



PRIFYSGOL CYMRU
Y Drindod Dewi Sant
UNIVERSITY OF WALES
Trinity Saint David
SWANSEA - ABERTAWE



Design & Analysis of Extended Surfaces

ADVANCED THERMOFLUID MECHANICS (ACMA6011)

Joshua U'Dell
BOC A LINDE COMPANY
UNIVERSITY OF WALES TRINITY SAINT DAVID

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1.0 Introduction

Fins, or extended surfaces, have played a crucial role in heat energy management within various engineering applications from jet engines and industrial compressors through to cryogenic vaporisers and pump motor housings. By increasing the surface area available to participate in transferring heat from or into the appliance. Typically fins are used to improve the cooling of engineering equipment such as the fins that can be seen on air cooled 2 stroke engines used by Harley Davidson motorcycles, the heat transfer can be used to pull heat from the ambient air to warm up cryogenic fluids, this is widely used within air separation plants. These vaporisers are simply pipes with extended surfaces.

This report will explore the historical evolutions of extended surface usage within the automotive industry and more recent usage within the micro-processor industry.

2.0 Evolution of Fins in Automotive Design

Nicolaus Otto is widely regarded as creating the first commercially available internal combustion engine in 1876, but it didn't become widespread until the early 20th century. During this time engineers had to solve the problem of excess heat being produced by the engines. Fins seemed to be the perfect solution to this problem as they were light weight and could easily be added to the housing of the engine unlike other solutions such as liquid cooling.

During the 1930's and 1940's, air-cooled internal combustion engines with passive fins were common practice in aircraft engines, small vehicles and motorcycles. The well know Volkswagen Beetle was powered by a 4-cylinder air cooled engine with prominent fins (Figure 1), many aircraft such as the Pratt and Whitney R-2800 employed massive radial fins (Figure 2) to manage thermal energy and maintain operation temperatures at high altitudes (Gunston, 2006).

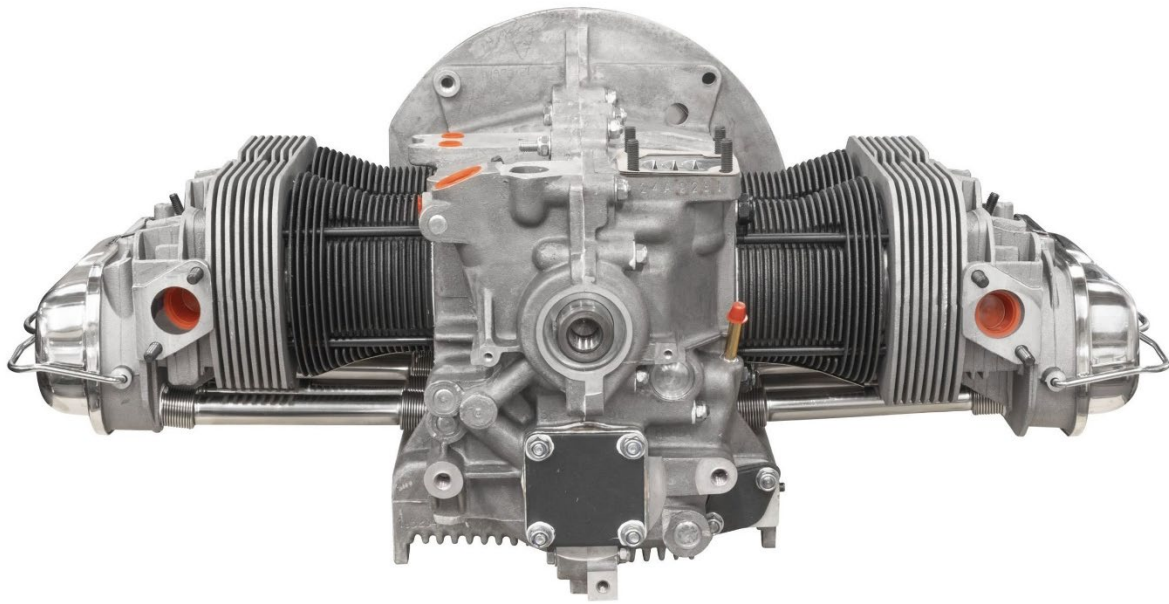


Figure 1 Volkswagen Beetle 4 Cylinder air-cooled engine (JBUGS, 2025)

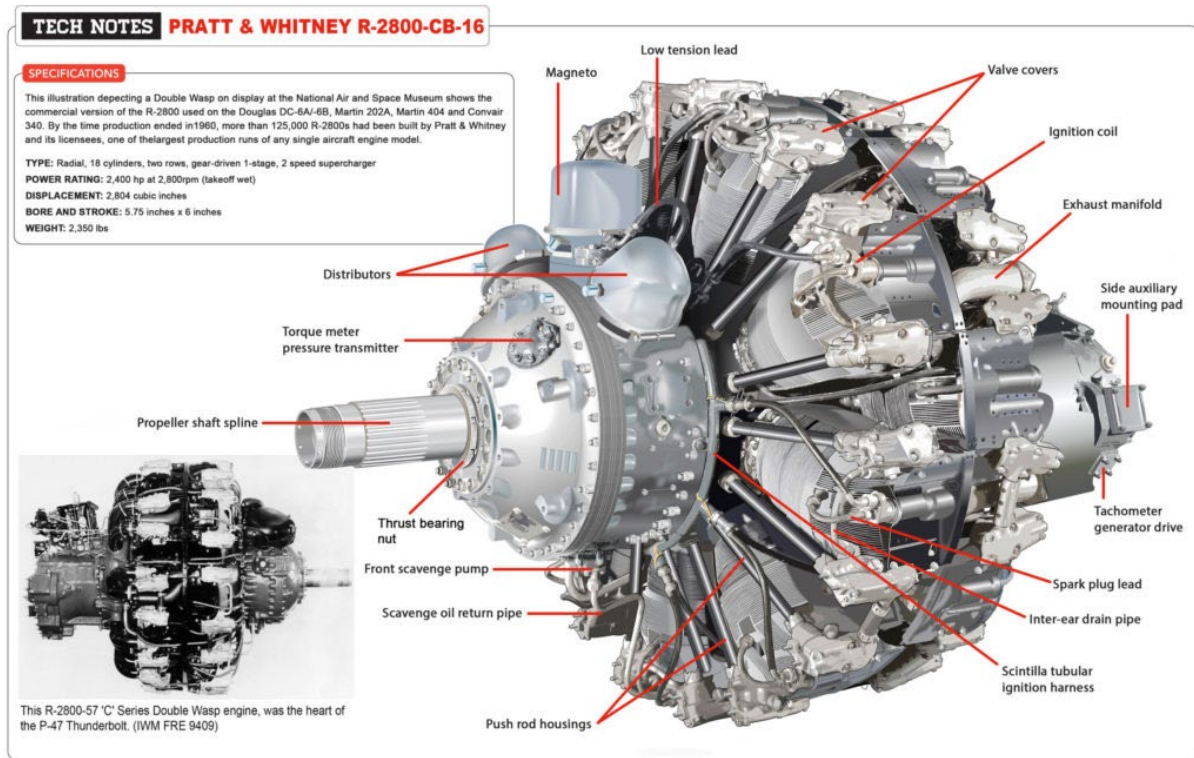


Figure 2 Pratt and Whitney R-2800 engine diagram (HistoryNet, 2018)

in the 1950's engines became more and more powerful, liquid cooling started to replace air cooling, although fins and extended surface remain in radiators and intercooler designs. Car radiator design uses tightly packed tubes covered in fins to

transfer heat out of the coolant and into the air. Radiator geometry didn't change much in these decades but advancements were made with the materials used. Designers moved towards aluminium over the older copper designs due to aluminium's lighter weight whilst still having good thermal properties (Hucho, 1998).

With enhancement in computer modelling designers in the late 20th century began refining the fin geometry and using computers to calculate fin design vs weight. Engineers also designed louvered and corrugated systems that significantly increased turbulence and therefore improved heat transfer rates (Bejan and Kraus, 2003).

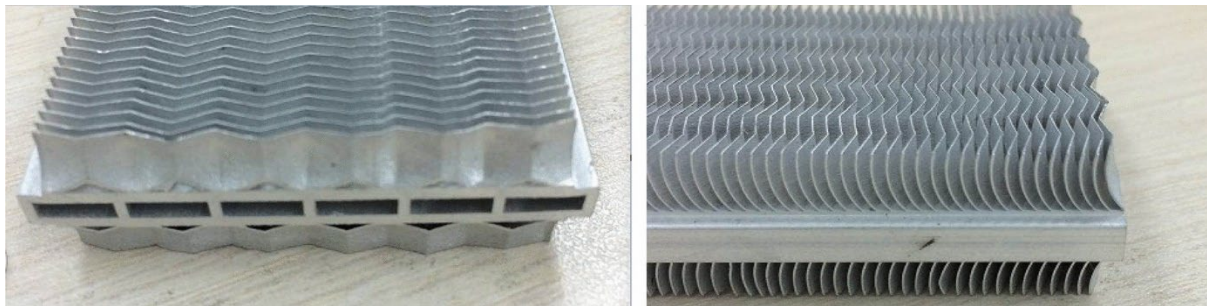


Figure 3 louvered corrugated fin design (Springer Nature, 2003)

3.0 Modern automotive fin applications

In the 21st century fins are used extensively as a means to remove heat energy from undesirable areas. Fins can be seen in modern automotive radiators, intercooler, turbochargers, transmission oil coolers and more recently battery management systems in electric vehicles (EVs). With environmental concerns bringing rise to hybrid and electric vehicles battery cooling has become a hot topic in vehicle design. Fins are used in almost every battery thermal management system (Burke and Miller, 2011).

4.0 Fins and Extended Surfaces in Microprocessors

The computer and therefore microprocessor industry has seen an exponential growth in power consumption, for example the intel 4004 microprocessor, a truly groundbreaking design from 1971 consumed 150 milliwatts under normal operation, comparing this to gaming Central Processing Unit's (CPU) of today such as the AMD Threadripper CPU that can pull 400 watts during use shows the immense rise in power consumption in this industry. With these ever more power hungry microprocessors comes unwanted heat being generated by the components. Fins have been used as a means to dissipate this heat to then be extracted by fans within the computer systems (Bar-Cohen and Kraus, 1999).

Both liquid and air cooling systems are used within computer systems. Some engineers avoid liquid cooling due to issues if there are any leaks in the system, air cooling is considered much safer than liquid cooling due to the sealing issue and other issues such as corrosion.

The first microprocessor heat syncs were simple copper or aluminium blocks glued to the microprocessor; these blocks had simple fins machined into the (Figure 4).



Figure 4 Circuit board heat sync (Future Publishing, 2018)

Microprocessor heat syncs can vary in size depending on the heat output of the microprocessor, they are normally passively cooled by convection into the surrounding air.

More modern microprocessor heat syncs will incorporate larger fins and use fans to move air through the heat sync. This allows the fins to dissipate the heat quicker, these fans can be linked using computer program to the power usage fo the CPU, meaning if the computer is computing more for instance when gaming or performing calculations the fans will spin faster to dissipate the extra heat being generated.

Some more complex heat syncs used in high end computer systems and servers will incorporate vapour chambers and heat pipes to aid transferring the heat from the microprocessor to the fins. (Lasance, 2005).

Recent advancements in fins have come from advancements in material science such as the following:

- Additive manufacturing (3D Printing)
 - This allows designers to create computer calculated heat syncs that would not be manufacturable using traditional methods such as mills and lathes.
- Phase change materials
 - Phase changing materials are being researched and tested in systems to enhance the heat transfer rates and remove the requirement for complex feedback systems.
- Bio-Inspired Designs
 - Inspired by structures found in nature engineers have managed to improve thermal dissipation by promoting turbulence in systems. The human vascular system, leaves and coral formations have all been used to create these bio inspired systems.

Engineers are researching these areas to;

- Increase efficiency
- Miniature designs

- Save energy
- Increase the lifespan
- Enable flexibility in design

5.0 Concussion

The use of fins and extended surfaces has been fundamental in both the automotive and the microprocessor industry, with out this simple yet effective technology engineers would have to use much more complex and risky cooling systems such as liquid cooling. The lack of maintenance and moving parts makes fins the ideal solution for most applications. With groundbreaking research constantly happening in the field of additive manufacturing, nano structure, bio science and other specialities only time will tell what the coming years have to offer in terms of thermal management of engineering equipment. But it cannot be argues that fins and extended surface have played a key role in allowing various engineering industries to make the breakthrough they have over the decades.

6.0 Finite fin optimum mL value

A finite fin is one that has a set length and in this instance exhibits an adiabatic tip boundary condition. It is commonly said that the value of mL should be no greater than 2.65. the graph below has been produced using Microsoft Excel and plots the ratio of Q_{finite} with an adiabatic tip with the rate for and infinitely long fin Q_{∞} against a function of mL .

The formula used for the ratio of heat transfer for Q_{finite} and Q_{∞} is $\frac{Q_{finite}}{Q_{\infty}} = \tanh (mL)$

Below is the derivation of this formula.

$$Q_{finite} = -kA_c \left. \frac{dT}{dx} \right|_{x=0} = kA_c m \theta_b \tanh(mL)$$

$$Q_{infinite} = -kA_c \left. \frac{dT}{dx} \right|_{x=0} = kA_c m \theta_b$$

$$\frac{Q_{finite}}{Q_{infinite}} = \frac{kA_c m \theta_b \tanh(mL)}{kA_c m \theta_b} = \tanh(mL)$$

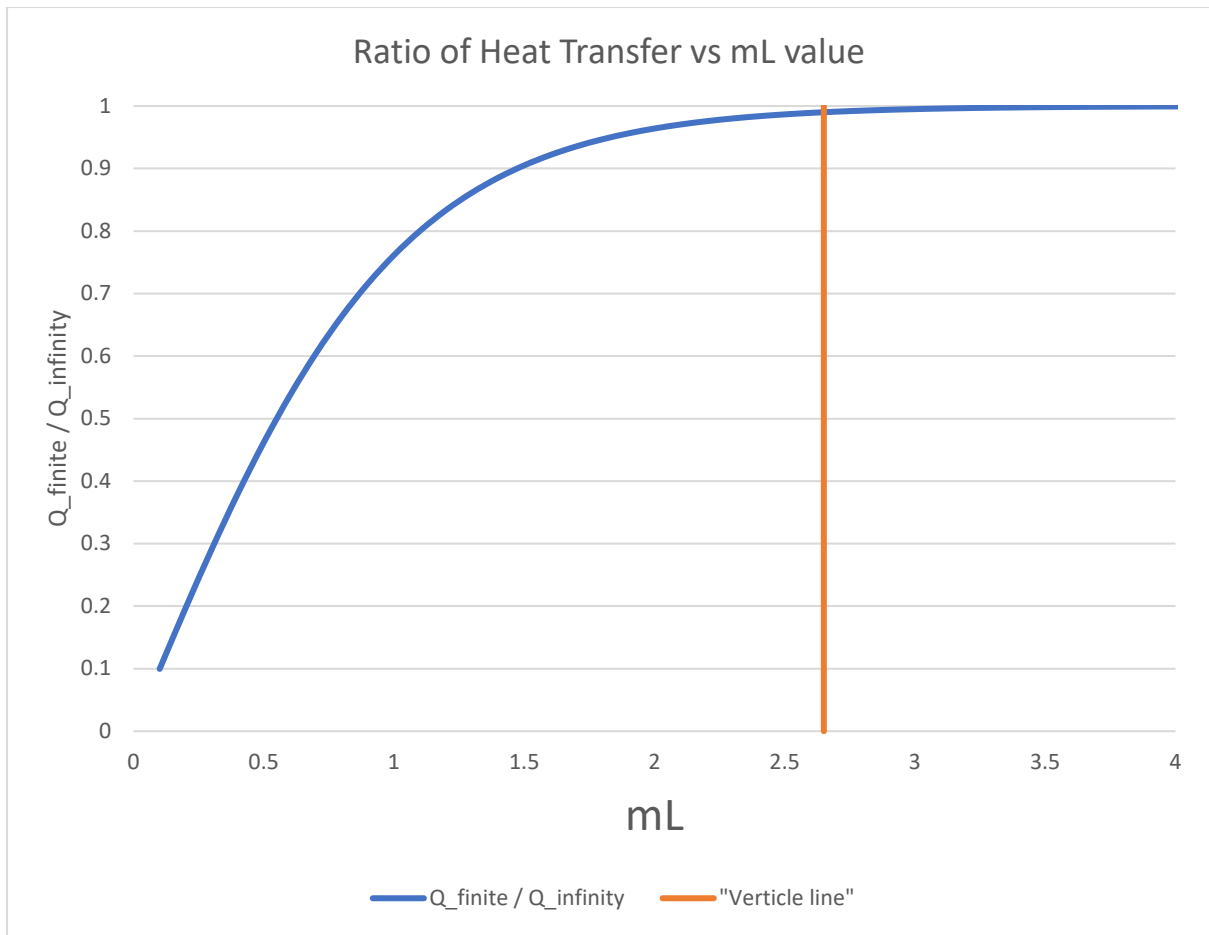


Figure 5 Ratio of heat transfer vs mL value graph

As can be seen from the above graph, at $mL \approx 2.65$ there is minimal improvement of heat flow through a fin. For this reason, it is considered that the mL value should not exceed 2.65 as there is no benefit and would result in material and weight that is not required. The values for this graph can be found in appendix A.

7.0 Very long fin calculations

Task given: A very long rod of diameter 7.5 mm has one end attached to a heated surface which is maintained at a constant temperature of 110 °C. The surface of the rod is exposed to an ambient air temperature of 18 °C. For the four materials detailed below;

Material properties:

2024 Aluminium alloy: $h = 30 \text{ W/m}^2 \text{ K}$ and, $k = 186 \text{ W/m K}$

Brass (70 Cu/30 Zn): $h = 30 \text{ W/m}^2 \text{ K}$ and, $k = 99 \text{ W/m K}$

Copper: $h = 15 \text{ W/m}^2 \text{ K}$ and, $k = 398 \text{ W/m K}$

304 Stainless Steel: $h = 7.5 \text{ W/m}^2 \text{ K}$ and, $k = 16 \text{ W/m K}$

1) Determine the temperature distribution along the rods by computing and plotting a temperature scale from 0 to 110 °C. It is suggested that you analyse the 'very long rods' up to a length of 0.4 m in increments of 10 mm. Plot all four temperature distributions on the same axes for a direct comparison.

To calculate the temperature distribution along the four rods the following formula is used:

$$T(x) = T_{\infty} + (T_b - T_{\infty})e^{-mx}$$

$T(x)$ = Temp along the rod at x distance from the base in mm

T_{∞} = Temp at the tip (theoretically this is the temprature of the ambient air)

T_b = Temp at the base of the rod

$$m = \sqrt{\frac{hP}{kA_c}}$$

h = heat transfer coefficient

P = perimeter of the fin cross – section

A_c = Cross – sectional area of the fin

k = thermal conductivity of the fin

L = length of the fin

Excel is used to calculate the temperature at x in 10mm intervals and then plotted in a graph to visualise the results.

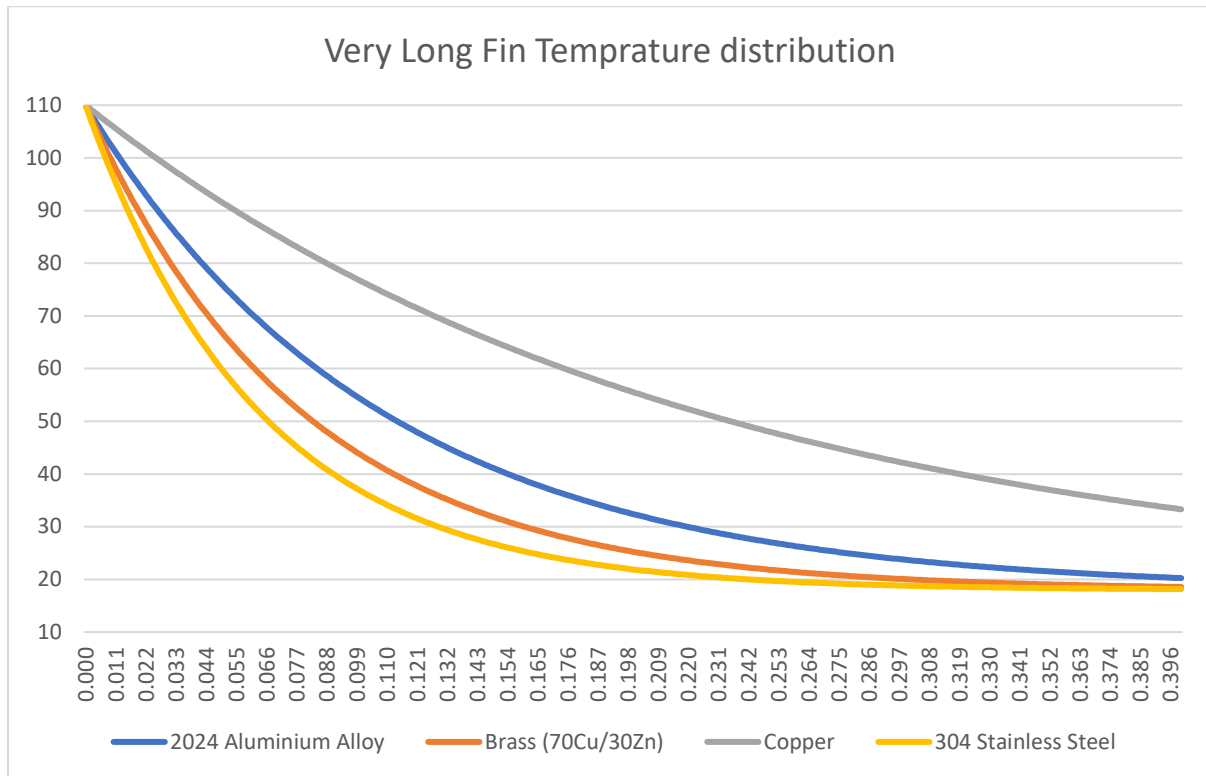


Figure 6 Temperature distribution very long fin calculation

The values for the above graph can be found in appendix B.

2) Determine the corresponding values of heat loss for the four rods analysed above.

To calculate the heat loss values for each fin the following formula is used:

$$Q_{infinite} = kA_c m (T_b - T_{\infty})$$

The m values for each material can be found using the previously mentioned formula.

$$m = \sqrt{\frac{hP}{kA_c}}$$

$$m_{Aluminium} = \sqrt{\frac{30 * 2\pi * \frac{0.0075}{2}}{186 * \pi * \frac{0.0075^2}{2}}} = 9.275$$

$$m_{Brass} = \sqrt{\frac{30 * 2\pi * \frac{0.0075}{2}}{99 * \pi * \frac{0.0075^2}{2}}} = 12.713$$

$$m_{Copper} = \sqrt{\frac{15 * 2\pi * \frac{0.0075}{2}}{398 * \pi * \frac{0.0075^2}{2}}} = 4.483$$

$$m_{Stainless Steel} = \sqrt{\frac{7.5 * 2\pi * \frac{0.0075}{2}}{16 * \pi * \frac{0.0075^2}{2}}} = 15.811$$

$$Q_{infinite Aluminium} = 186 * \pi * \frac{0.0075^2}{2} * 9.275 * (110 - 18) = 7.012 \text{ watts}$$

$$Q_{infinite Brass} = 99 * \pi * \frac{0.0075^2}{2} * 12.713 * (110 - 18) = 5.115 \text{ watts}$$

$$Q_{infinite Copper} = 398 * \pi * \frac{0.0075^2}{2} * 4.483 * (110 - 18) = 7.252 \text{ watts}$$

$$Q_{infinite Stainless Steel} = 16 * \pi * \frac{0.0075^2}{2} * 15.811 * (110 - 18) = 1.028 \text{ watts}$$

3) Determine the length of each of the four rods based on the assumption of an optimum length fin to provide an estimate of the heat loss. How do these values of heat loss compare with those from part 2) above?

To calculate the optimum length for each rod the mL value of 2.65 is applied, this can simply be done by dividing the m value by 2.65.

This gives the following results:

$$L_{opt} = \frac{2.65}{m}$$

$$L_{opt\ Aluminum} = \frac{2.65}{9.275} = 0.286\ Meters$$

$$L_{opt\ Brass} = \frac{2.65}{12.713} = 0.208\ Meters$$

$$L_{opt\ Copper} = \frac{2.65}{4.483} = 0.591\ Meters$$

$$L_{opt\ Stainless\ Steel} = \frac{2.65}{15.811} = 0.168\ Meters$$

A new heat loss value can now be calculated using the below formula, the results from this can be seen in the table below.

$$Q_{fin} = kA_c m(T_b - T_{\infty}) \tanh(mL)$$

Material	Infinite Length Heat Loss Value (w)	Optimum Length (mL = 2.65) heat loss value (w)
2024 Aluminium Alloy	7.012	6.942
Brass (70Cu/30Zn)	5.0115	5.065
Copper	7.252	7.180
304 Stainless Steel	1.028	1.018

Using the optimum length value of mL = 2.65 in this instance gives very similar heat loss results. In some cases, this shows that the rod can be shorter and give similar results. Engineers could use this to work out a usable length as the optimal length may not be desirable in the area available in the machine or circuit board.

4) *Determine the temperature distribution for the four rods for their corresponding optimum lengths.*

To generate the temperature distribution graph the same steps as before can be followed but the calculation used must be the appropriate one for a finite rod.

$$T(x) = (T_b - T_{\infty}) \frac{\cosh[m(L - x)]}{\cosh(mL)} + T_{\infty}$$

The optimum values are used for the length, a graph of the calculated temperature distribution can be seen below.

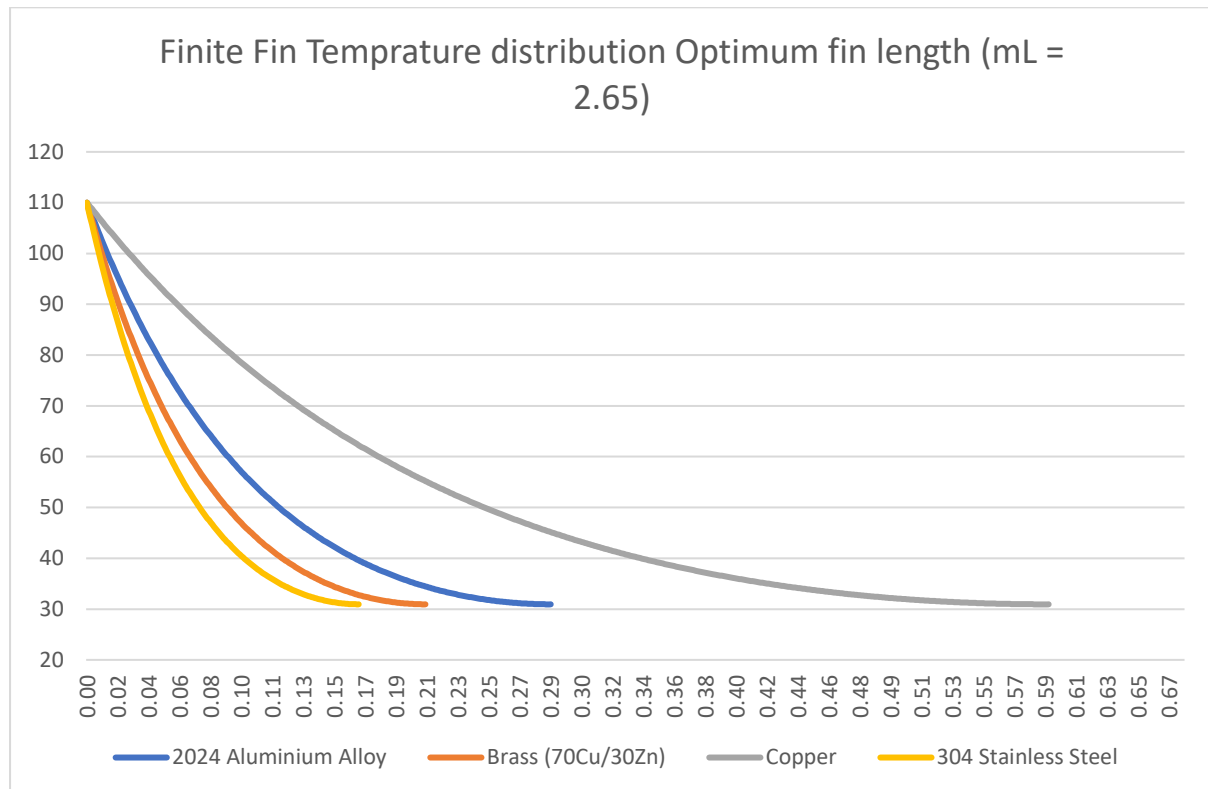


Figure 7 Temperature distribution, optimum rod length ($mL=2.65$)

5) For a more accurate prediction of temperature distribution $T(x)$ for the infinite fin approximation, a larger value of the parameter mL would be required. From the equation to determine $T(x)$ and recognising a requirement that the tip temperature is very close to the fluid temperature, it can be shown that $e^{-mL} < 0.02$. Using this relationship, determine a more accurate length for each of the four rods. How do these results compare with the temperature distributions plotted in Part 1 and those determined in Part 4) above?

Taking $e^{-mL} < 0.02$ means that the tip temperature is within 2% of the ambient temperature. Taking the natural logarithm of 2% gives a value of mL that can be used to determine a more accurate optimal length of the rods.

$$-mL < \ln(0.02) \Rightarrow mL > -\ln(0.02) \approx 3.912$$

Dividing each materials m value by the inverse natural log of 2% gives the more accurate optimal lengths for each rod. The values are shown below.

Material	Optimum Length (mL = 2.65) (Meters)	Optimal Length using $e^{-mL} < 0.02$ (Meters)
2024 Aluminium Alloy	0.286	0.422
Brass (70Cu/30Zn)	0.208	0.308
Copper	0.591	0.873
304 Stainless Steel	.0168	0.247

The larger value of mL gives a much longer optimal length for the rods. At these lengths the rod would be too long for most operations but this shows how in some cases doubling the length of the rod doesn't achieve much more thermal management.

8.0 References

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9.0 Appendices

9.1 Values for Figure 5 Ratio of heat transfer vs mL value graph

mL	$\frac{Q_{\text{finite}}}{Q_{\text{infinity}}}$ (tanh(Ml))
0.1	0.09966799
0.2	0.19737532
0.3	0.29131261
0.4	0.37994896
0.5	0.46211716
0.6	0.53704957
0.7	0.60436778
0.8	0.66403677
0.9	0.71629787
1	0.76159416
1.1	0.80049902
1.2	0.83365461
1.3	0.86172316
1.4	0.88535165
1.5	0.90514825
1.6	0.92166855
1.7	0.93540907
1.8	0.94680601
1.9	0.95623746
2	0.96402758
2.1	0.97045194
2.2	0.97574313
2.3	0.9800964
2.4	0.98367486
2.5	0.9866143

2.6	0.9890274
2.7	0.99100745
2.8	0.99263152
2.9	0.99396317
3	0.99505475
3.1	0.99594936
3.2	0.9966824
3.3	0.99728296
3.4	0.99777493
3.5	0.9981779
3.6	0.99850794
3.7	0.99877824
3.8	0.9989996
3.9	0.99918087
4	0.9993293

9.2 Figure 6 Temperature distribution very long fin calculation

Infinitely Long Fin				
x value (m)	2024 Aluminium Alloy	Brass (70Cu/30Zn)	Copper	304 Stainless Steel
0.000	110.0000	110.0000	110.0000	110.0000
0.001	109.1507	108.8378	109.5885	108.5568
0.002	108.3092	107.6903	109.1787	107.1362
0.003	107.4754	106.5573	108.7709	105.7379
0.004	106.6494	105.4386	108.3648	104.3616
0.005	105.8310	104.3341	107.9606	103.0068
0.006	105.0202	103.2435	107.5582	101.6733
0.007	104.2168	102.1666	107.1576	100.3607
0.008	103.4209	101.1034	106.7587	99.0687

0.009	102.6323	100.0536	106.3617	97.7970
0.010	101.8509	99.0171	105.9664	96.5452
0.011	101.0768	97.9937	105.5729	95.3131
0.012	100.3099	96.9832	105.1812	94.1003
0.013	99.5500	95.9854	104.7912	92.9065
0.014	98.7971	95.0003	104.4029	91.7314
0.015	98.0512	94.0276	104.0164	90.5748
0.016	97.3122	93.0672	103.6316	89.4363
0.017	96.5800	92.1189	103.2486	88.3157
0.018	95.8546	91.1826	102.8672	87.2126
0.019	95.1358	90.2581	102.4876	86.1269
0.020	94.4237	89.3453	102.1097	85.0582
0.021	93.7182	88.4441	101.7334	84.0062
0.022	93.0192	87.5542	101.3588	82.9708
0.023	92.3266	86.6756	100.9860	81.9516
0.024	91.6404	85.8080	100.6147	80.9484
0.025	90.9606	84.9514	100.2452	79.9609
0.026	90.2870	84.1057	99.8773	78.9889
0.027	89.6197	83.2706	99.5110	78.0322
0.028	88.9585	82.4461	99.1464	77.0905
0.029	88.3034	81.6320	98.7834	76.1635
0.030	87.6544	80.8282	98.4220	75.2511
0.031	87.0113	80.0345	98.0623	74.3530
0.032	86.3742	79.2509	97.7041	73.4690
0.033	85.7430	78.4771	97.3476	72.5988
0.034	85.1176	77.7131	96.9926	71.7424
0.035	84.4980	76.9588	96.6393	70.8993
0.036	83.8841	76.2140	96.2875	70.0695
0.037	83.2758	75.4787	95.9373	69.2526
0.038	82.6732	74.7526	95.5886	68.4486
0.039	82.0762	74.0356	95.2416	67.6573

0.040	81.4846	73.3278	94.8960	66.8783
0.041	80.8985	72.6289	94.5520	66.1115
0.042	80.3179	71.9388	94.2096	65.3568
0.043	79.7425	71.2574	93.8687	64.6139
0.044	79.1725	70.5846	93.5293	63.8827
0.045	78.6078	69.9204	93.1914	63.1629
0.046	78.0483	69.2645	92.8551	62.4544
0.047	77.4939	68.6169	92.5202	61.7571
0.048	76.9447	67.9775	92.1869	61.0707
0.049	76.4005	67.3461	91.8550	60.3950
0.050	75.8614	66.7228	91.5246	59.7300
0.051	75.3272	66.1073	91.1957	59.0753
0.052	74.7979	65.4996	90.8683	58.4310
0.053	74.2736	64.8996	90.5424	57.7967
0.054	73.7541	64.3071	90.2178	57.1724
0.055	73.2394	63.7221	89.8948	56.5579
0.056	72.7294	63.1446	89.5732	55.9531
0.057	72.2241	62.5743	89.2530	55.3577
0.058	71.7236	62.0112	88.9343	54.7717
0.059	71.2276	61.4552	88.6170	54.1948
0.060	70.7362	60.9063	88.3011	53.6271
0.061	70.2493	60.3643	87.9866	53.0682
0.062	69.7670	59.8291	87.6735	52.5181
0.063	69.2891	59.3007	87.3618	51.9766
0.064	68.8156	58.7790	87.0516	51.4436
0.065	68.3464	58.2639	86.7427	50.9189
0.066	67.8817	57.7552	86.4352	50.4025
0.067	67.4211	57.2530	86.1290	49.8942
0.068	66.9649	56.7572	85.8243	49.3939
0.069	66.5129	56.2676	85.5209	48.9014
0.070	66.0650	55.7842	85.2188	48.4167

0.071	65.6213	55.3069	84.9181	47.9395
0.072	65.1816	54.8356	84.6188	47.4699
0.073	64.7461	54.3703	84.3208	47.0076
0.074	64.3145	53.9108	84.0241	46.5525
0.075	63.8869	53.4572	83.7288	46.1046
0.076	63.4633	53.0093	83.4347	45.6638
0.077	63.0436	52.5670	83.1420	45.2298
0.078	62.6278	52.1304	82.8506	44.8026
0.079	62.2158	51.6992	82.5605	44.3822
0.080	61.8076	51.2735	82.2717	43.9683
0.081	61.4031	50.8532	81.9842	43.5610
0.082	61.0024	50.4382	81.6980	43.1600
0.083	60.6054	50.0284	81.4131	42.7653
0.084	60.2121	49.6238	81.1294	42.3768
0.085	59.8224	49.2243	80.8470	41.9944
0.086	59.4363	48.8299	80.5659	41.6180
0.087	59.0538	48.4404	80.2860	41.2475
0.088	58.6748	48.0559	80.0074	40.8828
0.089	58.2993	47.6762	79.7300	40.5239
0.090	57.9272	47.3013	79.4538	40.1705
0.091	57.5586	46.9312	79.1789	39.8227
0.092	57.1934	46.5657	78.9053	39.4804
0.093	56.8316	46.2049	78.6328	39.1434
0.094	56.4731	45.8486	78.3616	38.8118
0.095	56.1179	45.4968	78.0916	38.4853
0.096	55.7660	45.1494	77.8228	38.1639
0.097	55.4174	44.8065	77.5552	37.8476
0.098	55.0719	44.4679	77.2887	37.5363
0.099	54.7297	44.1335	77.0235	37.2298
0.100	54.3906	43.8034	76.7595	36.9281
0.101	54.0547	43.4774	76.4966	36.6312

0.102	53.7218	43.1556	76.2350	36.3389
0.103	53.3920	42.8378	75.9745	36.0513
0.104	53.0653	42.5240	75.7151	35.7681
0.105	52.7416	42.2142	75.4569	35.4894
0.106	52.4208	41.9084	75.1999	35.2150
0.107	52.1031	41.6063	74.9441	34.9450
0.108	51.7882	41.3081	74.6893	34.6791
0.109	51.4763	41.0137	74.4357	34.4175
0.110	51.1673	40.7230	74.1833	34.1599
0.111	50.8611	40.4359	73.9320	33.9064
0.112	50.5577	40.1525	73.6817	33.6569
0.113	50.2571	39.8727	73.4327	33.4113
0.114	49.9593	39.5964	73.1847	33.1696
0.115	49.6643	39.3236	72.9378	32.9316
0.116	49.3720	39.0542	72.6921	32.6974
0.117	49.0823	38.7882	72.4474	32.4668
0.118	48.7954	38.5256	72.2039	32.2399
0.119	48.5111	38.2663	71.9614	32.0165
0.120	48.2294	38.0103	71.7200	31.7966
0.121	47.9503	37.7575	71.4797	31.5802
0.122	47.6738	37.5080	71.2405	31.3671
0.123	47.3999	37.2615	71.0023	31.1574
0.124	47.1285	37.0182	70.7652	30.9510
0.125	46.8596	36.7780	70.5292	30.7479
0.126	46.5931	36.5408	70.2942	30.5479
0.127	46.3292	36.3065	70.0603	30.3511
0.128	46.0676	36.0753	69.8274	30.1573
0.129	45.8085	35.8470	69.5955	29.9666
0.130	45.5518	35.6215	69.3647	29.7789
0.131	45.2974	35.3989	69.1350	29.5941
0.132	45.0454	35.1791	68.9062	29.4122

0.133	44.7957	34.9621	68.6785	29.2332
0.134	44.5484	34.7478	68.4518	29.0570
0.135	44.3033	34.5363	68.2261	28.8835
0.136	44.0604	34.3274	68.0014	28.7128
0.137	43.8199	34.1211	67.7778	28.5448
0.138	43.5815	33.9175	67.5551	28.3793
0.139	43.3453	33.7164	67.3334	28.2165
0.140	43.1113	33.5179	67.1127	28.0562
0.141	42.8795	33.3218	66.8930	27.8985
0.142	42.6498	33.1283	66.6743	27.7432
0.143	42.4223	32.9372	66.4566	27.5904
0.144	42.1968	32.7485	66.2398	27.4399
0.145	41.9734	32.5622	66.0240	27.2918
0.146	41.7521	32.3782	65.8092	27.1461
0.147	41.5328	32.1966	65.5953	27.0026
0.148	41.3156	32.0173	65.3824	26.8614
0.149	41.1003	31.8402	65.1705	26.7224
0.150	40.8871	31.6653	64.9595	26.5855
0.151	40.6758	31.4927	64.7494	26.4509
0.152	40.4664	31.3223	64.5403	26.3183
0.153	40.2590	31.1540	64.3321	26.1878
0.154	40.0535	30.9878	64.1248	26.0594
0.155	39.8499	30.8238	63.9185	25.9329
0.156	39.6482	30.6618	63.7131	25.8085
0.157	39.4484	30.5018	63.5086	25.6860
0.158	39.2504	30.3439	63.3050	25.5654
0.159	39.0542	30.1880	63.1024	25.4468
0.160	38.8598	30.0340	62.9006	25.3299
0.161	38.6672	29.8820	62.6997	25.2149
0.162	38.4764	29.7319	62.4998	25.1018
0.163	38.2874	29.5837	62.3007	24.9904

0.164	38.1001	29.4373	62.1026	24.8807
0.165	37.9145	29.2929	61.9053	24.7728
0.166	37.7307	29.1502	61.7089	24.6665
0.167	37.5485	29.0094	61.5133	24.5619
0.168	37.3681	28.8703	61.3187	24.4590
0.169	37.1893	28.7330	61.1249	24.3577
0.170	37.0121	28.5974	60.9320	24.2579
0.171	36.8366	28.4635	60.7400	24.1598
0.172	36.6627	28.3313	60.5488	24.0632
0.173	36.4904	28.2008	60.3584	23.9680
0.174	36.3197	28.0720	60.1690	23.8744
0.175	36.1506	27.9447	59.9803	23.7823
0.176	35.9830	27.8191	59.7925	23.6916
0.177	35.8170	27.6951	59.6056	23.6023
0.178	35.6525	27.5726	59.4195	23.5144
0.179	35.4895	27.4517	59.2342	23.4279
0.180	35.3281	27.3323	59.0497	23.3427
0.181	35.1681	27.2144	58.8661	23.2589
0.182	35.0096	27.0980	58.6833	23.1764
0.183	34.8526	26.9831	58.5013	23.0952
0.184	34.6970	26.8696	58.3201	23.0153
0.185	34.5429	26.7575	58.1398	22.9366
0.186	34.3901	26.6469	57.9602	22.8592
0.187	34.2388	26.5377	57.7814	22.7830
0.188	34.0889	26.4298	57.6035	22.7079
0.189	33.9404	26.3233	57.4263	22.6341
0.190	33.7932	26.2182	57.2500	22.5614
0.191	33.6474	26.1144	57.0744	22.4898
0.192	33.5030	26.0119	56.8996	22.4194
0.193	33.3598	25.9107	56.7256	22.3501
0.194	33.2180	25.8107	56.5523	22.2818

0.195	33.0776	25.7121	56.3799	22.2147
0.196	32.9384	25.6146	56.2082	22.1485
0.197	32.8004	25.5185	56.0373	22.0835
0.198	32.6638	25.4235	55.8671	22.0194
0.199	32.5284	25.3297	55.6977	21.9564
0.200	32.3943	25.2371	55.5291	21.8943
0.201	32.2614	25.1457	55.3612	21.8332
0.202	32.1298	25.0554	55.1941	21.7731
0.203	31.9993	24.9663	55.0277	21.7139
0.204	31.8701	24.8783	54.8621	21.6556
0.205	31.7420	24.7914	54.6972	21.5983
0.206	31.6152	24.7056	54.5330	21.5418
0.207	31.4895	24.6209	54.3696	21.4863
0.208	31.3649	24.5373	54.2069	21.4316
0.209	31.2416	24.4547	54.0449	21.3777
0.210	31.1193	24.3731	53.8837	21.3248
0.211	30.9982	24.2926	53.7232	21.2726
0.212	30.8782	24.2131	53.5634	21.2213
0.213	30.7593	24.1347	53.4043	21.1707
0.214	30.6415	24.0572	53.2459	21.1210
0.215	30.5248	23.9806	53.0883	21.0720
0.216	30.4092	23.9051	52.9313	21.0238
0.217	30.2946	23.8305	52.7750	20.9764
0.218	30.1811	23.7569	52.6195	20.9297
0.219	30.0687	23.6841	52.4646	20.8838
0.220	29.9572	23.6123	52.3104	20.8385
0.221	29.8469	23.5414	52.1570	20.7940
0.222	29.7375	23.4714	52.0042	20.7502
0.223	29.6291	23.4023	51.8521	20.7070
0.224	29.5218	23.3341	51.7006	20.6646
0.225	29.4154	23.2667	51.5499	20.6228

0.226	29.3100	23.2002	51.3998	20.5816
0.227	29.2056	23.1345	51.2504	20.5411
0.228	29.1022	23.0696	51.1016	20.5013
0.229	28.9997	23.0056	50.9536	20.4620
0.230	28.8981	22.9423	50.8062	20.4234
0.231	28.7975	22.8799	50.6594	20.3854
0.232	28.6978	22.8183	50.5133	20.3480
0.233	28.5991	22.7574	50.3679	20.3111
0.234	28.5012	22.6973	50.2231	20.2749
0.235	28.4043	22.6380	50.0789	20.2392
0.236	28.3082	22.5794	49.9354	20.2041
0.237	28.2130	22.5215	49.7926	20.1695
0.238	28.1188	22.4644	49.6504	20.1355
0.239	28.0253	22.4080	49.5088	20.1020
0.240	27.9328	22.3523	49.3678	20.0690
0.241	27.8411	22.2973	49.2275	20.0365
0.242	27.7502	22.2431	49.0878	20.0046
0.243	27.6602	22.1895	48.9487	19.9731
0.244	27.5710	22.1365	48.8103	19.9422
0.245	27.4827	22.0843	48.6725	19.9117
0.246	27.3951	22.0327	48.5353	19.8817
0.247	27.3084	21.9817	48.3987	19.8522
0.248	27.2225	21.9314	48.2627	19.8231
0.249	27.1373	21.8818	48.1273	19.7945
0.250	27.0530	21.8327	47.9925	19.7664
0.251	26.9694	21.7843	47.8584	19.7387
0.252	26.8866	21.7365	47.7248	19.7114
0.253	26.8046	21.6893	47.5918	19.6846
0.254	26.7233	21.6427	47.4595	19.6581
0.255	26.6427	21.5967	47.3277	19.6321
0.256	26.5630	21.5513	47.1965	19.6065

0.257	26.4839	21.5064	47.0659	19.5813
0.258	26.4056	21.4621	46.9359	19.5565
0.259	26.3280	21.4184	46.8064	19.5321
0.260	26.2511	21.3752	46.6776	19.5081
0.261	26.1749	21.3326	46.5493	19.4844
0.262	26.0995	21.2905	46.4216	19.4611
0.263	26.0247	21.2489	46.2944	19.4382
0.264	25.9506	21.2078	46.1679	19.4156
0.265	25.8772	21.1673	46.0419	19.3934
0.266	25.8045	21.1273	45.9164	19.3716
0.267	25.7324	21.0878	45.7915	19.3501
0.268	25.6610	21.0488	45.6672	19.3289
0.269	25.5903	21.0103	45.5435	19.3080
0.270	25.5202	20.9723	45.4203	19.2875
0.271	25.4508	20.9347	45.2976	19.2673
0.272	25.3820	20.8976	45.1755	19.2474
0.273	25.3139	20.8610	45.0539	19.2279
0.274	25.2464	20.8249	44.9329	19.2086
0.275	25.1795	20.7892	44.8124	19.1896
0.276	25.1132	20.7540	44.6925	19.1710
0.277	25.0475	20.7192	44.5731	19.1526
0.278	24.9825	20.6848	44.4542	19.1345
0.279	24.9180	20.6509	44.3359	19.1167
0.280	24.8541	20.6174	44.2181	19.0992
0.281	24.7908	20.5844	44.1008	19.0820
0.282	24.7282	20.5517	43.9840	19.0650
0.283	24.6660	20.5195	43.8678	19.0483
0.284	24.6045	20.4877	43.7521	19.0319
0.285	24.5435	20.4562	43.6369	19.0157
0.286	24.4831	20.4252	43.5222	18.9997
0.287	24.4233	20.3946	43.4080	18.9840

0.288	24.3640	20.3643	43.2944	18.9686
0.289	24.3052	20.3345	43.1812	18.9534
0.290	24.2470	20.3050	43.0686	18.9385
0.291	24.1893	20.2759	42.9564	18.9237
0.292	24.1322	20.2471	42.8448	18.9092
0.293	24.0756	20.2187	42.7336	18.8950
0.294	24.0195	20.1907	42.6230	18.8809
0.295	23.9639	20.1630	42.5129	18.8671
0.296	23.9089	20.1357	42.4032	18.8535
0.297	23.8543	20.1087	42.2940	18.8401
0.298	23.8003	20.0821	42.1854	18.8270
0.299	23.7467	20.0558	42.0772	18.8140
0.300	23.6937	20.0298	41.9695	18.8012
0.301	23.6411	20.0042	41.8622	18.7886
0.302	23.5890	19.9788	41.7555	18.7763
0.303	23.5374	19.9538	41.6492	18.7641
0.304	23.4863	19.9292	41.5434	18.7521
0.305	23.4357	19.9048	41.4381	18.7403
0.306	23.3855	19.8807	41.3333	18.7287
0.307	23.3358	19.8570	41.2289	18.7173
0.308	23.2865	19.8335	41.1250	18.7060
0.309	23.2377	19.8104	41.0216	18.6949
0.310	23.1893	19.7875	40.9186	18.6840
0.311	23.1414	19.7649	40.8160	18.6733
0.312	23.0940	19.7426	40.7140	18.6627
0.313	23.0469	19.7206	40.6124	18.6523
0.314	23.0004	19.6989	40.5112	18.6421
0.315	22.9542	19.6774	40.4105	18.6320
0.316	22.9085	19.6562	40.3103	18.6221
0.317	22.8631	19.6353	40.2105	18.6124
0.318	22.8182	19.6146	40.1111	18.6028

0.319	22.7738	19.5942	40.0122	18.5933
0.320	22.7297	19.5741	39.9137	18.5840
0.321	22.6860	19.5542	39.8157	18.5748
0.322	22.6428	19.5346	39.7181	18.5658
0.323	22.5999	19.5152	39.6210	18.5569
0.324	22.5574	19.4961	39.5243	18.5482
0.325	22.5154	19.4772	39.4280	18.5396
0.326	22.4737	19.4585	39.3321	18.5311
0.327	22.4324	19.4401	39.2367	18.5228
0.328	22.3915	19.4219	39.1417	18.5146
0.329	22.3509	19.4039	39.0471	18.5065
0.330	22.3107	19.3862	38.9530	18.4986
0.331	22.2710	19.3687	38.8592	18.4908
0.332	22.2315	19.3514	38.7659	18.4831
0.333	22.1925	19.3343	38.6730	18.4755
0.334	22.1538	19.3175	38.5806	18.4680
0.335	22.1154	19.3008	38.4885	18.4607
0.336	22.0774	19.2844	38.3968	18.4535
0.337	22.0398	19.2682	38.3056	18.4464
0.338	22.0025	19.2521	38.2148	18.4393
0.339	21.9655	19.2363	38.1243	18.4325
0.340	21.9289	19.2207	38.0343	18.4257
0.341	21.8926	19.2053	37.9447	18.4190
0.342	21.8567	19.1901	37.8555	18.4124
0.343	21.8211	19.1750	37.7667	18.4060
0.344	21.7858	19.1602	37.6782	18.3996
0.345	21.7509	19.1455	37.5902	18.3933
0.346	21.7163	19.1311	37.5026	18.3871
0.347	21.6819	19.1168	37.4153	18.3811
0.348	21.6480	19.1027	37.3285	18.3751
0.349	21.6143	19.0887	37.2420	18.3692

0.350	21.5809	19.0750	37.1559	18.3634
0.351	21.5478	19.0614	37.0703	18.3577
0.352	21.5151	19.0480	36.9849	18.3521
0.353	21.4826	19.0347	36.9000	18.3466
0.354	21.4505	19.0217	36.8155	18.3411
0.355	21.4186	19.0088	36.7313	18.3358
0.356	21.3871	18.9960	36.6475	18.3305
0.357	21.3558	18.9834	36.5641	18.3253
0.358	21.3248	18.9710	36.4811	18.3202
0.359	21.2941	18.9588	36.3984	18.3152
0.360	21.2637	18.9466	36.3161	18.3103
0.361	21.2336	18.9347	36.2341	18.3054
0.362	21.2037	18.9229	36.1526	18.3006
0.363	21.1742	18.9112	36.0714	18.2959
0.364	21.1449	18.8997	35.9905	18.2913
0.365	21.1158	18.8883	35.9101	18.2867
0.366	21.0871	18.8771	35.8299	18.2822
0.367	21.0586	18.8660	35.7502	18.2778
0.368	21.0303	18.8551	35.6708	18.2734
0.369	21.0024	18.8443	35.5917	18.2691
0.370	20.9746	18.8336	35.5130	18.2649
0.371	20.9472	18.8231	35.4347	18.2607
0.372	20.9200	18.8127	35.3567	18.2566
0.373	20.8930	18.8024	35.2791	18.2526
0.374	20.8663	18.7923	35.2018	18.2487
0.375	20.8398	18.7823	35.1248	18.2448
0.376	20.8136	18.7724	35.0482	18.2409
0.377	20.7876	18.7627	34.9720	18.2371
0.378	20.7619	18.7530	34.8960	18.2334
0.379	20.7364	18.7435	34.8205	18.2298
0.380	20.7112	18.7341	34.7452	18.2262

0.381	20.6861	18.7248	34.6703	18.2226
0.382	20.6613	18.7157	34.5957	18.2191
0.383	20.6368	18.7066	34.5215	18.2157
0.384	20.6124	18.6977	34.4476	18.2123
0.385	20.5883	18.6889	34.3740	18.2090
0.386	20.5644	18.6802	34.3008	18.2057
0.387	20.5407	18.6716	34.2278	18.2025
0.388	20.5173	18.6631	34.1553	18.1993
0.389	20.4940	18.6547	34.0830	18.1962
0.390	20.4710	18.6465	34.0110	18.1931
0.391	20.4482	18.6383	33.9394	18.1901
0.392	20.4256	18.6302	33.8681	18.1871
0.393	20.4032	18.6223	33.7971	18.1841
0.394	20.3810	18.6144	33.7265	18.1812
0.395	20.3590	18.6067	33.6561	18.1784
0.396	20.3373	18.5990	33.5861	18.1756
0.397	20.3157	18.5914	33.5164	18.1728
0.398	20.2943	18.5840	33.4470	18.1701
0.399	20.2731	18.5766	33.3779	18.1675
0.400	20.2521	18.5693	33.3091	18.1648

9.3 Excel file



Joshua U'Dell
ACMA6011 Assignment