Fermilab

Particle Physics Division

Mechanical Department Engineering Note

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Project: NOvA

Title: APD Drier System - Conceptual Design Proposal

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Abstract Summary:

Water permeation has shown to be a problem in the NOvA APD enclosures, which are passively dried by desiccant in the sealed enclosure. This water permeation damages and reduces the performance of the APDs. An active drying system is proposed which will keep the water concentration below the specification dew point of -25°C. Three types of designs were analyzed: Vacuum drying, conductance drying, and flow through drying, and the conductance drying is recommended as the best solution. Detailed calculations are contained in the report, which show the conductance system would be able to dry up to 150 ug/day water permeation into the APD enclosure, over 40 times higher than the 3.5 ug/day specification. A component selection and cost estimate are also given in the report.

APD Drier Conceptual Design Proposal

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Scope of Specific Problem

The APDs on the NOvA detector are experiencing damage from moisture from surrounding air. The APDs are held at -15^{o}C, which is much lower than the dew point in most environments and it is not possible to dehumidify air below around 5^{o}C using a conventional condensing dehumidifier. Even with a correctly seated O-ring, water can permeate through the O-rings, fittings, hoses, other plastic/rubber system components and damage the APDs.

Information on Condensation/Dew point/Frost point:

Condensation or Deposition (vapor changing to solid) of water vapor on a surface happens when that surface temperature is lower than the saturation temperature corresponding to the partial pressure of water vapor in the environment. One lowers the dew point in an environment by reducing the partial pressure of water in the air. This can be done by taking water out of the air by condensing dehumidifiers or by using desiccant dehumidification which can lower the dew-point to -40^{o}C.

Solution Methods:

Three drying systems were considered and are discussed here. The first design being a vacuum system which continuously pumps on the APD enclosures, pulling out moisture and drying them out. The second design, and recommended one, is a pressurized system which purges manifolds connected directly to the APD enclosures and relies on the molecular conductance of water vapor in air to dry the APD enclosures. The third design considered is a system which flows dry air into each APD enclosure and out the other side, routed in either series or parallel configuration.

Option 1: Vacuum System

Another way of lowering the partial pressure of water in an environment is by lowering the absolute pressure of the environment itself. Calculations show if we take ambient air at 25^{o}C with a 10^{o}C dew point (80% Relative Humidity) and lower the pressure down to ~0.78 psia, we also lower the partial pressure of water low enough to produce a new dew point (frost point at this temperature) of -17^{o}C, which is the temperature of the APD cold side. If we pull this partial vacuum on the APDs enclosures, we prevent condensation and frosting, and we only need 1 hole per APD enclosure. Unfortunately this would require somewhat large pipes due to the difficulty in pumping a low pressure (high specific volume) fluid.

Option 2: Dry purged manifold conductance system

This system works by providing a dry manifold in which dry gas in continuously purges and exits out the end. APD enclosures are connected to this manifold by hose fittings which are screwed into the APD spacer. Any water vapor which permeates into the APD enclosures will be drawn into the manifold by molecular diffusion and purged out the end. The pressure in the manifold should also be kept as low as possible since the molecular diffusion rate is inversely proportional to absolute pressure. Detailed calculation were performed which show the APDs and manifold may be connected in 24 rows, each running North the entire length of the detector, 480 in a row of 15 Di-Blocks. Calculations show 1/8" tube will suffice for purging the manifolds with 3 SCFH each. The specification calls for the system to be capable of keeping a -25^{o}C dew point with an APD water permeation rate of 3.5 micrograms per day. Calculations show the proposed system would be capable providing this dew point even with up to 150 micrograms per day, even at ambient conditions of 25^{o}C and 90% relative humidity; the building is required to have a relative humidity under 50%.

Option 3: Flow through system

Although flowing a large amount of dry air or nitrogen over the cold APD surface would surely prevent condensation/frosting, this would require two holes in each APD housing for an inlet and outlet. If flowing through APD enclosures in series this method may also raise the heat load seen by the TEC substantially, putting more load on the TECs and the water cooling system, and increase the water temperature rise across the groups of TECs in series disrupting the TEC controllers.

It is possible to run a small amount of dry air through APD enclosures if they are routed in parallel using a manifold and place a flow restriction on the outlet side of the APDs. Calculations show even with the smallest readily available orifice (1/100th inch diameter) would flow over 100 times the flow rate of the conductance system and would need much larger hoses, or a complex hose routing scheme. If we run the outlet ports to manifolds of 64 or more APD enclosures in a group and use one flow restriction for each group we could use small hose, but we have no way of balancing the flow rate of the parallel routes, and cannot guarantee all of the parallel paths have any flow at all. This would mean we would have to rely on diffusion, just like the conductance system, but we would have extra water permeating into the system from all the extra hose and fittings. Overall this design adds cost, complexity, permeation, and additional failure modes to the system without any guaranteed benefit over the dry purged manifold conductance system.

Design Conditions:

- Design Dryness:
  - Dew point: -25°C
  - Water concentration: 0.552 gm/m³
- Ambient Conditions:
  - Temperature: 25°C
  - Relative Humidity: 90%
  - Atmospheric pressure: 14 psia
- Water Transport into each APD
  - 35 micrograms/day (10 times the specification by Mat Muether)
- Dry Air Supply
  - Dew point: -40°C
  - Water concentration: 0.121 gm/m³

System and Component Overview:

A piping and instrumentation diagram is shown in Figure 1, which includes the compressors and air driers as well as backup nitrogen which will automatically takeover in case of failure of the main drier system. The tees and hoses which make up the manifold and offshoot hoses are shown in Figure 2; these must be tested for solid fitment and permeation rates.

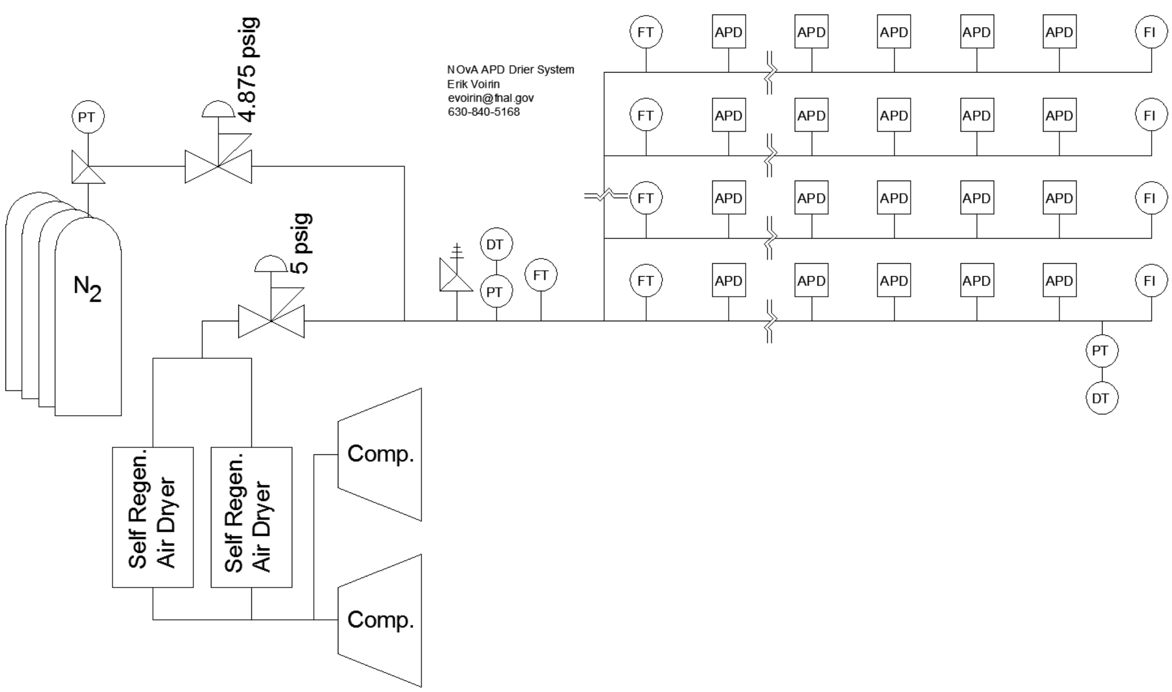

Figure 1: Piping and Instrumentation Diagram.

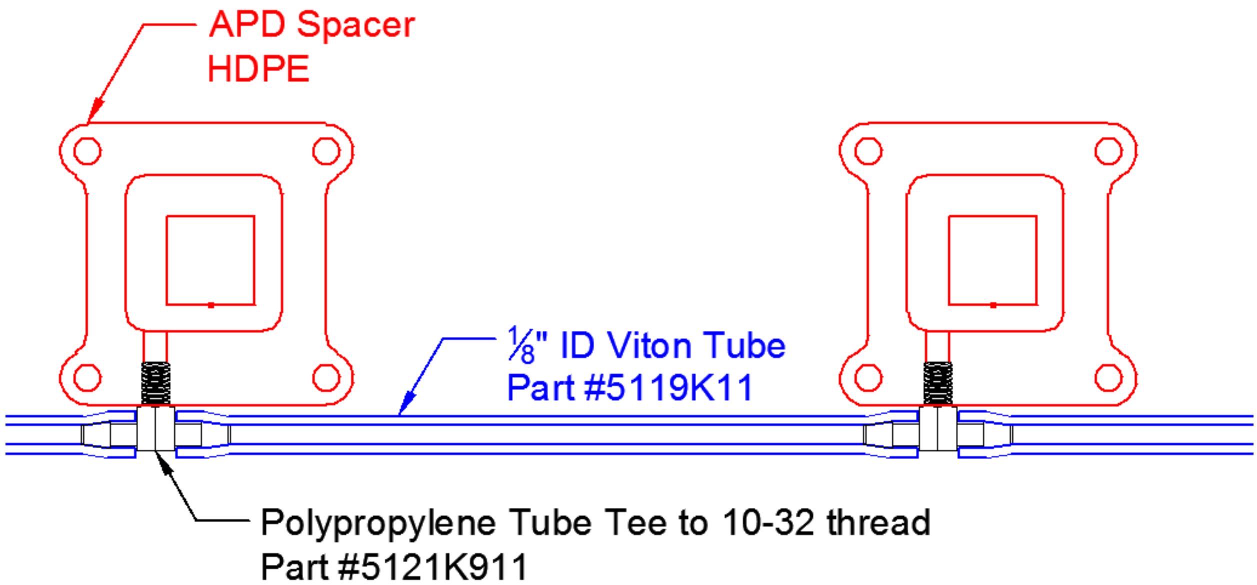

Figure 2: Proposed parts for manifold and tubing connections

System Analysis and Results:

Figure 3 shows the Dew point at each of the 480 tees and APDs in each row; the APD water concentration is somewhat consistent throughout the line regardless of the buildup of water in the manifold due to the pressure drop of the flow decreasing absolute pressure and increasing molecular diffusion rates. These calculations were done using the water permeation rate is 35micrograms per day (10 times higher than the spec of 3.5) This is with 5psig at the beginning of the line, and 1 psig at the exit of the tube which corresponds to a flow rate of 3 SCFH through each manifold. These calculations also take into account all flow which would leak out of the APDs according to the leak specification of "10 inHg/hr @ 25inHg vacuum" and assume all water must exit through the manifold outlets, not taking advantage of water exiting through any APD leaks.

Figure 4 shows the limits of the system, 150 micrograms per day water permeation into each APD enclosure, 40 times higher than the specification. Figures 5 and 6 show water concentration at each node for 35 micrograms/day and 150 micrograms per day APD water permeation respectively, along with other dew point concentrations of -25^{o}C ,-20 ^{o}C, and -15 ^{o}C for reference. Figure 7 shows the expected water concentrations using the specification of 3.5 micrograms per day. This shows an increase in water concentration from the air drier of only 19mg/m^3 or 4.6% of the increase allowed to reach a dew point of -25^{o}C. Figure 8 shows the water concentration differences of the APD enclosure and manifold using 35ug/day water permeation and a low temperature (-15^{o}C) diffusion coefficient of 0.148 cm^2/sec.

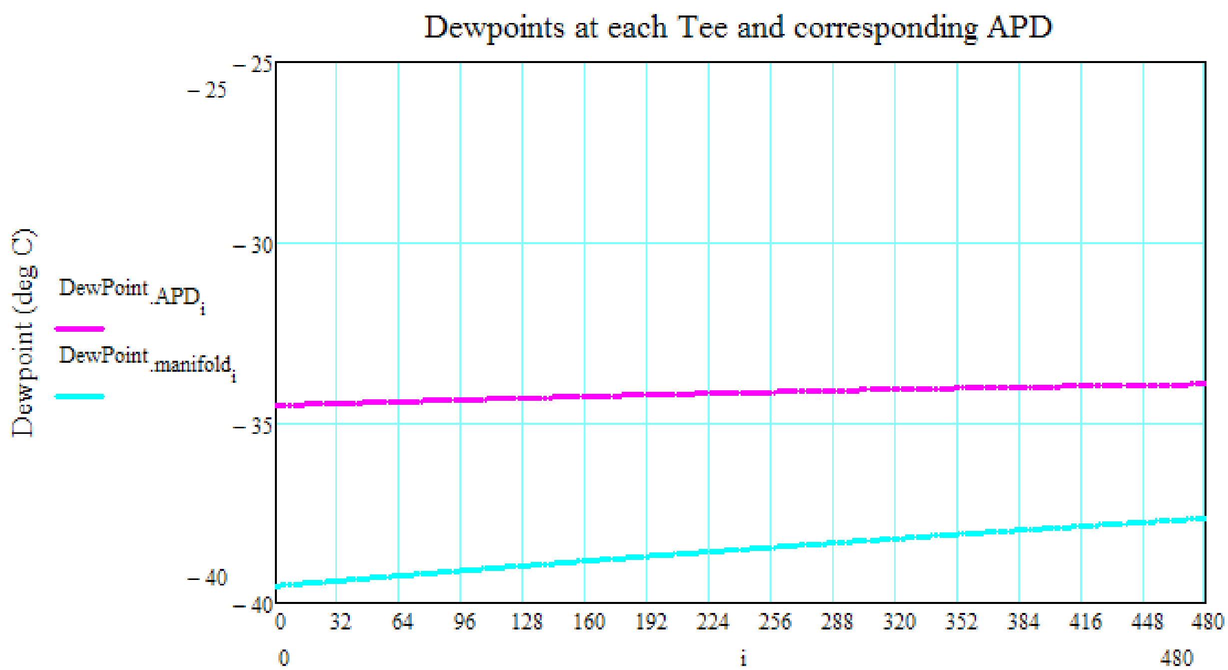

Figure 3: Dew points along manifold and corresponding APD enclosure with 35ug/day into APD enclosure.

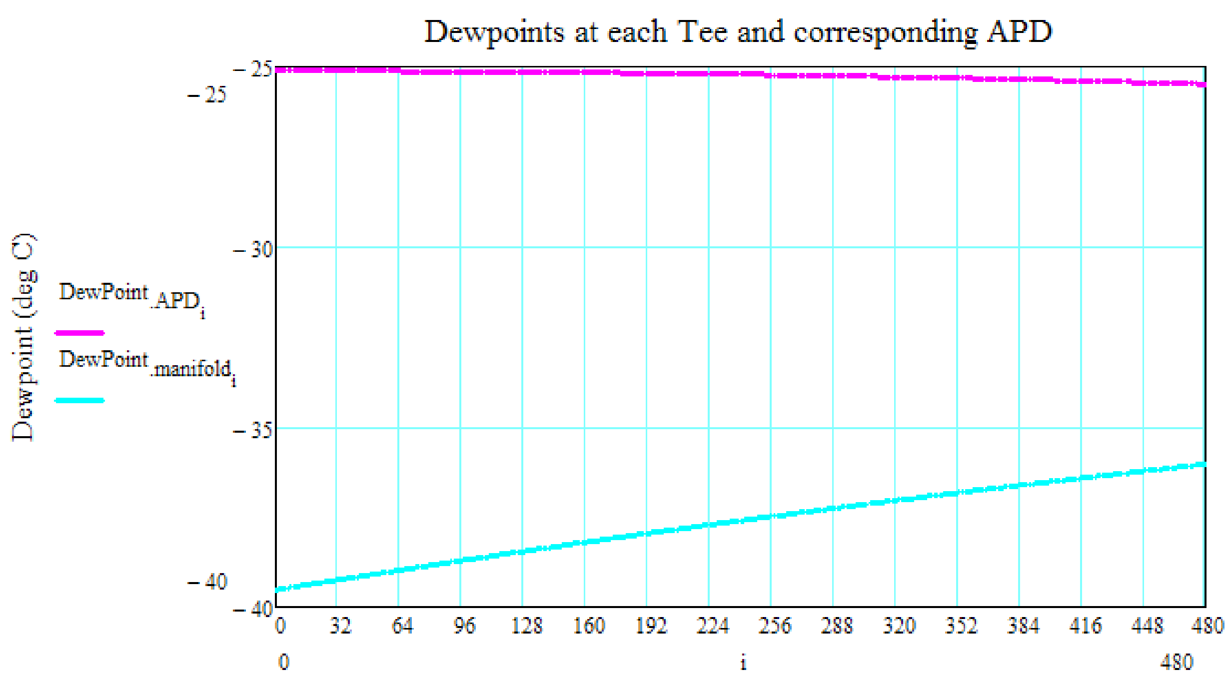

Figure 4: Dew points along manifold and corresponding APD enclosure with 150ug/day into APD enclosure.

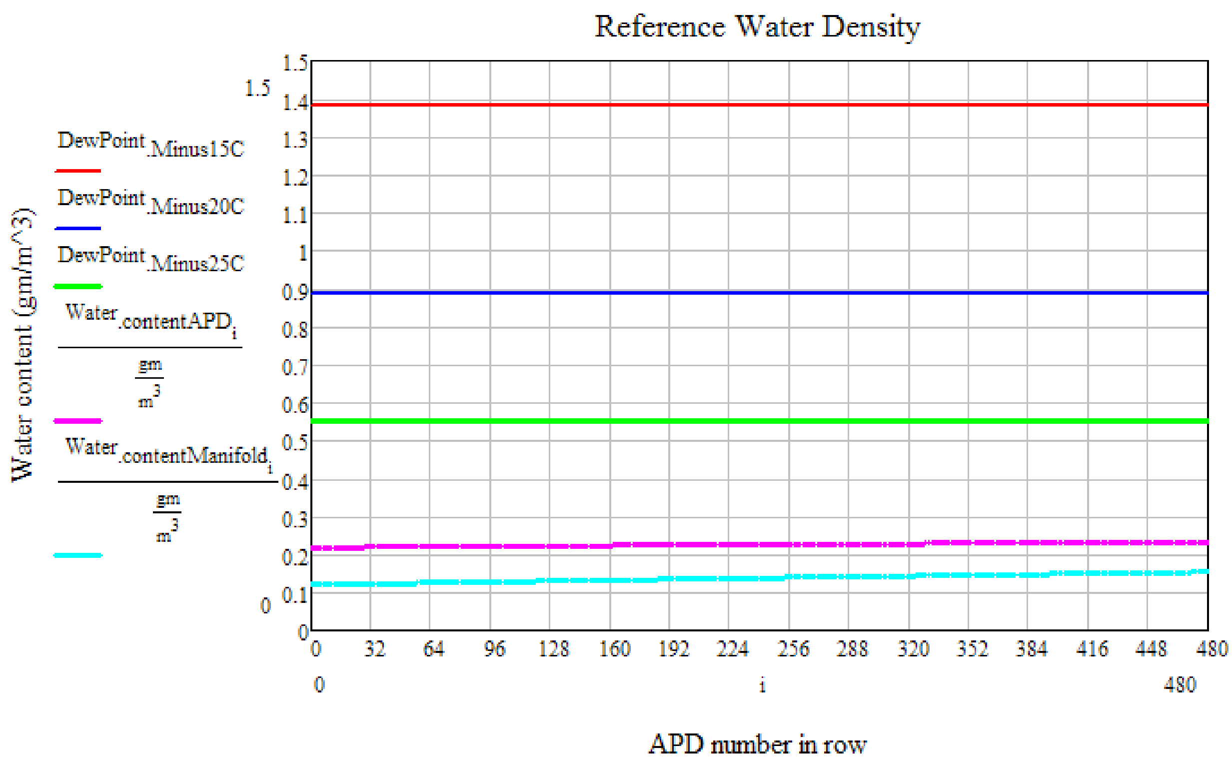

Figure 5: Reference water concentrations with 35ug/day into APD enclosure.

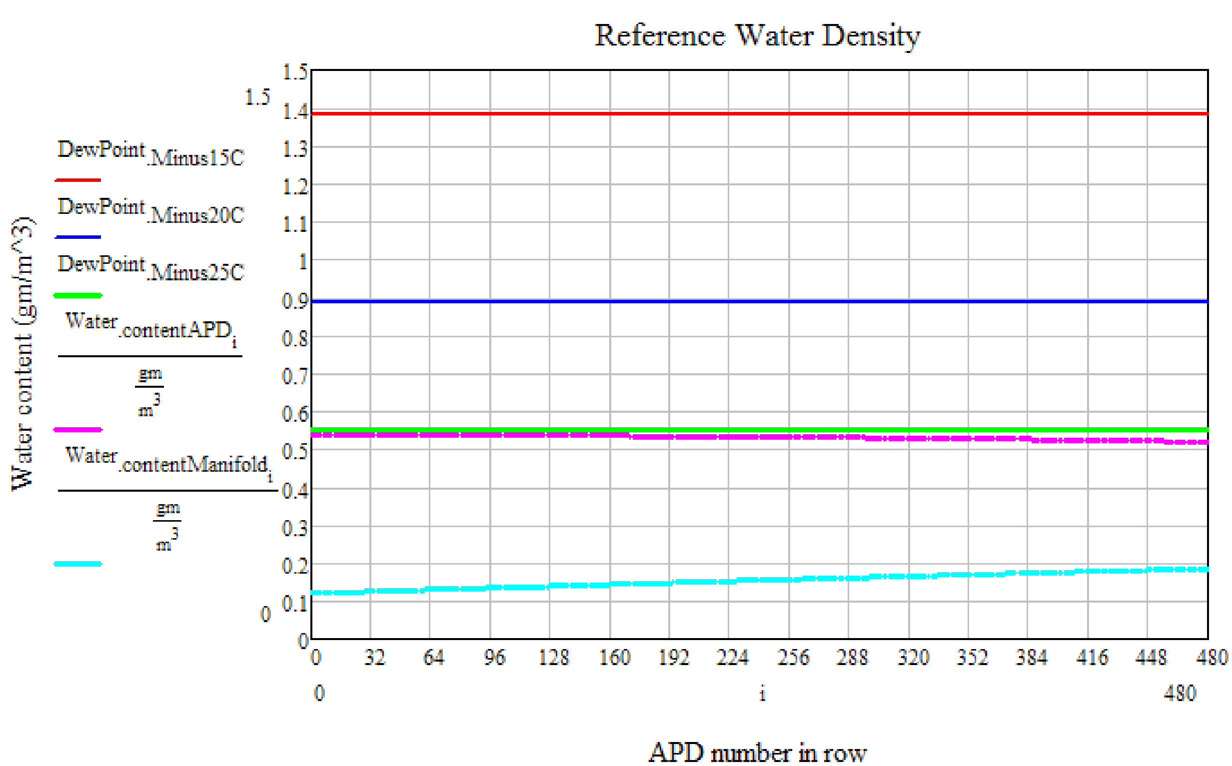

Figure 6: Reference water concentrations with 150ug/day into APD enclosure.

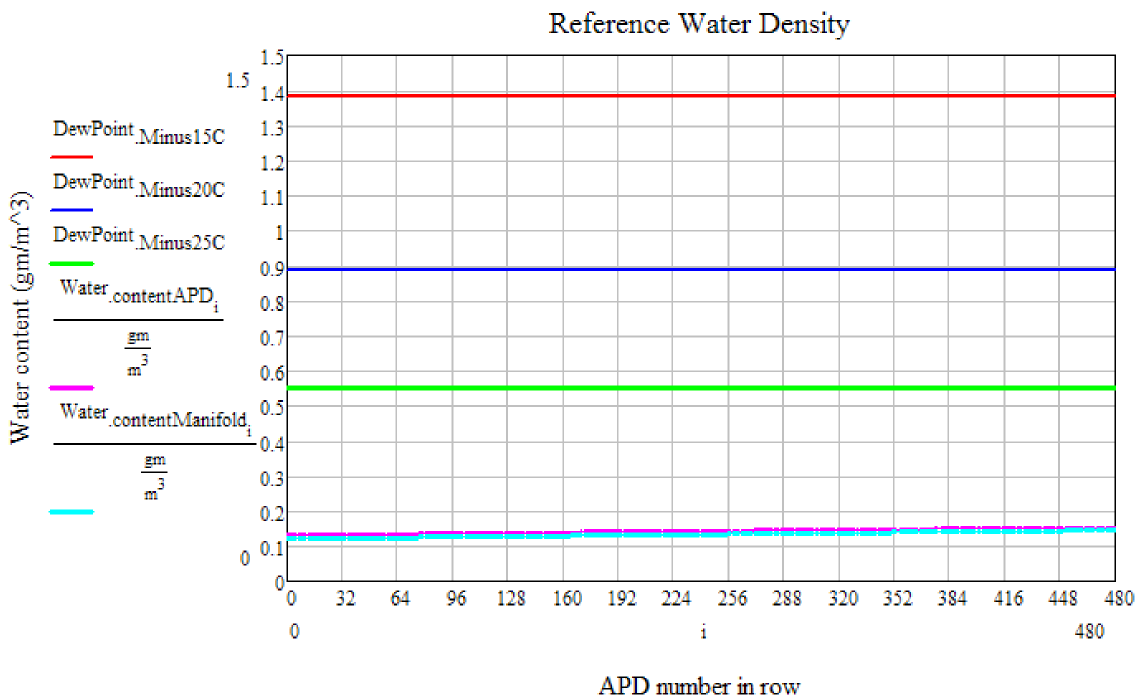

Figure 7: Reference Water concentrations at each node using 3.5ug/day APD water permeation rates from specification. Ambient Conditions are 25C and 90% relative humidity.

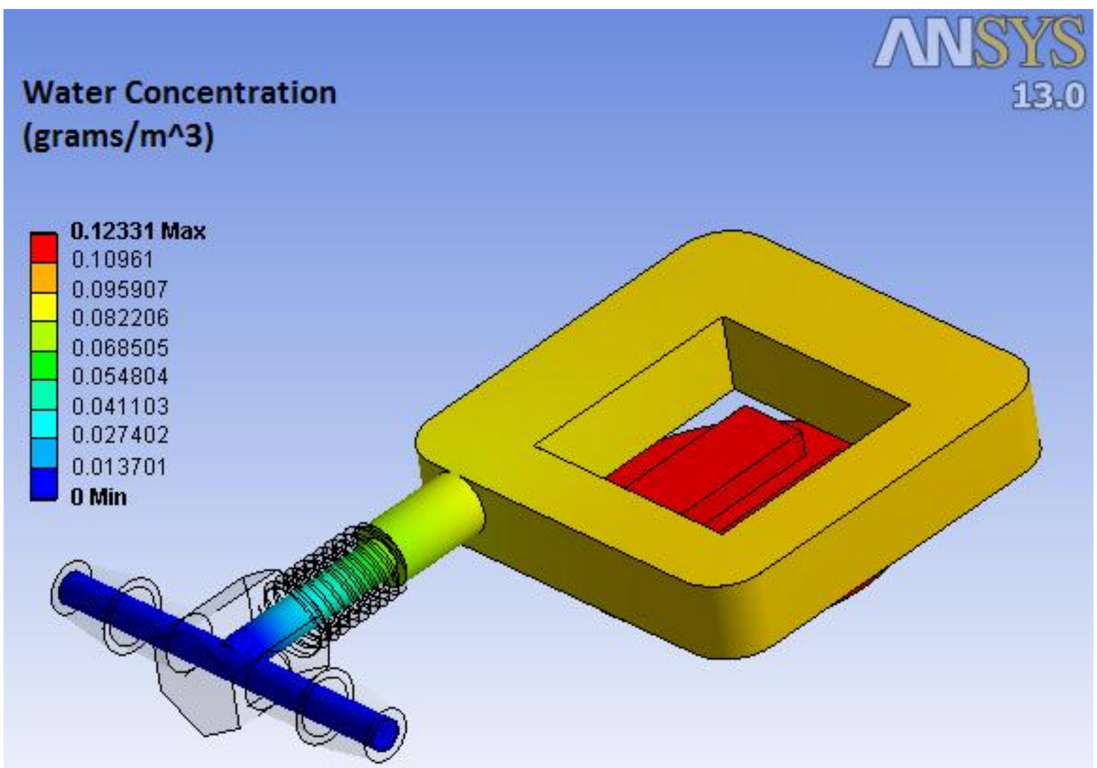

Figure 8: Water Concentration Difference from APD to Manifold with 35ug/day, diffusion coefficient 0.148cm2/sec

Cost Estimate:

Part	Description	Supplier	Part Number	price	per	Quantity	Cost
APD Manifold Tubing	Viton tubing 1/8" ID x 1/4" OD	McMaster	5119K11	$3.27	per foot	5000	$16,350
Threaded/Barbed Tees	Polypropylene Tee	McMaster	5121K911	$0.44	each	11520	$5,069
Air Drier	10 SCFM @ -40 Dew point	McMaster	1156K14	$1,772.26	each	2	$3,545
Flow transmitter	Flow transmitter on each line of APDs	Omega	FMA-A2108	$585.00	each	24	$14,040
Rotameters	0.4 - 5 SCFH range with flow control	McMaster	5079K64	$49.74	each	24	$1,194
Pressure Indicators	dry gauge (0-5 psig range)	McMaster	4026K152	$57.23	each	24	$1,374
Main Manifold Hose	1/2" OD HDPE Hose	McMaster	50375K83	$0.25	per foot	150	$38
Main Manifold Fittings	1/2" Compression Fitting	McMaster	5272K164	$27.71	each	24	$665
Pressure Transmitter	Setra C207			$250.00	each	3	$750
Relief Valve				$50.00	each	1	$50
Nitrogen Bottles				$100.00	each	4	$400
Pressure Regulator				$350.00	each	2	$700
Dewpoint transmitter	May already have 2 to recycle			$2,000.00	each	2	$4,000
Compressor				$1,500.00	each	2	$3,000
PLC and Control System	Lumped with Water system?			$250.00	each	15	$3,750

Total System Cost	$54,923
Contingency	50%
Total System Cost with Contingency	**$80,000**

APPENDIX A
Detailed Design Calculations and Analyses

Calculations for pressurized APD drier system

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Gas Properties and Dewpoint Data

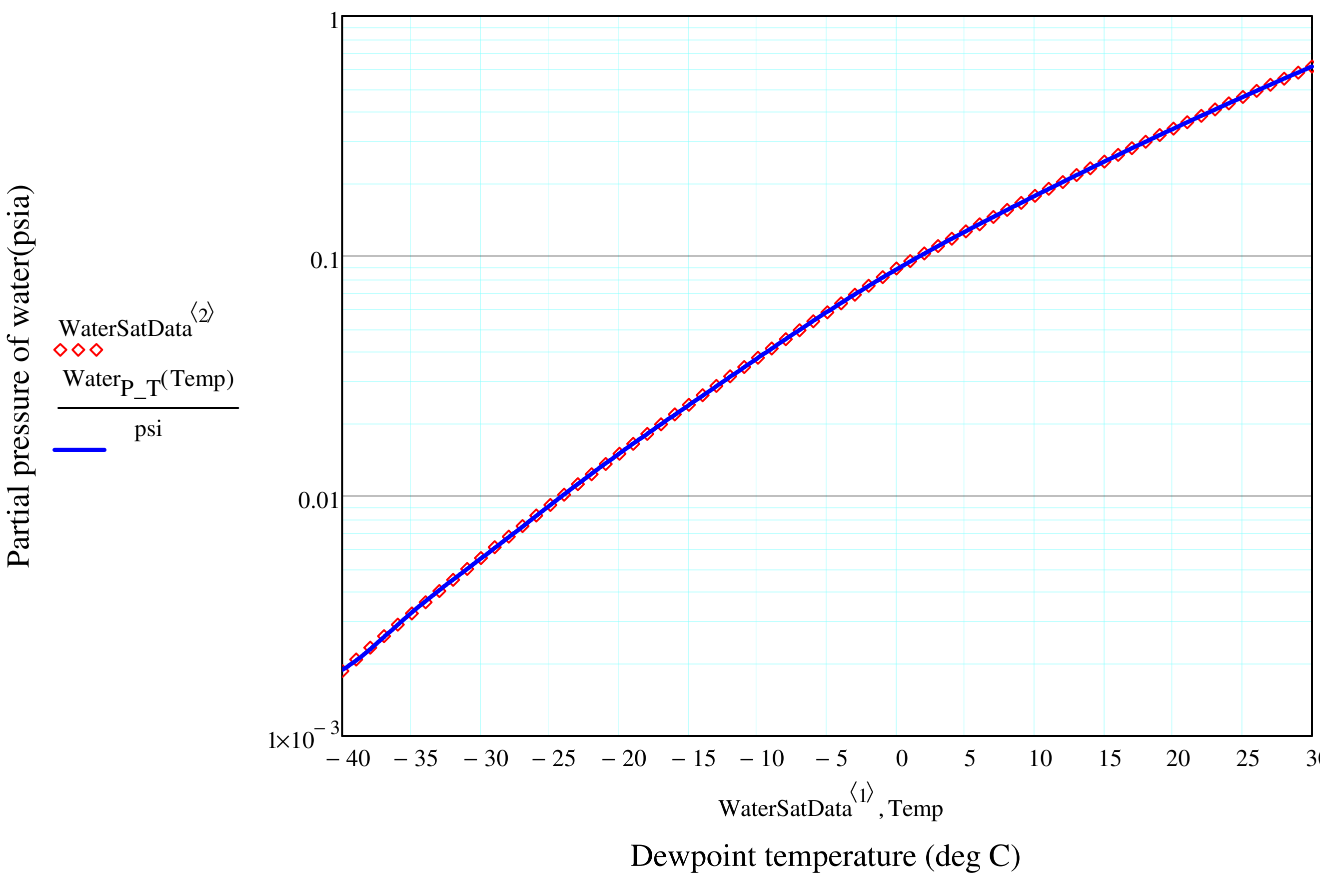
Dewpoint Data Curve fits

$$Water_{P\_T}(Temp) := interp\left(regress\left(WaterSatData^{\langle 1\rangle}, WaterSatData^{\langle 2\rangle}, 12\right), WaterSatData^{\langle 1\rangle}, WaterSatData^{\langle 2\rangle}, Temp\right)\cdot psi$$

$$Water_{\rho\_T}(Temp) := interp\left(regress\left(WaterSatData^{\langle 1\rangle}, WaterSatData^{\langle 3\rangle}, 12\right), WaterSatData^{\langle 1\rangle}, WaterSatData^{\langle 3\rangle}, Temp\right)\cdot \frac{kg}{m^3}$$

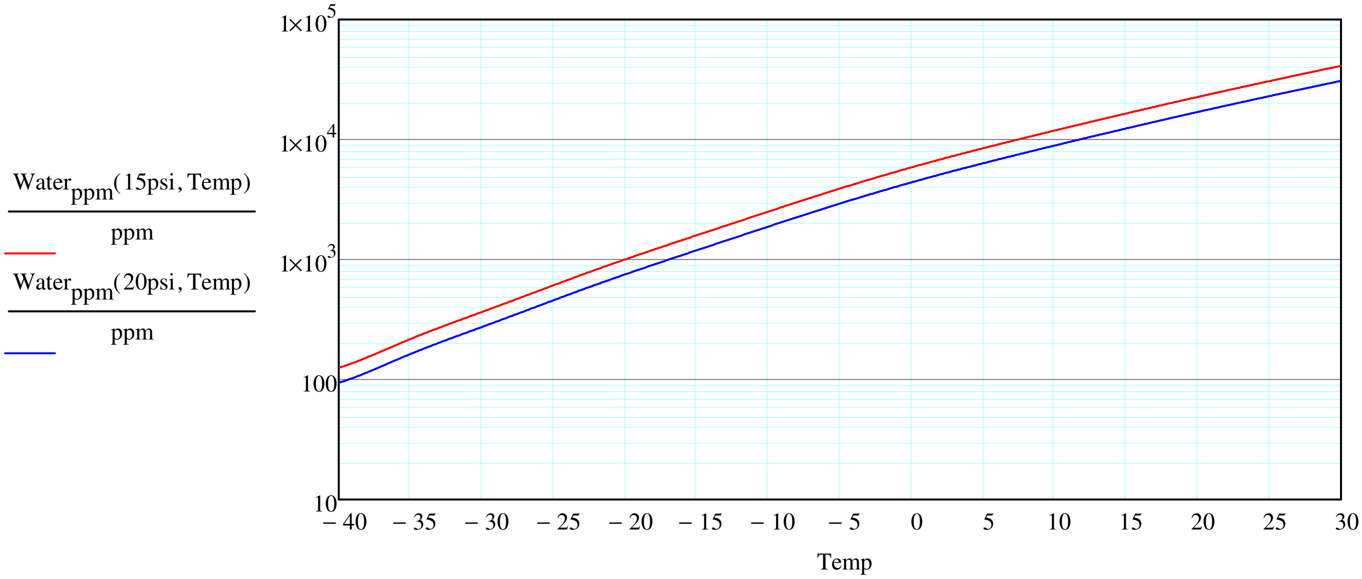
$$Water_{\rho\_P}(press) := interp\left(regress\left(WaterSatData^{\langle 2\rangle}, WaterSatData^{\langle 3\rangle}, 12\right), WaterSatData^{\langle 2\rangle}, WaterSatData^{\langle 3\rangle}, press\right)\cdot \frac{kg}{m^3}$$

$$DewPoint_{T\_\rho}(Dens) := interp\left(regress\left(WaterSatData^{\langle 3\rangle}, WaterSatData^{\langle 1\rangle}, 20\right), WaterSatData^{\langle 3\rangle}, WaterSatData^{\langle 1\rangle}, Dens\right)$$



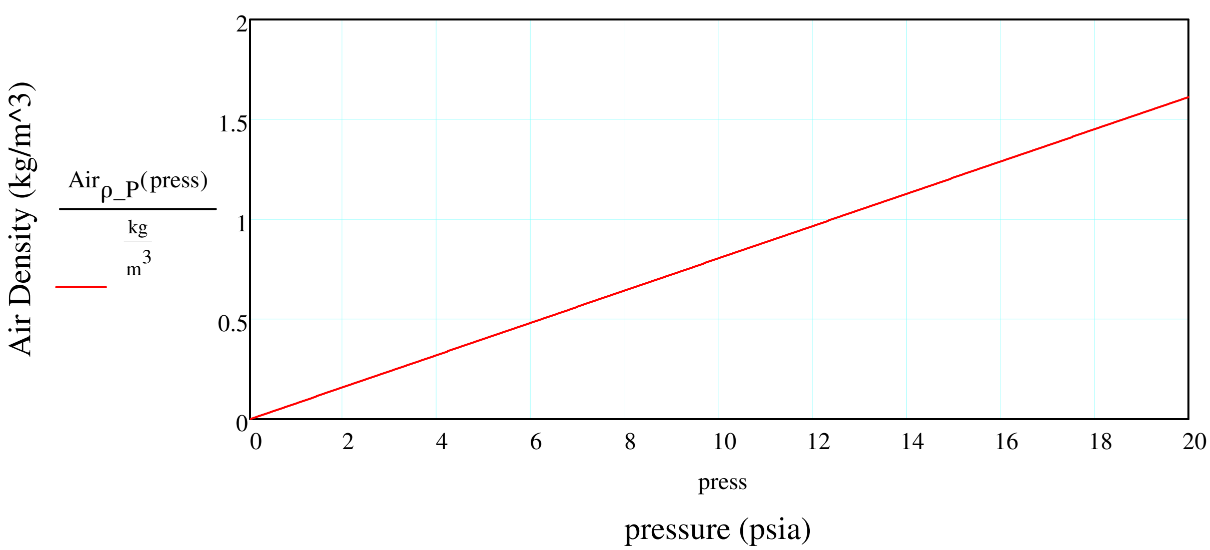
Function for water ppm with respect to static pressure and dewpoint temperature

$$\text{Water}_{ppm}(\text{press}, \text{Temp}) := \frac{\text{Water}_{P\_T}(\text{Temp})}{\text{press}}$$



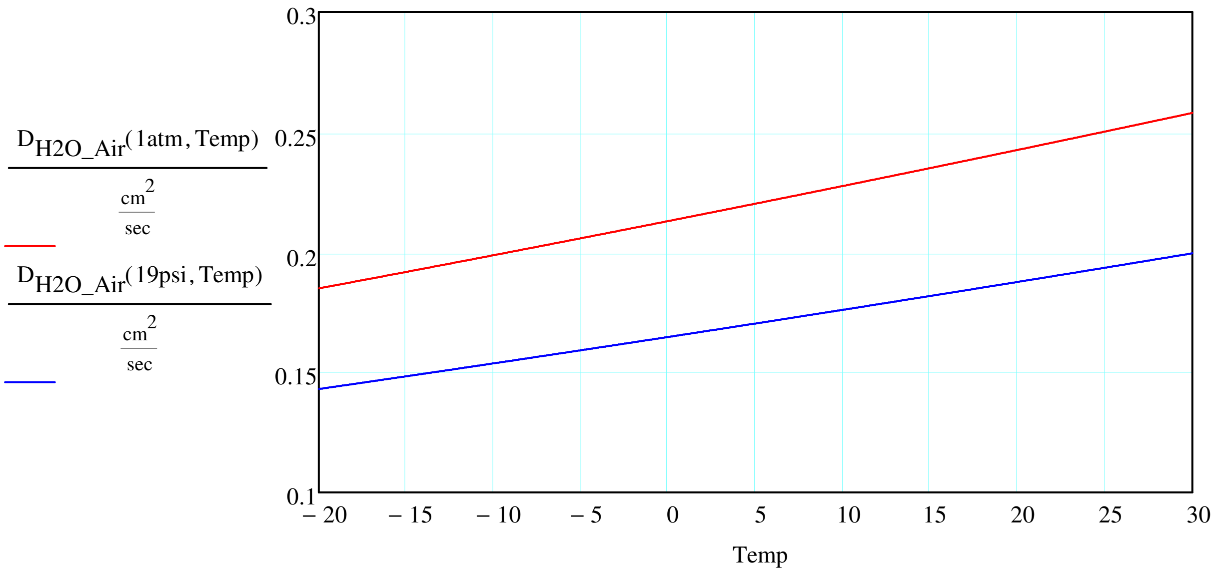
Air Data (density with respect to static pressure)

$$\text{Air}_{\rho\_P}(\text{press}) := \text{interp}\left(\text{regress}\left(\text{AirDensityData}^{\langle 1\rangle}, \text{AirDensityData}^{\langle 2\rangle}, 2\right), \text{AirDensityData}^{\langle 1\rangle}, \text{AirDensityData}^{\langle 2\rangle}, \text{press}\right)\cdot\frac{\text{kg}}{\text{m}^3}$$



Mass diffusion coefficient of Water Vapor in air WRT temperature and pressure

$$D_{H2O\_Air}(Press, Temp) := interp\left(regress\left(Diff_{Data}^{\langle 1\rangle}, Diff_{Data}^{\langle 2\rangle}, 4\right), Diff_{Data}^{\langle 1\rangle}, Diff_{Data}^{\langle 2\rangle}, Temp\right)\cdot\frac{cm^2}{sec}\cdot\frac{1atm}{Press}$$



System and Site Specifications and Requirements

Number of APDs which need to be dried

$num_{row} := 24$ $num_{inRow} := 32$ $num_{DB} := 15$ $num_{APDs} := num_{row}\cdot num_{inRow}\cdot num_{DB} = 11520$

Specifications say APD enclosure must be drier than dewpoint of -25C

$Dewpoint_{Design} := -25$

Partial pressure and density of water at design dewpoint

$Water_{P\_T}\left(Dewpoint_{Design}\right) = 0.009\cdot psi$ $Water_{\rho\_T}\left(Dewpoint_{Design}\right) = 0.552\cdot\frac{gm}{m^3}$ $Water_{\rho\_T}(-15) = 1.383\cdot\frac{gm}{m^3}$

That puts us at 40% of the water content of a dew point of -15C

$$\frac{Water_{\rho\_T}\left(Dewpoint_{Design}\right)}{Water_{\rho\_T}(-15)} = 40\cdot\%$$

Properties of Water as an ideal gas

$$M_{H2O} := 18.015\frac{kg}{kmol}$$

$$R_u := 8.3144621\frac{J}{mol\cdot K} \qquad R_{H2O} := \frac{R_u}{M_{H2O}} = 461.53\frac{m^2}{K\cdot s^2} \qquad \rho_{H2O\_STD} := \frac{1atm}{R_{H2O}\cdot 293K} = 0.749\frac{kg}{m^3}$$

Determine Dry Air Flow Needed

Partial Pressure of water at 25C and 90% relative humidity

$ExitWaterContent := 25\%$ *(of dewpoint design)*

$Relative_{Humidity} := 90\%$ *(ambient)*

$$Ambient_{water} := Water_{P\_T}(25)\left(Relative_{Humidity}\right) = 2852.112\,Pa$$

Atmospheric pressure at NOvA site (elevation at detector bottom ~370m)

$$P_{NOvA} := 14psi$$

Flow of dry air will be supplied at 5 psig

$$Air_{pressure} := P_{NOvA} + 5psi$$

Water permeation through APD per NOvA doc-5550

$$Water_{PermeationData} := 3.5\frac{\mu g}{day}$$

For a reality check we will run a mass transfer Analysis on one of the O-rings which was tested: McMaster Part #5577K19: An FDA approved Viton O-ring 0.070" width by 0.801" ID. NOvA DOC-5550 gives a rate of 0.735micrograms/day

$$Flux_{OringMeasured} := 0.735\frac{\mu g}{day}$$

We will seat the O-ring poorly, and not crush it to proper specs.

$$groove := 220.5mil - 159mil = 0.062\cdot in \qquad d_{Oring} := 0.070in \qquad crush_{percent} := \frac{d_{Oring} - groove}{d_{Oring}} = 12.143\cdot\%$$

$$t_{crush} := d_{Oring}\cdot\left(1 - crush_{percent}\right) = 0.0615\cdot in \qquad Area_{Oring} := \frac{\pi}{4}\cdot d_{Oring}^{\ 2}$$

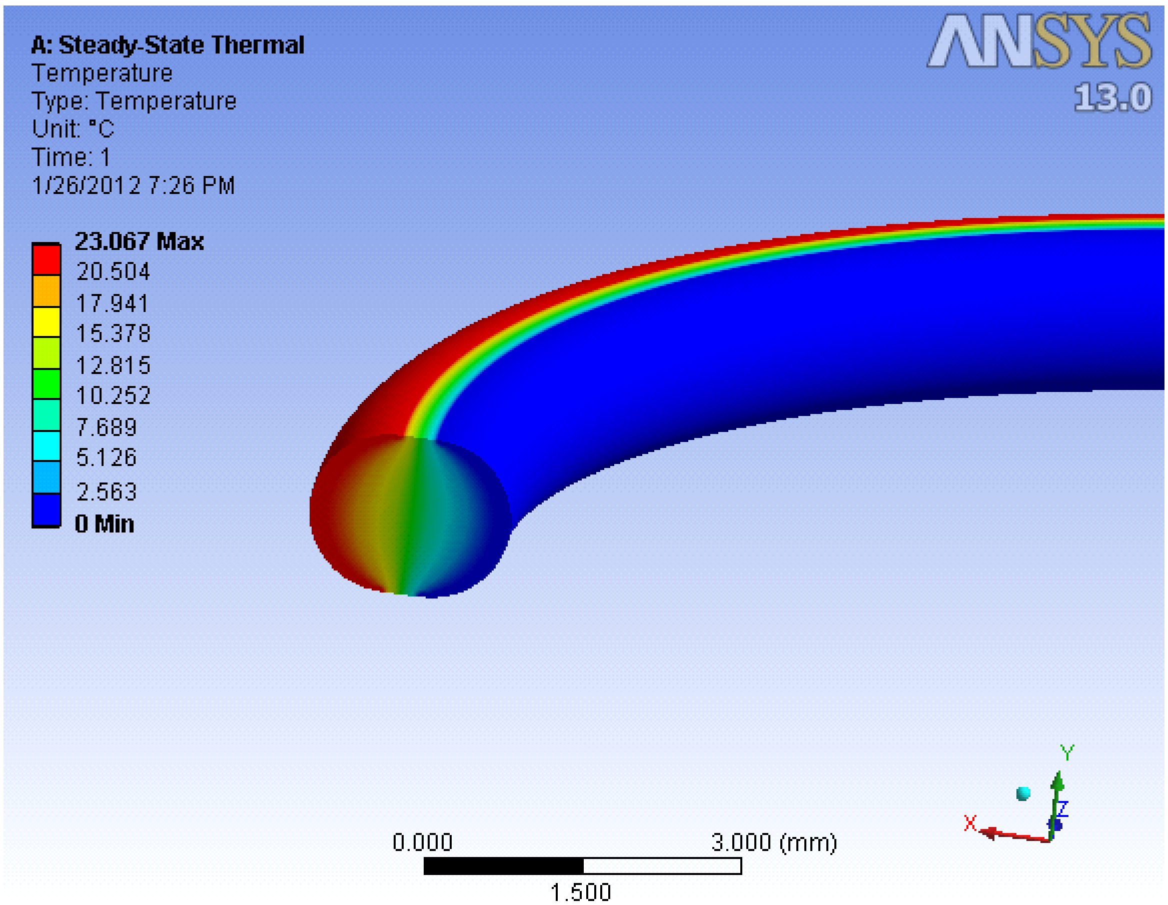
$$width_{flat} := \frac{Area_{Oring} - \frac{\pi}{4} \cdot t_{crush}^{2}}{t_{crush}} = 0.01427 \cdot in$$

Diffusion and Permeation Rates of Viton

$$D_{viton} := 4 \cdot 10^{-7} \frac{cm^2}{sec}$$

http://lpc1.clpccd.cc.ca.us/lpc/tswain/permeation.pdf

$$P_{viton} := 40 \cdot 10^{-15} \frac{m^2}{sec \cdot hPa} \cdot \rho_{H2O\_STD} = 0.026 \cdot \frac{gm \cdot mm}{m^2 \cdot day \cdot kPa}$$



$$Flux_{OringD}(\Delta C) := \Delta C \cdot 4.697 \times 10^{-12} \frac{m^3}{s}$$

$$Flux_{OringD}\left(Water_{\rho\_T}(25) \cdot 90\%\right) = 8.425 \cdot \frac{\mu g}{day}$$

$$Flux_{OringP}(\Delta P) := \Delta P \cdot 3.419 \times 10^{-11} \frac{gm}{s \cdot kPa}$$

$$Flux_{OringP}\left(Water_{P\_T}(25) \cdot 90\%\right) = 8.425 \cdot \frac{\mu g}{day}$$

$$\frac{Flux_{OringD}\left(Water_{\rho\_T}(25) \cdot 90\% - Water_{\rho\_T}(25) \cdot 10\%\right)}{Flux_{OringMeasured}} = 10$$

This shows we calculate a value 10 times higher than the measurements for the same conditions. Therefore we will multiply all measured permeation rates times 10.

Design Permeation Rate (multiply by 10)

$$Water_{PermeationPerAPD} := Water_{PermeationData} \cdot 10 = 35 \cdot \frac{\mu g}{day}$$

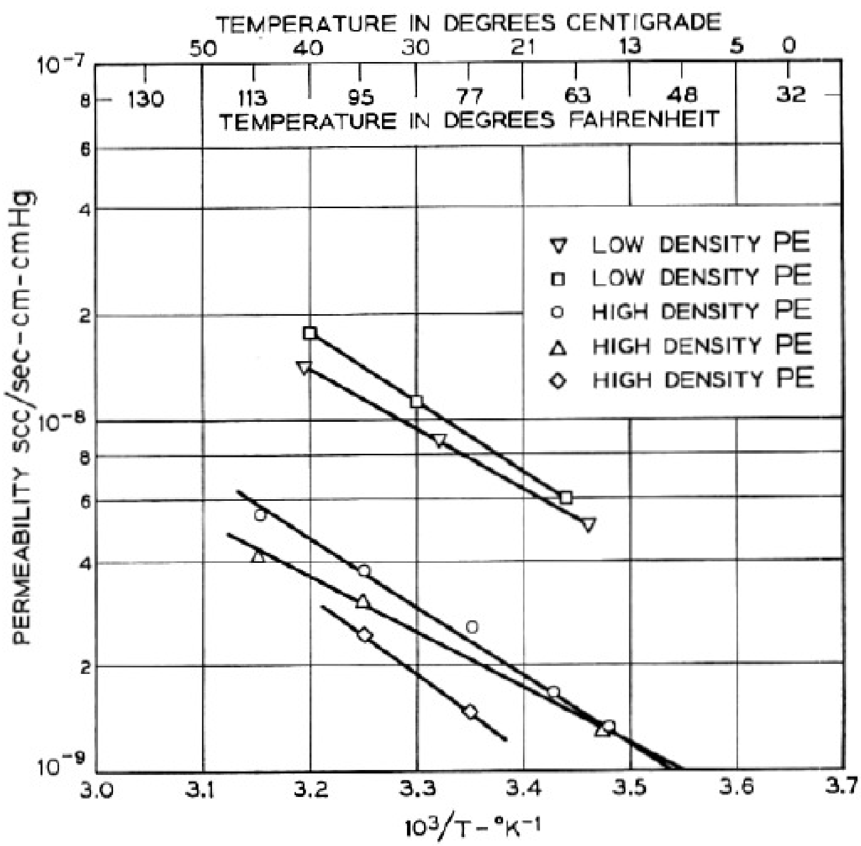
$$Water_{Permeation\_APDseal} := Water_{PermeationPerAPD} \cdot num_{APDs} = 0.403 \cdot \frac{gm}{day}$$

Calculate air supply needed to dry this vapor flow into the system

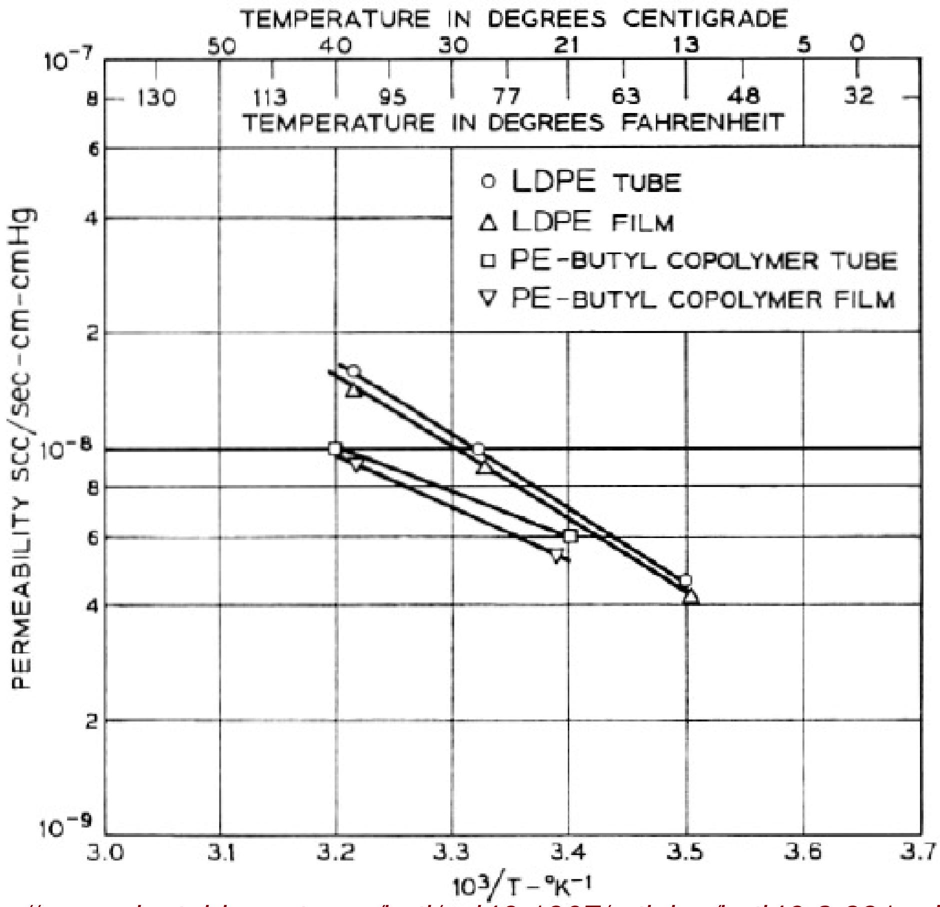
$$APD_{PermFlowNeeded} := \frac{Water_{Permeation\_APDseal}}{Water_{\rho\_T}\left(Dewpoint_{Design}\right)(ExitWaterContent)} = 4.3 \cdot \frac{ft^3}{hr}$$

$$APD_{PermFlowNeeded} := APD_{PermFlowNeeded} \cdot \left(\frac{Air_{\rho\_P}\left(\frac{Air_{pressure}}{psi}\right)}{Air_{\rho\_P}\left(\frac{1atm}{psi}\right)} \right) = 5.56 \cdot SCFH$$

Permeation Data for Several materials



http://www.alcatel-lucent.com/bstj/vol46-1967/articles/bstj46-2-391.pdf



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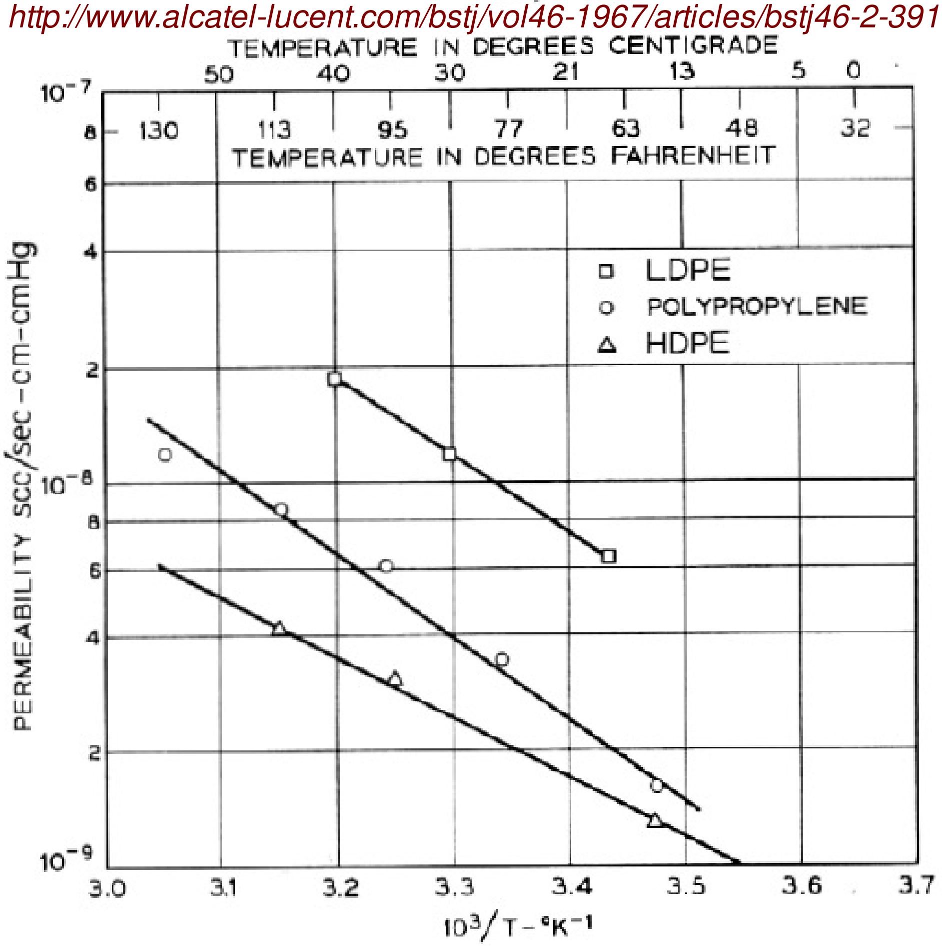

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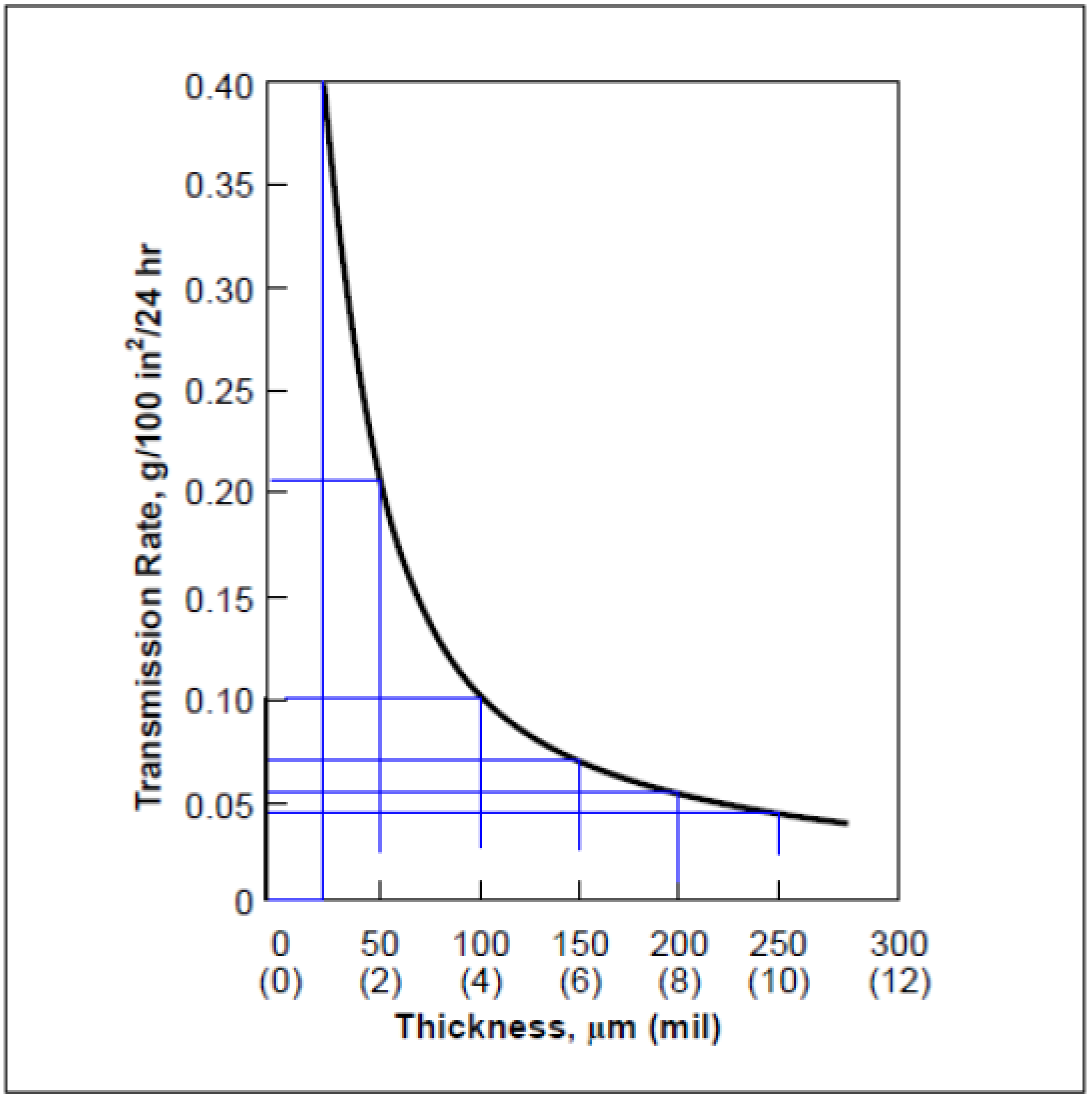


http://www.rjchase.com/permeation_effects.pdf

$$P_{HDPE} := 2.5 \cdot 10^{-9} \frac{mL}{sec \cdot cm \cdot cmHg} \cdot (\rho_{H2O\_STD}) = 0.012 \cdot \frac{gm \cdot mm}{day \cdot m^2 \cdot kPa}$$

$$P_{PP} := 3.5 \cdot 10^{-9} \frac{mL}{sec \cdot cm \cdot cmHg} \cdot (\rho_{H2O\_STD}) = 0.017 \cdot \frac{gm \cdot mm}{day \cdot m^2 \cdot kPa}$$

$$P_{viton} = 0.026 \cdot \frac{gm \cdot mm}{day \cdot m^2 \cdot kPa}$$

http://lpc1.clpccd.cc.ca.us/lpc/tswain/permeation.pdf

$$P_{LDPE} := 1 \cdot 10^{-8} \frac{mL}{sec \cdot cm \cdot cmHg} \cdot (\rho_{H2O\_STD}) = 0.049 \cdot \frac{gm \cdot mm}{day \cdot m^2 \cdot kPa}$$

$$Flux_{FEP}(t_{seal}) := \frac{0.42}{\frac{t_{seal}}{mil}} \cdot \frac{gm}{100in^2 \cdot day} \qquad t_{FEP} := 0.017in \qquad \Delta p := 1.0711psi \qquad \Delta C := 0.051242 \frac{kg}{m^3}$$

$$P_{FEP} := \frac{0.42 \cdot \frac{gm \cdot mil}{100in^2 \cdot day}}{\Delta p} = 0.022391 \cdot \frac{gm \cdot mm}{day \cdot m^2 \cdot kPa}$$

Convert to Diffusion Coefficient

$$J = D \cdot \left(\frac{d}{dx}\phi\right)$$

$$D = \frac{J}{\left(\frac{d}{dx}\phi\right)} \qquad D = \frac{Flux_{FEP}(t_{seal})}{\frac{\Delta C}{t_{seal}}} = \frac{\frac{\frac{0.42}{t_{seal}} \cdot \frac{gm}{100in^2 \cdot day}}{mil}}{\frac{\Delta C}{t_{seal}}} \rightarrow D = \frac{0.081964013894851879318 \cdot gm \cdot m^3 \cdot mil}{day \cdot in^2 \cdot kg}$$

$$D_{FEP} := \frac{0.081964013894851879318 \cdot gm \cdot m^3 \cdot mil}{day \cdot in^2 \cdot kg} = 3.735 \times 10^{-11} \frac{m^2}{s}$$

$$P_{toD} := \left(\frac{D_{FEP}}{P_{FEP}}\right) = 1.441 \times 10^{5} \frac{m^2}{s^2}$$

$D_{LDPE} := P_{LDPE} \cdot P_{toD} = 8.097 \times 10^{-11} \frac{m^2}{s}$ $\qquad P_{LDPE} = 0.049 \cdot \frac{gm \cdot mm}{day \cdot m^2 \cdot kPa}$ *(@25C)*

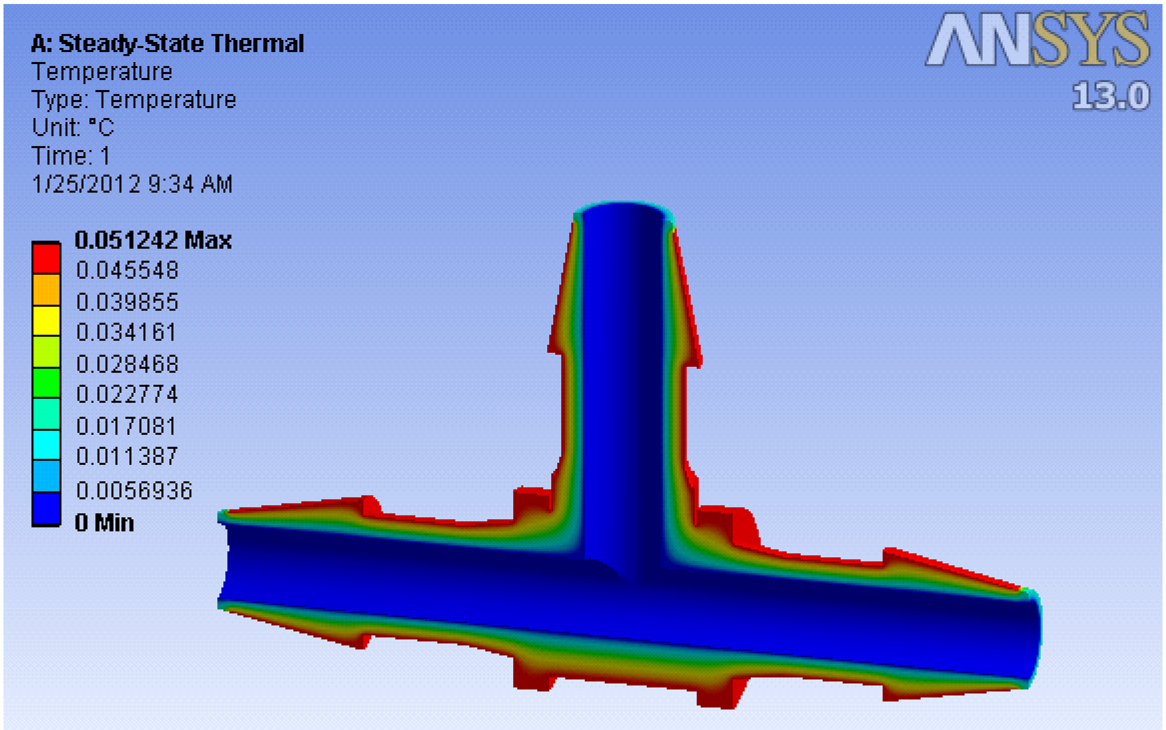
$D_{viton} = 4 \times 10^{-11} \frac{m^2}{s}$ $\qquad P_{viton} = 0.026 \frac{gm \cdot mm}{day \cdot m^2 \cdot kPa}$ *(@25C)*

$D_{FEP} = 3.735 \times 10^{-11} \frac{m^2}{s}$ $\qquad P_{FEP} = 0.022 \cdot \frac{gm \cdot mm}{day \cdot m^2 \cdot kPa}$ *Conservative (@40C)*

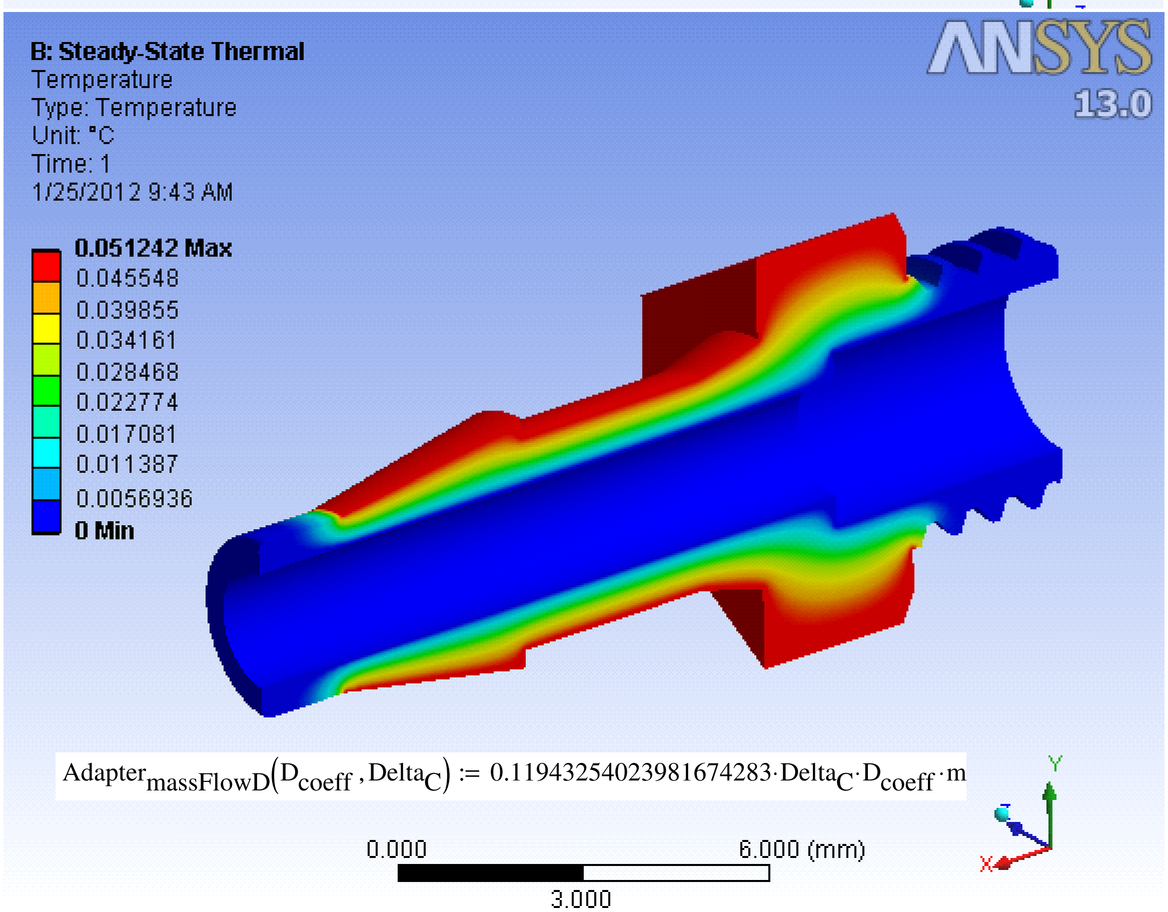
$D_{PP} := P_{PP} \cdot P_{toD} = 2.834 \times 10^{-11} \frac{m^2}{s}$ $\qquad P_{PP} = 0.017 \cdot \frac{gm \cdot mm}{day \cdot m^2 \cdot kPa}$ *(@25C)*

$D_{HDPE} := P_{HDPE} \cdot P_{toD} = 2.024 \times 10^{-11} \frac{m^2}{s}$ $\qquad P_{HDPE} = 0.012 \cdot \frac{gm \cdot mm}{day \cdot m^2 \cdot kPa}$ *(@25C)*

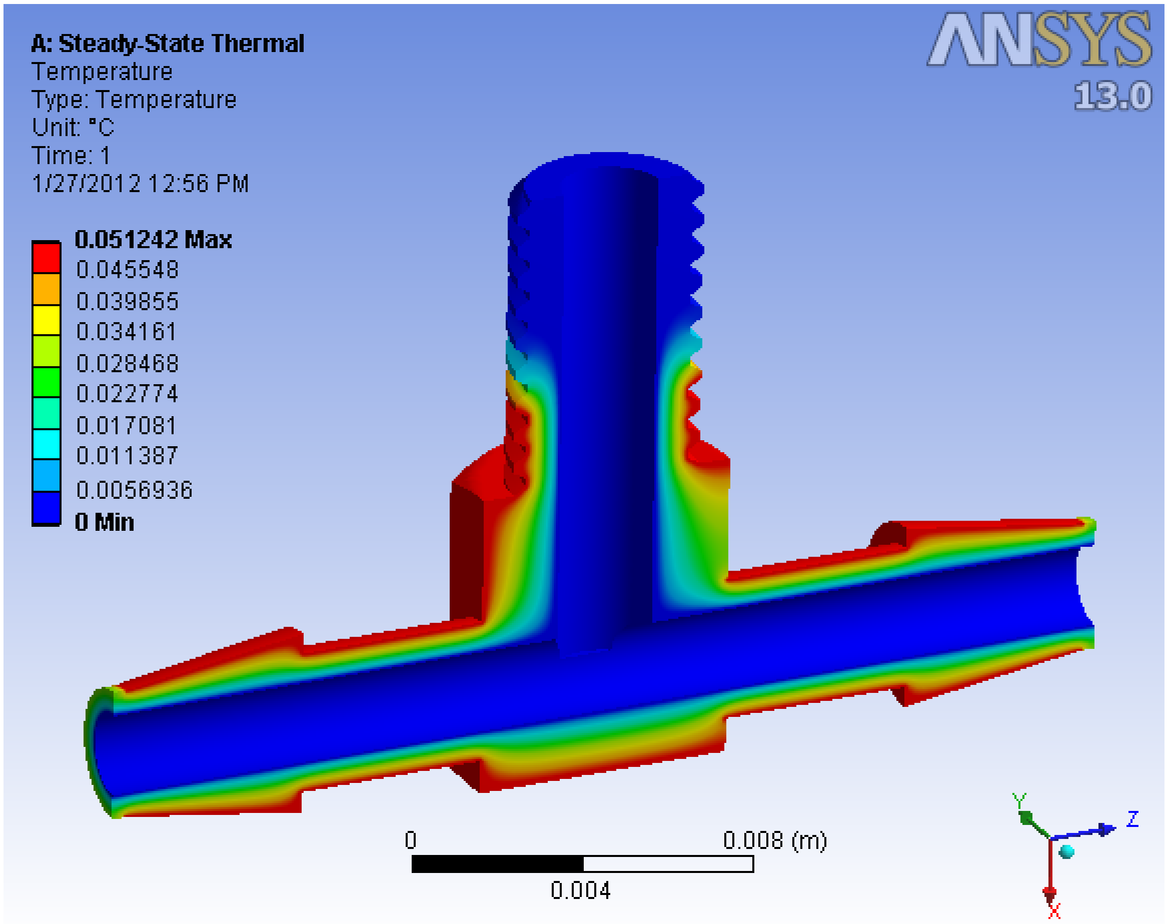
Find mass transfer of plastic components



$$Tee_{massFlowD}(D_{coeff}, Delta_C) := 0.407428087708641875 37 \cdot Delta_C \cdot D_{coeff} \cdot m$$



$$Adapter_{massFlowD}(D_{coeff}, Delta_C) := 0.119432540239816742 83 \cdot Delta_C \cdot D_{coeff} \cdot m$$



$$Offshot_{TeeMassFlow}(D_{coeff}, Delta_C) := 0.29468364 \cdot (Delta_C \cdot D_{coeff})\ m$$

$$Offshot_{TeeMassFlow}\left[D_{PP}, Water_{\rho\_T}(25)(Relative_{Humidity})\right] = 14.979 \cdot \frac{\mu g}{day}$$

Determine Mass transfer resistance of hose (Two seperate types)

Size of hose:

$ID_{hose} := 0.125in$ $\quad OD_{hose} := 0.25in$ $\quad t_{FEP} := 0.017in$ $\quad ID_{PE} := ID_{hose} + 2 \cdot t_{FEP}$

Equivilent radial "area / thickness"

$$Area_{FEP} := \frac{2\pi}{\ln\left(\frac{ID_{PE}}{ID_{hose}}\right)} = 26.116 \qquad Area_{PE} := \frac{2\pi}{\ln\left(\frac{OD_{hose}}{ID_{PE}}\right)} = 13.884$$

Water Permeation Resistance of FEP and Polyethelene

$$R_{FEP} := \frac{1}{Area_{FEP} \cdot P_{FEP}} = 1.478 \times 10^{14} \frac{1}{s}$$

$$R_{PE} := \frac{1}{Area_{PE} \cdot P_{LDPE}} = 1.282 \times 10^{14} \frac{1}{s}$$

$$R_{FEP\_D} := \frac{1}{Area_{FEP} \cdot D_{FEP}} = 1.025 \times 10^{9} \frac{s}{m^2}$$

$$R_{PE\_D} := \frac{1}{Area_{PE} \cdot D_{LDPE}} = 8.896 \times 10^{8} \frac{s}{m^2}$$

Water Permeation Resistance of Hose

$$R_{hose} := R_{FEP} + R_{PE} = 3.194 \cdot \frac{1}{\left(\frac{gm \cdot mm}{kPa \cdot m^2 \cdot day}\right)}$$

$$R_{hose\_D} := R_{FEP\_D} + R_{PE\_D} = 1.915 \times 10^{9} \frac{s}{m^2}$$

Mass flux equation

$$FluxHose(\Delta P) := \frac{\Delta P}{R_{hose}}$$

$$FluxHose\_D(\Delta C) := \frac{\Delta C}{R_{hose\_D}}$$

Calculate mass flux per length of hose in both units of ΔP and ΔC to check for consistancy

$$FluxHose\left[Water_{P\_T}(25)\left(Relative_{Humidity}\right) - Water_{P\_T}(-40)\right] = 22.578 \cdot \frac{\mu g}{in \cdot day}$$

$$FluxHose\_D\left[Water_{\rho\_T}(25)\left(Relative_{Humidity}\right) - Water_{\rho\_T}(-40)\right] = 23.655 \cdot \frac{\mu g}{in \cdot day}$$

quite consistant, good

We could also use Viton Hose (more expensive, but easier to install)

$$Area_{Viton} := \frac{2\pi}{\ln\left(\frac{OD_{hose}}{ID_{hose}}\right)} = 9.065$$

$$R_{Viton\_D} := \frac{1}{Area_{Viton} \cdot D_{viton}}$$

$$R_{Viton} := \frac{1}{Area_{Viton} \cdot P_{viton}}$$

$$FluxVitonHose\_D(\Delta C) := \frac{\Delta C}{R_{Viton\_D}}$$

$$FluxVitonHose(\Delta P) := \frac{\Delta P}{R_{Viton}}$$

$$FluxVitonHose\_D\left[Water_{\rho\_T}(25)\left(Relative_{Humidity}\right) - Water_{\rho\_T}(-40)\right] = 16.424 \cdot \frac{\mu g}{in \cdot day}$$

How much hose is in the system?

$APD_{pitch} := 5.25in$ $\quad Length_{Detector} := APD_{pitch} \cdot 32 \cdot 15 = 210 \cdot ft$

$num_{APD} := 11520$ $\quad Jumper_{hose} := 4.3in$

$$Length_{hose} := num_{APD} \cdot \left(Jumper_{hose}\right) = 4128 \cdot ft$$

Total water mass flow into system

$$\Delta P_{max} := Water_{P\_T}(25)\left(Relative_{Humidity}\right) - Water_{P\_T}(-40) = 2839.106\,Pa$$

$$\Delta C_{max} := Water_{\rho\_T}(25)\left(Relative_{Humidity}\right) - Water_{\rho\_T}(-40) = 20.64 \cdot \frac{gm}{m^3}$$

$$H2O_{fromHose} := FluxHose\left(\Delta P_{max}\right) \cdot Length_{hose} = 12.945 \cdot \frac{\mu g}{sec}$$

$$H2O_{fromTees} := Tee_{massFlowD}\left(D_{LDPE}, \Delta C_{max}\right) \cdot num_{APD} = 7.844 \cdot \frac{\mu g}{sec}$$

$$H2O_{fromAdapters} := Adapter_{massFlowD}\left(D_{PP}, \Delta C_{max}\right) \cdot num_{APD} = 0.805 \cdot \frac{\mu g}{sec}$$

$$H2O_{fromThreadedTees} := Offshot_{TeeMassFlow}\left(D_{PP}, \Delta C_{max}\right) \cdot num_{APD} = 1.986 \frac{\mu g}{sec}$$

$Multiplier := 10$

$$H2O_{fromAPD} := Water_{PermeationData} \cdot Multiplier \cdot num_{APD} = 4.667 \cdot \frac{\mu g}{sec}$$

$$System_{H2O\_Flux} := \begin{pmatrix} H2O_{fromHose} \\ H2O_{fromAPD} \\ H2O_{fromThreadedTees} \\ H2O_{fromTees} \\ H2O_{fromAdapters} \end{pmatrix} = \begin{pmatrix} 1.294 \times 10^{-8} \\ 4.667 \times 10^{-9} \\ 1.986 \times 10^{-9} \\ 7.844 \times 10^{-9} \\ 8.048 \times 10^{-10} \end{pmatrix} \cdot \frac{kg}{sec} \qquad \sum_{n=1}^{3} System_{H2O\_Flux_n} = 19.597 \cdot \frac{\mu g}{sec}$$

$$Purge_{Flow.Needed} := \frac{\sum_{n=1}^{3} System_{H2O\_Flux_n}}{\left(Water_{\rho\_T}\left(Dewpoint_{Design}\right) \cdot 25\%\right)} = 18.057 \cdot \frac{ft^3}{hr}$$

Laminar leak rates from discussion with Mat Muether (25inHg vacuum test)

$Laminar_{LeakTypical} := 1\frac{inHg}{hr}$ $Laminar_{LeakLarge} := 10\frac{inHg}{hr}$

$d_{tubetest} := 0.25in$ $l_{tubetest} := 1ft$

$Vol_{tubetest} := \frac{\pi}{4} \cdot d_{tubetest}^{2} \cdot l_{tubetest}$ $Vol_{APD} := 4.3mL$

$VolAPDtest := Vol_{APD} + Vol_{tubetest} = 13.953 \cdot mL$

$DP_{test} := 25inHg$ $P_{test} := 14.4psi - DP_{test} = 2.117 \cdot psi$

$$mass_{changeTypical} := \frac{\left(Air_{\rho\_P}\left(\frac{P_{test} + Laminar_{LeakTypical} \cdot hr}{psi}\right) - Air_{\rho\_P}\left(\frac{P_{test}}{psi}\right)\right) \cdot VolAPDtest}{hr \cdot DP_{test}} = 44.967 \cdot \frac{\mu g}{hr \cdot psi}$$

$$mass_{changeLarge} := \frac{\left(Air_{\rho\_P}\left(\frac{P_{test} + Laminar_{LeakLarge} \cdot hr}{psi}\right) - Air_{\rho\_P}\left(\frac{P_{test}}{psi}\right)\right) \cdot VolAPDtest}{hr \cdot DP_{test}} = 449.713 \cdot \frac{\mu g}{hr \cdot psi}$$

$$Leak_{flowNeeded} := mass_{changeLarge} \cdot num_{APDs} \cdot \left(Air_{pressure} - P_{NOvA}\right) = 25.903 \cdot \frac{gm}{hr}$$

$$APD_{flowLeak}\left(Air_{pressure}\right) := mass_{changeLarge} \cdot \left(Air_{pressure} - P_{NOvA}\right)$$

for later program

$$Vol_{flowLeakSTP} := \frac{Leak_{flowNeeded}}{Air_{\rho\_P}\left(\frac{1atm}{psi}\right)} = 0.772 \cdot SCFH$$

$$SystemFlow := Vol_{flowLeakSTP} + Purge_{Flow.Needed} = 18.829 \cdot SCFH$$

$$SystemFlow = 0.314 \cdot SCFM$$

Solve for water diffusion from APD enclosure to dry manifold

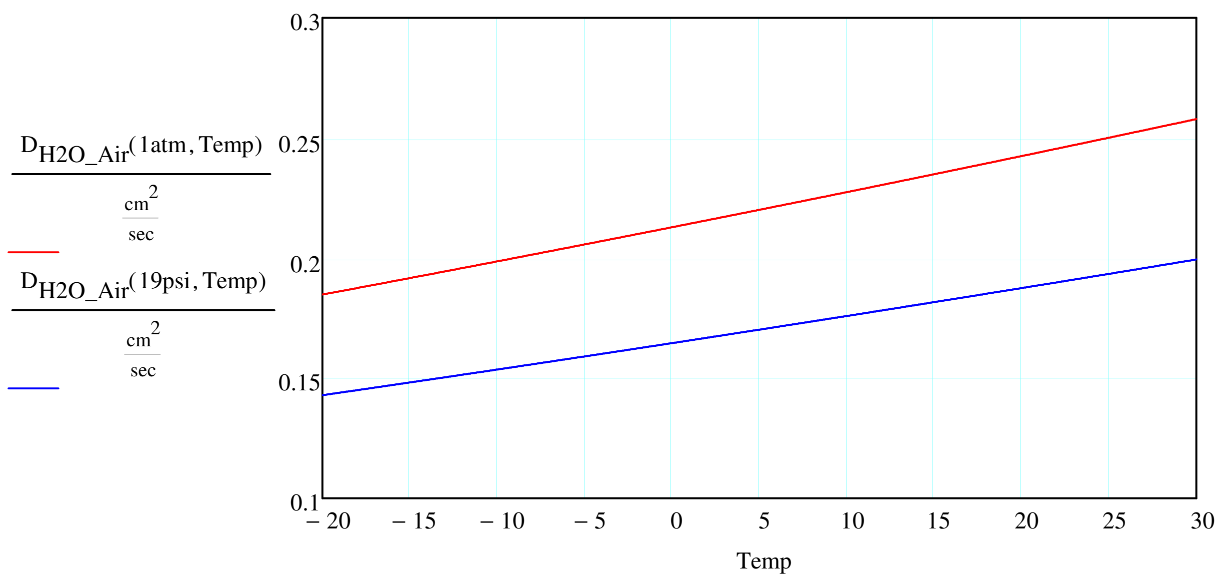
Mass transport is analogous to heat energy transport, so we can map over to temperature and solve a thermal model of the APD enclosure and through the connecting tube.

WaterConcentration = Temperature   Mass = Energy   MassFlow = HeatFlow

$$\frac{gr}{m^3} = K \qquad gr = J \qquad \frac{gr}{sec} = \frac{J}{sec} = W$$

Mass diffusion coefficient of Water Vapor in air WRT temperature and pressure

$$D_{H2O\_Air}(Press, Temp) := interp\left(regress\left(Diff_{Data}^{\langle 1\rangle}, Diff_{Data}^{\langle 2\rangle}, 4\right), Diff_{Data}^{\langle 1\rangle}, Diff_{Data}^{\langle 2\rangle}, Temp\right)\cdot\frac{cm^2}{sec}\cdot\frac{1atm}{Press}$$



Solve the mass transport equation (Ficks Law)

$$J = D\cdot\left(\frac{d}{dx}C\right)$$

$$mass_{flux} = Diffusion_{Coefficient}\cdot\frac{\Delta WaterConcentration}{path_{Length}}$$

$$\frac{mass_{generation}}{path_{area}} = Diffusion_{Coefficient}\cdot\frac{\Delta WaterConcentration}{path_{Length}} \text{ solve}, \Delta WaterConcentration \rightarrow \frac{mass_{generation}\cdot path_{Length}}{Diffusion_{Coefficient}\cdot path_{area}}$$

$$Air_{\rho\_P}\left(\frac{1atm}{psi}\right) = 1.184\,\frac{kg}{m^3}$$

$$c_{pDmass} := \frac{1}{Air_{\rho\_P}\left(\frac{1atm}{psi}\right)} = 8.444\times 10^{-4}\cdot\frac{gr}{gr\cdot\frac{gr}{m^3}}$$

$$c_{pDheat} := c_{pDmass}\cdot\left(\frac{\frac{J}{kg\cdot K}}{\frac{gr}{kg\cdot\frac{gr}{m^3}}}\right) = 0.844\cdot\frac{J}{kg\cdot K}$$

$$D_{H2O} := D_{H2O\_Air}\left(P_{NOvA} + 5psi, 20\right) = 0.188\cdot\frac{cm^2}{sec}$$

$$k_{heat} := D_{H2O}\cdot c_{pDheat}\cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right) = 1.876\times 10^{-5}\cdot\frac{W}{m\cdot K}$$

$$k_{mass} := D_{H2O}\cdot c_{pDmass}\cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right) = 1.876\times 10^{-5}\cdot\frac{\frac{gr}{sec}}{m\cdot\frac{gr}{m^3}}$$

$$k_{mass} = 1.876\times 10^{-5}\,\frac{m^2}{s}$$

Use directly threaded fitting

$L_{directThread} := 0.65in$ $\quad d_{directThread} := 0.095in$ $\quad A_{directThread} := \frac{\pi}{4}\cdot d_{directThread}^{\;2}$

$$Delta_{Water}(WaterPerm) := \frac{WaterPerm\cdot L_{directThread}}{A_{directThread}\cdot D_{H2O\_Air}\left(P_{NOvA} + 4psi, 20\right)}$$

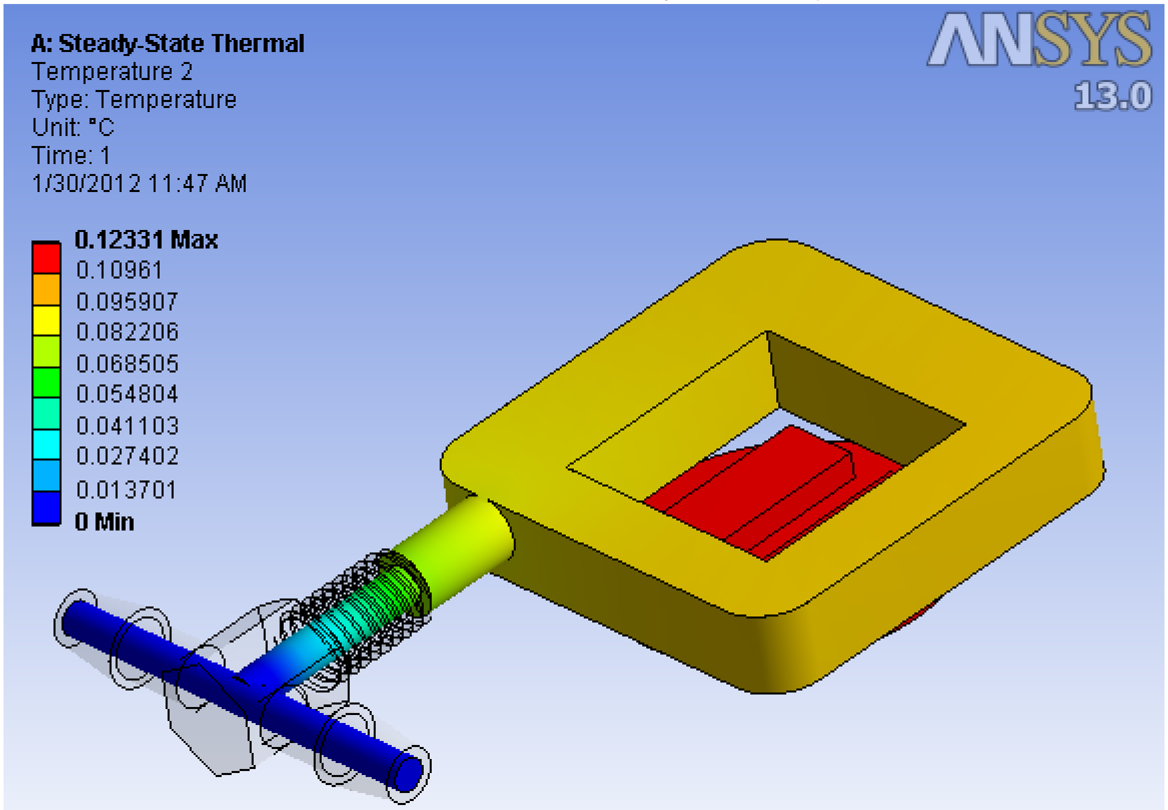
$$Delta_{Water}\left(\frac{35\mu g}{day}\right) = 73.844\cdot\frac{mg}{m^3}$$

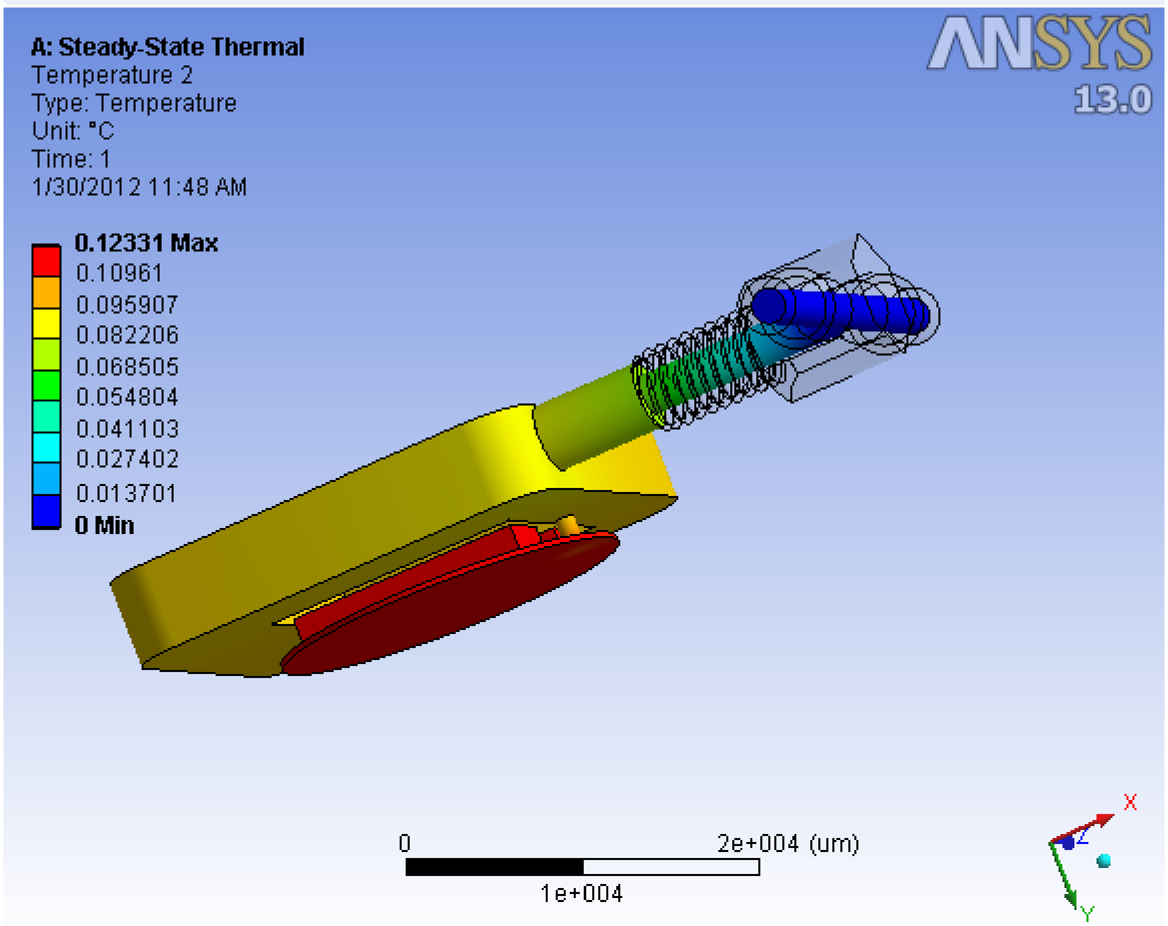
$$Percent_{Design} := \frac{Delta_{Water}\left(\frac{35\mu g}{day}\right)}{Water_{\rho\_T}\left(Dewpoint_{Design}\right)} = 13.38\cdot\%$$

$$Delta_{Water}\left(APD_{maxPerm}\right) = Water_{\rho\_T}\left(Dewpoint_{Design}\right) - Water_{\rho\_T}(-40)$$

$$APD_{maxPerm} := Find\left(APD_{maxPerm}\right) = 204.355\cdot\frac{\mu g}{day}$$

10 ug/day into bottom O-ring, 25ug/day into rest of enclosure. Diffusion coefficient 0.148 cm^2/sec. Hole in PCB is 0.045" in diameter, which is the only diffusion path to the rest of the APD enclosure.





$$Percent_{DesignCriteria} := \frac{0.12331\,\frac{gm}{m^3}}{Water_{\rho\_T}\left(Dewpoint_{Design}\right)} = 22.343\cdot\%$$

$$\Delta C_{H2O}\left(APD_{flux}, Press, Temp\right) := \left(\frac{APD_{flux}}{35\,\frac{\mu g}{day}}\right)\cdot\left(0.12331\cdot\frac{gm}{m^3}\right)\cdot\left(\frac{D_{H2O\_Air}(19psi, -15)}{D_{H2O\_Air}(Press, Temp)}\right)$$

Pipe or Tube Manifold Sizing (Pressure Drop Calculations)

$SystemFlowSpec := 1.2SCFM$ $\qquad Air_{pressure} = 19\cdot psi$

$d_{manifold} := 0.125in$ $\qquad A_{manifold} := \frac{\pi}{4}\cdot d_{manifold}^{\;2}$ $\qquad \mu_{air} := 0.000018453Pa\cdot sec$

$Length_{Detector} := 5.25in\cdot 32\cdot 15$

$$manifold_{flow} := \frac{SystemFlowSpec\cdot\left(\frac{1atm}{Air_{pressure}}\right)}{num_{row}} = 0.03867355\cdot\frac{ft^3}{min}$$

$$V_{flowMan} := \frac{manifold_{flow}}{A_{manifold}} = 2.305\,\frac{m}{s}$$

$$Re := \frac{Air_{\rho\_P}\left(\frac{Air_{pressure}}{psi}\right)\cdot V_{flowMan}\cdot d_{manifold}}{\mu_{air}} = 607.396$$

Laminar flow

$f := \frac{64}{Re} = 0.105$ $\qquad \Delta P := f\cdot\left(\frac{Length_{Detector}}{d_{manifold}}\cdot\frac{V_{flowMan}^{\;2}}{2}\cdot Air_{\rho\_P}\left(\frac{Air_{pressure}}{psi}\right)\right) = 1.254\cdot psi$

System could consist of 1/8" ID tube manifolds running the entire length of the detector with any size tubes connecting the manifolds to the APD enclosures.

Mathematically equivalent we can calculate according to standard conditions and multiply by a correction factor for pressure: (P1/P2) this means it only depends on the volume flow rate of the gas, not the mass flow rate of the pressurized gas. so using constant mass flow rate we just divide by the pressure ratio.

$manifold_{flow} := \frac{SystemFlowSpec}{num_{row}} = 0.05\cdot SCFM$ $\qquad V_{flowMan} := \frac{manifold_{flow}}{A_{manifold}} = 2.98\,\frac{m}{s}$

$$Re := \frac{Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\cdot V_{flowMan}\cdot d_{manifold}}{\mu_{air}} = 607.338 \qquad f := \frac{64}{Re} = 0.105$$

$$\Delta P := f\cdot\left(\frac{Length_{Detector}}{d_{manifold}}\cdot\frac{V_{flowMan}^{2}}{2}\cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\right) = 1.621\cdot psi$$

$$manifold_{flow} := \frac{SystemFlowSpec}{num_{row}} = 0.05\cdot SCFM \qquad V_{flowMan} := \frac{manifold_{flow}}{A_{manifold}} = 2.98\frac{m}{s}$$

$$Re := \frac{Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\cdot V_{flowMan}\cdot d_{manifold}}{\mu_{air}} = 607.338 \qquad f := \frac{64}{Re} = 0.105$$

$$\Delta P_{tube} := f\cdot\left(\frac{1}{d_{manifold}}\cdot\frac{V_{flowMan}^{2}}{2}\cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\right)\cdot\left(\frac{1atm}{Air_{pressure}}\right) = 0.006\cdot\frac{psi}{ft}$$

$$\Delta P_{tubes} := Length_{Detector}\cdot\Delta P_{tube} = 1.254\cdot psi$$

$$d_{tee} := 0.080in \qquad A_{tee} := \frac{\pi}{4}\cdot d_{tee}^{2} \qquad L_{tee} := 0.994in \qquad num_{tees} := 15\cdot 32 = 480$$

$$manifold_{flow} := \frac{SystemFlowSpec}{num_{row}} = 0.05\cdot SCFM \qquad V_{flowTee} := \frac{manifold_{flow}}{A_{tee}} = 7.277\frac{m}{s}$$

$$Re := \frac{Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\cdot V_{flowTee}\cdot d_{tee}}{\mu_{air}} = 948.965 \qquad f := \frac{64}{Re} = 0.067$$

$$\Delta P_{tee} := f\cdot\left(\frac{L_{tee}}{d_{tee}}\cdot\frac{V_{flowTee}^{2}}{2}\cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\right) = 0.004\cdot\frac{psi}{tee}$$

$$\Delta P_{tees} := \Delta P_{tee}\cdot num_{tees} = 1.829\cdot psi$$

Sudden contractions/Enlargements

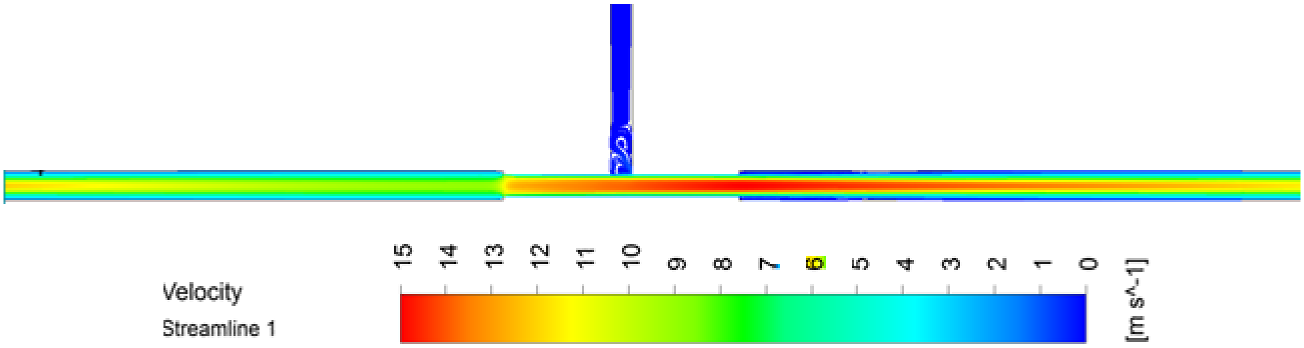
$$\beta := \frac{d_{tee}}{d_{manifold}} = 0.64 \qquad K_C := 0.5\left(1-\beta^{2}\right)^{2} = 0.174 \qquad K_E := \left(1-\beta^{2}\right)^{2} = 0.349$$

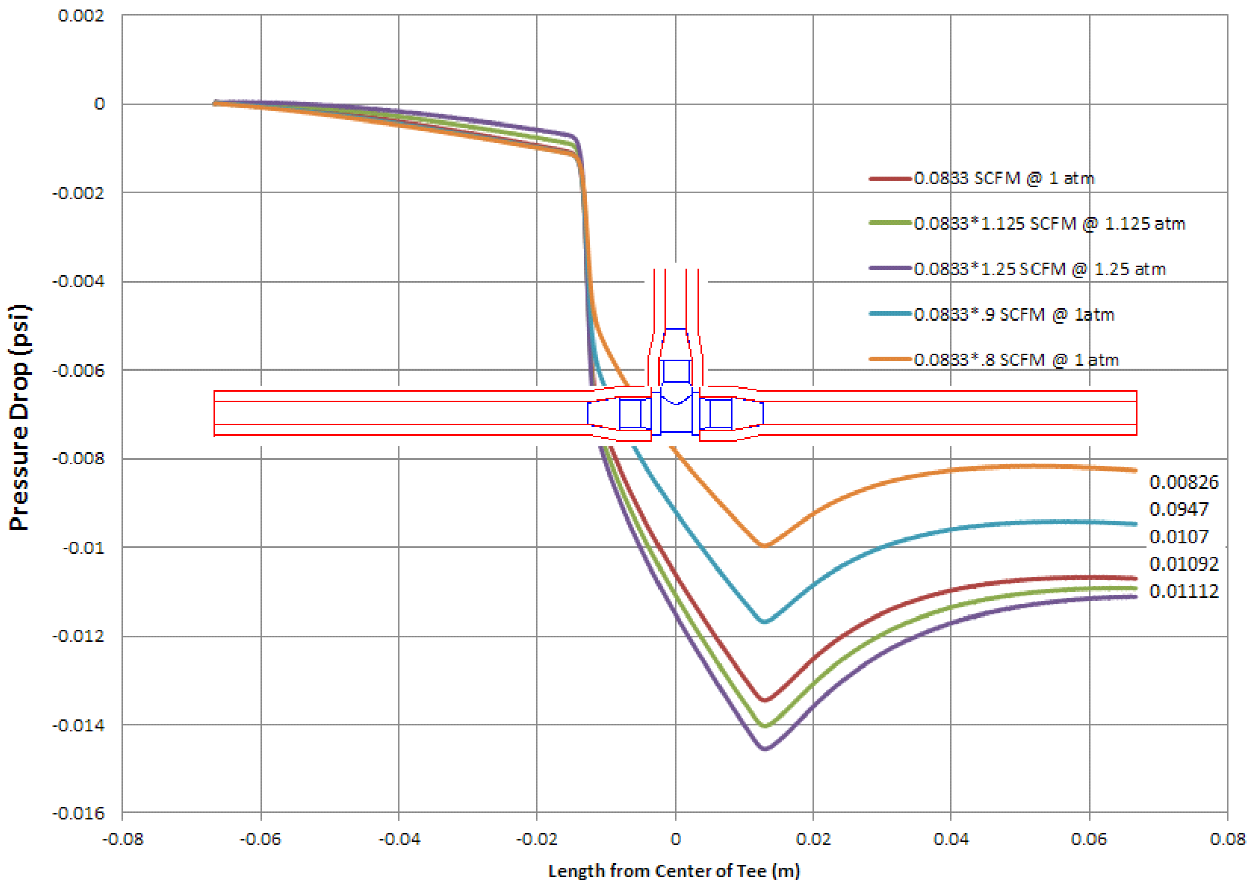
$$\Delta P_{Cont\_Exp} := 480\cdot\left(K_C + K_E\right)\cdot\left(\frac{V_{flowTee}^{2}}{2}\cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right)\right) = 1.141\cdot psi$$

Total Pressure Drop

$$DP_{total} := \Delta P_{tees} + \Delta P_{tubes} + \Delta P_{Cont\_Exp} = 4.224\cdot psi$$

Since all these calculations are for fully developed flow, they may not be accurate as our flow travels through hundreds on contractions/expansions and never becomes fully developed. For this reason we will run a parametric CFD model of an equivalent section of the tube/tees which uses periodic boundary conditions simulating an infinite number of these in a row.



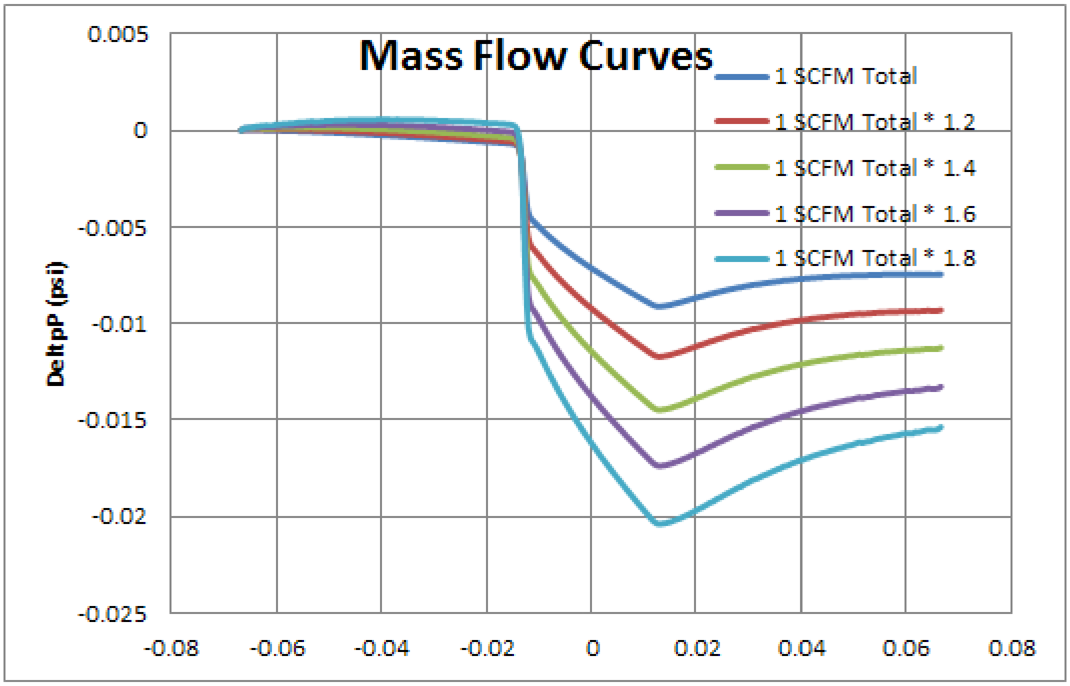


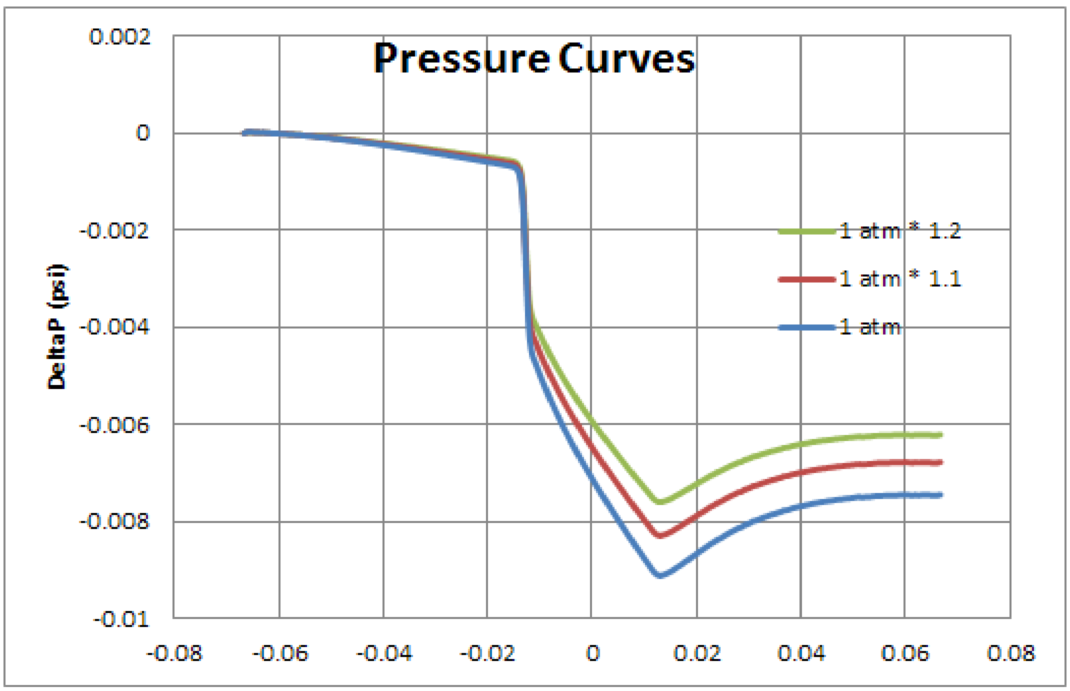
Curve fit to CFD Data:

$$\Delta P_{CFD}(Press, mass_{flow}) := \left[0.001867709 \cdot \left(\frac{mass_{flow}}{46.578\ \frac{mg}{sec}}\right)^2 + 0.008834883 \cdot \frac{mass_{flow}}{46.578\ \frac{mg}{sec}}\right] \cdot psi \cdot \frac{atm}{Press}$$

for later program

Using Different Tee fittings with only 0.08" opening we have a different pressure drop function:





$$\Delta P_{CFD}(Press, mass_{flow}) := \left[1.797677936 \cdot \left(\frac{mass_{flow}}{\frac{gm}{sec}}\right)^2 + 0.307049852 \cdot \frac{mass_{flow}}{\frac{gm}{sec}} - 0.000687299\right] \cdot psi \cdot \frac{1atm}{Press}$$ *for later program*

Detailed System Analysis

We will write a program to calculate the mass flow rates, pressures, water concentrations, ΔC.APD to manifold, and dew points at each node along a route. We will make several parameters which we can change at will and recalculate to study the design space and affects of slight variable changes

Water content of air coming out of the drier:

$Dewpoint_{atDrier} := -40$

$Water_{contentDrier\rho} := Water_{\rho\_T}(Dewpoint_{atDrier}) = 0.121 \cdot \frac{\mu g}{mL}$

$Water_{\rho\_T}(Dewpoint_{Design}) = 0.552 \cdot \frac{\mu g}{mL}$

$Water_{contentDrierP} := Water_{P\_T}(Dewpoint_{atDrier}) = 13.006 \cdot Pa$

$Water_{P\_T}(Dewpoint_{Design}) = 63.18\,Pa$

Pressure From The Drier

Permeation rate of hose, this will be tested.

$P_{Drier} := 5psi + P_{NOvA}$

$Flux_{Tubes}(\Delta C) := FluxVitonHose\_D(\Delta C)$

$SystemFlowSpec := 1.2SCFM$

$Water_{PermeationPerAPD} := 35 \frac{\mu g}{day}$

green values are parameters to change for design space analysis

$APD_{flux} := Water_{PermeationPerAPD}$

$Diff_{Temp} := 20$

$ManifoldFlowSpec := \frac{SystemFlowSpec}{num_{rows}} = 0.05 \cdot SCFM$

$ManifoldFlowSpec = 3 \cdot SCFH$

$manifold_{Mflow} := ManifoldFlowSpec \cdot Air_{\rho\_P}\left(\frac{1atm}{psi}\right) = 27.947 \cdot \frac{mg}{sec}$

Water Permeation through tubes and APDs

$Tee_{hose} := 4.28in$

$tube_{length\_node} := Tee_{hose} = 4.28 \cdot in$

Partial Pressure of water at 25C and 90% relative humidity

$Ambient_{waterP} := Water_{P\_T}(25)(90\%) = 2852.112\,Pa$

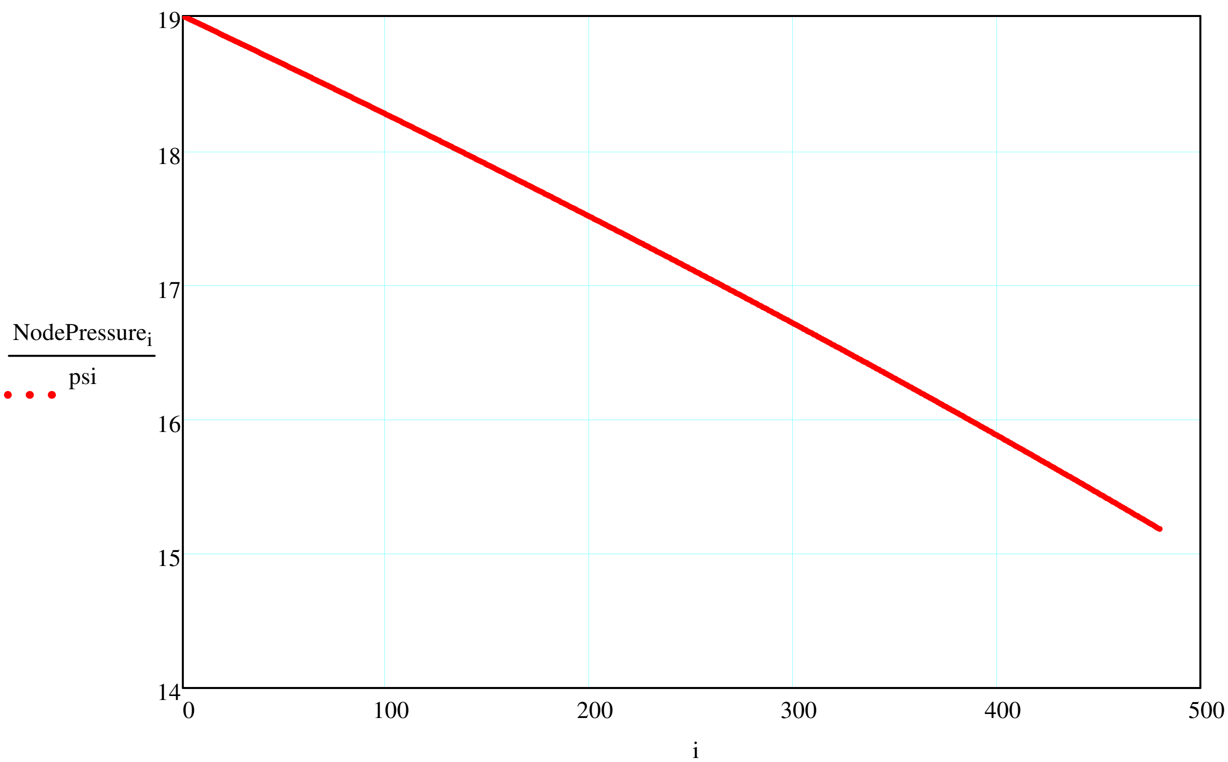
$Ambient_{water\rho} := Water_{\rho\_T}(25)(90\%) = 20.761 \cdot \frac{\mu g}{mL}$

$mass_{intoHosePM} = FluxHose(\Delta C)$

$num_{APDinROW} := 15 \cdot 32 = 480$

$Offshot_{TeeMassFlow}\left[D_{PP}, Water_{\rho\_T}(25)\left(Relative_{Humidity}\right)\right]$

$$
NodePressure := \left|
\begin{array}{l}
NodePressure_0 \leftarrow P_{Drier} \\
manifold_{massflow_0} \leftarrow manifold_{Mflow} \\
\text{for } i \in 1 .. num_{APDinROW} \\
\quad \left|
\begin{array}{l}
Leak_{outAPD_i} \leftarrow APD_{flowLeak}\left(NodePressure_{i-1}\right) \\
DP_{node_i} \leftarrow \Delta P_{CFD}\left(NodePressure_{i-1}, manifold_{massflow_{i-1}}\right) \\
manifold_{massflow_i} \leftarrow manifold_{massflow_{i-1}} - Leak_{outAPD_i} \\
NodePressure_i \leftarrow NodePressure_{i-1} - DP_{node_i}
\end{array}
\right. \\
\text{return } NodePressure
\end{array}
\right.
$$



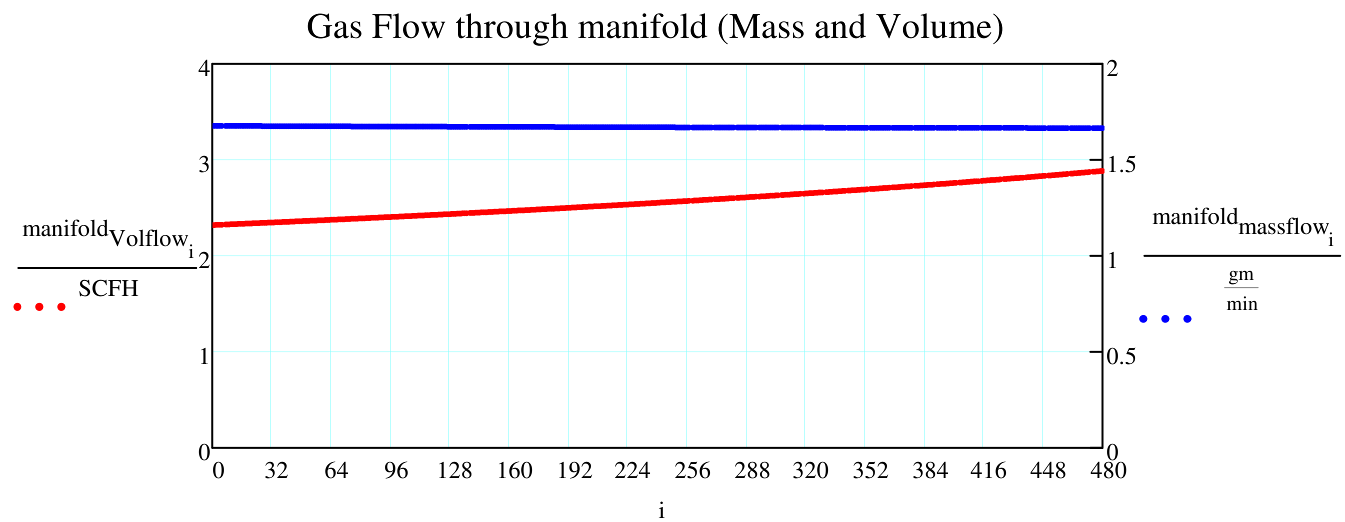
$NodePressure_{480} = 15.18 \cdot psi$

$$Water_{content} := \left| \begin{array}{l} Water_{content_0} \leftarrow Water_{contentDrier\rho} \\ \text{for } i \in 1..num_{APDinROW} \\ \quad \left| \begin{array}{l} manifold_{Volflow_i} \leftarrow \dfrac{manifold_{massflow_i}}{Air_{\rho\_P}\left(\dfrac{NodePressure_i}{psi}\right)} \\ WaterPermeating_i \leftarrow Flux_{Tubes}\left(Ambient_{water\rho} - Water_{content_{i-1}}\right) \cdot tube_{length\_node} + APD_{flux} \\ WaterPermeatingTee_i \leftarrow Offshot_{TeeMassFlow}\left(D_{PP}, Ambient_{water\rho} - Water_{content_{i-1}}\right) \\ Water_{content_i} \leftarrow Water_{content_{i-1}} + \dfrac{WaterPermeating_i}{manifold_{Volflow_i}} + \dfrac{WaterPermeatingTee_i}{manifold_{Volflow_i}} \end{array} \right. \\ \text{return } Water_{content} \end{array} \right.$$

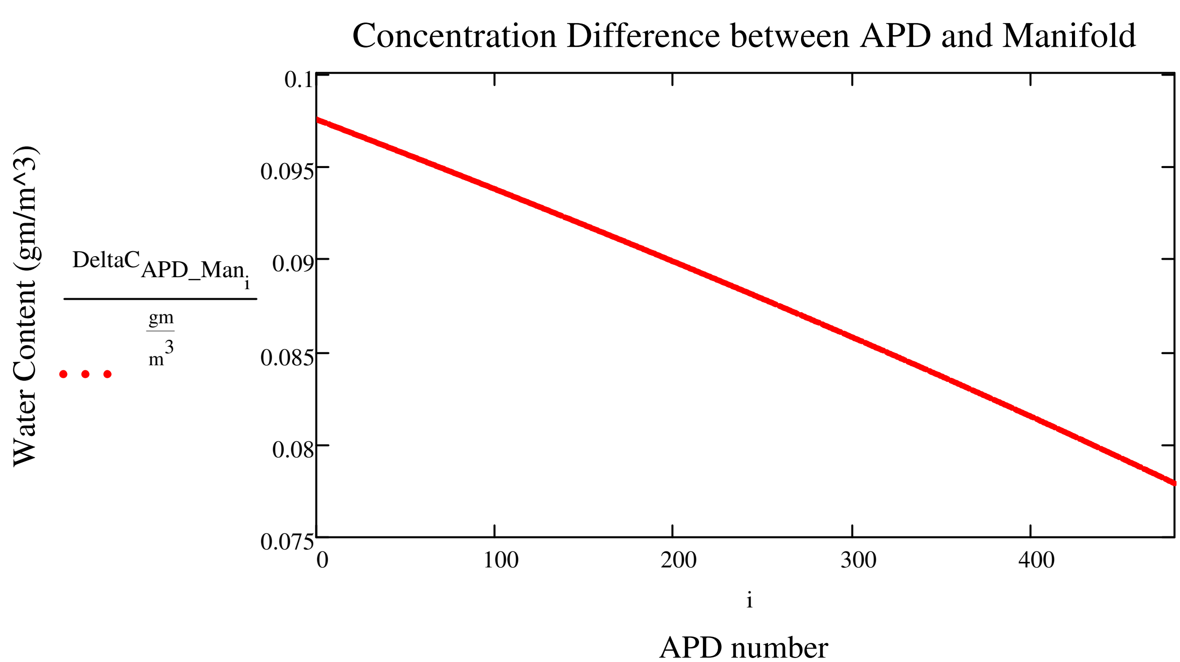
$$WaterPermeating := \left| \begin{array}{l} Water_{content_0} \leftarrow Water_{contentDrier\rho} \\ \text{for } i \in 1..num_{APDinROW} \\ \quad \left| \begin{array}{l} manifold_{Volflow_i} \leftarrow \dfrac{manifold_{massflow_i}}{Air_{\rho\_P}\left(\dfrac{NodePressure_i}{psi}\right)} \\ WaterPermeating_i \leftarrow Flux_{Tubes}\left(Ambient_{water\rho} - Water_{content_{i-1}}\right) \cdot tube_{length\_node} + APD_{flux} \\ WaterPermeatingTee_i \leftarrow Offshot_{TeeMassFlow}\left(D_{PP}, Ambient_{water\rho} - Water_{content_{i-1}}\right) \\ Water_{content_i} \leftarrow Water_{content_{i-1}} + \dfrac{WaterPermeating_i}{manifold_{Volflow_i}} + \dfrac{WaterPermeatingTee_i}{manifold_{Volflow_i}} \end{array} \right. \\ \text{return } WaterPermeating \end{array} \right.$$

$$manifold_{Volflow} := \left| \begin{array}{l} Water_{content_0} \leftarrow Water_{contentDrier\rho} \\ \text{for } i \in 1..num_{APDinROW} \\ \quad \left| \begin{array}{l} manifold_{Volflow_i} \leftarrow \dfrac{manifold_{massflow_i}}{Air_{\rho\_P}\left(\dfrac{NodePressure_i}{psi}\right)} \\ WaterPermeating_i \leftarrow Flux_{Tubes}\left(Ambient_{water\rho} - Water_{content_{i-1}}\right) \cdot tube_{length\_node} + APD_{flux} \\ WaterPermeatingTee_i \leftarrow Offshot_{TeeMassFlow}\left(D_{PP}, Ambient_{water\rho} - Water_{content_{i-1}}\right) \\ Water_{content_i} \leftarrow Water_{content_{i-1}} + \dfrac{WaterPermeating_i}{manifold_{Volflow_i}} + \dfrac{WaterPermeatingTee_i}{manifold_{Volflow_i}} \end{array} \right. \\ \text{return } manifold_{Volflow} \end{array} \right.$$

$$DewPoint_{manifold} := \left| \begin{array}{l} \text{for } i \in 0..num_{APDinROW} \\ \quad DewPoint_{manifold_i} \leftarrow DewPoint_{T\_\rho}\left(\dfrac{Water_{content_i}}{\frac{kg}{m^3}}\right) \\ \text{return } DewPoint_{manifold} \end{array} \right.$$



$$DeltaC_{APD\_Man} := \left| \begin{array}{l} \text{for } i \in 0..num_{APDinROW} \\ \quad DeltaC_{APD\_Man_i} \leftarrow \Delta C_{H2O}\left(APD_{flux}, NodePressure_i, Diff_{Temp}\right) \\ \text{return } DeltaC_{APD\_Man} \end{array} \right.$$



$$DewPoint_{APD} := \left| \begin{array}{l} \text{for } i \in 0 .. num_{APDinROW} \\ \quad DewPoint_{APD_i} \leftarrow DewPoint_{T\_\rho}\left(\dfrac{Water_{content_i} + DeltaC_{APD\_Man_i}}{\dfrac{kg}{m^3}}\right) \\ \text{return } DewPoint_{APD} \end{array} \right.$$