Testing Photomultiplier Tubes for nEXO's Outer Detector

2024 CASST Competition
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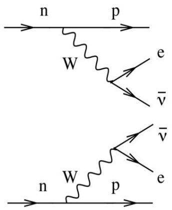
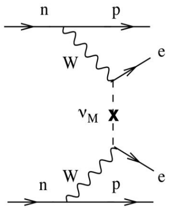
Queen's University
August 19 2024

Outline

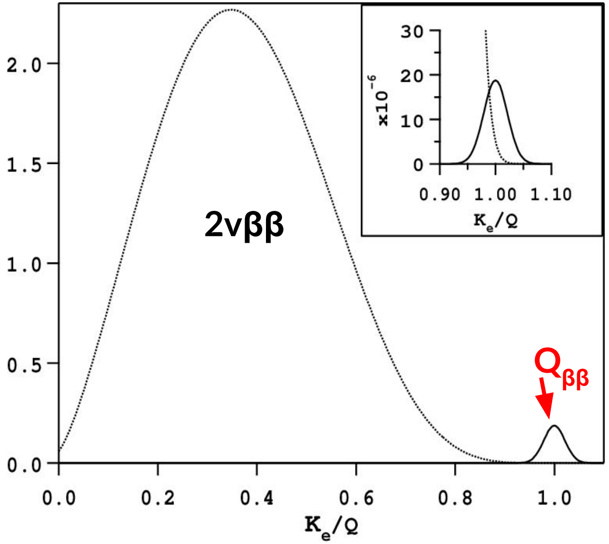
- Introduction to $0\nu\beta\beta$ and nEXO
- Designing the PMT testing Setup Cooling Loop
  - Intro to the PMT Testing Setup
  - Initial Design Ideas
  - Calculations
  - Bill of Materials and Concerns
  - Improved Design
  - Calculations
  - Final Bill of Materials
- Future Setup
  - Design
  - Calculations
  - Bill of Materials
- Data Analysis Script Improvements
  - Data Management Improvements
  - FFT and Peak Isolation Stress Test
- Conclusion

2νββ vs 0νββ

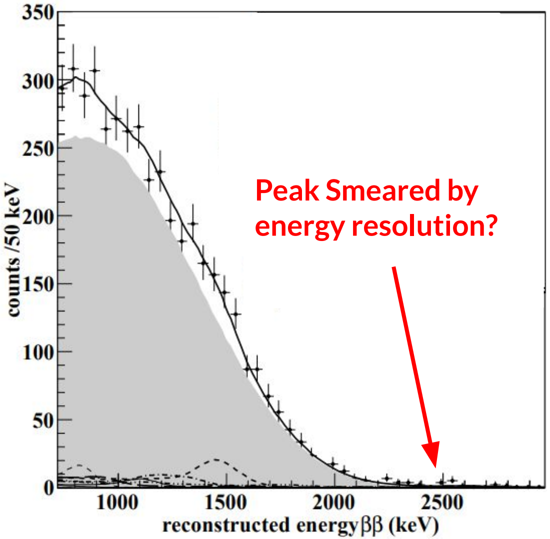




0νββ signature is peak at nucleus Q value



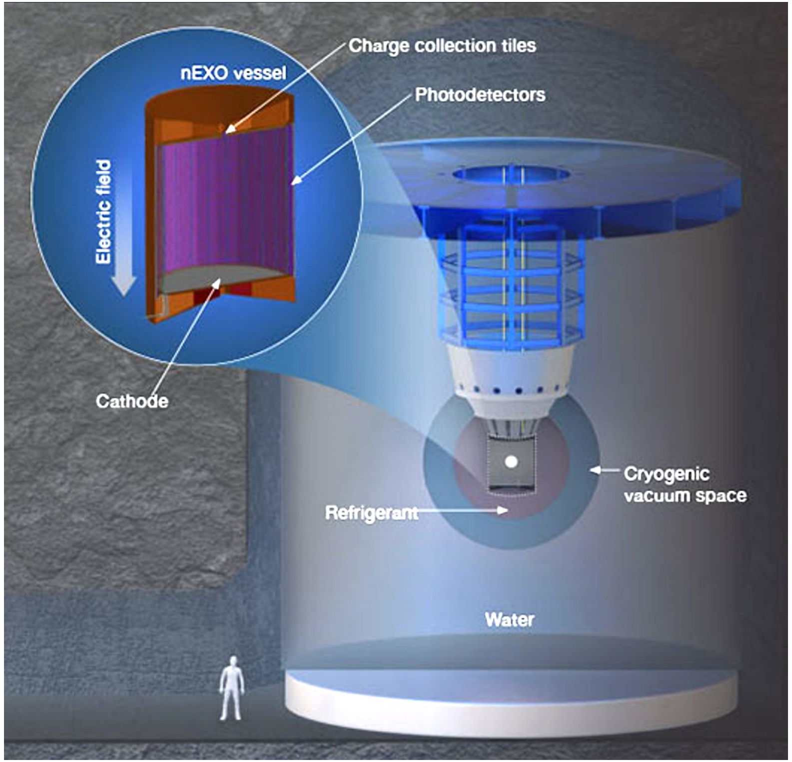
2νββ spectrum measured in ^{136}Xe with EXO-200!



Adapted from: https://arxiv.org/pdf/1108.4193

nEXO Experiment

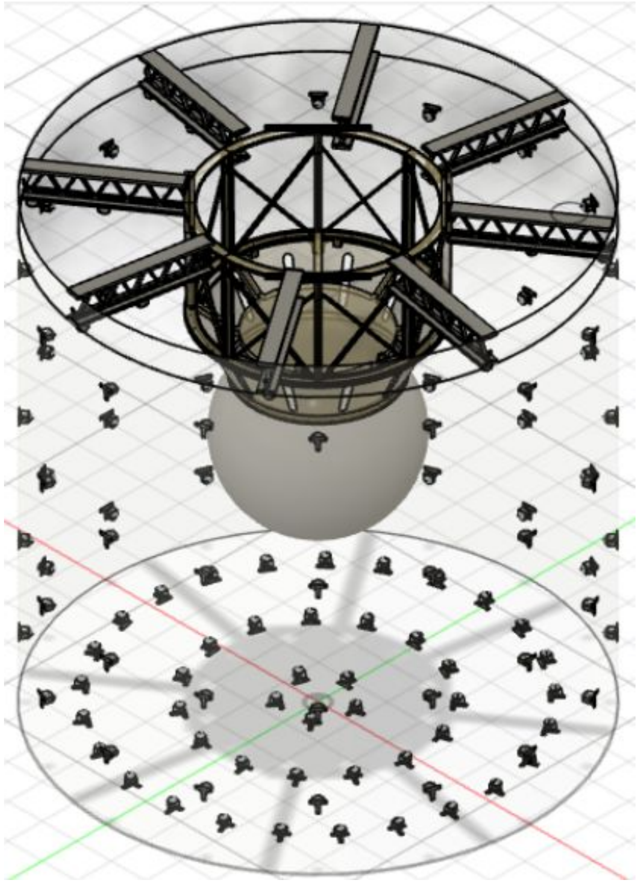
- 5-tonne single-phase liquid Xenon Time Projection Chamber (TPC)
- Enriched to 90% in isotope ^{136}Xe
- OD used for passive and active shielding
- Target half-life sensitivity of $1.35 \cdot 10^{28}$ years



Source: https://nexo.llnl.gov/nexo-overview

nEXO Outer Detector (OD)

- Passive and active shielding
- Q value for 0νββ $^{136}Xe \rightarrow {}^{136}Ba$ is **2458 keV** [1]
- Muons passing through TPC can create neutrons that can create energy signatures around Q value :(
- OD is veto for TPC by detecting Cherenkov radiation :)

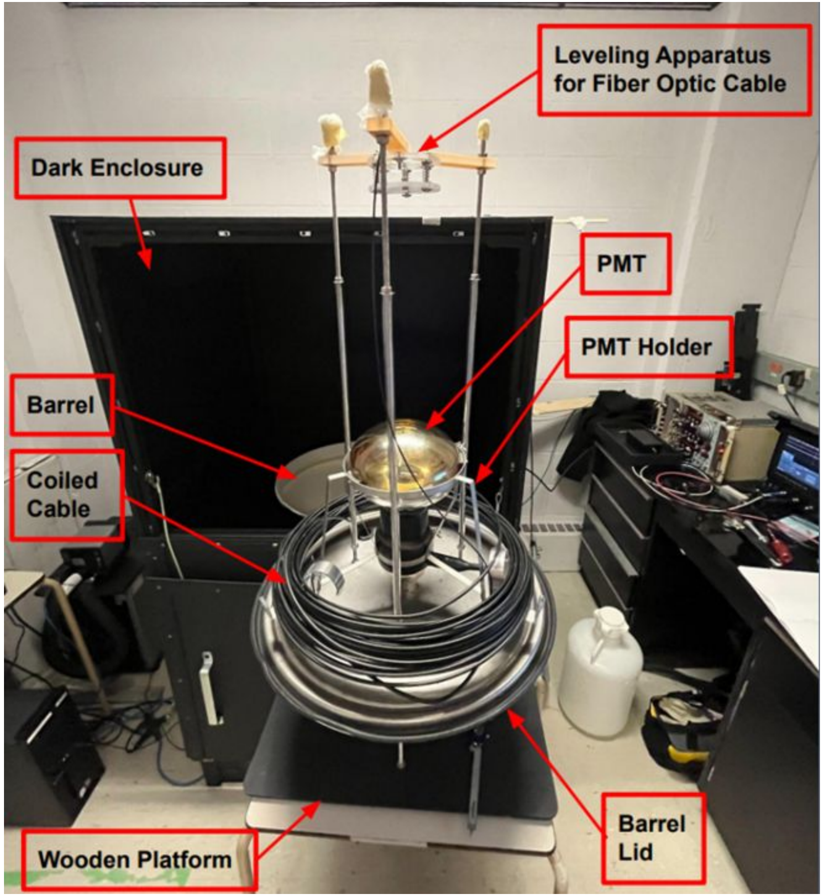


Source: https://escholarship.mcgill.ca/concern/theses/j9602648j

[1] Search for double-beta decay of 136Xe to excited states of 136Ba with the KamLAND-Zen experiment https://arxiv.org/pdf/1509.03724

The PMT Testing Setup

- Located at Laurentian University
- PMT attached to barrel lid
- Barrel lid in dark enclosure
- This will help learn for future setups

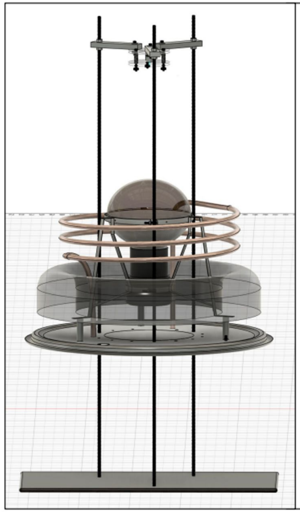


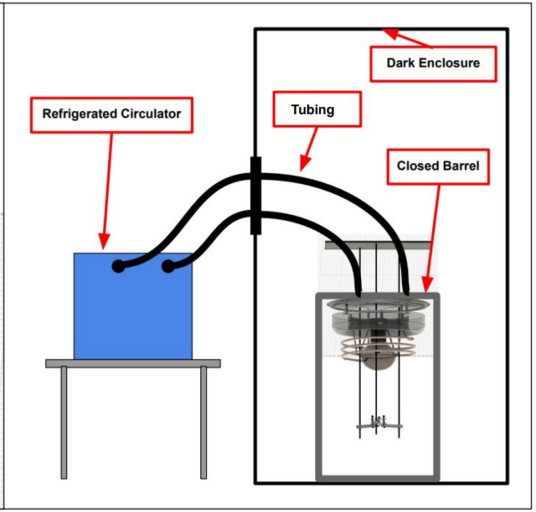
The PMT Testing Setup

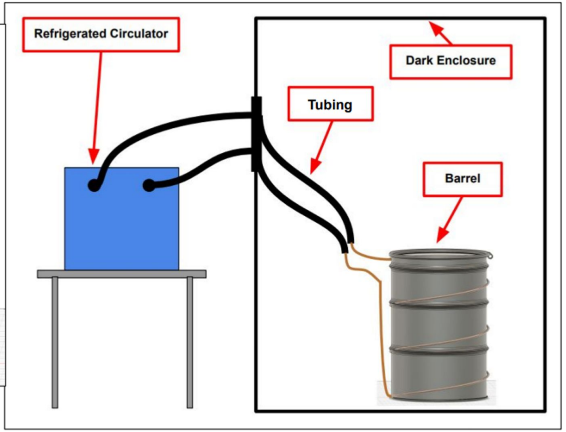
- Barrel needs a way to change and keep stable temperature
- OD will be held at 12°C
- PolyScience AP15R-40-A11B refrigerated circulator

Design Ideas

- Coil Inside Barrel
- Coil Outside Barrel
- Each setup has some pros/cons
- I updated CAD models in Fusion 360







Calculations — Simple

Time to cool barrel from 25 °C to 10 °C,

P = 956 W (Cooling Capacity at 17.5 °C)

Time with no heat leaking in barrel :

$$Q = mc\Delta T \qquad t = \frac{Q}{P}$$

t = 4.07 Hours

Time with Insulation with an R-Value of 2:

$$\frac{dQ}{dt} = U \cdot A \cdot \Delta T = \frac{1}{R} \cdot A \cdot \Delta T$$

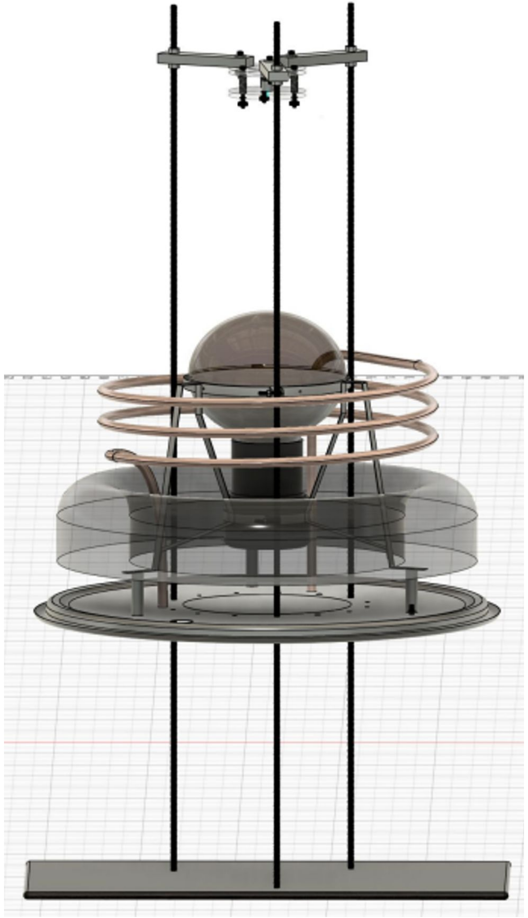
t = 4.14 Hours

Calculations — Coil in Barrel

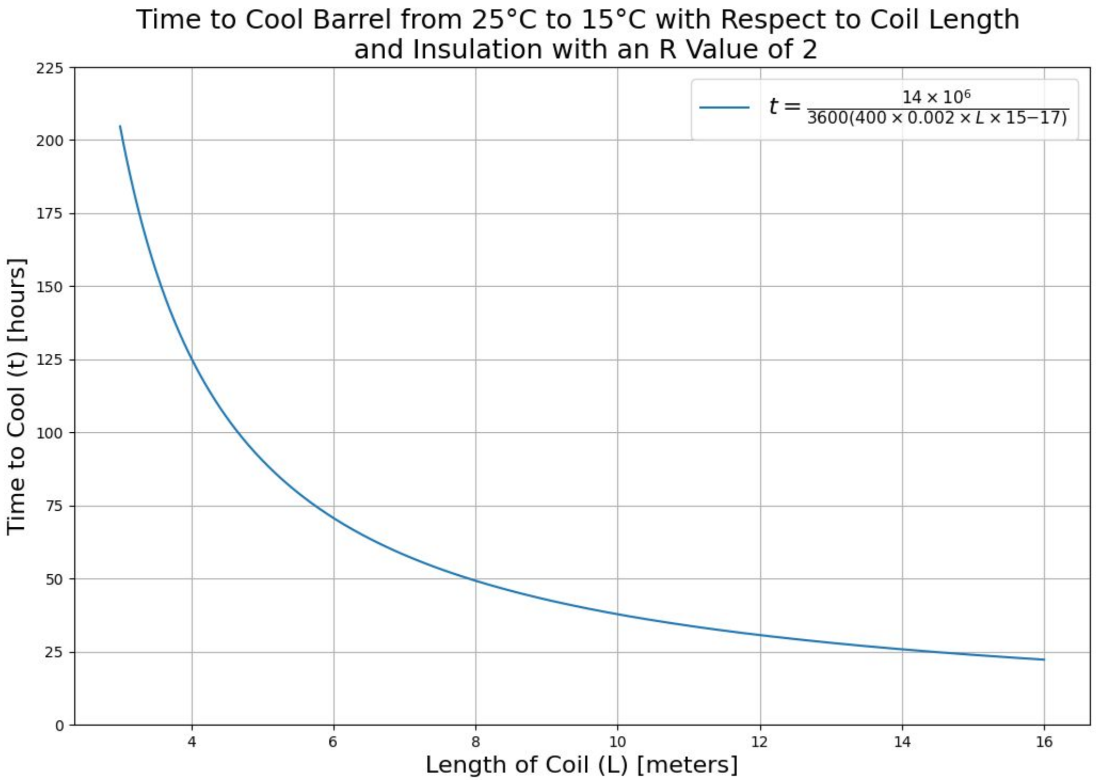
$$\frac{d}{dt}Q = U \cdot A \cdot \Delta T \qquad A = 0.0127 \cdot \pi \cdot L$$

1. **dQ/dt < 956 W** – Area of coil is bottleneck cooling
2. **dQ/dt = 956 W** – Coil exchanges heat at the same rate as the cooler: **L = 4m**
3. **dQ/dt > 956 W** – Making coil longer has no cooling benefits

Will Cool in 4.14 Hours if more than 4m of tubing is used



Calculations — Coil Outside of Barrel

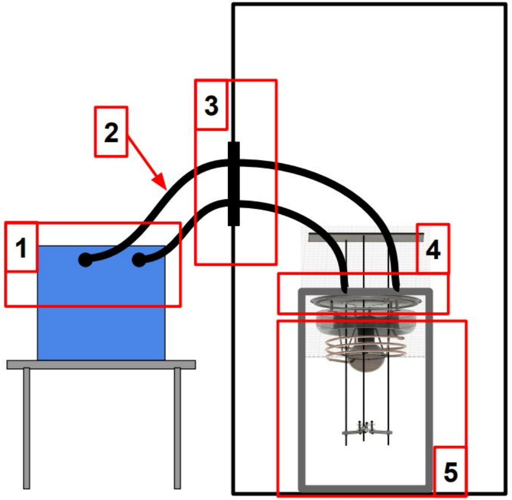


$$A = L \cdot 0.002$$

- Too Long to cool
- Don't want to use more than 15m of coil

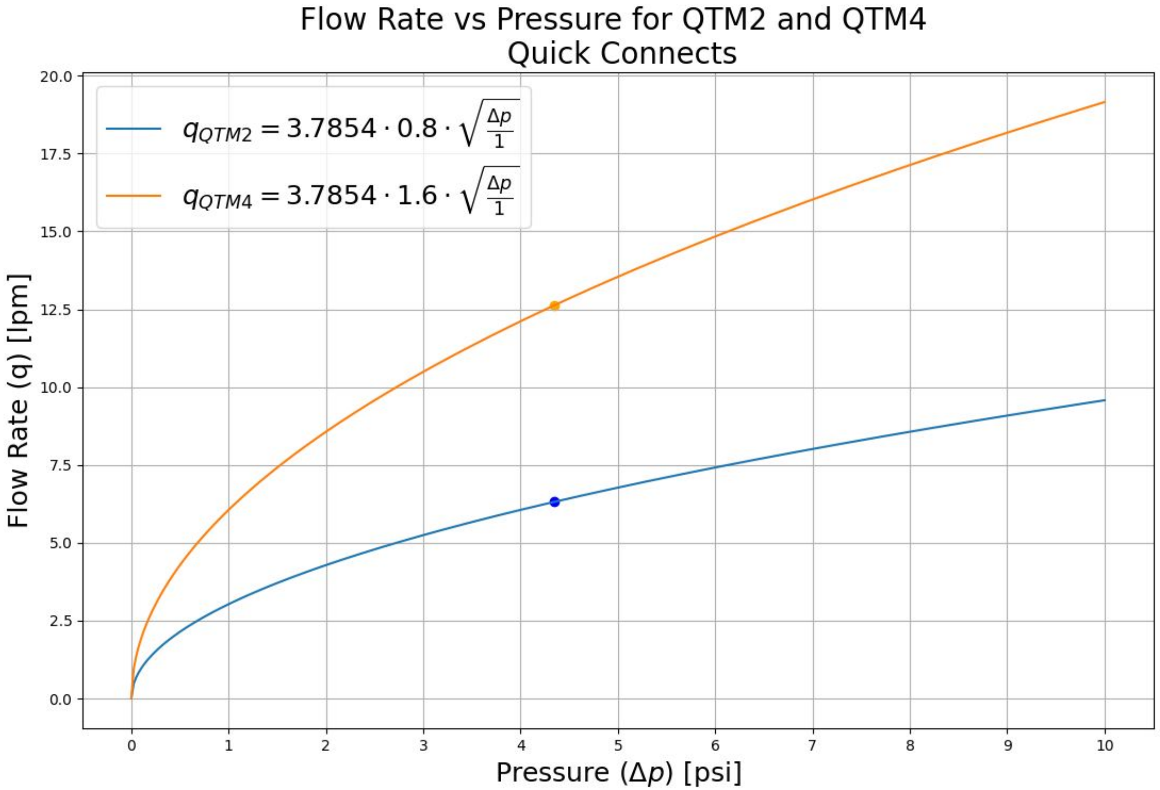
Bill of Materials

- Still concerns with setup
- Coil in barrel could interfere with detection
- Setup has additional Issues…



DESIGN A						
Material	Link	Quantity	Supplier	Part Number	Cost/Unit (USD)	Total (USD)
Section 1						
Barbed Fitting	https://www.mcmaster.com/5357K39/	2	McMaster-CARR	5357K39	$ 5.36	$ 10.72
Hose Clamp (10 pack)	https://www.mcmaster.com/5415K33/	1	McMaster-CARR	5415K33	$ 11.84	$ 11.84
Section 2						
Soft PVC Tubbing (50 ft)	https://www.mcmaster.com/5231K89/	1	McMaster-CARR	5231K89	$ 69.00	$ 69.00
Soft PVC Tubbing Insulation (6 ft)	https://www.mcmaster.com/44745K23/	7	McMaster-CARR	44745K23	$ 11.72	$ 82.04
Section 3						
Through Wall Connector	https://www.mcmaster.com/6696K58/	2	McMaster-CARR	6696K58	$ 126.86	$ 253.72
NPT (Male) X NPT (Male) connector	https://www.mcmaster.com/44665K151/	4	McMaster-CARR	44665K151	$ 3.47	$ 13.88
Barbed Fitting (5 pack)	https://www.mcmaster.com/5346k38/	1	McMaster-CARR	5346K38	$ 16.92	$ 16.92
Section 4						
Through Wall Connector	https://www.mcmaster.com/6696K58/	2	McMaster-CARR	6696K58	$ 126.86	$ 253.72
Quick Connect Body (NPT Male) (IN CAD)	atersystems.com/products/lq6d10006blu-valved-pipe-thread	4	Fresh Water Systems	LQ6D10006BLU	$ 104.00	$ 416.00
Quick Connect Stem (Barbed) (IN CAD)	atersystems.com/products/lq6d22006blu-valved-in-line-	2	Fresh Water Systems	LQ6D22006BLU	$ 73.00	$ 146.00
Quick Connect Stem (NPT Male) (IN CAD)	https://www.usplastic.com/catalog/item.aspx?itemid=102531	2	USP	LQ6D24006BLU	$ 115.88	$ 231.76
Push-to-Connect to NPT Female	https://www.mcmaster.com/5483K47/	2	McMaster-CARR	5483K37	$ 7.99	$ 15.98
Section 5						
Barrel Insulation	https://www.mcmaster.com/9349K9/	8	McMaster-CARR	9349K9	$ 30.67	$ 245.36
Copper Tubbing (50 ft)	https://www.mcmaster.com/5174K24-5174K6/	1	McMaster-CARR	5174K24	$ 159.91	$ 159.91
If we want to use Swagelock quick connects it is an extra $1000 USD on top of the current subtotal					**Subtotal (USD)**	$ 1,926.85

Quick Connect Concerns

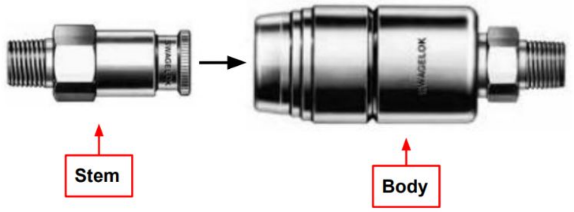


Cooler max Pressure: **4.35 Psi**

Cooler max Flow Rate: **20.1 lpm**

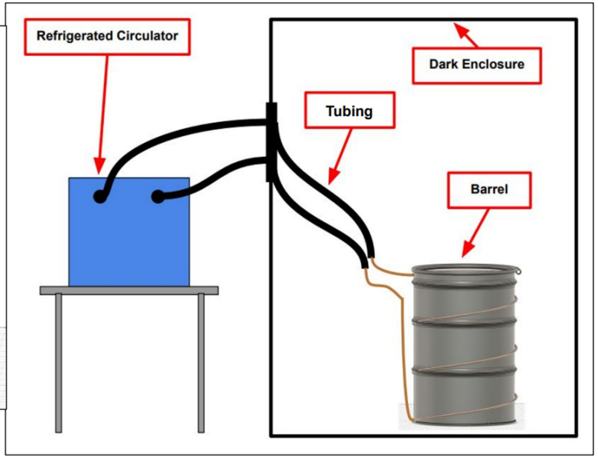
$$q = N_1 C_v \sqrt{\frac{\Delta p}{G}}$$

Series	Spillage cm^3
QTM2	0.1
QTM4	0.2
QTM8	1.0



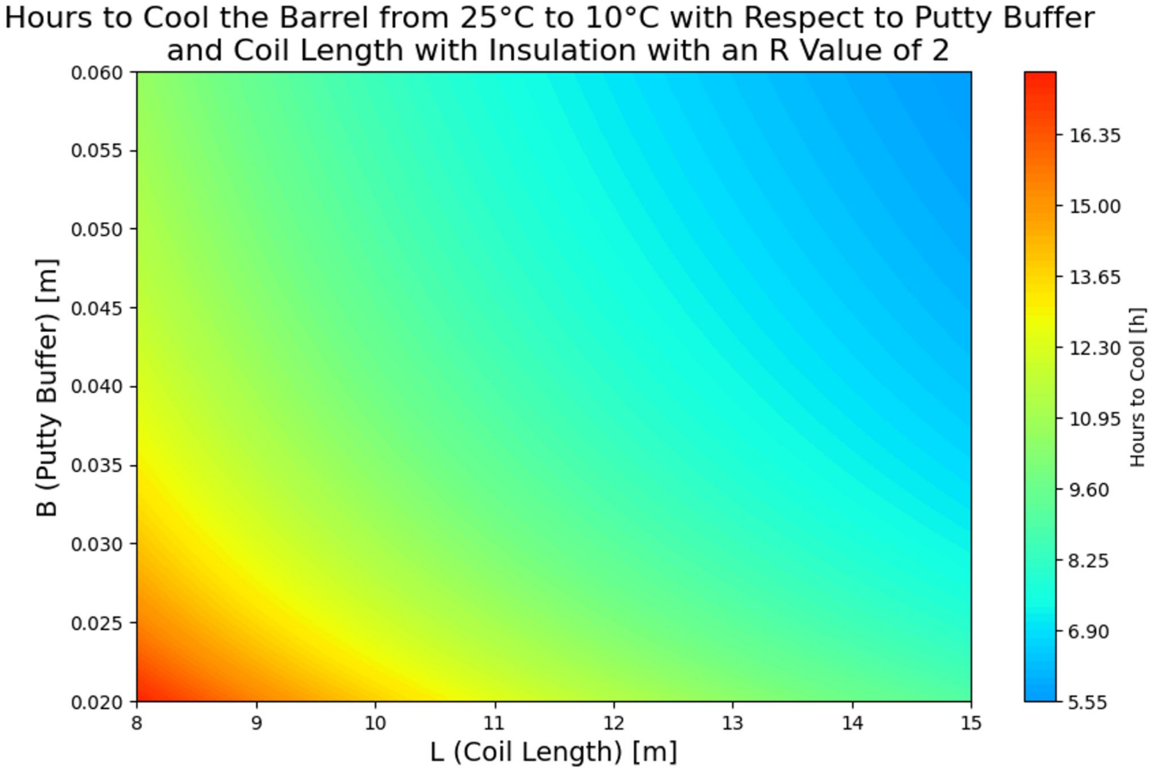
Improved Design

- TRACIT-1100 heat transfer compound
- Heat transfer coefficient: 114-227 W/m²*K
- Relatively inexpensive solution
- Avoids quick connect flow and spillage issues
- Avoids coil interfering with detection issues



Calculations

- Used thermal resistance
- Putty buffer is amount of putty on either side of tubing
- Cooling time reasonable making this option feasible



Heat Transfer Coefficient	Area
$U_{\text{copper-putty}} = 114\,\text{W}/(\text{m}^2 \cdot \text{K})$	$A_{\text{cp}} = 0.0127 \cdot \pi \cdot L$
$U_{\text{steel-water}} = 400\,\text{W}/(\text{m}^2 \cdot \text{K})$	$A_{\text{sw}} = L \cdot 2 \cdot B$
$U_{\text{putty-steel}} = 114\,\text{W}/(\text{m}^2 \cdot \text{K})$	$A_{\text{ps}} = L \cdot 2 \cdot B$

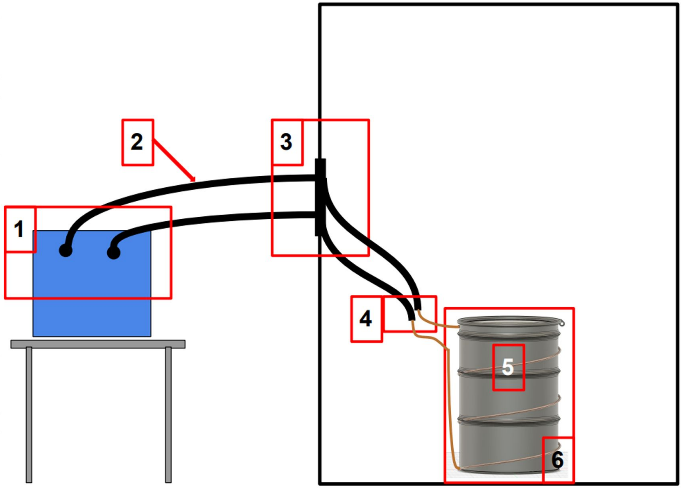
$$R_{tot} = \sum \frac{1}{U \cdot A}$$

$$\frac{dQ}{dt} = \frac{\Delta T}{R_{tot}}$$

$$t = \frac{14 \cdot 10^6}{3600\left(\frac{15}{\frac{1}{114 \cdot 0.0127 \cdot \pi \cdot L} + \frac{1}{400 \cdot 2 \cdot B \cdot L} + \frac{1}{114 \cdot 2 \cdot B \cdot L}} - 17\right)}$$

Final Bill of Materials

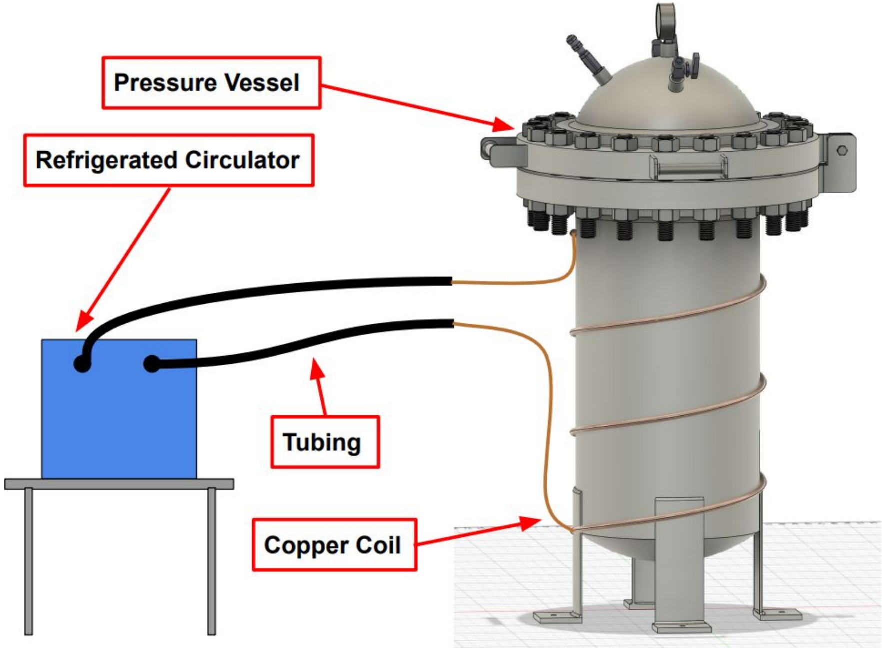
- Avoids issues with previous set up by putting coil outside of barrel
- BOM was ordered



Name	Description	Link	Quantity	Supplier	Part Number	Cost/Unit (USD)	Total (USD)	Image	Diagram Letter
Section 1									
Barbed Fitting	Aluminum, Hose ID 1/2", 1/4" NPT Male	https://www.mcmaster.com/5357K39/	2	McMaster-CARR	5357K39	$ 5.36	$ 10.72		A
Hose Clamps	5/8"-15/16"	https://www.mcmaster.com/45945K63/	10	McMaster-CARR	45945K63	$ 6.47	$ 64.70		B
Section 2									
Soft PVC Tubing	25 ft/unit, ID 1/2", OD 3/4"	https://www.mcmaster.com/5231K89/	1	McMaster-CARR	5231K89	$ 34.50	$ 34.50		A
Tubing Insulation	6 ft/unit, R value 2	https://www.mcmaster.com/44745K23/	4	McMaster-CARR	44745K23	$ 11.72	$ 46.88		B
Cable Holder	Fit up to 3 1/4" Diamiter	https://www.mcmaster.com/6912K45/	5	McMaster-CARR	6912K45	$ 7.80	$ 39.00		C
Section 3									
Through Wall Connector	3/8" NPT Female, Stainless Steel	https://www.mcmaster.com/6696K58/	2	McMaster-CARR	6696K58	$ 126.86	$ 253.72		A
Barbed Fitting	Aluminum, Hose ID 1/2", 3/8" NPT Male	https://www.mcmaster.com/5357K41/	4	McMaster-CARR	5357K41	$ 5.64	$ 22.56		B
Section 4									
Brass Push-to-Connect Fitting	For 3/8" tube ID and 1/2" tube OD, 1/2" NPT Male	https://www.mcmaster.com/5483K47/	2	McMaster-CARR	5483K47	$ 7.99	$ 15.98		A
NPT Female Barbed Fitting	Hose ID 1/2", 1/2" NPT Female, Brass	https://www.mcmaster.com/5346K57/	2	McMaster-CARR	5346K57	$ 4.33	$ 8.66		B
Section 5									
Copper Tubing	ID 3/8", OD 1/2", 50 ft/unit	https://www.mcmaster.com/5174K24-5174K6/	1	McMaster-CARR	5174K24	$ 159.91	$ 159.91		A
Heat-Transfer Putty	1 Gallon, Look at SDS for more info	https://www.mcmaster.com/3568K43/	2	McMaster-CARR	3568K43	$ 98.33	$ 196.66		B
Instant-Bonding Adhesive	2 FL. oz /container	https://www.mcmaster.com/7605a13/	1	McMaster-CARR	7605A13	$ 7.87	$ 7.87		C
Tube Clamps **(Price is CAD)**	Copper, 10 Clamps/ Bag	https://www.homedepot.ca/product/dahl-1-2-tube-	2	The Home Depot	1000148597	$ 6.70	$ 13.40		D
Section 6									
Bubble Sheet Insulation	48"x25 ft, For all sides, 4.2 R value	https://www.mcmaster.com/9367K21/	1	McMaster-CARR	9367K21	$ 79.37	$ 79.37		A
Fiberglass Insulation	48"x10 ft, For sides, 3.8 R value	https://www.mcmaster.com/9346K11/	1	McMaster-CARR	9346K11	$ 25.16	$ 25.16		B
Hard Foam Insulation	4 Feet x 48", 1" Thick, 5 R value	https://www.mcmaster.com/9255K11/	1	McMaster-CARR	9255K11	$ 49.58	$ 49.58		C
Soft Foam Insulation	1/2" Thick, 36" Wide, 4 Feet Long, 2 R value	https://www.mcmaster.com/93265K46/	1	McMaster-CARR	93265K46	$ 25.20	$ 25.20		D
Bags	For fiberglass insulation, 55"x45"x85"	https://www.mcmaster.com/1066T22/	2	McMaster-CARR	1066T22	$ 4.61	$ 9.22		E
Other									
Paper Towel	Paper, 12 Rolls/ Pack	https://www.mcmaster.com/4501T202/	1	McMaster-CARR	4501T202	$ 53.57	$ 53.57		
Pipe Cutter Blade	Steel	https://www.mcmaster.com/2757A21/	1	McMaster-CARR	2757A21	$ 2.59	$ 2.59		
						Total (USD pre tax)	**$ 1,144.41**		

Design

- Same as successful barrel design
- Heat transfer putty will be used, and coil is outside pressure vessel
- I made CAD model for PV from scratch in Fusion 360

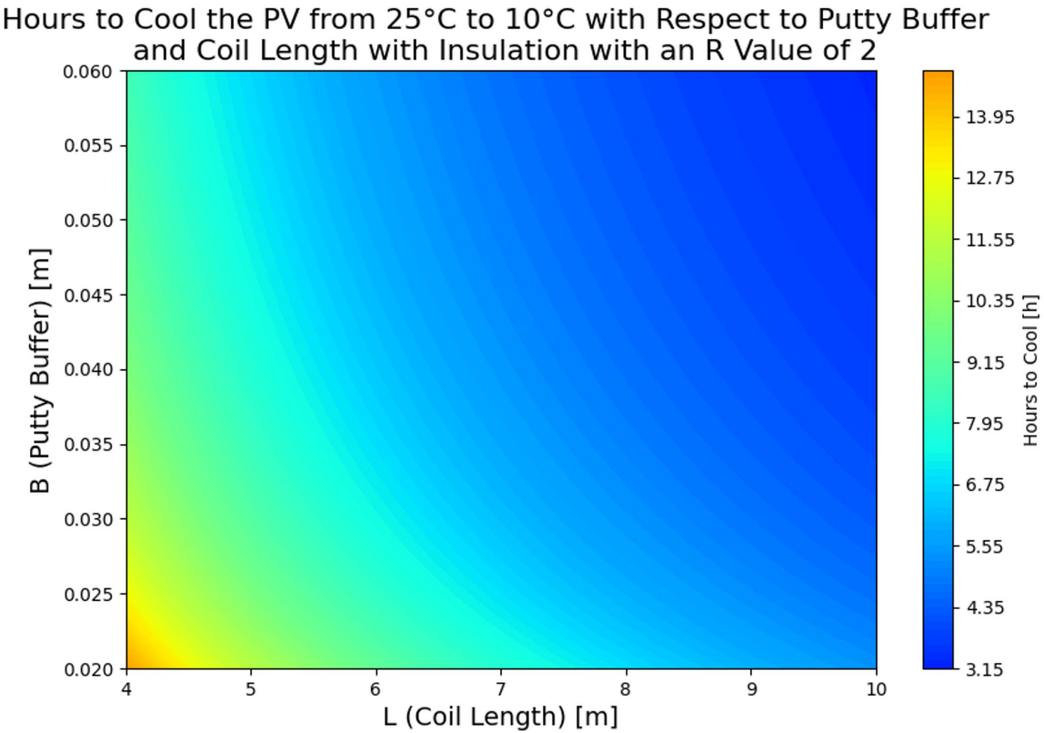


Calculations

- Fast cooling time
- Can use less coil for PV due to this
- This is good for space reasons since PV is smaller than barrel

Heat Transfer Coefficient or Thermal Conductivity	Area
$U_{\text{copper-putty}} = 114\,\mathrm{W/(m^2 \cdot K)}$	$A_{\text{cp}} = 0.0127 \cdot \pi \cdot L$
$U_{\text{steel-water}} = 400\,\mathrm{W/(m^2 \cdot K)}$	$A_{\text{sw}} = L \cdot 2 \cdot B$
$U_{\text{putty-steel}} = 114\,\mathrm{W/(m^2 \cdot K)}$	$A_{\text{ps}} = L \cdot 2 \cdot B$
$K_{\text{wall}} = 45\,\mathrm{W/(m \cdot K)}$	$A_{\text{w}} = L \cdot 2 \cdot B$

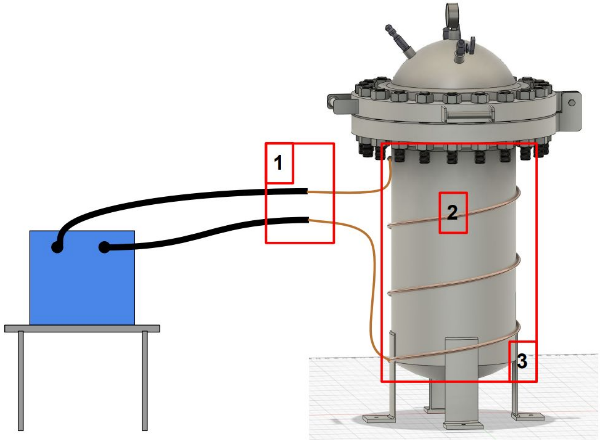
$$R = \frac{d}{k \cdot A} = \frac{1}{U \cdot A}$$



$$t = \frac{53 \cdot 10^5}{3600\left(\left(\frac{15}{\frac{0.025}{45 \cdot L \cdot 2B} + \frac{1}{114 \cdot 0.0127 \cdot \pi \cdot L} + \frac{1}{114 \cdot 2B \cdot L} + \frac{1}{400 \cdot 2B \cdot L}}\right) - 17\right)}$$

Bill of Materials

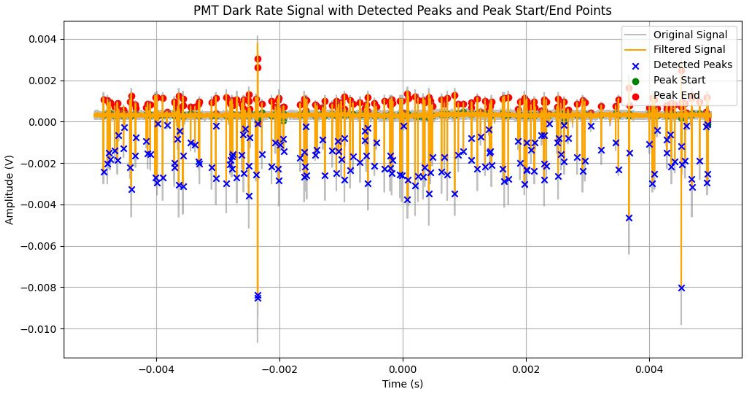
- Very affordable BOM
- Can reuse parts from barrel setup

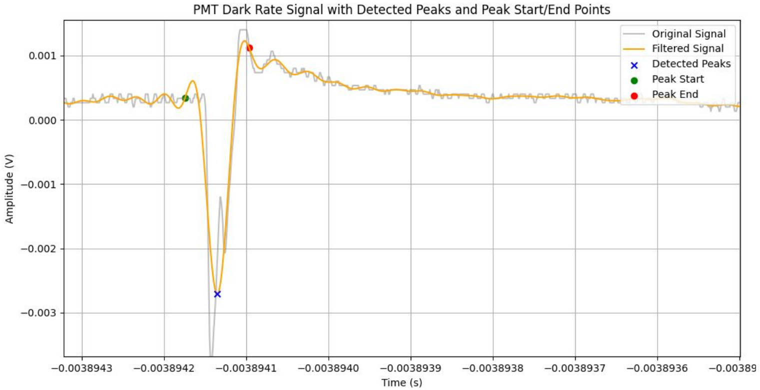


Name	Description	Link	Quantity	Supplier	Part Number	Cost/Unit (USD)	Total (USD)	Image	Diagram Letter
Section 1									
Brass Push-to-Connect Fitting	For 3/8" tube ID and 1/2" tube OD, 1/2" NPT Male	https://www.mcmaster.com/5483K47/	2	McMaster-CARR	5483K47	$ 7.99	$ 15.98		A
NPT Female Barbed Fitting	Hose ID 1/2", 1/2" NPT Female, Brass	https://www.mcmaster.com/5346K57/	2	McMaster-CARR	5346K57	$ 4.33	$ 8.66		B
Hose Clamps	10 pack, 5/8"-1 1/16"	https://www.mcmaster.com/5076K43/	1	McMaster-CARR	5076K43	$ 12.23	$ 12.23		C
Section 2									
Heat-Transfer Putty	1 Gallon, Look at SDS for more info	https://www.mcmaster.com/3568K43/	1	McMaster-CARR	3568K43	$ 98.33	$ 98.33		A
Tube Clamps **(COST IN CAD)**	10 Clamps /pack, For 1/2" OD tube, Copper	edepot.ca/product/dahl-1-2-tube-clamps-solid-	1	The Home Depot Canada	1000148597	$ 6.70	$ 6.70		B
Copper Tubbing	ID 3/8", OD 1/2", 50 ft/unit	https://www.mcmaster.com/5174K24-5174K6/	1	McMaster-CARR	5174K24	$ 159.91	$ 159.91		C
Instant-Bonding Adhesive	0.9 FL. oz /container	https://www.mcmaster.com/5551T73/	3	McMaster-CARR	5551T73	$ 9.43	$ 28.29		D
Section 3									
Bubble Sheet Insulation	48"x25 ft, For all sides, 4.2 R value	https://www.mcmaster.com/9367K21/	1	McMaster-CARR	9367K21	$ 79.37	$ 79.37		A
Fiberglass Insulation	48"x10 ft, For sides, 3.8 R value	https://www.mcmaster.com/9346K11/	1	McMaster-CARR	9346K11	$ 25.16	$ 25.16		B
Bags	For fiberglass insulation, 55"x45"x85"	https://www.mcmaster.com/1066T22/	2	McMaster-CARR	1066T22	$ 4.61	$ 9.22		C
						Total (USD pre tax)	**$ 443.85**		

How the Code Works

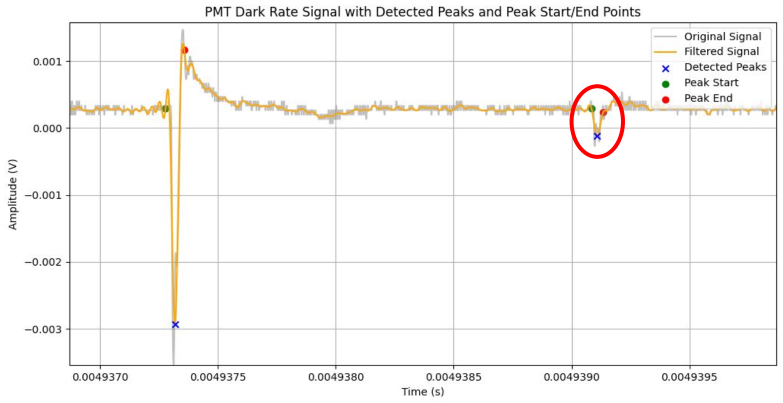
- The oscilloscope captures chunks of PMT data
- FFT is applied to convert the data to the frequency domain for filtering
- Inverse FFT brings it back to time domain
- Peak detection marks the start and end of peaks based on set amplitude thresholds
- I made a script that lets me analyze what is happening visually

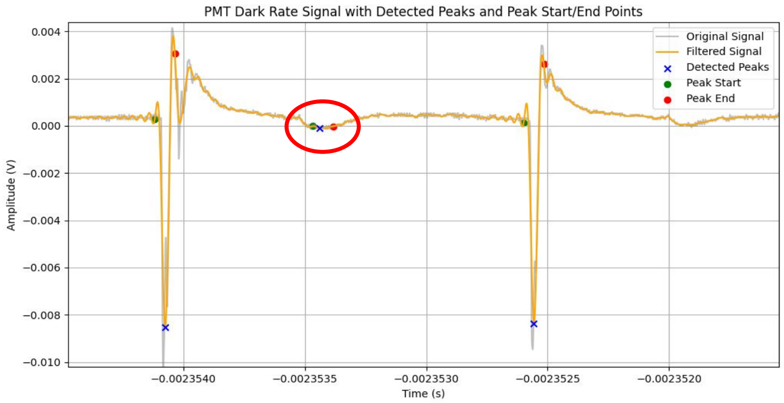




Issue Found through Testing

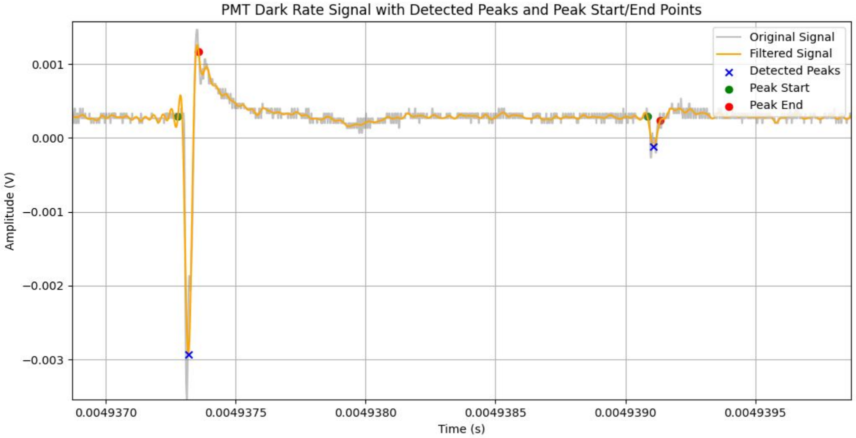
- Code is marking peaks that are too small as signals
- Easy fix!
- Can adjust thresholds for peak detection to >-0.0005 V (peaks are negative)
- Can verify if it works with visualization code I made

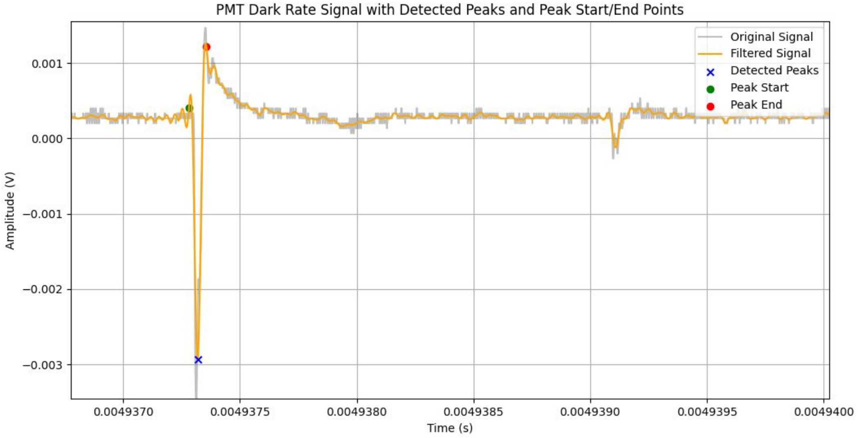




Improvement Results

- Quick fix, but important issue to discover
- Would have had incorrect dark rate





Conclusion

- Designed multiple potential cooling systems
- Made CAD models for the various setups
- Did calculations to identify the best approach
- Made bills of materials for multiple designs and ordered parts for the final design
- Did the above for the future testing setup (Pressure Vessel)
- Made improvements to how data is managed for data analysis
- Stress tested FFT and peak isolation scripts and made improvements

Acknowledgements

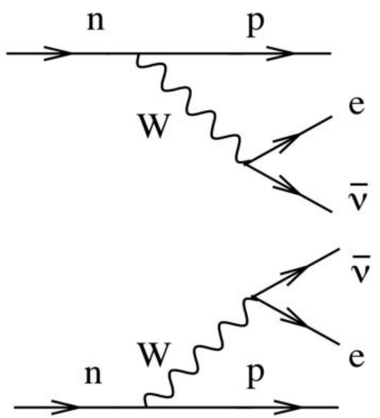
Thank you to:

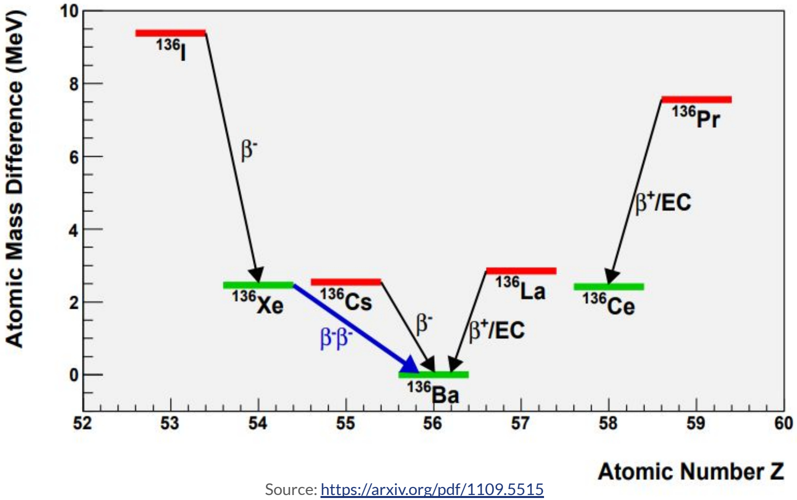
- Dr. Erica Caden
- Anita Masuskapoe
- Dr. Ubi Wichoski
- SNOLAB and the nEXO collaboration for making this great summer possible!

Backups

Double Beta Decay – 2νββ

- 2νββ decay is rare
- Candidate isotopes: even-even nuclei where single β decay is forbidden
- Observed in 14 isotopes





Source: https://arxiv.org/pdf/1109.5515

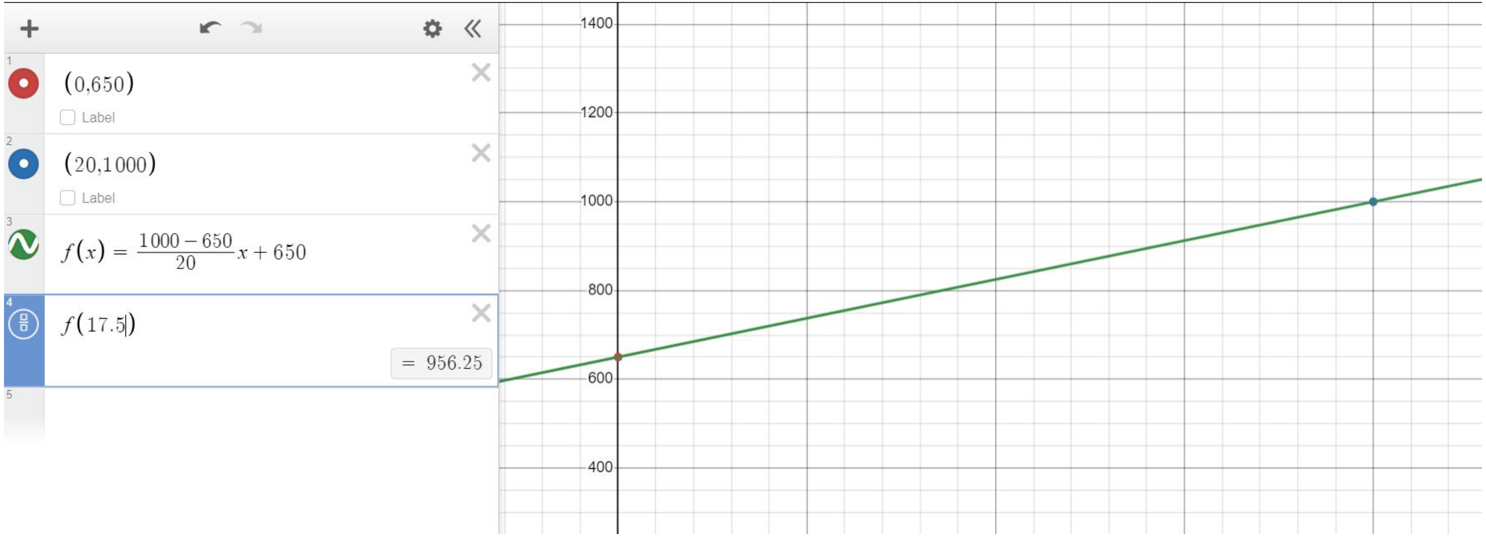
Isotopes that can Undergo 2vββ

Nuclide	Half-life, 10^{21} years	Mode	Transition	Method	Experiment
^{48}Ca	$0.064^{+0.007}_{-0.006} \pm ^{+0.012}_{-0.009}$	$\beta^-\beta^-$		direct	NEMO-3[11]
^{76}Ge	1.926 ±0.094	$\beta^-\beta^-$		direct	GERDA[10]
^{78}Kr	$9.2^{+5.5}_{-2.6} \pm 1.3$	εε		direct	BAKSAN[10]
^{82}Se	0.096 ± 0.003 ± 0.010	$\beta^-\beta^-$		direct	NEMO-3[10]
^{96}Zr	0.0235 ± 0.0014 ± 0.0016	$\beta^-\beta^-$		direct	NEMO-3[10]
^{100}Mo	0.00693 ± 0.00004	$\beta^-\beta^-$		direct	NEMO-3[10]
	$0.69^{+0.10}_{-0.08} \pm 0.07$	$\beta^-\beta^-$	$0^+ \rightarrow 0^+_1$		Ge coincidence[10]
^{116}Cd	0.028 ± 0.001 ± 0.003 $0.026^{+0.009}_{-0.005}$	$\beta^-\beta^-$		direct	NEMO-3[10] ELEGANT IV[10]
^{128}Te	7200 ± 400 1800 ± 700	$\beta^-\beta^-$		geochemical	[10]
^{130}Te	0.82 ± 0.02 ± 0.06	$\beta^-\beta^-$		direct	CUORE-0[12]
^{124}Xe	18 ± 5 ± 1	εε		direct	XENON1T[13]
^{136}Xe	2.165 ± 0.016 ± 0.059	$\beta^-\beta^-$		direct	EXO-200[10]
^{130}Ba	(0.5 – 2.7)	εε		geochemical	[14][15]
^{150}Nd	$0.00911^{+0.00025}_{-0.00022} \pm 0.00063$	$\beta^-\beta^-$		direct	NEMO-3[10]
	$0.107^{+0.046}_{-0.026}$	$\beta^-\beta^-$	$0^+ \rightarrow 0^+_1$		Ge coincidence[10]
^{238}U	2.0 ± 0.6	$\beta^-\beta^-$		radiochemical	[10]

Linear Interpolation for Cooling Capacity

- Most Calculations Look at cooling time from 25 °C to 10 °C
- Middle is 17.5 °C
- Cooling Capacity at 20 °C is 1000 W and at 0 °C is 650 W

Average Cooling Capacity is:
956 W



Calculations - Simple

Time to cool from 25 °C to 10 °C

Simple Calculation Perfect Insulation:

$$55\text{GAL} \cdot \frac{3.78\text{L}}{\text{GAL}} + 15\text{L} = 208\text{L} + 15\text{L} = 223\text{L}$$

$$Q = mc\Delta T = 223\,\text{kg} \cdot 4184\,\frac{\text{J}}{\text{kg}^\circ\text{C}} \cdot 15^\circ\text{C} = 14 \cdot 10^6\,\text{J}$$

Coolers Max Cooling Capacity is **956 W**

$$t = \frac{Q}{P} = \frac{14 \cdot 10^6\,\text{J}}{956\,\frac{\text{J}}{\text{s}}} \cdot \frac{1\,\text{h}}{3600\,\text{s}} \approx \boxed{4.07\,\text{hours}}$$

Simple Calculation with R-Value 2 Insulation:

$$\frac{dQ}{dt} = U \cdot A \cdot \Delta T = \frac{1}{R} \cdot A \cdot \Delta T$$

$$\frac{dQ}{dt} = \frac{1}{2\,\text{m}^2\text{K}} \cdot 2.27\,\text{m}^2 \cdot 15\,\text{K} = 17.0\,\text{W}$$

$$956\,\text{W} - 17\,\text{W} = 939\,\text{W}$$

$$t = \frac{Q}{P} = \frac{14 \cdot 10^6\,\text{J}}{939\,\frac{\text{J}}{\text{s}}} \cdot \frac{1\,\text{h}}{3600\,\text{s}} \approx \boxed{4.14\,\text{hours}}$$

Calculations — Coil in Barrel

$$\frac{d}{dt}Q = U \cdot A \cdot \Delta T$$

Cooling Capacity depends only on A. This gives 3 cases for dQ/dt that only depend on A:

1. dQ/dt < 956 W – Area of coil is bottleneck cooling
2. dQ/dt = 956 W – Coil exchanges heat at the same rate as the cooler
3. dQ/dt > 956 W – Making coil longer has no cooling benefits

$$A = 0.0127 \cdot \pi \cdot L$$

$$\frac{d}{dt}Q = U \cdot 0.0127 \cdot \pi \cdot L \cdot \Delta T$$

$$L = \frac{\frac{d}{dt}Q}{U \cdot 0.0127 \cdot \pi \cdot \Delta T}$$

$$L = \frac{956\,\mathrm{W}}{400\,\frac{\mathrm{W}}{\mathrm{m^2 K}} \cdot 0.0127\,\mathrm{m} \cdot \pi \cdot 15\,\mathrm{K}} = \boxed{4\,\mathrm{m}}$$

Increasing coil length past 4m has no benefits

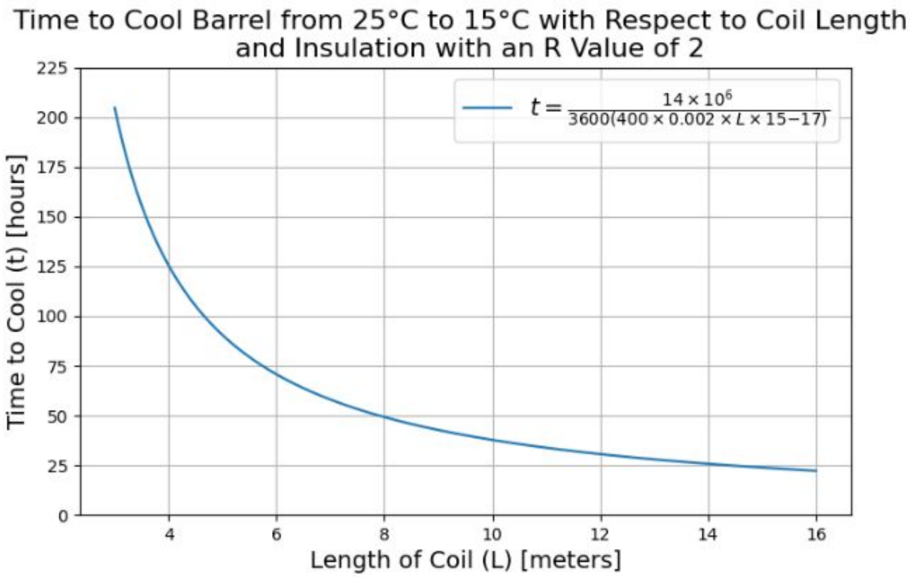
Calculations — Coil Outside of Barrel

$$A = L \cdot 0.002$$

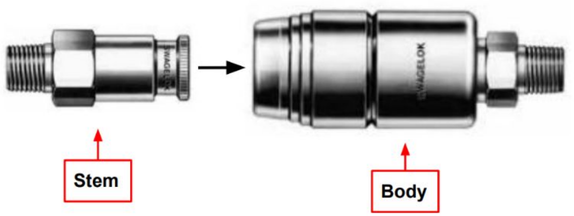
$$\frac{d}{dt}Q = 400\,\frac{\mathrm{W}}{\mathrm{m^2K}} \cdot (0.002 \cdot L)\,\mathrm{m}^2 \cdot 15\,\mathrm{K}$$

$$t = \frac{14 \cdot 10^6}{3600\left(\frac{dQ}{dt} - 17\mathrm{W}\right)}$$

$$t = \frac{14 \cdot 10^6}{3600 \cdot (400 \cdot 0.002 \cdot L \cdot 15 - 17)}$$



Quick Connect Concerns

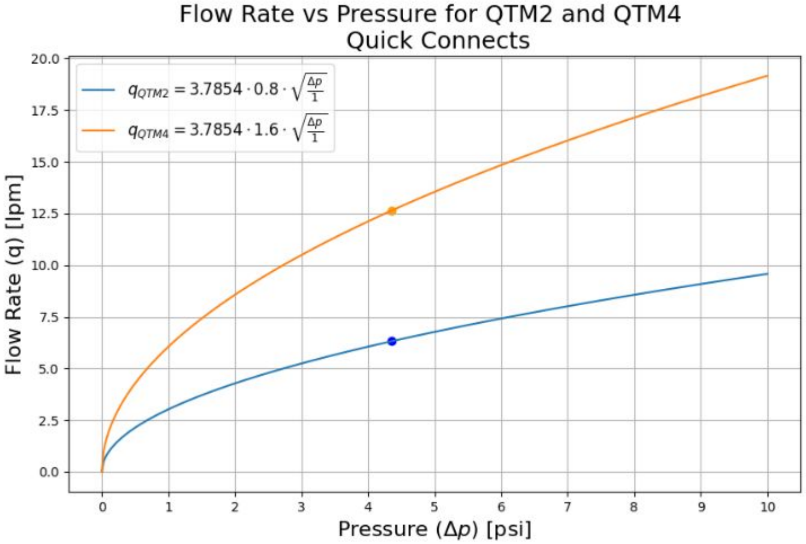


Series	Spillage cm³
QTM2	0.1
QTM4	0.2
QTM8	1.0

$$q = N_1 C_v \sqrt{\frac{\Delta p}{G}}$$

$$q_{QTM2} = 3.7854 \cdot 0.8 \sqrt{\frac{4.35}{1}} = 6.32 \, \text{lpm}$$

$$q_{QTM4} = 3.7854 \cdot 1.6 \sqrt{\frac{4.35}{1}} = 12.63 \, \text{lpm}$$



Calculations Outside Barrel Final

$$R_{tot} = \sum \frac{1}{U \cdot A}$$

$$\frac{dQ}{dt} = \frac{\Delta T}{R_{tot}}$$

Heat Transfer Coefficient	Area
$U_{\text{copper-putty}} = 114\,\text{W}/(\text{m}^2 \cdot \text{K})$	$A_{\text{cp}} = 0.0127 \cdot \pi \cdot L$
$U_{\text{steel-water}} = 400\,\text{W}/(\text{m}^2 \cdot \text{K})$	$A_{\text{sw}} = L \cdot 2 \cdot B$
$U_{\text{putty-steel}} = 114\,\text{W}/(\text{m}^2 \cdot \text{K})$	$A_{\text{ps}} = L \cdot 2 \cdot B$

$$\frac{dQ}{dt} = \frac{15}{\frac{1}{114 \cdot 0.0127 \cdot \pi \cdot L} + \frac{1}{400 \cdot 2 \cdot B \cdot L} + \frac{1}{114 \cdot 2 \cdot B \cdot L}}$$

$$t = \frac{14 \cdot 10^6}{3600\left(\frac{dQ}{dt} - 17\text{W}\right)}$$

$$t = \frac{14 \cdot 10^6}{3600\left(\frac{15}{\frac{1}{114 \cdot 0.0127 \cdot \pi \cdot L} + \frac{1}{400 \cdot 2 \cdot B \cdot L} + \frac{1}{114 \cdot 2 \cdot B \cdot L}} - 17\right)}$$

Calculations PV

$$Q = mc\Delta T = 84.28\,\mathrm{kg} \cdot 4181\,\frac{\mathrm{J}}{\mathrm{kg}^\circ\mathrm{C}} \cdot 15^\circ\mathrm{C}$$

$$Q = 53 \cdot 10^5\,\mathrm{J}$$

$$t = \frac{53 \cdot 10^5}{939 \cdot 3600} = \boxed{1.57\ \text{hours}}$$

Heat Transfer Coefficient or Thermal Conductivity	Area
$U_{\text{copper-putty}} = 114\,\mathrm{W/(m^2 \cdot K)}$	$A_{\text{cp}} = 0.0127 \cdot \pi \cdot L$
$U_{\text{steel-water}} = 400\,\mathrm{W/(m^2 \cdot K)}$	$A_{\text{sw}} = L \cdot 2 \cdot B$
$U_{\text{putty-steel}} = 114\,\mathrm{W/(m^2 \cdot K)}$	$A_{\text{ps}} = L \cdot 2 \cdot B$
$K_{\text{wall}} = 45\,\mathrm{W/(m \cdot K)}$	$A_{\text{w}} = L \cdot 2 \cdot B$

$$R_{\text{tot}} = \frac{d_{\text{w}}}{k_{\text{w}} \cdot A_{\text{w}}} + \frac{1}{U_{\text{cp}} \cdot A_{\text{cp}}} + \frac{1}{U_{\text{ps}} \cdot A_{\text{ps}}} + \frac{1}{U_{\text{sw}} \cdot A_{\text{sw}}}$$

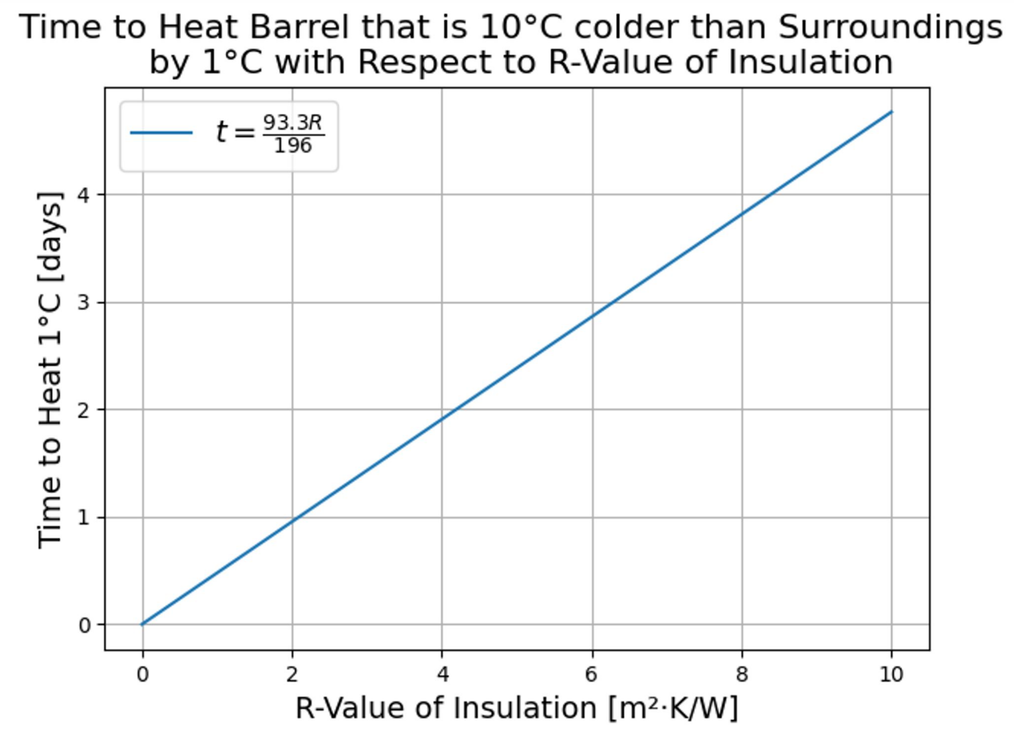
$$t = \frac{53 \cdot 10^5}{3600\left(\left(\frac{15}{\frac{0.025}{45 \cdot L \cdot 2B} + \frac{1}{114 \cdot 0.0127 \cdot \pi \cdot L} + \frac{1}{114 \cdot 2B \cdot L} + \frac{1}{400 \cdot 2B \cdot L}}\right) - 17\right)}$$

Time for Exterior to Heat Barrel by 1 ˚C wrt R-Value

$$Q = mc\Delta T = 223.175\,\text{kg} \cdot 4181\,\frac{\text{J}}{\text{kg}^\circ\text{C}} \cdot 1^\circ\text{C}$$

$$Q = 93.3 \cdot 10^4\,\text{J}$$

$$t = \frac{Q}{\frac{d}{dt}Q} = \frac{93.3 \cdot 10^4}{86400 \cdot 2.27 \cdot 10} R = \frac{93.3}{196} R$$



Data Management Improvements

```
PMT_Data_Folder
├── Other Folders and files (not relevant)
└── Data
    ├── 1
    │   ├── Other files (not relevant)
    │   └── pmt-1560_noise_closed_loff-2023-11-23
    │       ├── C2pmt-1560-noise-000000
    │       ├── C2pmt-1560-noise-000001
    │       ├── C2pmt-1560-noise-000002
    │       └── ...
    ├── 2
    │   ├── Other files (not relevant)
    │   └── pmt-1560_noise_closed_loff-2023-12-4
    │       ├── C2pmt-1560-noise-000000
    │       ├── C2pmt-1560-noise-000001
    │       ├── C2pmt-1560-noise-000002
    │       └── ...
    └── ...
```

Having to hard code file and folder names every time you change something.

Data Management Improvements

```
PMT_Data_Folder
├── Other Folders and files (not relevant)
└── Data
    ├── Subfolder
    │   ├── Other files (not relevant)
    │   └── Sub-Subfolder
    │       ├── Data File
    │       ├── Data File
    │       └── ...
    ├── Subfolder
    │   ├── Other files(not relevant)
    │   └── Sub-SubFolder
    │       ├── Data File
    │       ├── Data File
    │       └── ...
    └── ...
```

Only having to put things in the right folder when you change something.

Data File Example

1 > pmt-1560_noise_closed_loff-2023-11-23 > C2pmt-1560-noise-000000.txt

```
LECROYWS3054z,46730,Waveform
Segments,1,SegmentSize,10000002
Segment,TrigTime,TimeSinceSegment1
#1,23-Nov-2023 14:47:51,0
Time,Ampl
-0.005000000467,0.00026666667
-0.004999999467,0.00026666667
-0.004999998467,0.0002
-0.004999997467,0.0002
-0.004999996467,0.00026666667
-0.004999995467,0.00026666667
-0.004999994467,0.00026666667
-0.004999993467,0.00026666667
-0.004999992467,0.00033333333
-0.004999991467,0.00033333333
-0.004999990467,0.00033333333
-0.004999989467,0.00026666667
-0.004999988467,0.0002
-0.004999987467,0.0002
-0.004999986467,0.00026666667
-0.004999985467,0.00026666667
-0.004999984467,0.00026666667
-0.004999983467,0.00026666667
-0.004999982467,0.00026666667
-0.004999981467,0.00033333333
-0.004999980467,0.00026666667
-0.004999979467,0.00026666667
-0.004999978467,0.0002
-0.004999977467,0.0002
-0.004999976467,0.0002
-0.004999975467,0.00026666667
-0.004999974467,0.00026666667
-0.004999973467,0.00026666667
-0.004999972467,0.00026666667
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-0.004999970467,0.00026666667
-0.004999969467,0.0002
```