accurate pressure difference.
- The 0.1 in. wall thickness is above the minimum wall thickness.
- Cap at bottom of the manifolds will be 0.5 in. which is also above the minimum wall thickness

Von Mises Stress Calcs (For Min Wall Thickness)		
t = (sqrt(3)*P*r)/(2*σ)		
Pressure Difference (P)	675	psi
Inner Radius (r)	0.5	in
Yield Strength (304 steel)	20.8	ksi
Inlet Manifold Minimum Wall Thickness		
Yield Strength (@1000F) (σ)	12480	psi
Wall Thickness (t)	0.02342015816	in
Outlet Manifold Minimum Wall Thickness		
Yield Strength(@900F) (σ)	12480	psi
Wall Thickness (t)	0.02342015816	in
Chosen Wall Thickness For Both		
Wall Thickness (t)	0.1	in

Manifold Costs

- Stock
  - 1 foot 304 Stainless Steel round rod 1.25” diameter: **$43.75**
- Manufacturing
  - also **$0.00**

Bill of Materials

Item	Vendor	Part #	Unit Cost	Amount	Total Cost
Smooth-Bore Seamless 304 Stainless Steel Tubing 3/8" OD, 0.035" Wall Thickness, 6 Ft Straight	McMaster	89895K737	$30.73	8	$245.84
Tube Bending/Manifold Brazing/Pressure Vessel Attachment (hopefully)	Berrien		$0.00	1	$0.00
JB WELD EXTREME HEAT	JB tools	37901	$4.79	1	$4.79
1.25" Stainless Round Bar 304/304L Annealed Cold Finish	OnlineMetals	90	$43.75	1	$43.75
Vermiculite Coated Fiberglass Fabric (2 yards)	Newtex	a-600	$49.95	1	$49.95
Stainless Sheet 12 Gauge (304 Grade)	All Metals Inc.	SSH10544	$11.34 + $15.44	1	$26.74
304 Stainless Steel Plate	Midwest Steel and Aluminum	304SSPLT12	$24.92 + $11.84	1	$36.76
1020 Steel Tube 8" OD, .5" Wall Thickness, 5"	Speedy Metals		$56.00	1	$56.00
				TOTAL	$463.83

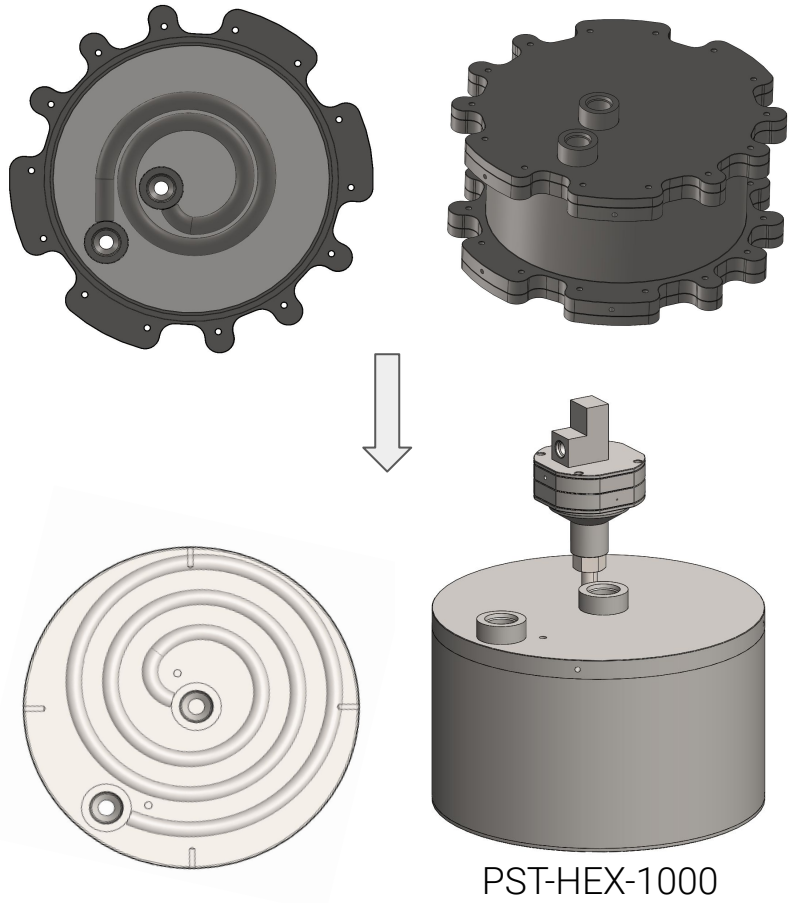
Next Steps

- Incorporate any changes from this PDR feedback
- Confirm Berrien can weld/braze the pressure vessel
  - If they cannot, find/price out options for this and determine final vendor
- Work with Berrien to define logistics for manufacturing and what we need to provide them
- Final tolerancing & drawings
- Finalize all costs & bill of materials

- Question/thought:
  - To reduce the length of tubing required from the COPVs and back down to the ox dome, should we move pressurant inlet/outlets to bottom of HX OR position this design “upside down” in airframe for mounting?

Design Overview

- Pressure vessel, tubing, and manifolds will be brazed or welded together to prevent use of expensive metal o-rings and reduce mass
  - Change from last design which used o-rings to seal and flanges for fastening
- Inner diameter: 7.9 in (was 7.57 in)
- Outer diameter, shell: 8 in (was 7.67 in)
- Height:
  - Pressure vessel only: 5.1 in (was 6 in)
  - Pressure vessel with manifolds: 5.576 in (was 6.476 in)
- Mass: 16.76 lbs (was 30.66 lbm)
  - 2 manifolds: 1.28 lbm (was 1.53 lbm)
  - Tubing: 5.52 lbm (was 2.24 lbm)
  - Pressure Vessel Shell: 1.6 lbm (was 11.55 lbm)
  - Top cover: 6.93 lbm (was 7.7 lbm)
  - Bottom cover: 1.43 lbm (was 7.64 lbm)
- Total mass including GG: 18.54 lbm
- Exhaust gases will come in the center and flow out, pressurant will come in outside and flow to center (counterflow)
  - Allows use of AISI 1020 steel hollow cylinder for shell (less expensive) as shell will only see 500F
  - Will use 304 SS for top and bottom covers to meet 1300F temperature



PST-HEX-1000

Questions?

Reference Slides

Gas Generator Mass Flow Rate Calculation

$$\left(\frac{Cp_{EG}\left(T_{EG,in}-T_{EG,out}\right)}{Cp_{N2}\left(T_{N2,out}-T_{N2,in}\right)}\right)\left(OF\ ratio\cdot mdot_{Fuel,\,GG}+mdot_{Fuel,\,GG}\right)=mdot_{N2,\,LD2}+\frac{OF\ ratio\cdot mdot_{Fuel,\,GG}}{\rho_{Ox}}\left(\rho_{N2,\,Ox\ Tank}\right)+\frac{mdot_{Fuel,\,GG}}{\rho_{Fuel}}\left(\rho_{N2,\,Fuel\ Tank}\right)$$

$$q = m_h c_{p,h}(T_{h,i} - T_{h,o}) \qquad (11.6b)$$

$$q = m_c c_{p,c}(T_{c,o} - T_{c,i}) \qquad (11.7b)$$

Steady Flow Energy Equation per "Fundamentals of Heat and Mass Transfer, 7th Edition", Bergman, Levine. p. 711.

$Cp_{EG} = specific\ heat,\ exhaust\ gas$

$Cp_{N2} = specific\ heat,\ nitrogen$

$T_{EG,\,in} = temperature,\ exhaust\ gas,\ in$

$T_{EG,\,out} = temperature,\ exhaust\ gas,\ out$

$T_{N2,\,out} = temperature,\ nitrogen,\ out$

$T_{N2,\,in} = temperature,\ nitrogen,\ in$

$OF\ ratio = oxidizer\ to\ fuel\ ratio,\ GG$

$mdot_{Fuel_{GG}} = mass\ flow\ rate,\ fuel,\ GG$

$mdot_{N2,\,LD2} = required\ mass\ flow\ rate,\ nitrogen,\ LD2$

$\rho_{Ox} = density,\ oxidizer\ in$ tank

$\rho_{Fuel} = density,\ fuel\ in$ tank

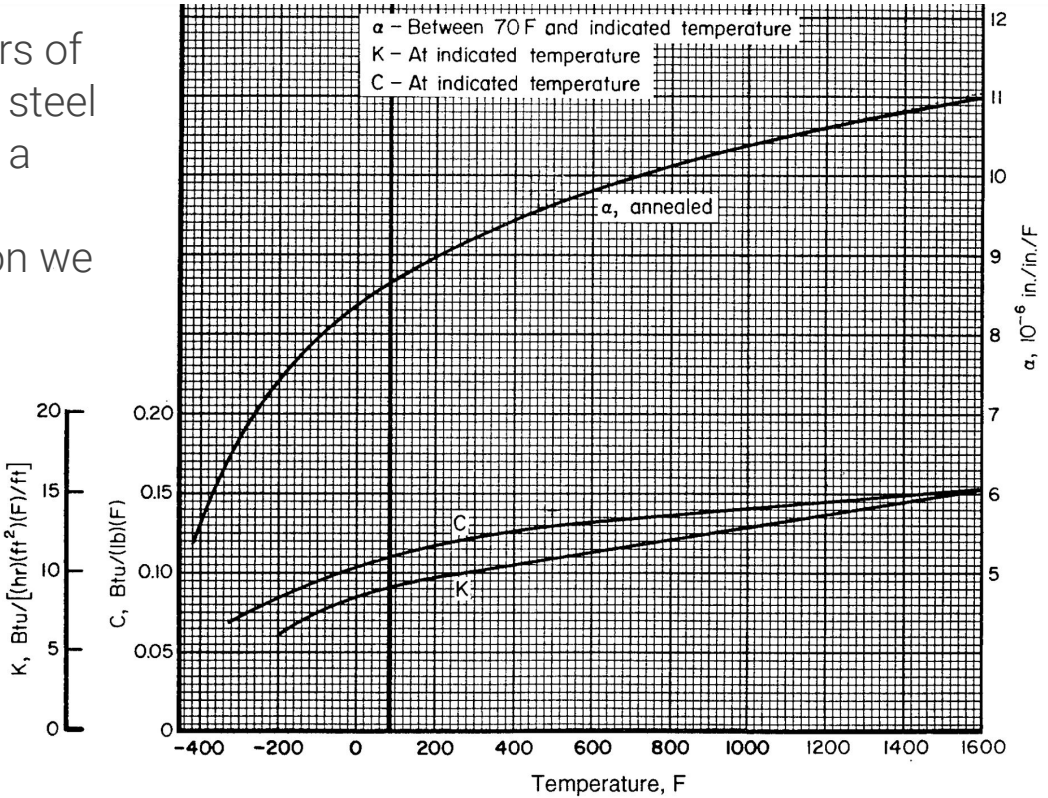
$\rho_{N2,\,Ox\ Tank} = density,\ nitrogen\ in\ oxidizer$ tank

$\rho_{N2,\,Fuel\ Tank} = density,\ nitrogen\ in\ fuel$ tank

- Equated 11.6b & 11.7b as qdot will be equal
- Rearranged to solve for mdat_N2[m_c]
- Set equal to total required mdot_N2 for vehicle
- Used MATLAB solve function to solve for mdot_Fuel_GG and OF ratio to solve for mdot_GG_total

Material: Manifolds and Covers

- The manifolds and top and bottom covers of the pressure vessel will be 304 stainless steel because other materials have too low of a temperature rating.
- 304 Stainless Steel is the cheapest option we have for the required temperature rating



Typical Values of U

Table 4.1. *Typical values of U* [W / m^{2}K] *for tubular, non-finned heat exchangers*

Fluid 1	**Fluid 2** gas, 1 bar	gas, ≥ 25 bar	liquid, high viscosity[1]	liquid, low viscosity[2]	phase change
gas, 1 bar	5... 35	10...60	15... 50	20... 70	20... 70
gas, ≥ 25 bar	10... 60	100... 400	100... 400	150... 500	200... 500
liquid, high μ	15... 50	100... 400	100... 400	200... 500	200... 900
liquid, low μ	20... 70	150... 500	200... 500	400... 1700	500... 2000
phase change	20... 70	200... 500	200... 900	500... 2000	700... 2500

1 for example most oils
2 for example water

Table 4.2. *Typical values of U* [W / m^{2}K] *plate-type heat exchanger*

Fluid 1	**Fluid 2** gas, <10 bar	liquid
gas, < 10 bar	10... 35	20... 60
liquid	20... 60	200... 1200

"Heat Exchanger Dimensioning"- p. 34