ABSTRACT

VERGARA GONZALEZ, PEDRO PABLO. Development of Scaling Laws for Electrothermal Plasma Sources with Geometry Variables. (Under the direction of Dr. Mohamed Bourham and Dr. John Gilligan.)

Development of operational scaling laws for electrothermal plasma discharges can be a useful quick tool to provide information on the capillary plasma exit parameters. While a computational modeling code exists for this purpose, the scaling laws can provide simplified prediction with good accuracy in a shorter time as compared to the longer running time of codes. Additionally, it will facilitate the practical identification of the particular capillary geometry and the input discharge current that produce certain desired exit parameters. Therefore, it is a simple technique to narrow down the options of geometry and input current that can be input into the code for a more accurate calculation of the exits parameters and the axial behavior of the plasma parameters inside the electrothermal source. The computer code ETFLOW was used as the source of data for the fitting and semi-empirical modeling of the scaling laws. The ETFLOW code provides the axial and temporal plasma parameters of the electrothermal plasma discharge for chosen capillary geometry, sleeve material and discharge current. Data were obtained for 53 pure materials and 2 compounds for an electrothermal plasma discharge, for currents ranged from 3 to 90 KA, inner capillary radii ranged from 0.6 to 2.5 mm and capillary lengths from 7 to 14 cm. The data were analyzed to determine how changes in the discharge current, inner radius and capillary length affect the maximum values of the exit parameters. From data analysis, scaling laws where developed for the exit values of temperature, heat flux, bulk velocity, pressure and total ablated mass. Moreover, two temperature scaling laws

were developed that only depends on the material parameters, capillary geometry and peak current of the discharge. The results of the scaling laws equations were compared against the data generated by the ETFLOW code. It was found that the maximum error obtain for the general scaling laws for the temperature, heat flux, bulk velocity, total ablated mass and pressure are 3.04%, 12%, 5.13%, 19.41% and 22.08%, respectively as compared to the ETFLOW results. For the case of specific pure material temperature scaling laws, the maximum errors are 11.3% and 15%. The total ablated mass scaling law error was found to be less than 20% for peak currents less than 40 KA when compared to experimental data. It was concluded that the scaling laws predictions have good accuracy of the exit parameters as compared to the actual code runs. However, corrections should be made to the coefficients of these equations for non-ideal plasma conditions that are prevalent at high peak currents.

Development of Scaling Laws for Electrothermal Plasma Sources with Geometry Variables

by
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DEDICATION

This thesis is dedicated to my wife, Carmen Gloria, who has given me all her love, support and understanding, without her by my side and my little daughter, Amelia, nothing would have any meaning. Also, to my parents, Veronica and Pedro Pablo, who have taught me throughout their guidance and example how to achieve my goals, with perseverance, devotion and respect toward others.

BIOGRAPHY

Pedro Pablo Vergara Gonzalez was born in Santiago Chile, in January 14 of 1981. His school and High school studies were done in Colegio del Verbo Divino in Santiago from which he graduated in 1998. From 1999 to 2000 he studied business administration in Universidad de Chile, from where he quitted following his technological and scientific passion. He did the course work for Electronic Engineering in Universidad Mayor from 2001 to 2006 (Engineering in Chile is a 6 years career), from where he obtained his bachelor and professional degree in 2009 first ranking of his class. He worked as an engineer in DTS for four years from 2006 to 2009 in the defense division making radar detection systems for the navy and aviation of his country. In 2010 he moved to USA to prepare the necessary test for graduate studies. At the beginning of 2011 he got married with Carmen Gloria Garcia Signorelli. In 2011 he began his studies of M.S. in Nuclear Engineering at North Carolina State University, where he remained during the course of this work.

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Chapter 1

Introduction

1.1 The Confined Capillary Electrothermal Plasma Discharges

A confined capillary electrothermal (ET) plasma discharge is a type of plasma formation produced by an arc through a high current electric pulsed discharge in the range of several kilo amperes. The capillary has a small radius in the order of millimeters and length of several centimeters. This discharge produces high-density plasma up to $10^{28}/m^3$ with temperature as high as 3eV. The system consists of a high voltage 317μF capacitor, which can be charged to a maximum of 10kV to deliver up to 100kA discharge current, connected to an electrode (cathode) via a high voltage spark gap switch that discharges when triggered by a high voltage pulse. Upon discharge an electric arc propagates through the capillary sleeve and radiatively heats the inner wall of the capillary as a black-body.

The arc's high temperature ablates the wall of the inner sleeve and the evaporated sleeve material is dissociated and ionized forming the plasma. The plasma is ejected through the exit of the capillary producing a high velocity, high pressure plasma jet.

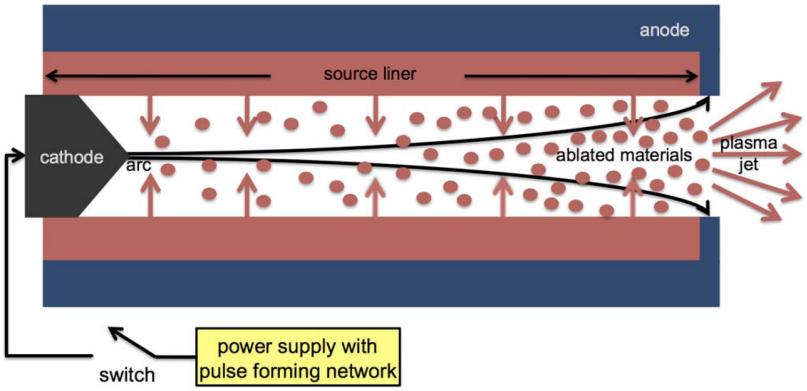


Figure 1.1: Capillary discharge generating an electrothermal plasma jet, picture taken from Winfrey et al [1].

The sleeve material of the capillary can be fabricated from any material or compound in tubular shape to fit inside the capillary. For an electrically conductive sleeve material, the sleeve must have two insulator end-pieces to isolate it from the cathode and the anode.

Electrothermal plasma discharges have uses in many applications such as space satellite thrusters [2], high velocity launchers [3–5], fusion reactor pellet accelerators [6, 7] and as high heat flux sources [8]. Over the last decades there have been researches conducted to theoretically model electrothermal plasma capillary discharges [1, 9, 10] and developing computer codes to simulate their performance. These models have achieved a good level of accuracy with reasonable running times.

1.2 Purpose of the study

The main goal of this study was to develop general scaling laws that could predict with acceptable accuracy, the exit plasma parameters from electrothermal sources, i.e. temperature, heat flux, bulk velocity, pressure and total ablated mass. The scaling law equations must include the geometrical configuration of the capillary, the input discharge current and the properties of the capillary sleeve material. Scaling laws equations were developed for the purpose of having a fast and easy way to calculate the exit parameters without the need to run the full computational simulation. The code provides the full information on the plasma parameters and their axial behavior inside the capillary, thus the scaling laws can provide an easy way to calculate the needed input current for a particular capillary geometry and material to achieve a specific desired exit parameters. For example, if it is desired to conduct an experiment on material hardening of a substrate at the exit of the capillary then one can use the scaling laws to calculate the exit parameters and use the discharge current and geometry in the full code to obtain the full simulation. The scaling laws can provide information on the exit bulk velocity of the plasma ions/atoms necessary to implant the substrate. The scaling law will provide the form of the peak discharge current and the corresponding capillary geometry that provides such desired exit velocity and the amount of mass ejected from the source towards the substrate. Hence, the scaling laws will save the computational time and efforts of the full code to obtain these parameters. Furthermore, the scaling laws equations could be used by an optimization software that could find an optimal configuration to obtain the desired parameters.

Chapter 2

Essential 1-D, Time-Dependent Capillary Plasma Model

Development of the scaling laws was made using the data obtained from the ETFLOW code. This code is an evolution of many computational codes that solve the basic governing equations of a capillary discharge [9, 11–13]. The code has incorporated the change in the friction coefficient according to the changes in the Reynolds number, the essential equation of state, the radiation heat transport with the vapor shield effect, and the ideal and non-ideal models for the plasma conductivity [14]. ETFLOW was written as a 1-D time-dependent code in FORTRAN and translated into Visual Basic for Application (VBA) environment, which is the version used in this work.

2.1 Governing Equations and Assumptions

2.1.1 Mass Continuity equation

The mass continuity equation is written as:

$$\frac{\partial n}{\partial t} = \dot{n}_{ablation} - \frac{\partial vn}{\partial z} \tag{2.1}$$

In this equation, n is the plasma number density, v is the velocity, $\dot{n}_{ablation}$ is the mass ablated from the capillary inner wall. The ablated mass comes from the plasma thermal radiation onto the inner wall of the capillary sleeve and is modeled as a black-body radiating heat flux to the wall.

The number density of the ablated material is modeled as:

$$\dot{n}_{ablation} = \frac{2q''_{rad}}{H_{sub}AR} \tag{2.2}$$

Here, A is the mass of the plasma atoms (kg/atoms), R is the inner radius of the capillary in meters, q''_{rad} is the radiation heat flux which is assumed to be a fraction of the black body radiation as a result of the vapor shielding mechanism. H_{sub} is the enthalpy of sublimation and vaporization in joules, and the $2/R$ factor is the result of transferring volume to surface heat flux.

The radiative heat flux is written as:

$$q''_{rad} = f\sigma_{SB}T^4 \tag{2.3}$$

Where f is the fraction of the heat flux that reaches the wall through the vapor shielding, σ_{SB} is the Stephan-Boltzmann constant and T is the plasma kinetic temperature.

The vapor shielding fraction is given by:

$$f = \frac{\rho H_{sub}}{P+\rho U+\rho H_{sub}} \tag{2.4}$$

In this case ρ is the plasma density (Kg/m^3), P is the kinetic pressure, U is the plasma internal energy and H_{sub} is the heat of sublimation of the linear (inner sleeve) material [9]. This assumes that there are no other radiative or combustion melting energy losses.

2.1.2 Conservation of Momentum

The equation of conservation of momentum is written as:

$$\frac{\partial v}{\partial t} + \frac{1}{\rho}\frac{\partial P}{\partial z} + \frac{1}{2}\frac{\partial v^2}{\partial z} + \frac{\dot{n}_{ablation}}{n}v + \frac{2\tau_w}{\rho R} = 0 \tag{2.5}$$

Here, τ_w is the viscous drag and is explained in detail in the work of Hurley et al [9], the $\frac{1}{\rho}\frac{\partial P}{\partial z}$ term is the change in momentum due to the pressure gradient, $\frac{\dot{n}_{ablation}}{n}v$ is the change in the momentum due to the slowing down of the flow and $\frac{2\tau_w}{\rho R}$ is the effect of viscous

drag [9]. Since the kinetic plasma pressure is much higher than the magnetic pressure, and the aspect ratio (capillary radius/capillary length) is very small, the effect of JXB is neglected in the code formalism.

2.1.3 Conservation of Energy

The equation of conservation of energy is written as:

$$n\frac{\partial U}{\partial t} = \eta J^2 - \frac{2q''}{R} - P\frac{\partial v}{\partial z} - \frac{1}{2}\dot{\rho}_{ablation}v^2 - \dot{n}_{ablation}U - v\frac{\partial (nU)}{\partial z} \tag{2.6}$$

In this equation, η is the plasma resistivity and J is the discharge current density. The term ηJ^2 is the Joule heating, $\frac{2q''}{R}$ is the loss in internal energy due to thermal radiation, $P\frac{\partial v}{\partial z}$ is the change in internal energy due to the plasma flow work, $\frac{1}{2}\dot{\rho}_{ablation}v^2$ is the change in kinetic energy due to ablated mass, $\dot{n}_{ablation}U$ is the loss in internal energy due to cold ablated material entering the plasma, $\frac{1}{2}\dot{\rho}_{ablation}v^2$ is the change in the internal energy because of particles leaving and entering the cell [9].

The plasma resistivity is the addition of the resistivity due to electron-ion and electron-neutral collisions. For the ideal case the resistivity is given by the Spitzer model [15]:

$$\eta_{ie} = 38\overline{Z}ln(\Lambda)/\alpha_e T^{3/2} \tag{2.7}$$

For the non-ideal plasma case the resistivity is given by the energy averaged momentum transport model of Zaghloul-Bourham-Doster-Powell [16]:

$$\eta_{ei} = \frac{38\overline{Z}}{\alpha_e T^{3/2}} \left(\frac{\pi}{2} sin(\frac{3}{2\Lambda}) \left[1 - \frac{2}{\pi} Si(\frac{3}{2\Lambda}) - \frac{2}{\pi} \frac{Ci(3/2\Lambda)}{tan(3/2\Lambda)} \right] \right) \quad (2.8)$$

The internal energy is modeled as:

$$U = \overline{I} + H_{sub} + \frac{3}{2} kT(1 + \overline{Z}) \quad (2.9)$$

Where, $\overline{I}$ is the internal energy due to ionization, H_{sub} is the enthalpy of sublimation, the term $3kT(1 + \overline{Z})/2$ is the internal energy due to thermal motion and $\overline{Z}$ is the average charge state [9, 14, 17].

2.2 Capillary Code Configuration

ETFLOW is written in FORTRAN and runs in VBA environment on Excel. The configurations of the parameters are made in the *Main* spread sheet, as shown in Figure 2.1. As it can be seen, it has all the necessary input parameters that must be configured before it can produce results for a particular electrothermal plasma discharge. Also, it should be noted that since it is in a spread sheet it is very easy for the user to input the desired parameters. The code divides the Capillary's length in eleven nodes, with the exit node being the eleventh one of the capillary. This node is from where the data for this work was taken to determine the scaling laws of the exit parameters.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Program ET-flow version Ver 2.00 - 2008 - Excel VBA Macro Code								101325		current data (E=External file)	
2	ElectroThermal flow code										E	
3	By M.A. Abd Al-Halim and A.L Winfrey											
4	Ref : 'TITAN' --> TIme dependent Two dimensional heat and current trANsport										run (C= check current only)	
5	Original ver: Fortran Code by H. Ngo, Fall 1998 and updated by B. Lambert, Fall 2000											
6												
7	Vo(kV)	Co(uF)	Lo(nH)	ro(ohm)	P (Pa)			Axial Z node #			ideal or non ideal case	
8	100	70	70	0.05	2660			11			ideal	
9												
10	KMAX	Δ t	Ifactor									
11	100000	1E-10	1									
12												
13	Rplasma(	Rsleeve(m)	Rwall(m)	Rcham(m)	Lcap(m)	Lcham(m)				9	Sleeve (A: Abl. C: Comb. N: None)	
14	0.00198	0.0035719	0.0051594	0.085	0.09	0.7					A	
15												
16	Sleeve	wall	combust 1	combust 2							Gas (C: Comb. N: None)	
17	26	210	27	28							N	
18	choose the row No. from "material" sheet											
19												
20	188											
21		Formula	Name	Z	Phase	Structure	note	(atom/molecule)	Mass	melting	vaporization	sublimation	disso
22	sleeve	C	carbon (grap	6	S			1	12.011	117	355.8	711.28	
23	wall	C16H14O3	Lexan	compound				33	254.2848			13731.40944	
24	combust.	N	nitrogen	7	G			1	14.0067	0.72	5.577		
25	combust.	O	oxygen	8	G			1	15.9994	0.444	6.82	8.204	

Figure 2.1: ETFLOW main configuration spread sheet

First, it is needed to input the lengths of the capillary sleeve and the chamber, however, the chamber in this work was held unchanged. Also, the inner dimension of the sleeve which is also considered to be the plasma radius (Rplasma) and outer sleeve's radius (Rsleeve), which is held unchanged in this work. These input parameters are shown in Figure 2.2.

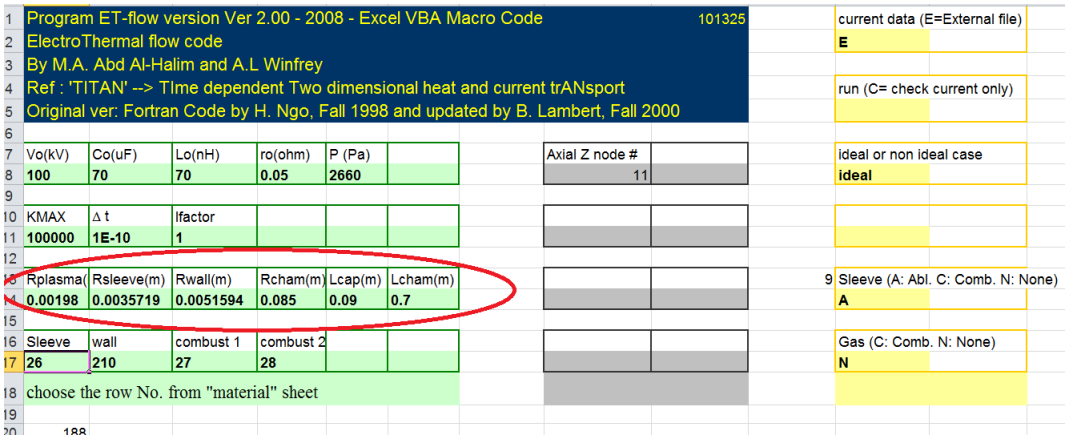
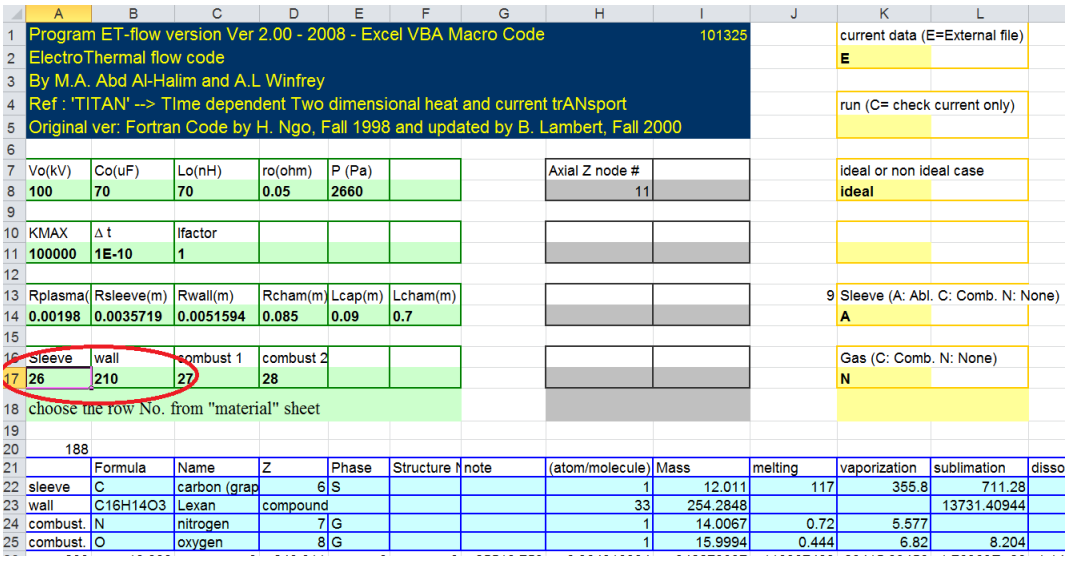


Figure 2.2: ETFLOW geometrical configuration screen

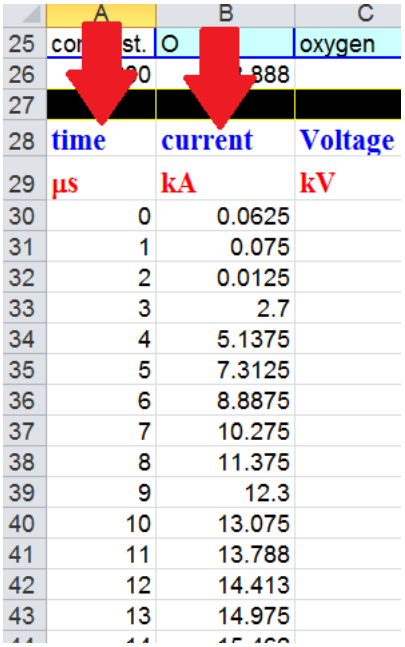
The material of the sleeve and the wall are also input parameters, however, the wall material does not affect the calculations and only the parameters of the sleeve material are used in the calculations. The code has a materials library that does include the entire periodic table, as well as many insulators and compounds. Selection of the sleeve material is done by simple writing its number in the cell designated for the material, as depicted in Figure 2.3. The code will automatically take the selected material's parameters from the library database and input them in the equations during the execution of the code.



Program ET-flow version Ver 2.00 - 2008 - Excel VBA Macro Code								101325			current data (E=External file)	
ElectroThermal flow code											E	
By M.A. Abd Al-Halim and A.L Winfrey												
Ref : 'TITAN' --> TIme dependent Two dimensional heat and current trANsport											run (C= check current only)	
Original ver: Fortran Code by H. Ngo, Fall 1998 and updated by B. Lambert, Fall 2000												
Vo(kV)	Co(uF)	Lo(nH)	ro(ohm)	P (Pa)			Axial Z node #				ideal or non ideal case	
100	70	70	0.05	2660			11				ideal	
KMAX	Δ t	Ifactor										
100000	1E-10	1										
Rplasma(	Rsleeve(m)	Rwall(m)	Rcham(m)	Lcap(m)	Lcham(m)					9	Sleeve (A: Abl. C: Comb. N: None)	
0.00198	0.0035719	0.0051594	0.085	0.09	0.7						A	
Sleeve	wall	combust 1	combust 2								Gas (C: Comb. N: None)	
26	210	27	28								N	
choose the row No. from "material" sheet												
188												
	Formula	Name	Z	Phase	Structure	note	(atom/molecule)	Mass	melting	vaporization	sublimation	disso
sleeve	C	carbon (grap	6	S			1	12.011	117	355.8	711.28	
wall	C16H14O3	Lexan	compound				33	254.2848			13731.40944	
combust.	N	nitrogen	7	G			1	14.0067	0.72	5.577		
combust.	O	oxygen	8	G			1	15.9994	0.444	6.82	8.204	

Figure 2.3: ETFLOW sleeve and wall configuration screen

The file of the discharge current is to be introduced in the designated cells where each row holds the current amplitude at a specific time in microsecond. The specific time is configuring in the adjacent column, as shown in Figure 2.4. The discharge current file can be an actual one from an experiment or an artificial one generated by the built in circuit module for any desired amplitude, shape and pulse duration.



	A	B	C
25	cor st.	O	oxygen
26	00	888	
27			
28	time	current	Voltage
29	µs	kA	kV
30	0	0.0625	
31	1	0.075	
32	2	0.0125	
33	3	2.7	
34	4	5.1375	
35	5	7.3125	
36	6	8.8875	
37	7	10.275	
38	8	11.375	
39	9	12.3	
40	10	13.075	
41	11	13.788	
42	12	14.413	
43	13	14.975	

Figure 2.4: ETFLOW current and time configuration screen

The code has also the option of running combustion cases in which the set of governing equations are different than the equations of ablation. The code for this study was only used for the ablation without any combustion. The input on the 'main' spreadsheet must indicate which modules to use and hence the appropriate instruction must be entered into the cells to indicate which modules to use (A: for ablation, C: for combustion and N: for none). Also, it has to be configured if the code runs for an ideal or non-ideal plasma case, as shown in Figure 2.5.

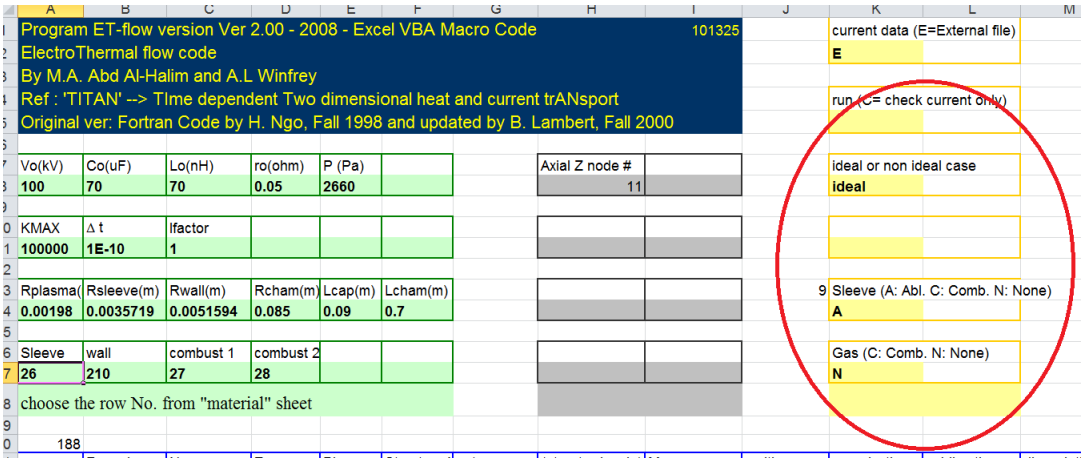


Figure 2.5: ETFLOW case configuration screen

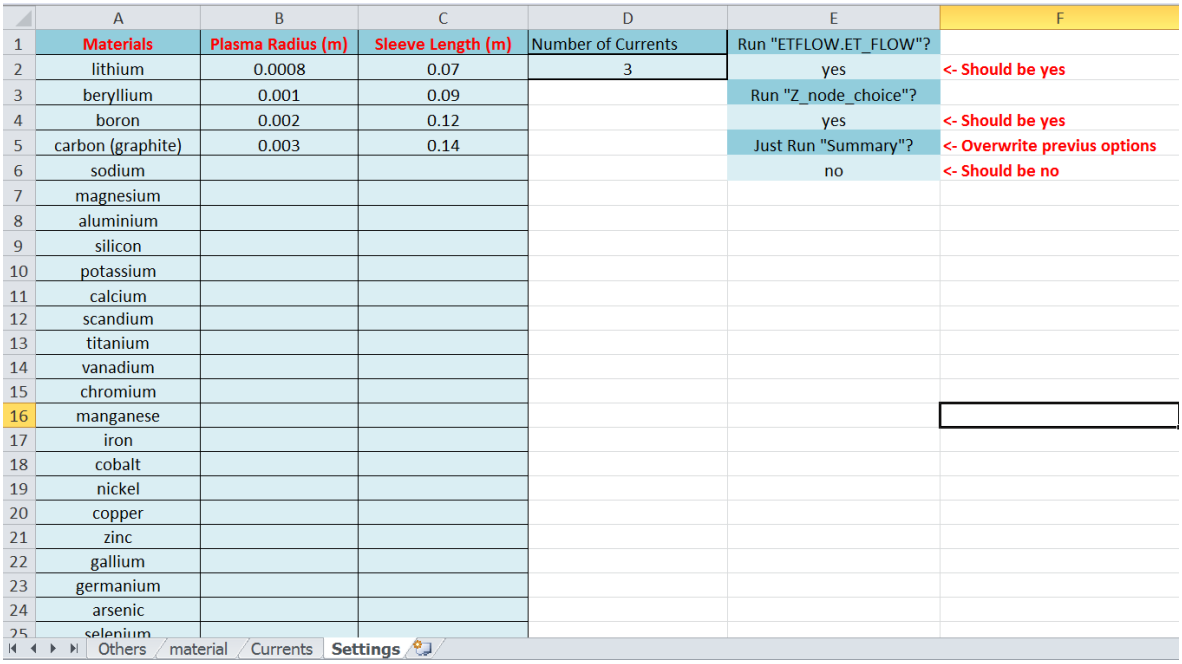
After having the entire configuration set up, the code can be set to run and will take about 30 to 40 minutes to give the full results for an ideal case with a current of about 200 μs of pulse width. After the run is completely executed the parameters of the selected node will show up on the screen as shown in Figure 2.6, from where one can select the needed data. These parameters are also automatically plotted for the exit node, however, other nodes are also tabulated and can be plotted if the code is instructed to plot. Axial behavior of the parameters can also be plotted when instructed to plot. Additionally, comparison plots can be generated by choosing which parameters to compare to each other and at what time steps.

27				240.011			4695.0371	0.073551018	4714663.514	2.3906E+05
28	time	current	Voltage	TIME			T	RHO	RHOU	PRESS
29	μs	kA	kV	μs			K	kg/m^3		N/m^2
30	0	0.0625		0.00012			5102.1335	0.000752436	48586.23207	2657.61928
31	1	0.075		0.00026			5101.0957	0.000751781	48542.9988	2654.76419
32	2	0.0125		0.00044			5099.854	0.000750994	48491.11949	2651.34091
33	3	2.7		0.00064			5098.3699	0.00075005	48428.86592	2647.23746
34	4	5.1375		0.00089			5096.599	0.000748917	48354.16522	2642.3205
35	5	7.3125		0.00119			5094.4907	0.000747558	48264.53173	2636.43172
36	6	8.8875		0.00155			5091.9892	0.000745925	48156.98592	2629.384
37	7	10.275		0.00198			5089.0358	0.000743966	48027.95828	2620.95751
38	8	11.375		0.0025			5085.5743	0.000741615	47873.17595	2610.89645

Figure 2.6: ETFLOW output parameters of specific node

2.3 ETFLOW Code Automation

The code ETFLOW takes around 30 minutes to run for each configured case, for a chosen material, specific inner radius, length and current. Therefore, an automated code named *autoPIPE* was developed to run the code hundreds of times to fulfill various configurations. The autoPIPE code automates ETFLOW code runs, take the data from it and produce summaries of the plasma parameters. The autoPIPE code setting tab screen is shown in Figure 2.6, and the autoPIPE code source listing is shown in Appendix C.



	A	B	C	D	E	F
1	Materials	Plasma Radius (m)	Sleeve Length (m)	Number of Currents	Run "ETFLOW.ET_FLOW"?	
2	lithium	0.0008	0.07	3	yes	<- Should be yes
3	beryllium	0.001	0.09		Run "Z_node_choice"?	
4	boron	0.002	0.12		yes	<- Should be yes
5	carbon (graphite)	0.003	0.14		Just Run "Summary"?	<- Overwrite previus options
6	sodium				no	<- Should be no
7	magnesium					
8	aluminium					
9	silicon					
10	potassium					
11	calcium					
12	scandium					
13	titanium					
14	vanadium					
15	chromium					
16	manganese					
17	iron					
18	cobalt					
19	nickel					
20	copper					
21	zinc					
22	gallium					
23	germanium					
24	arsenic					
25	selenium					

Others | material | Currents | Settings

Figure 2.7: autoPIPE code settings tab screen

As shown in Figure 2.7 the *settings* tab configures the sleeve materials, and the inner radius and length of the capillary sleeve. Also, it sets the number of discharge currents that will be run for each material, radius and length. The material's identification are written under *column* A and they have to match exactly the *materials* tab of ETFLOW code. The code will make runs for each material, inner radius, length and currents. That is, if one configures 4 materials, with 4 radii, 4 lengths and 4 discharge currents, then the code will run ETFLOW to 256 times.

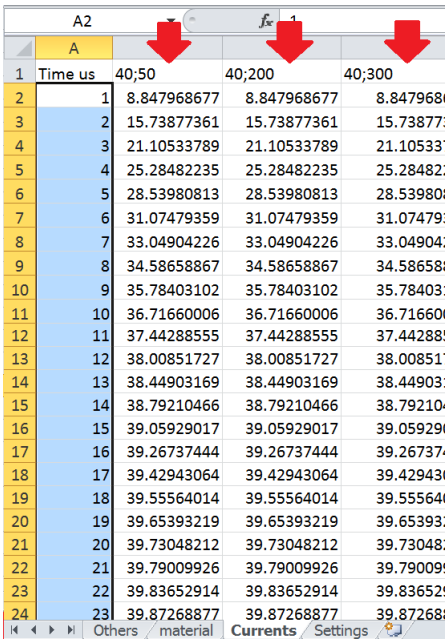
Under *column* E in the *settings* tab, as shown in Figure 2.8, the user can configure if it is desired to run ETFLOW or if just want to run the summaries. This is need when the user just wants the summaries of some materials. Also, if there was an error during the ETFLOW process, such as truncation error, and it is needed to summaries previous materials information, the materials to be summarized are the ones listed under the Materials column.

	A	B	C	D	E	F
1	Materials	Plasma Radius (m)	Sleeve Length (m)	Number of Currents	Run "ETFLOW.ET_FLOW"?	
2	lithium	0.0008	0.07	3	yes	<- Should be yes
3	beryllium	0.001	0.09		Run "Z_node_choice"?	
4	boron	0.002	0.12		yes	<- Should be yes
5	carbon (graphite)	0.003	0.14		Just Run "Summary"?	<- Overwrite previus options
6	sodium				no	<- Should be no
7	magnesium					
8	aluminium					
9	silicon					
10	potassium					
11	calcium					
12	scandium					
13	titanium					
14	vanadium					
15	chromium					
16	manganese					
17	iron					
18	cobalt					
19	nickel					
20	copper					
21	zinc					
22	gallium					
23	germanium					
24	arsenic					
25	selenium					

Others | material | Currents | Settings

Figure 2.8: autoPIPE code settings tab screen, showing run configuration.

The discharge currents to be configured in ETFLOW are set in the *Currents* tab, starting from *column* B, as shown in Figure 2.9. Each cell in the column, starting from row 2, must contain the amplitude of the current at the corresponding time of the same row in microseconds. If in the *settings* tab it was set that the program would run for 3 currents, then, the code will take as first current the one in *column* A, the second current as the one in *column* B and the third in *column* C. If more currents are configured the software will continue to take the currents from the next columns.



	A			
1	Time us	40;50	40;200	40;300
2	1	8.847968677	8.847968677	8.847968
3	2	15.73877361	15.73877361	15.73877
4	3	21.10533789	21.10533789	21.10533
5	4	25.28482235	25.28482235	25.28482
6	5	28.53980813	28.53980813	28.53980
7	6	31.07479359	31.07479359	31.07479
8	7	33.04904226	33.04904226	33.04904
9	8	34.58658867	34.58658867	34.58658
10	9	35.78403102	35.78403102	35.78403
11	10	36.71660006	36.71660006	36.71660
12	11	37.44288555	37.44288555	37.44288
13	12	38.00851727	38.00851727	38.00851
14	13	38.44903169	38.44903169	38.44903
15	14	38.79210466	38.79210466	38.79210
16	15	39.05929017	39.05929017	39.05929
17	16	39.26737444	39.26737444	39.26737
18	17	39.42943064	39.42943064	39.42943
19	18	39.55564014	39.55564014	39.55564
20	19	39.65393219	39.65393219	39.65393
21	20	39.73048212	39.73048212	39.73048
22	21	39.79009926	39.79009926	39.79009
23	22	39.83652914	39.83652914	39.83652
24	23	39.87268877	39.87268877	39.87268

Figure 2.9: autoPIPE Currents Tab.

The code contains a second macros call *(ClearResultsWorkbook)* that when activated erases all the tabs with exception of *Others*, *material*, *Currents* and *Settings* Tabs. The name of the file is *"autoPIPE V2.4.xls"* and it must run in the same folder of the ETFLOW *"ETF27 PIPE.xls"*.

Chapter 3

Influence of Geometry and Peak Current on Plasma Parameters

3.1 Influence of Geometry on Plasma Parameters

In order to develop scaling laws for the capillary plasma discharge dependent on its geometry, it is first required to understand how a change in the geometry affects the parameters. In this section it will be shown how the plasma parameters change due to geometry variation in the capillary's radius and length. Two pure elements, carbon and titanium, and one compound (Lexan polycarbonate $C_{16}H_{14}O_3$) are compared. All the 53 elements and the two compounds analyzed during the course of this work follow the same behavior of these three materials. The data shown in this part was taken from the results given by the code ETFLOW for the configured conditions.

3.1.1 Influence of Capillary Radius on Plasma Parameters

The following figures show how the plasma temperature (Figure 3.1), heat flux (Figure 3.2), bulk velocity (Figure 3.3), total ablated mass (Figure 3.4) and pressure (Figure 3.5) are changing when the radius of the capillary sleeve changes. The data shows a carbon "graphite" case for a 40 KA peak discharge current and a capillary length of 9 cm, along with sleeves from Lexan polycarbonate and a titanium case for the same geometric parameters but for a peak current of 18.888 KA. For each case it has been fitted to a power law ($Parameter = aR^b$), where "parameter" is any of the plasma parameters under consideration, (R) is the capillary sleeve radius and (a) and (b) are the fit coefficients. For all exit plasma parameters shown in Figures 11 through 15, it is clear that the "parameter" magnitude decreases with increased sleeve radius. This is expected because the increase in the capillary sleeve's radius, which is the plasma radius, increases the plasma volume but the discharge current is at the same magnitude and pulse width. Hence, it is expected that plasma temperature, pressure, velocity and total ablated mass will decrease as a result of reduction in the radiative heat flux due to volume enlargement. The difference between the materials behavior lies on the magnitude of the plasma parameter and how fast the magnitude changes as a result of increased radius.

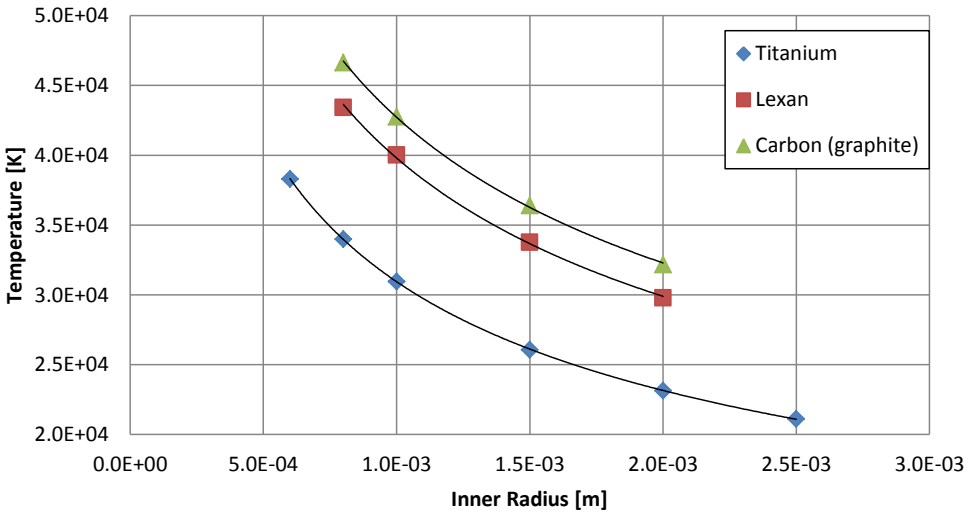


Figure 3.1: Variation in plasma temperature due to changes in inner radius.

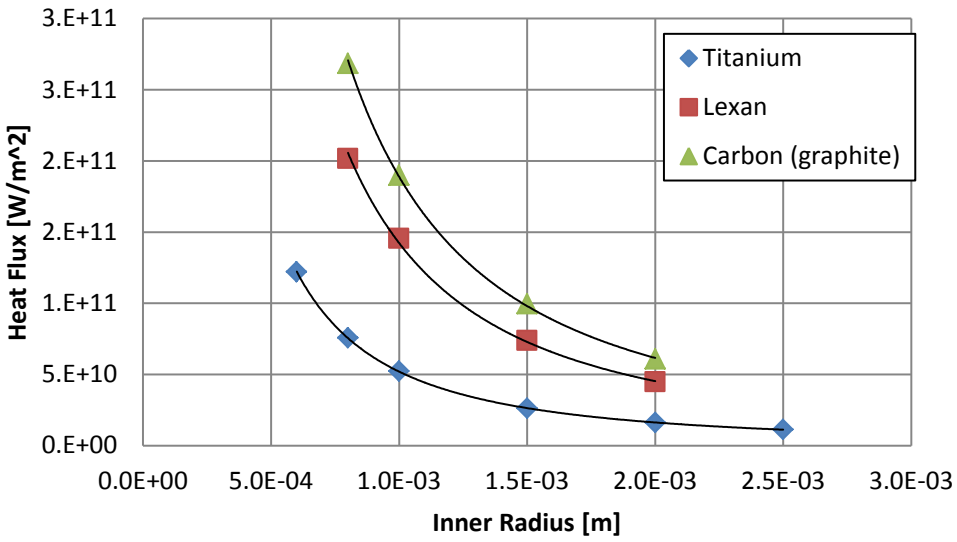


Figure 3.2: Variation in radiative heat flux due to changes in inner radius.

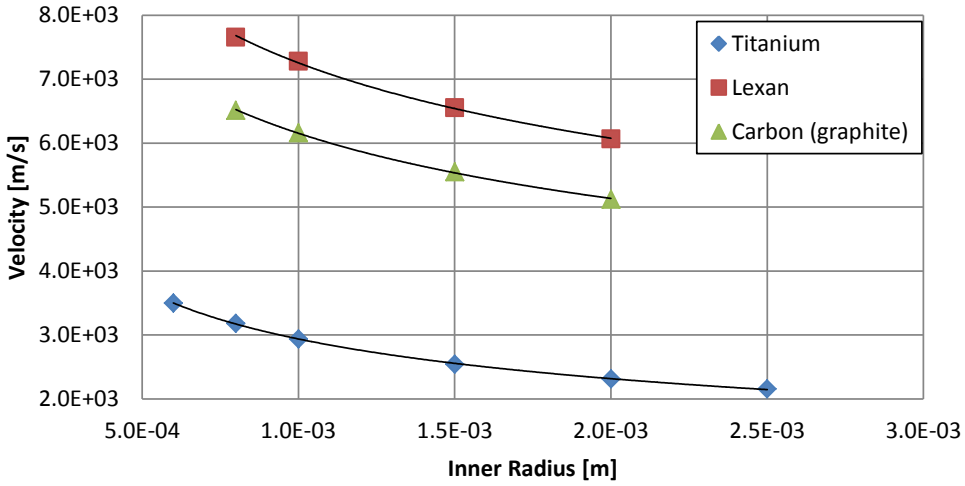


Figure 3.3: Variation in plasma bulk velocity due to changes in inner radius.

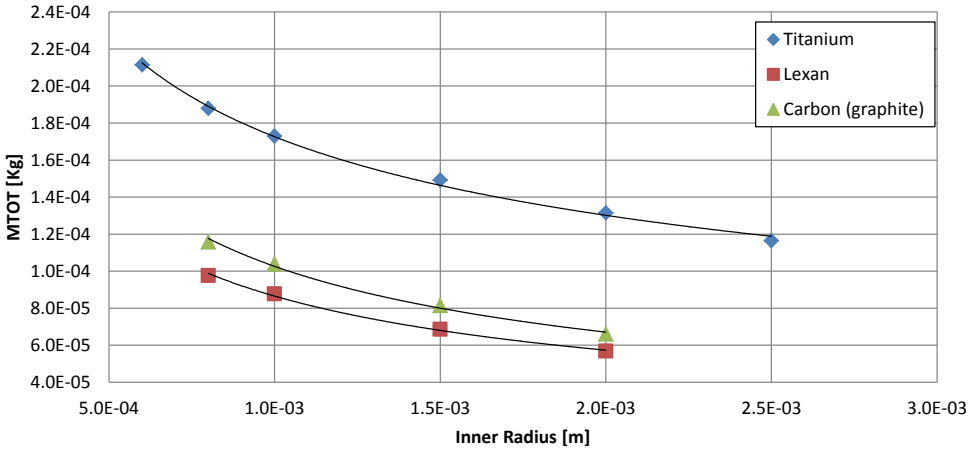


Figure 3.4: Variation in total ablated mass due to changes in inner radius.

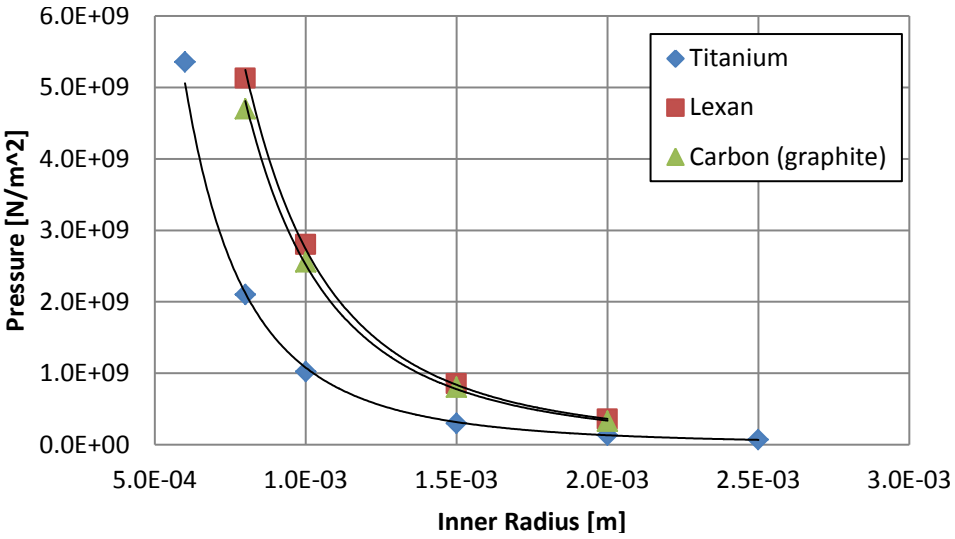


Figure 3.5: Variation in plasma exit pressure due to changes in inner radius.

3.1.2 Influence of Capillary Length on Plasma Parameters

The same procedure has been followed to investigate the change in the plasma parameters as a function of the change in the capillary sleeve's length. The following figures show how the plasma temperature (Figure 3.6), radiative heat flux (Figure 3.7), plasma bulk velocity (Figure 3.8), total ablated mass (Figure 3.9) and the exit pressure (Figure 3.10) change due to the change in capillary sleeve's length. The shown data are for carbon "graphite" and Lexan sleeves at 40kA peak discharge current with a capillary length of 9cm and inner radius of 2mm. The titanium data were obtained for the same geometric parameters but for a peak current of 18.888kA. For each case it has been fitted to a power law ($Parameter = aL^b$), where "parameter" is any of the plasma parameters under consideration, (L) is the capillary sleeve length and (a) and (b) are the fit coefficients. Here it is clear that the change in the length doesn't affect the temperature, heat flux and

bulk velocity. This can be explained in view of the fact that the extension of the length extends the electric arc length inside the capillary, which is the initial responsible factor for the total joule heating and hence the radiative heat flux would remain unaffected which in turn translates to the effective plasma temperature. The plasma bulk velocity at the exit coincides with the ion sound speed $v = (kT/M)^{1/2}$ and hence the velocity will only change if the temperature changes. On the other hand, the total ablated mass and the pressure increase with increased length, which results primarily from the increase in ablation as the total inner surface area exposed to heat flux has increased. This will result in increasing pressure due to the fact that the kinetic pressure depends on the density and the temperature. Since, the temperature is almost flat but the density increases (from increased ablation), one should expect the pressure to also increase.

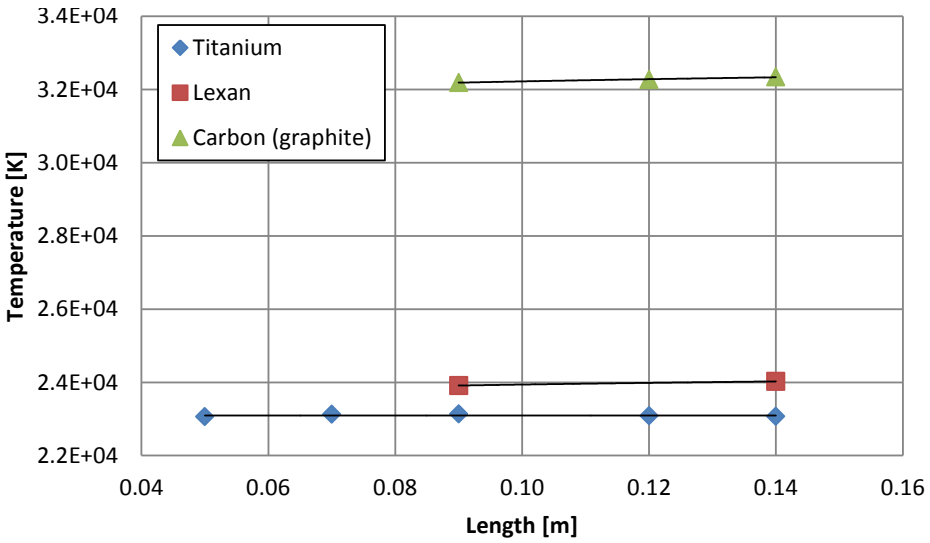


Figure 3.6: Variation in plasma temperature due to changes in Length.

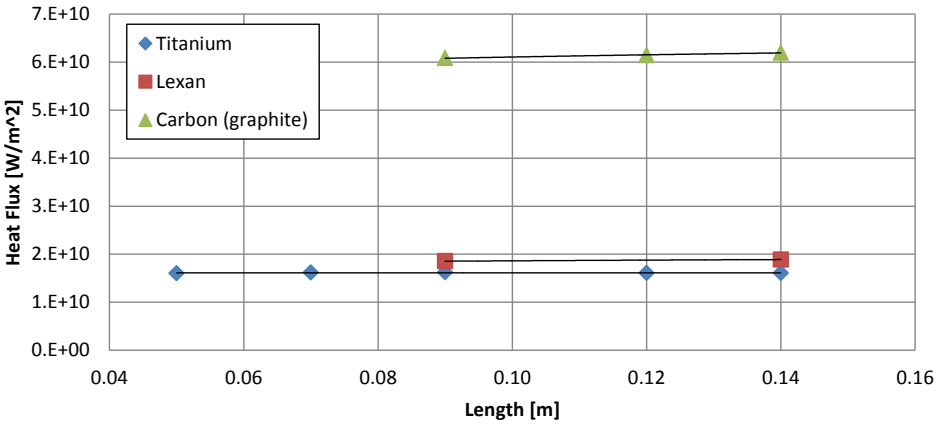


Figure 3.7: Variation in radiative heat flux due to changes in Length.

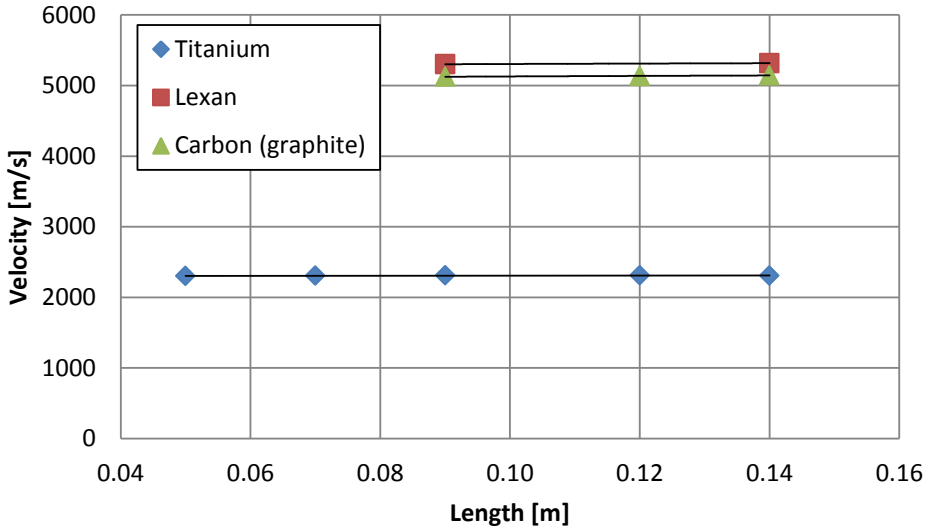


Figure 3.8: Variation in plasma bulk velocity due to changes in Length.

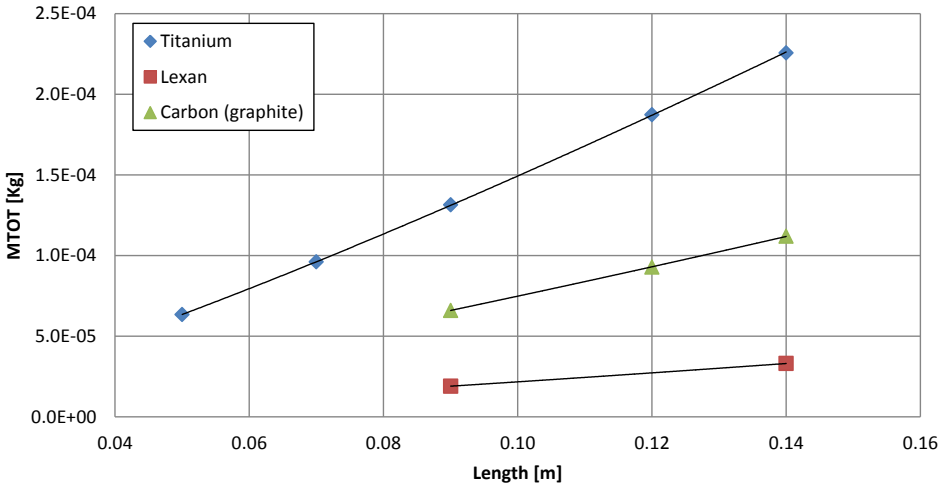


Figure 3.9: Variation in total ablated mass due to changes in Length.

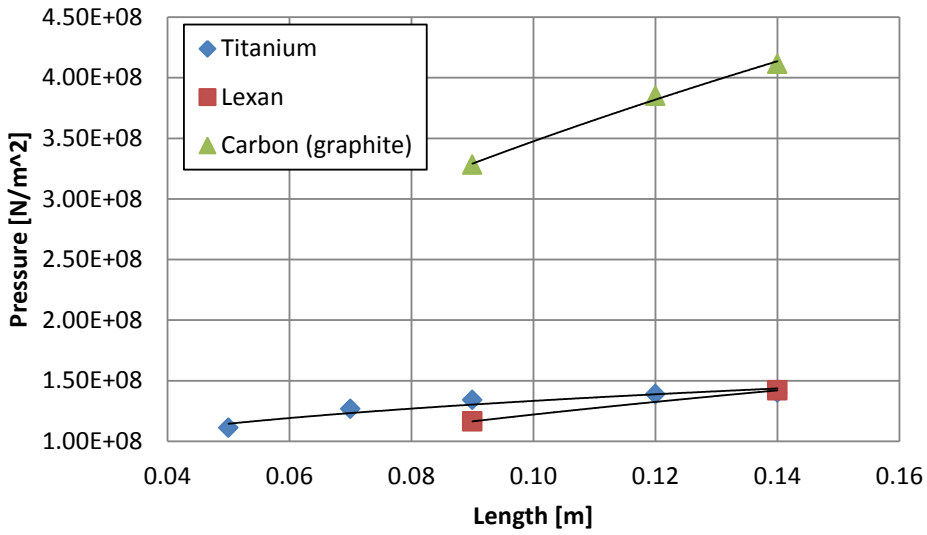


Figure 3.10: Variation in exit plasma pressure due to changes in Length.

3.2 Effect of Peak Discharge Current on Plasma Parameters

To construct a generalized scaling law for the plasma parameters of an electrothermal capillary discharge, the geometric conditions are not enough to fully develop a scaling model without including the variation in the magnitude of the discharge current. The discharge current is the one that drives the process of ablation and plasma formation, the source of joule heating and consequently is the source of heat flux and the ablation process.

The following figures show how the temperature (Figure 3.11), radiative heat flux (Figure 3.12), plasma bulk velocity (Figure 3.13), total ablated mass (Figure 3.14) and exit plasma pressure (Figure 3.15) change with the change in the magnitude of the discharge current. The data show the effect of increased peak discharge current on the parameters obtained for carbon, titanium and Lexan for a capillary length of 9 cm and a internal radius of 2mm. For each case it has been fitted to a power law ($Parameter = a\, {I_{peak}}^{b}$), where "parameter" is any of the plasma parameters under consideration, (I_{peak}) is the peak discharge current and (a) and (b) are the fit coefficients. As can be seen from the graphs there is an increase in the magnitude of all parameters as a result of the increase in the magnitude of the discharge current. This is expected due to the fact that the increase in the magnitude of the discharge current results in an increases joule heating (ηJ^2), wall ablation, radiation heat flux and a consequently increase in the temperature, pressure and velocity.

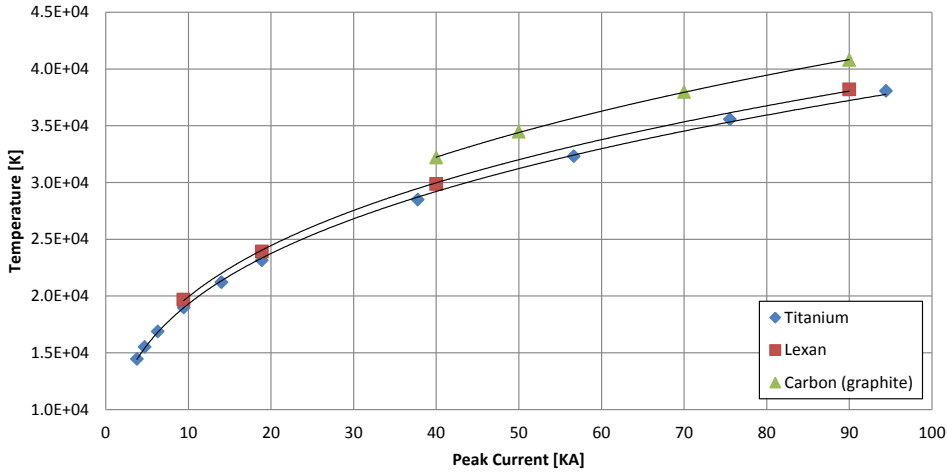


Figure 3.11: Variation in palsma temperature due to changes in the peak current.

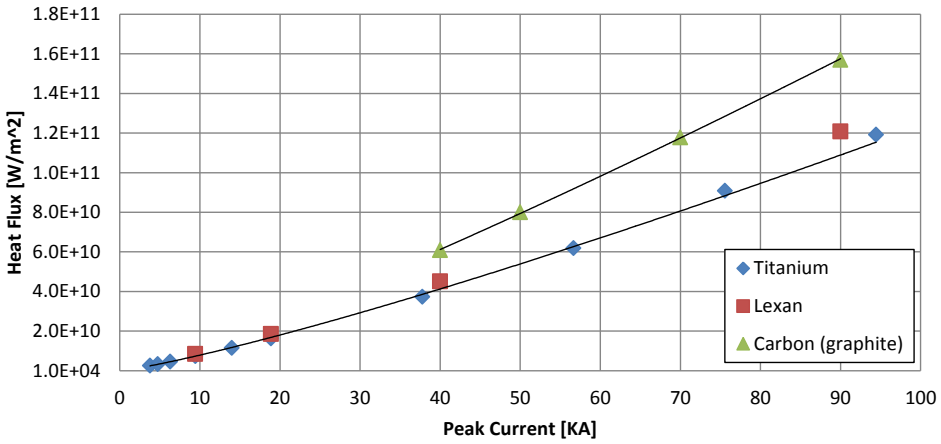


Figure 3.12: Variation in radiative heat flux due to changes in the peak current.

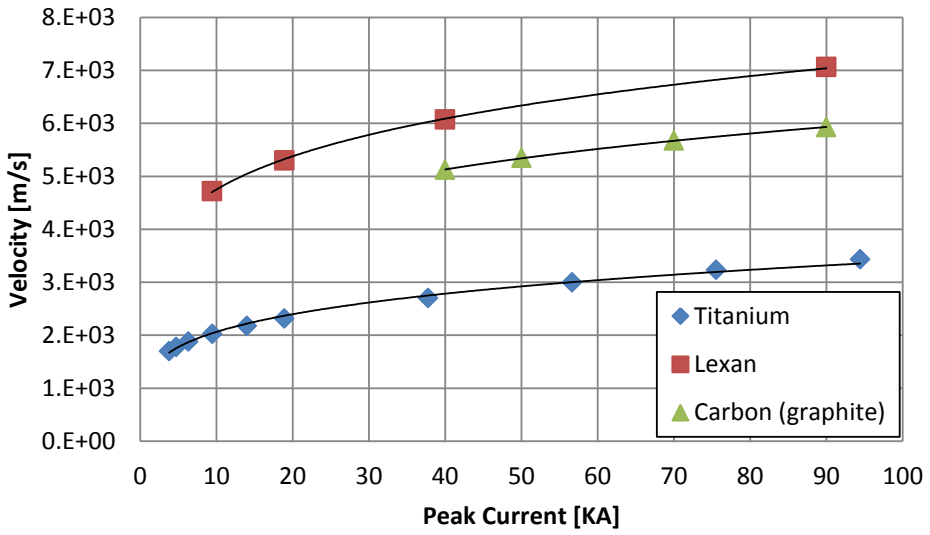


Figure 3.13: Variation in plasma bulk velocity due to changes in the peak current.

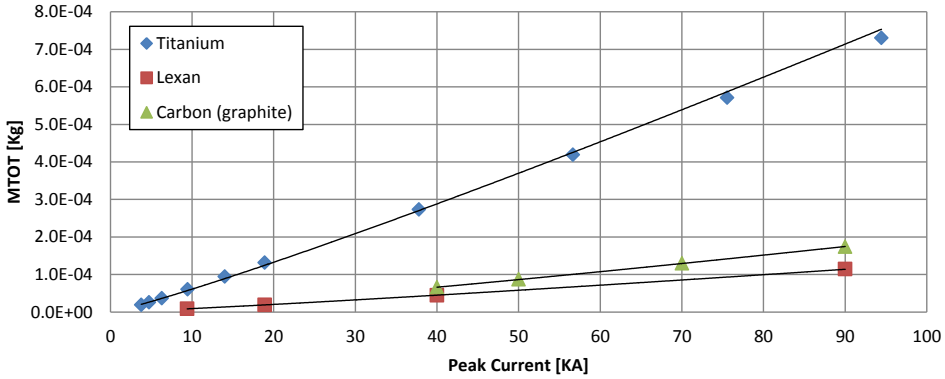


Figure 3.14: Variation in total ablated mass due to changes in the peak current.

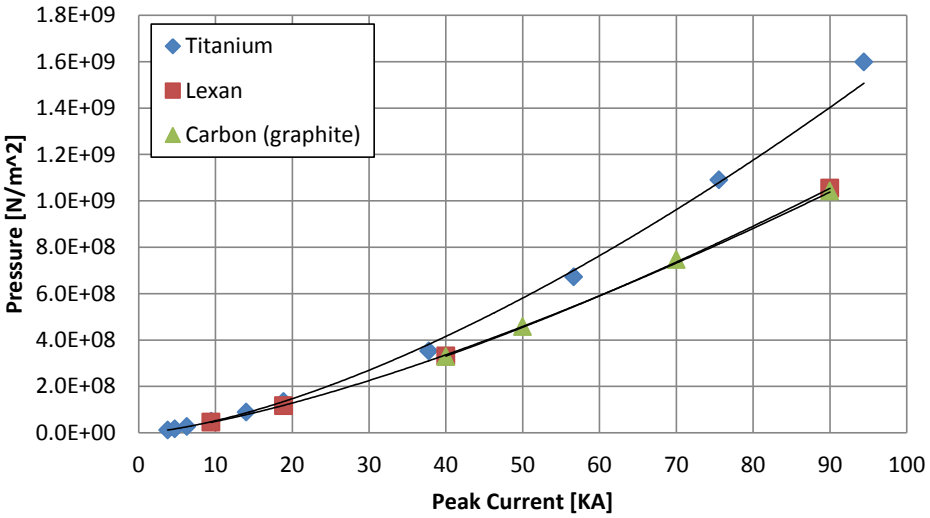


Figure 3.15: Variation in plasma exit pressure due to changes in the peak current.

Chapter 4

Scaling Laws of Capillaries

Scaling laws are equations that can be developed based on semi-empirical techniques of data fitting; either are fitted to theoretical data or fitted to experimental data or results from a complex computational process under a specific range of conditions. Their purpose is to simplify the calculation of certain parameter and have an approximate prediction of the value within a tolerable error. Also, they are used to predict outcomes when there is no simplified theoretical formalism to derive the results. In the current study of the electrothermal plasma capillary discharges, these equations are used to calculate the maximum exit values of the temperature, heat flux, pressure, bulk velocity and the total mass ablated resulting from the discharge.

4.1 Developing Generalized Scaling Laws

To develop generalized scaling laws for the electrothermal plasma capillary discharge it was necessary to collect data from the results of the 1-D, time-dependent code ETFLOW to assemble a collection of data sufficient for semi-empirical modeling. The ETFLOW code calculates the axial and temporal behavior of all the discharge parameters. From these results, the maximum value of the temperature, bulk velocity, radiative heat flux and pressure at the exit of the capillary were recorded. Also, the total mass ablated during the discharge was registered. The code was run for 53 elements and 2 compounds in order to generate sufficient data for the development of scaling laws. For each element and compound the capillary radius, length and discharge current were varied to cover a wide range of geometry alterations and peak discharge currents. The range of the capillary's radius was set from 0.6 to 2.5mm, and the range of lengths varied from 7 to 14cm. The magnitude of the discharge current was varied from 3 to 90 kA, however, for most elements the currents were set from 40 to 90 kA. Also, the pulse width measured at full with at half maximum (FWHM) was varied from 54 to 311μs.

It was noted that the only parameters that had a significant variation with the pulse width are the total ablated mass and the pressure. For the rest of the parameters this value was not considered.

Each parameter was analyzed using the software DataFit, Matlab, Libreoffice and Excel to find the most appropriate equation to fit the data and do the regressions to find the equation's coefficients.

A general scaling law for temperature, heat flux and plasma bulk exit velocity can be expressed by a generalized equation in the form of $T, q'', v \sim aL^b r^c I_{max}^d$, such that:

$$T = aL^b r^c I_{max}^d \tag{4.1}$$

$$q'' = aL^b r^c I_{max}^d \tag{4.2}$$

$$v = aL^b r^c I_{max}^d \tag{4.3}$$

Where the coefficients a, b, c and d vary for each scaling law. The length (L) and the radius (r) are in meters and the discharge current (I_{max}) is the peak value in amperes. Equation (4.1) gives the temperature (^oK), Equation (4.2) yields the heat flux (W/m^2), and Equation (4.3) provides the bulk exit velocity in meters per second (m/s). The coefficients a, b, c and d for the temperature, heat flux and bulk velocity are listed in the Appendix A.1, A.2 and A.3, respectively, for all tested elements and compounds.

It was found that further analysis could be done for the temperature equation. From Table A.1 in Appendix A.1 it can be seen that the coefficient c and d are fairly constant with an average value of -0.39 and 0.29, respectively. Also they have a standard deviation of 7.83% and 5.69%, respectively. Therefore, it was concluded that this values can remain constant rendering equation (4.1) as (4.4).

$$T = aL^b R^{-0.39} I_{max}^{0.29} \tag{4.4}$$

The coefficients of this formula were re-fitted and are presented in appendix A.1 in Table A.2.

Coefficient b was plotted against the atomic number (Z) and a curve was fitted, which gives: $b = c1\, ln(Z) + c2$, where $c1$ and $c2$ are constants. Figure 4.1 shows the plot of the coefficient b vs Z and the fitted equation. It must be noted that this analysis is only for pure elements and not for compounds.

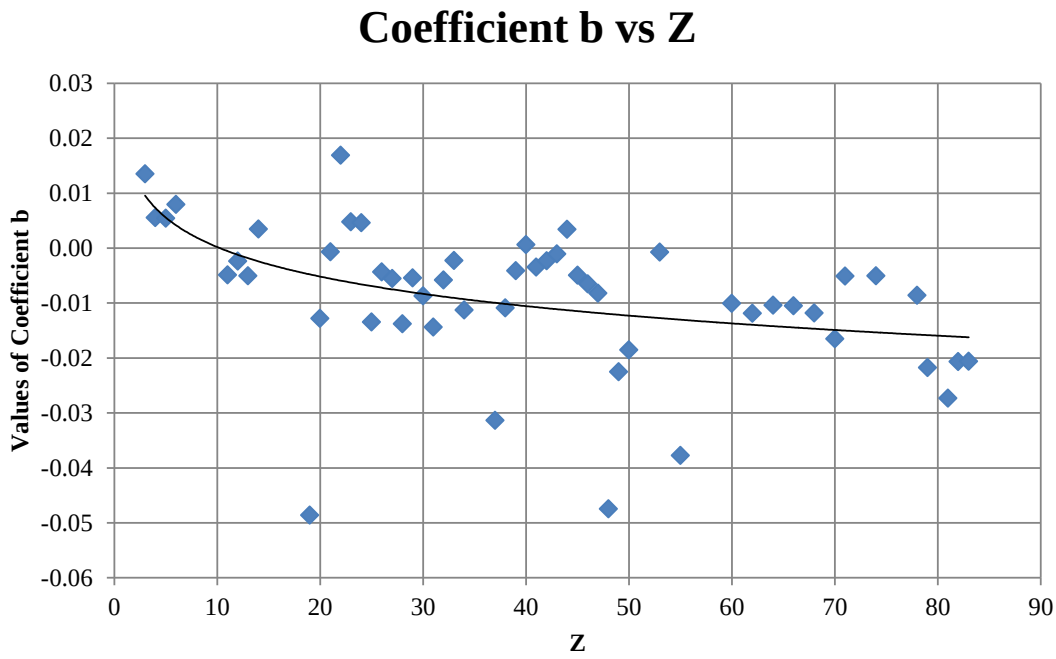


Figure 4.1: Coefficient (b) versus the element atomic number (Z), for the second temperature scaling law.

The coefficient (b) has an average value of -0.0089 with a maximum value of 0.0168 and a minimum value of -0.0486. Therefore, one can say that the scaling law has a low dependency on the Length of the capillary sleeve. Thus, a deviation from this curve will cause a small impact in the error value.

The coefficient (a) was found to correspond to the multiplication of a few material parameters elevated each one to a certain power times a constant. That is:

$$a = c_3 Z^{c4} H_p^{c5} k^{c6} \rho^{c7} C_p^{c8} \tag{4.5}$$

Where c_3, c_4, c_5, c_6, c_7 and c_8 are constants and are given in Table 4.1, Z is the atomic number, H_p is the sublimation enthalpy or, the sum of the melting and vaporization enthalpy, k is the thermal conductivity, ρ is the density and C_p is the specific heat.

Table A.3 in Appendix A.1 shows the value of (a) versus the calculated values. It should be noticed that the maximum error, for the 53 materials and 2 compounds, was 5.34% for Gold.

Second developed scaling law for the plasma temperature is given by:

$$T = c_3 Z^{c_4} H_p^{c_5} k^{c_6} \rho^{c_7} C_p^{c_8} L^{\alpha} R^{-0.39} I_{max}^{0.29} \tag{4.6}$$

Where α is given by:

$$\alpha = -0.00838\, ln(Z) + 0.021573 \tag{4.7}$$

Table 4.1: Constants of the second temperature scaling law

Coefficient	Value
c3	31.28288
c4	-0.01584
c5	0.197188
c6	-0.01362
c7	0.004025
c8	0.040474

In order to render a more easy calculation for the temperature, the second scaling law was simplified by taking only the enthalpy as the variable for calculating the coefficient (a). Therefore, a third scaling law for the temperature is given by:

$$T = c_9 H_p^{c10} L^{\alpha} R^{-0.39} I_{max}^{0.29} \tag{4.8}$$

Where the constants c_9 and c_{10} are given in Table 4.2.

Table 4.2: Constants of the third temperature scaling law

Coefficient	Value
c9	31.3456097
c10	0.2279275

Table A.4 in Appendix A.1 shows the difference between the coefficient (a) and the calculated values, with a maximum error of 9.65% for Lithium and Tungsten.

For the total ablated mass m_{total} (or MTOT) and the plasma exit pressure, it was noted that the pulse width of the discharge current must be considered. This variable is presented in the equation as FWHM (Full width at Half Maximum) for these parameters and they are presented as follow, where the coefficients a, b, c and e differs for each equation:

$$m_{total} = aL^b R^c I_{max}^{(d+(FWHM)^e)} \tag{4.9}$$

$$P = aL^b R^c I_{max}^{(d*(FWHM)^e)} \tag{4.10}$$

In these equations, the length and radius are in meters and the maximum discharge current is in amperes. Equation (4.9) gives the total ablated mass in Kilograms and equation (4.10) yields the pressure in Newton per meter square (N/m^2)

The coefficients for the total ablated mass scaling law are presented in Table A.7 in Appendix A.4, and the coefficients for the pressure scaling law are presented in Table A.8 in Appendix A.5.

4.2 Validation of the Scaling Laws with Code Predictions and Experimental Data

For each element and compound the scaling laws were compared to the values given by the ETFLOW code. The relative error between the value given by the equation and the one calculated by the code can be found in Appendix B for all the equations.

The errors shown in Appendix B are the maximum error encounter by a given material, i.e. the maximum error found for all the length, radius and currents for each specific material and compound.

For the first temperature scaling law the errors are shown in Table B.1 in Appendix B.1 It can be seen that the maximum error is 3.04% for Potassium and the minimum error is 0.30% for Molybdenum.

For the second temperature scaling law the errors are shown in Table B.2 in Appendix B.1 It can be seen that the maximum error is 11.30% for Iodine and the minimum error is 0.79% for Aluminium. For the third temperature scaling law the errors are shown in Table B.3 in Appendix B.1 It can be seen that the maximum error is 15.48% for Tungsten and the minimum error is 1.02% for Boron.

Since the heating in an electrothermal plasma discharge is modeled as a black body radiation, one may be tempted to use Stephan-Boltzmann relation to calculate the heat flux from the temperature obtained by the last three scaling laws. However, since the relation have the temperature to the fourth power the error propagation is excessive. Therefore, the scaling law for the heat flux should be used for the second and third scaling

law. For the first scaling law the error propagation of the heat flux scaling law is the same as using Stephan-Boltzmann relation.

The uncertainty propagation for non-related variables is:

$$\sigma_f^2 = \sum_i \left(\frac{df}{dx_i}\right)^2 \sigma_i^2 \tag{4.11}$$

Then for Stephan-Boltzmann relation:

$$\sigma_{q''}^2 = \left(4\sigma_{SB}T^3\right)^2 \sigma_T^2 \tag{4.12}$$

Were σ_{SB} is the Sthephan-Boltzmann constant, $\sigma_{q''}$ is the standard deviation of the heat flux, σ_T is the standard deviation of the temperature and T is the temperature.

Taking the square root and multiplying both sides by $1/(q^{''}T)$.

$$\sigma_{q''\%} = 4\sigma_{T\%} \tag{4.13}$$

This obtains the Heat flux error propagation in percentage, which is four times the error obtained in the temperature.

The sensitivity check for the heat flux scaling law is shown in Table B.4 in Appendix B.2 The maximum error is 12.12% for Potassium and the minimum is 1.19% for Molybdenum.

The error obtained in the first temperature scaling law for Potassium was 3.04%, and if to multiply it by 4 the result is 12.16%. For Molybdenum the error attained by the same

equation was 0.30%, and if to multiply it by 4 the product is 1.2%. As it can be seen these are the same errors reach by the heat flux scaling law. Therefore, for this case one can use the black body radiation equation.

For the Bulk exit velocity the errors are shown in Table B.5 in Appendix B.3. The maximum error was 5.13% for Neodymium and the minimum error was 0.24% for carbon.

For the total ablated mass (MTOT, m_{total}) scaling law the sensitivity test is shown in Table B.6 in Appendix B.4. The maximum error is 19.41% for Chromium and the minimum is 3.37% for Teflon. However, the minimum error for a pure material is 3.97% for Lithium.

The errors comparisons for the pressure scaling law are listed in Table B.7 in Appendix B.5 The maximum error is 22.08% for Iodine and the minimum was 6.73% for Lithium. The second largest error is 19.40% for titanium. Iodine is the only case seen that have an error above 20%. Table 4.3 shows the maximum errors in the developed scaling laws.

Table 4.3: Summary of scaling laws maximum errors

Scaling Law	Minimum Error	Maximum Error
Temperature First Fit	0.30%	3.04%
Temperature Second Fit	0.79%	11.30%
Temperature Third Fit	1.02%	15.48%
Heat Flux	1.19%	12.16%
Bulk Exit Velocity	0.24%	5.13%
Total ablated mass (MTOT)	3.37%	19.41%
Pressure	6.73%	22.08%

Due to experimental conditions the only parameter that can be directly measured with good accuracy is the total ablated mass. This is achieved by measuring the weight of the capillary sleeve before and after the electrothermal plasma discharge.

The results from Winfrey et al [1] were used to compare the total ablated mass scaling law calculations against the recorded experimental data. The table below shows the parameters of each shot, the measured ablated mass (MTOT), the prediction by the scaling law and the relative error between these two values. All data is for Lexan polycarbonate compound.

In this table, L is the Length of the capillary, r is the internal radius of the capillary, PW is the pulse width of the discharge current and I is the maximum amplitude of the current.

Table 4.4: Comparison between MTOT scaling law and experimental data.

N	L [m]	r [m]	PW [us]	I [A]	MTOT [kg]	Scaling Law	Error
1	0.09	0.002	70	9400	1.37E-05	1.48E-05	8.33%
2	0.09	0.002	70	9550	1.63E-05	1.51E-05	7.51%
3	0.09	0.002	60	17700	2.32E-05	2.64E-05	13.82%
4	0.09	0.002	70	18040	2.81E-05	3.06E-05	8.88%
5	0.09	0.002	50	28740	3.46E-05	3.86E-05	11.48%
6	0.09	0.002	50	29610	3.43E-05	3.98E-05	16.18%
7	0.09	0.002	50	28930	3.24E-05	3.88E-05	19.91%
8	0.09	0.002	47	41400	4.18E-05	5.42E-05	29.67%
9	0.09	0.002	47	38980	4.82E-05	5.08E-05	5.50%
10	0.09	0.002	47	42810	4.69E-05	5.62E-05	19.98%

It should be noted that, even though the coefficients of MTOT scaling law were calculated for an ideal plasma model the error for discharge currents above 18 KA are not substantial except for shot number 8. In the reference by Winfrey et al [1] it is shown that above 18 KA the non-ideal plasma model gives a better prediction of the total mass ablated.

In Ref. [10] by Kyoungjin Kim an indirect method was used to calculate the pressure at the capillary exit using the experimental data from Kohel et al, Ref. [18]. The approach is to use the picture taken of the plasma jet at the exit of the discharge and locate the mach disk and contact surface to calculate the pressure.

In Kim's work [10] for a Lexan capillary of length 0.03 m and internal diameter of 3 mm for a current maximum amplitude of 4600 A and a pulse width of 250 μs the pressure was shown to be 26.4 MPa.

By using the pressure scaling law one can compare the data to the ones predicted by the scaling law. That is, using equation (4.10) and the coefficients for Lexan combined with the parameter of the experiment, it is calculated that the maximum pressure at the exit

of the capillary discharge should be 24.4 MPa, which is an error of 7.45% with respect to the calculation made by Kim [10].

Chapter 5

Discussion and conclusions

Scaling laws for electrothermal plasma discharge were developed based on the actual runs of the electrothermal plasma code ETFLOW. The scaling laws calculations were compared to what was produced using the code and have shown reasonable results with acceptable errors. When compared to experimental data, these scaling laws are in good agreement with records acquired from the experimental facility at NC State University, and also compares favorably to results obtained by other researchers.

Three different scaling laws were develop for the plasma exit temperature. As it was shown in the heat flux scaling law, the Stephan-Boltzmann relation can be used only in the first temperature scaling law, because the error reached in the heat flux scaling law match those calculated by the uncertainty propagation. However, for the second and third temperature scaling laws the error propagation would be too high for an acceptable result. For example, the maximum error obtained for the second scaling law with Iodine was 11.30%; this would mean that the uncertainty in the heat flux using Stephan-Boltzmann

relation would be about 45.2%. This amount of uncertainty is not acceptable for any practical use.

Depending on the precision needed, the second or third temperature scaling laws can be used to calculate the exit temperature of an electrothermal plasma discharge for any other materials not listed in Appendix A. However, if the material used in the capillary is one listed in that appendix then it is recommended to use the first temperature scaling law due to the low maximum error achieved compare to the ones calculated by the code, which was a maximum of 3.04% for Potassium.

Besides for the temperature scaling law, it was found that there is no relation between the coefficients of the equations and the material parameters. Therefore, this research could not found a general scaling law for all the single materials for the case of heat flux, bulk velocity, total ablated mass and pressure. However, there is a substantial amount of materials for the ones the coefficients were calculated to provide a useful set of equations that can calculate the exit parameters of an electrothermal plasma discharge.

From the experimental data from Winfrey et al [1] it was shown that for currents below 40 KA the error is less than 20% when the total ablated mass is calculated by the scaling law. It should be noted that the coefficients of the scaling laws were calculated using an ideal plasma model which was shown in the reference [1] that is less accurate than a non-ideal plasma model for currents above 18 KA.

By comparing the pressure predicted by the scaling law with the one obtained indirectly by Kim [10], it was shown that the relative error between the scaling law and the work of Kim is only 7.45%.

From all the comparisons between the code, experimental data and the scaling laws; one can see that the ablated mass and the pressure predictions are very accurate with error less than 20% with the only exception for the pressure of a capillary made of Iodine, which yield a maximum error of 22.08%. Nevertheless, this proves that this can be used to accurately predict the exit values of an electrothermal plasma discharge. It is also important to mention that for a specific desired exit parameter, such as total ablated mass or pressure or velocity, these scaling laws can be inversely used to design the geometry of the capillary or determine the peak discharge current to produce such values.

Recommendations For Future Work

Since the coefficients of the scaling laws were calculated using an ideal plasma model, it is recommended that they are recalculated using a non-ideal plasma model for better accuracy for currents above 40 KA. However, it can be assumed that the scaling laws are not needed to be modified and only the coefficient should be adjusted.

One of the problems encounter in the software, is that for some materials at certain currents the program have a hard stop at "Sub BRENTSTATE" function. Before using a software or any macro that can automate ETFLOW, the user should be sure that the material will run for the range configured. This is one of the reasons that for most material the code was run between 40 and 90 kA. Another recommendation would be to find why this function does not give answer for certain materials with particular geometry and current conditions. Moreover, it should be changed or updated in order to provide full functionality.

The code take about 30 to 40 minutes to complete the calculations for each ideal case that it was run for 200 μs of current pulse width. Hence, if it is needed to run a range of 4 currents (different amplitude only) with 4 radii and 4 lengths that would imply 64 runs or around 37 hours. If we run that instead for a non-ideal case it would take more than an hour to run each case. Under these conditions, it would be advisable that ETFLOW be upgraded to multi-thread system or find a way to have multiple instances (parallel job) of it running at the same time.

More experimental data are needed to compare to the scaling laws to have a better understanding of the range in which they can be used. Therefore, this work only provides results within the range of applicability tested in this thesis. Another important work would be to find the relation between the coefficients and the material parameters so a more generalized scaling law could be developed.

REFERENCES

[1] A. L. Winfrey, M. A. A. Al-Halim, J. G. Gilligan, A. V. Saveliev, and M. A. Bourham, "A study of plasma parameters in a capillary discharge with calculations using ideal and nonideal plasma models for comparison with experiment," *IEEE Transactions on Plasma Science*, vol. 40, no. 3, pp. 843–852, 2012.

[2] T. Edamitsu and H. Tahara, "Experimental and numerical study of an electrothermal pulsed plasma thruster for small satellites," *Vacuum*, vol. 80, pp. 1223–1228, 9/7 2006.

[3] F. D. Witherspoon, R. L. Burton, and S. A. Goldstein, "A second generation emet railgun for secondary arc studies," *Magnetics, IEEE Transactions on*, vol. 27, no. 1, pp. 91–96, 1991. ID: 1.

[4] J. Dyvik, J. Herbig, R. Appleton, J. O'Reilly, and J. Shin, "Recent activities in electrothermal chemical launcher technologies at bae systems," *Magnetics, IEEE Transactions on*, vol. 43, no. 1, pp. 303–307, 2007. ID: 1.

[5] C. M. Edwards, M. A. Bourham, and J. G. Gilligan, "Experimental studies of the plasma-propellant interface for electrothermal-chemical launchers," *Magnetics, IEEE Transactions on*, vol. 31, no. 1, pp. 404–409, 1995. ID: 1.

[6] R. W. Kincaid and M. A. Bourham, "Electrothermal plasma gun as a pellet injector," *Fusion Technology*, vol. 26, no. 3, pp. 637–641, 1994. ID: 28546365.

[7] E. Y. Shcolnikov, A. V. Chebotarev, Y. A. Kulikov, A. V. Melnik, and S. V. Volkov, "High efficiency electrothermal accelerator," *Magnetics, IEEE Transactions on*, vol. 31, no. 1, pp. 447–451, 1995. ID: 1.

[8] J. Gilligan and M. Bourham, "The use of an electrothermal plasma gun to simulate the extremely high heat flux conditions of a tokamak disruption," *Journal of Fusion Energy*, vol. 12, pp. 311–316, 09/01 1993. J2: J Fusion Energ.

[9] J. D. Hurley, M. A. Bourham, and J. G. Gilligan, "Numerical simulation and experiment of plasma flow in the electrothermal launcher sirens," *Magnetics, IEEE Transactions on*, vol. 31, no. 1, pp. 616–621, 1995. ID: 1.

[10] K. Kim, "Time-dependent one-dimensional modeling of pulsed plasma discharge in a capillary plasma device," *Plasma Science, IEEE Transactions on*, vol. 31, no. 4, pp. 729–735, 2003. ID: 1.

[11] R. W. Kincaid, M. A. Bourham, and J. G. Gilligan, "Pellet acceleration using an ablation-controlled electrothermal launcher," in *Fusion Engineering, 1995. SOFE '95. Seeking a New Energy Era., 16th IEEE/NPSS Symposium*, vol. 2, pp. 1613–1616 vol.2, 1995. ID: 1.

[12] A. L. Winfrey, J. Gilligan, and M. Bourham, "A computational study of a capillary discharge pellet accelerator concept for magnetic fusion fueling," *Journal of Fusion Energy*, pp. 1–8, 06/01 2012. J2: J Fusion Energ.

[13] A. L. Winfrey, M. A. Al-Halim, A. Saveliev, J. Gilligan, and M. Bourham, "Enhanced performance of electrothermal plasma sources as fusion pellet injection drivers and space based mini-thrusters via extension of a flattop discharge current," *Journal of Fusion Energy*, pp. 1–7, 09/01 2012. J2: J Fusion Energ.

[14] R. J. Zollweg and R. W. Liebermann, "Electrical conductivity of non-ideal plasmas," *J. Appl. Phys.*, vol. 62(9), pp. 3621–3627, 1987.

[15] L. Spitzer and R. Harm, "Transport phenomena in a completely ionized gas," *Phys. Rev.*, vol. 89(5), pp. 977–981, 1953.

[16] M. R. Zaghloul, M. A. Bourham, J. M. Doster, and J. D. Powell, "On the average electron-ion momentum transport cross-section in ideal and nonideal plasmas," *Phys. Letters*, vol. A 262, pp. 86–89, 1999.

[17] J. D. Powell and A. E. Zielinski, "Capillary discharge in the electrothermal gun," *Magnetics, IEEE Transactions on*, vol. 29, no. 1, pp. 591–596, 1993. ID: 1.

[18] J. M. Kohel, L. K. Su, N. T. Clemens, and P. L. Varghese, "Emission spectroscopic measurements and analysis of a pulsed plasma jet," *Magnetics, IEEE Transactions on*, vol. 35, no. 1, pp. 201–206, 1999. ID: 1.

APPENDICES

Appendix A

Scaling Law Coefficients

A.1 Temperature

Table A.1: First Temperature Scaling Law Coefficients

Z	Name	Symbol	a	b	c	d
3	Lithium	Li	83.605803	0.016839	-0.410454	0.303487
4	Beryllium	Be	120.139643	0.003293	-0.389469	0.284887
5	Boron	B	129.560382	0.006393	-0.397063	0.285594
6	Carbon	C	130.370222	0.009215	-0.403032	0.285935
11	Sodium	Na	62.956776	0.003876	-0.418424	0.316048
12	Magnesium	Mg	83.886429	-0.003776	-0.396757	0.299640
13	Aluminium	Al	116.035822	-0.002271	-0.388169	0.290041
14	Silicon	Si	88.239114	0.004356	-0.415202	0.304102
19	Potassium	K	122.150799	-0.052420	-0.355280	0.277303
20	Calcium	Ca	71.124668	0.008588	-0.412433	0.309121

Continued on next page

Table A.1 (continued)

Z	Name	Symbol	a	b	c	d
21	Scandium	Sc	84.973458	-0.000358	-0.415018	0.303732
22	Titanium	Ti	90.259686	0.004636	-0.417323	0.302592
23	Vanadium	V	86.647820	-0.002898	-0.416736	0.305788
24	Chromium	Cr	101.403157	-0.008689	-0.409506	0.289441
25	Manganese	Mn	87.108968	-0.005610	-0.399166	0.303190
26	Iron	Fe	85.411160	-0.006581	-0.412889	0.304946
27	Cobalt	Co	92.364342	-0.005095	-0.406108	0.303765
28	Nickel	Ni	99.231028	-0.007443	-0.399302	0.299742
29	Copper	Cu	122.188220	-0.012715	-0.381645	0.287926
30	Zinc	Zn	140.361155	-0.007563	-0.358559	0.275190
31	Gallium	Ga	135.553047	-0.005797	-0.366238	0.284603
32	Germanium	Ge	104.321450	-0.001449	-0.396637	0.296355
33	Arsenic	As	119.710260	-0.006312	-0.382443	0.288384
34	Selenium	Se	231.848108	-0.004602	-0.322295	0.249196
37	Rubidium	Rb	178.465985	-0.051783	-0.312520	0.263355
38	Strontium	Sr	64.723720	0.011689	-0.417720	0.315115
39	Yttrium	Y	88.595319	0.005240	-0.414243	0.303271
40	Zirconium	Zr	72.403147	-0.006413	-0.442648	0.307975
41	Niobium	Nb	84.684067	-0.006035	-0.424225	0.308163
42	Molybdenum	Mo	84.020797	-0.007597	-0.423007	0.307719
43	Technetium	Tc	83.637107	-0.010271	-0.421092	0.307615
44	Ruthenium	Ru	90.568293	-0.003776	-0.413851	0.306725
45	Rhodium	Rh	100.289580	-0.006444	-0.403683	0.301126
46	Palladium	Pd	119.795059	-0.010930	-0.393830	0.283520
47	Silver	Ag	119.767922	-0.020817	-0.372754	0.290302
48	Cadmium	Cd	159.037406	-0.016426	-0.339823	0.268231
49	Indium	In	109.983714	-0.022569	-0.375383	0.292714

Continued on next page

Table A.1 (continued)

Z	Name	Symbol	a	b	c	d
50	Tin	Sn	107.695037	-0.010400	-0.387525	0.293207
53	Iodine	I	246.281536	-0.000333	-0.333174	0.237907
55	Caesium	Cs	160.879621	-0.049803	-0.307079	0.270206
60	Neodymium	Nd	76.325179	-0.006338	-0.413749	0.309224
62	Samarium	Sm	66.594378	-0.007946	-0.418073	0.312464
64	Gadolinium	Gd	73.840695	-0.010637	-0.419037	0.308770
66	Dysprosium	Dy	72.398814	-0.010103	-0.418745	0.309709
68	Erbium	Er	73.492283	-0.010478	-0.419728	0.309124
70	Ytterbium	Yb	56.855869	-0.007702	-0.421258	0.320552
71	Lutetium	Lu	80.714986	-0.011389	-0.419893	0.305714
74	Tungsten	W	81.622844	-0.008730	-0.429219	0.309970
78	Platinum	Pt	103.561201	-0.009021	-0.400955	0.298404
79	Gold	Au	142.870556	-0.014149	-0.368666	0.280751
81	Thallium	Tl	130.882963	-0.025441	-0.353378	0.284233
82	Lead	Pb	67.621175	-0.015386	-0.410884	0.312190
83	Bismuth	Bi	95.977582	-0.022593	-0.379574	0.294524
Formula	**Name**		**a**	**b**	**c**	**d**
C16H14O3	Lexan		139.346983	0.008927	-0.394286	0.278078
C2F4	Teflon		122.231638	0.011396	-0.412064	0.284787

Table A.2: Intermediate Temperature Scaling Law Coefficients

Z	Name	Symbol	a	b
3	Lithium	Li	110.207734	0.013506
4	Beryllium	Be	113.735255	0.005528
5	Boron	B	129.178453	0.005419
6	Carbon	C	135.470899	0.007929
11	Sodium	Na	99.747508	-0.004912
12	Magnesium	Mg	97.722642	-0.002396
13	Aluminium	Al	114.001610	-0.005052
14	Silicon	Si	121.765156	0.003460
19	Potassium	K	84.232913	-0.048617
20	Calcium	Ca	97.381463	-0.012795
21	Scandium	Sc	116.195898	-0.000689
22	Titanium	Ti	125.491928	0.016873
23	Vanadium	V	124.991848	0.004790
24	Chromium	Cr	118.711284	0.004618
25	Manganese	Mn	104.097578	-0.013476
26	Iron	Fe	118.042079	-0.004364
27	Cobalt	Co	118.875482	-0.005566
28	Nickel	Ni	115.422645	-0.013816
29	Copper	Cu	114.670536	-0.005455
30	Zinc	Zn	96.735095	-0.008693
31	Gallium	Ga	107.176365	-0.014415
32	Germanium	Ge	115.193055	-0.005795
33	Arsenic	As	112.772238	-0.002299
34	Selenium	Se	92.427095	-0.011302
37	Rubidium	Rb	82.631404	-0.031355
38	Strontium	Sr	97.514781	-0.010913

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Table A.2 (continued)

Z	Name	Symbol	a	b
39	Yttrium	Y	117.360826	-0.004145
40	Zirconium	Zr	126.623338	0.000628
41	Niobium	Nb	129.840390	-0.003464
42	Molybdenum	Mo	128.743344	-0.002332
43	Technetium	Tc	127.548052	-0.001055
44	Ruthenium	Ru	130.132129	0.003397
45	Rhodium	Rh	125.155107	-0.004933
46	Palladium	Pd	116.952674	-0.006533
47	Silver	Ag	109.689687	-0.008237
48	Cadmium	Cd	82.767561	-0.047451
49	Indium	In	102.846542	-0.022513
50	Tin	Sn	107.404894	-0.018517
53	Iodine	I	98.656895	-0.000772
55	Caesium	Cs	77.070902	-0.037742
60	Neodymium	Nd	107.880927	-0.010065
62	Samarium	Sm	101.448335	-0.011899
64	Gadolinium	Gd	109.676308	-0.010428
66	Dysprosium	Dy	108.369142	-0.010532
68	Erbium	Er	109.751404	-0.011828
70	Ytterbium	Yb	96.375399	-0.016542
71	Lutetium	Lu	118.195999	-0.005107
74	Tungsten	W	133.034651	-0.005075
78	Platinum	Pt	122.612776	-0.008629
79	Gold	Au	110.664189	-0.021740
81	Thallium	Tl	96.225512	-0.027300
82	Lead	Pb	98.108731	-0.020659

Continued on next page

Table A.2 (continued)

Z	**Name**	**Symbol**	**a**	**b**
83	Bismuth	Bi	94.396391	-0.020606
Formula	**Name**		**a**	**b**
C16H14O3	Lexan		126.404828	0.009218
C2F4	Teflon		134.060628	0.012227

Table A.3: Second Temperature Scaling Law Coefficient a Versus Calculated Coefficient a

Z	Name	Symbol	a	Calculated a	Error
3	Lithium	Li	110.21	109.02	1.08%
4	Beryllium	Be	113.74	118.38	4.08%
5	Boron	B	129.18	133.04	2.99%
6	Carbon	C	135.47	135.98	0.38%
11	Sodium	Na	99.75	94.43	5.33%
12	Magnesium	Mg	97.72	99.68	2.00%
13	Aluminium	Al	114.00	115.42	1.24%
14	Silicon	Si	121.77	122.37	0.50%
19	Potassium	K	84.23	88.72	5.33%
20	Calcium	Ca	97.38	98.71	1.36%
21	Scandium	Sc	116.20	119.91	3.20%
22	Titanium	Ti	125.49	124.50	0.79%
23	Vanadium	V	124.99	125.91	0.73%
24	Chromium	Cr	118.71	117.43	1.08%
25	Manganese	Mn	104.10	109.65	5.33%
26	Iron	Fe	118.04	118.64	0.51%
27	Cobalt	Co	118.88	118.60	0.23%
28	Nickel	Ni	115.42	117.08	1.44%
29	Copper	Cu	114.67	110.60	3.55%
30	Zinc	Zn	96.74	93.18	3.68%
31	Gallium	Ga	107.18	107.99	0.76%
32	Germanium	Ge	115.19	114.37	0.71%
33	Arsenic	As	112.77	110.12	2.35%
34	Selenium	Se	92.43	92.74	0.34%
37	Rubidium	Rb	82.63	83.88	1.51%

Continued on next page

Table A.3 (continued)

Z	Name	Symbol	a	Calculated a	Error
38	Strontium	Sr	97.51	97.03	0.50%
39	Yttrium	Y	117.36	118.63	1.08%
40	Zirconium	Zr	126.62	126.69	0.05%
41	Niobium	Nb	129.84	129.45	0.30%
42	Molybdenum	Mo	128.74	125.35	2.64%
43	Technetium	Tc	127.55	125.16	1.87%
44	Ruthenium	Ru	130.13	124.08	4.65%
45	Rhodium	Rh	125.16	120.71	3.55%
46	Palladium	Pd	116.95	112.98	3.40%
47	Silver	Ag	109.69	104.00	5.19%
48	Cadmium	Cd	82.77	87.18	5.33%
49	Indium	In	102.85	102.94	0.09%
50	Tin	Sn	107.40	107.40	0.00%
53	Iodine	I	98.66	93.40	5.33%
55	Caesium	Cs	77.07	79.86	3.62%
60	Neodymium	Nd	107.88	107.98	0.09%
62	Samarium	Sm	101.45	101.08	0.36%
64	Gadolinium	Gd	109.68	110.63	0.87%
66	Dysprosium	Dy	108.37	107.74	0.58%
68	Erbium	Er	109.75	109.04	0.65%
70	Ytterbium	Yb	96.38	94.23	2.23%
71	Lutetium	Lu	118.20	115.49	2.29%
74	Tungsten	W	133.03	127.11	4.45%
78	Platinum	Pt	122.61	117.79	3.93%
79	Gold	Au	110.66	104.76	5.34%
81	Thallium	Tl	96.23	94.94	1.34%
82	Lead	Pb	98.11	96.68	1.46%

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Table A.3 (continued)

Z	Name	Symbol	a	Calculated a	Error
83	Bismuth	Bi	94.40	94.81	0.44%

Table A.4: Third Temperature Scaling Law Coefficient a Versus Calculated Coefficient a

Z	Name	Symbol	a	Calculated a	Error
3	Lithium	Li	110.21	99.57	9.65%
4	Beryllium	Be	113.74	114.23	0.43%
5	Boron	B	129.18	130.50	1.02%
6	Carbon	C	135.47	140.03	3.37%
11	Sodium	Na	99.75	91.03	8.74%
12	Magnesium	Mg	97.72	97.76	0.04%
13	Aluminium	Al	114.00	117.25	2.85%
14	Silicon	Si	121.77	126.16	3.61%
19	Potassium	K	84.23	87.15	3.46%
20	Calcium	Ca	97.38	100.12	2.82%
21	Scandium	Sc	116.20	121.10	4.22%
22	Titanium	Ti	125.49	127.35	1.48%
23	Vanadium	V	124.99	130.16	4.13%
24	Chromium	Cr	118.71	122.61	3.28%
25	Manganese	Mn	104.10	108.68	4.40%
26	Iron	Fe	118.04	123.89	4.95%
27	Cobalt	Co	118.88	124.46	4.70%
28	Nickel	Ni	115.42	122.46	6.10%
29	Copper	Cu	114.67	118.17	3.05%
30	Zinc	Zn	96.74	95.21	1.57%
31	Gallium	Ga	107.18	111.29	3.84%
32	Germanium	Ge	115.19	120.72	4.80%
33	Arsenic	As	112.77	115.20	2.15%
34	Selenium	Se	92.43	89.98	2.65%
37	Rubidium	Rb	82.63	84.60	2.39%
38	Strontium	Sr	97.51	100.23	2.79%

Continued on next page

Table A.4 (continued)

Z	Name	Symbol	a	Calculated a	Error
39	Yttrium	Y	117.36	124.53	6.10%
40	Zirconium	Zr	126.62	135.22	6.79%
41	Niobium	Nb	129.84	140.69	8.36%
42	Molybdenum	Mo	128.74	137.86	7.08%
43	Technetium	Tc	127.55	135.64	6.35%
44	Ruthenium	Ru	130.13	136.22	4.68%
45	Rhodium	Rh	125.16	132.39	5.78%
46	Palladium	Pd	116.95	121.30	3.71%
47	Silver	Ag	109.69	113.69	3.64%
48	Cadmium	Cd	82.77	90.76	9.65%
49	Indium	In	102.85	109.64	6.60%
50	Tin	Sn	107.40	115.29	7.35%
53	Iodine	I	98.66	90.93	7.83%
55	Caesium	Cs	77.07	81.45	5.68%
60	Neodymium	Nd	107.88	114.68	6.31%
62	Samarium	Sm	101.45	105.69	4.18%
64	Gadolinium	Gd	109.68	116.00	5.77%
66	Dysprosium	Dy	108.37	114.17	5.36%
68	Erbium	Er	109.75	116.49	6.14%
70	Ytterbium	Yb	96.38	100.60	4.38%
71	Lutetium	Lu	118.20	125.25	5.97%
74	Tungsten	W	133.03	145.88	9.65%
78	Platinum	Pt	122.61	131.79	7.48%
79	Gold	Au	110.66	118.08	6.70%
81	Thallium	Tl	96.23	102.51	6.53%
82	Lead	Pb	98.11	104.29	6.30%
83	Bismuth	Bi	94.40	99.99	5.93%

A.2 Heat Flux

Table A.5: Heat Flux Scaling Law Coefficients

Z	Name	Symbol	a	b	c	d
3	Lithium	Li	2.733821	0.056977	-1.640106	1.213807
4	Beryllium	Be	11.589338	0.015682	-1.557933	1.141734
5	Boron	B	16.858893	0.014688	-1.560000	1.151990
6	Carbon	C	19.008801	0.029371	-1.560000	1.159820
11	Sodium	Na	0.843709	0.012136	-1.664712	1.273723
12	Magnesium	Mg	4.745162	0.000442	-1.555303	1.172271
13	Aluminium	Al	11.269343	-0.003321	-1.546346	1.156672
14	Silicon	Si	3.970971	-0.003427	-1.648798	1.206312
19	Potassium	K	13.029425	-0.206146	-1.420396	1.106999
20	Calcium	Ca	1.565872	0.009883	-1.630776	1.236066
21	Scandium	Sc	2.836401	0.000152	-1.662115	1.217791
22	Titanium	Ti	7.356579	0.078530	-1.624077	1.185710
23	Vanadium	V	3.148284	0.001056	-1.668267	1.226237
24	Chromium	Cr	7.072842	-0.013029	-1.624130	1.155598
25	Manganese	Mn	6.313420	-0.038341	-1.550622	1.174154
26	Iron	Fe	3.614139	-0.028376	-1.644688	1.207129
27	Cobalt	Co	6.482298	-0.022226	-1.593263	1.189512
28	Nickel	Ni	8.381080	-0.010292	-1.566518	1.181171
29	Copper	Cu	14.019738	-0.020612	-1.515312	1.154518
30	Zinc	Zn	25.198906	-0.036546	-1.431423	1.087752
31	Gallium	Ga	18.152440	-0.056602	-1.464225	1.136955

Continued on next page

Table A.5 (continued)

Z	Name	Symbol	a	b	c	d
32	Germanium	Ge	8.792188	-0.023300	-1.563708	1.169548
33	Arsenic	As	11.722817	-0.009192	-1.531375	1.154779
34	Selenium	Se	164.135368	-0.018326	-1.289183	0.996525
37	Rubidium	Rb	57.315039	-0.207131	-1.250082	1.053427
38	Strontium	Sr	0.993742	0.046805	-1.670924	1.260502
39	Yttrium	Y	2.888216	-0.032899	-1.654206	1.222581
40	Zirconium	Zr	2.855348	-0.001493	-1.682378	1.236675
41	Niobium	Nb	2.913340	-0.024191	-1.697111	1.232532
42	Molybdenum	Mo	2.765074	-0.031291	-1.692931	1.232037
43	Technetium	Tc	2.546185	-0.016868	-1.686999	1.242109
44	Ruthenium	Ru	3.835956	-0.005719	-1.656165	1.227501
45	Rhodium	Rh	5.693582	-0.025425	-1.615214	1.204859
46	Palladium	Pd	13.643144	-0.017188	-1.564601	1.130901
47	Silver	Ag	17.041102	-0.032940	-1.462761	1.153209
48	Cadmium	Cd	36.199173	-0.065707	-1.359293	1.072926
49	Indium	In	8.730784	-0.090023	-1.511239	1.159998
50	Tin	Sn	7.588435	-0.041490	-1.550216	1.172973
53	Iodine	I	208.115176	-0.001329	-1.332696	0.951630
55	Caesium	Cs	38.149025	-0.195077	-1.228320	1.080826
60	Neodymium	Nd	2.080750	-0.045147	-1.645365	1.231158
62	Samarium	Sm	1.114092	-0.031777	-1.672335	1.249874
64	Gadolinium	Gd	1.681289	-0.042555	-1.676275	1.235188
66	Dysprosium	Dy	1.555656	-0.040468	-1.675062	1.238853
68	Erbium	Er	1.650392	-0.041916	-1.679009	1.236591
70	Ytterbium	Yb	0.667001	-0.033796	-1.682060	1.272804
71	Lutetium	Lu	2.399822	-0.045569	-1.679711	1.222979
74	Tungsten	W	2.303853	-0.031725	-1.723804	1.244518

Continued on next page

Table A.5 (continued)

Z	Name	Symbol	a	b	c	d
78	Platinum	Pt	14.457689	-0.033323	-1.559181	1.149971
79	Gold	Au	27.935128	-0.082858	-1.481008	1.098391
81	Thallium	Tl	16.582092	-0.102663	-1.413527	1.136936
82	Lead	Pb	5.245189	-0.082607	-1.559967	1.159997
83	Bismuth	Bi	5.222592	-0.082425	-1.537166	1.160000
Formula	**Name**		**a**	**b**	**c**	**d**
C16H14O3	Lexan		24.248308	0.031728	-1.559831	1.110007
C2F4	Teflon		26.588436	0.048909	-1.560000	1.125300

A.3 Bulk Velocity

Table A.6: Bulk Velocity Scaling Law Coefficients

Z	Name	Symbol	a	b	c	d
3	Lithium	Li	183.165570	0.021329	-0.288123	0.179422
4	Beryllium	Be	142.004200	0.003716	-0.265928	0.191684
5	Boron	B	167.260327	0.010015	-0.273171	0.171961
6	Carbon	C	156.099141	0.005843	-0.260528	0.178240
11	Sodium	Na	107.478163	0.012596	-0.273564	0.180436
12	Magnesium	Mg	65.400205	-0.004089	-0.271320	0.209746
13	Aluminium	Al	72.505832	0.006947	-0.305572	0.188873
14	Silicon	Si	49.396580	0.002120	-0.313782	0.215113
19	Potassium	K	147.567112	-0.002236	-0.237321	0.149914
20	Calcium	Ca	29.848798	-0.018813	-0.303733	0.247165
21	Scandium	Sc	30.315598	-0.025168	-0.315417	0.239299
22	Titanium	Ti	35.478707	0.006760	-0.329319	0.220722
23	Vanadium	V	30.478738	-0.011332	-0.317607	0.233750
24	Chromium	Cr	48.608847	0.004818	-0.297776	0.200372
25	Manganese	Mn	47.275620	-0.016619	-0.271902	0.204715
26	Iron	Fe	33.044397	-0.008625	-0.309099	0.220525
27	Cobalt	Co	44.337064	-0.007961	-0.286742	0.204530
28	Nickel	Ni	51.486771	-0.002693	-0.277931	0.196797
29	Copper	Cu	60.496175	-0.003895	-0.260664	0.186527
30	Zinc	Zn	76.299992	-0.021297	-0.216413	0.173469
31	Gallium	Ga	61.710379	-0.003350	-0.269549	0.178274
32	Germanium	Ge	38.576081	-0.031058	-0.281270	0.205303
33	Arsenic	As	51.155915	-0.020167	-0.245493	0.194268
34	Selenium	Se	90.516949	-0.039567	-0.191256	0.156871

Continued on next page

Table A.6 (continued)

Z	Name	Symbol	a	b	c	d
37	Rubidium	Rb	100.101062	-0.044613	-0.207567	0.157713
38	Strontium	Sr	15.938917	-0.064887	-0.307709	0.259997
39	Yttrium	Y	16.631808	-0.054477	-0.324455	0.255360
40	Zirconium	Zr	17.931210	-0.040391	-0.324275	0.251215
41	Niobium	Nb	19.676309	-0.026146	-0.327090	0.242357
42	Molybdenum	Mo	19.433228	-0.013107	-0.339818	0.231232
43	Technetium	Tc	21.795256	-0.031694	-0.310624	0.233678
44	Ruthenium	Ru	25.919783	-0.017868	-0.303839	0.221311
45	Rhodium	Rh	30.894238	-0.016774	-0.294184	0.207968
46	Palladium	Pd	38.668077	-0.058531	-0.264741	0.188806
47	Silver	Ag	51.201126	-0.044073	-0.242936	0.177697
48	Cadmium	Cd	48.816898	-0.066476	-0.207763	0.180812
49	Indium	In	37.367620	-0.026982	-0.280293	0.189551
50	Tin	Sn	27.124986	-0.056236	-0.272960	0.214225
53	Iodine	I	73.047072	-0.041416	-0.195834	0.149900
55	Caesium	Cs	85.087520	-0.066476	-0.190105	0.156841
60	Neodymium	Nd	12.087348	-0.095309	-0.310396	0.264152
62	Samarium	Sm	10.208799	-0.099639	-0.317728	0.265084
64	Gadolinium	Gd	9.950375	-0.066477	-0.334412	0.262674
66	Dysprosium	Dy	9.820563	-0.066476	-0.332764	0.264462
68	Erbium	Er	9.475128	-0.066476	-0.336225	0.263943
70	Ytterbium	Yb	11.046111	-0.066477	-0.312341	0.250590
71	Lutetium	Lu	10.411990	-0.048449	-0.357039	0.246459
74	Tungsten	W	11.289272	-0.058428	-0.341489	0.240585
78	Platinum	Pt	20.552039	-0.066476	-0.277639	0.210457
79	Gold	Au	31.591415	-0.066476	-0.230729	0.193266
81	Thallium	Tl	34.329506	-0.092318	-0.231726	0.180762

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Table A.6 (continued)

Z	Name	Symbol	a	b	c	d
82	Lead	Pb	15.927734	-0.066477	-0.277614	0.222732
83	Bismuth	Bi	22.983046	-0.066477	-0.247422	0.204726
Formula	**Name**		**a**	**b**	**c**	**d**
C16H14O3	Lexan		189.099836	0.001083	-0.252417	0.179528
C2F4	Teflon		153.227453	0.006896	-0.241150	0.170054

A.4 Total Ablated Mass (MTOT)

Table A.7: Total Ablated Mass (MTOT) Scaling Law Coefficients

Z	Name	Symbol	a	b	c	d	e
3	Lithium	Li	4.08E-11	1.013225	-0.647000	-0.110800	0.067190
4	Beryllium	Be	1.08E-09	1.078738	-0.392000	-0.227400	0.063739
5	Boron	B	2.93E-10	1.068326	-0.501000	-0.186400	0.065846
6	Carbon	C	2.81E-10	1.175611	-0.549000	-0.180200	0.065062
11	Sodium	Na	3.39E-10	1.058392	-0.563000	-0.107900	0.063997
12	Magnesium	Mg	1.55E-08	1.165019	-0.255000	-0.210100	0.053526
13	Aluminium	Al	2.36E-09	1.065440	-0.373000	-0.184900	0.061043
14	Silicon	Si	1.90E-09	1.134210	-0.427000	-0.175600	0.059370
19	Potassium	K	1.17E-07	1.058451	-0.127000	-0.311000	0.058223
20	Calcium	Ca	9.68E-10	1.013698	-0.467000	-0.125000	0.060781
21	Scandium	Sc	1.10E-09	1.029081	-0.468000	-0.123600	0.057162
22	Titanium	Ti	9.33E-10	1.192430	-0.566000	-0.140600	0.058926
23	Vanadium	V	1.12E-09	1.028124	-0.467000	-0.136900	0.060565
24	Chromium	Cr	1.19E-09	1.182415	-0.547000	-0.175800	0.066045
25	Manganese	Mn	1.17E-08	1.019150	-0.301000	-0.206700	0.058320
26	Iron	Fe	4.69E-09	1.142820	-0.349000	-0.133100	0.057758
27	Cobalt	Co	5.17E-09	1.016012	-0.379000	-0.191600	0.059136
28	Nickel	Ni	6.75E-09	1.021547	-0.378000	-0.220000	0.060475
29	Copper	Cu	1.87E-08	1.148268	-0.281000	-0.185800	0.056174
30	Zinc	Zn	7.50E-08	0.964139	-0.273000	-0.346700	0.062946
31	Gallium	Ga	1.87E-08	0.972174	-0.249000	-0.214000	0.058992
32	Germanium	Ge	1.30E-08	1.223068	-0.415000	-0.236100	0.060101
33	Arsenic	As	1.03E-07	1.093487	-0.231000	-0.303900	0.057263
34	Selenium	Se	1.03E-06	1.062243	-0.098000	-0.374900	0.053568

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Table A.7 (continued)

Z	Name	Symbol	a	b	c	d	e
37	Rubidium	Rb	8.29E-07	0.995853	0.025000	-0.345600	0.058445
38	Strontium	Sr	9.40E-10	1.029045	-0.532000	-0.083700	0.060275
39	Yttrium	Y	5.37E-09	1.052883	-0.412000	-0.154400	0.055257
40	Zirconium	Zr	3.72E-09	1.070026	-0.541000	-0.229700	0.058622
41	Niobium	Nb	9.37E-10	1.053256	-0.528000	-0.105700	0.060516
42	Molybdenum	Mo	4.15E-09	1.082902	-0.428000	-0.143900	0.056768
43	Technetium	Tc	2.04E-09	1.031225	-0.469000	-0.126700	0.059483
44	Ruthenium	Ru	2.22E-09	1.029663	-0.458000	-0.123900	0.059454
45	Rhodium	Rh	3.78E-09	1.023231	-0.395000	-0.127300	0.059270
46	Palladium	Pd	1.38E-08	1.193468	-0.434000	-0.224900	0.061573
47	Silver	Ag	3.64E-08	0.983024	-0.250000	-0.222900	0.058702
48	Cadmium	Cd	8.29E-07	0.972662	-0.055000	-0.340500	0.056371
49	Indium	In	2.91E-08	0.999612	-0.271000	-0.215900	0.058815
50	Tin	Sn	3.54E-08	1.124846	-0.359000	-0.235400	0.054078
53	Iodine	I	7.71E-07	1.138325	-0.210000	-0.403300	0.063251
55	Caesium	Cs	2.07E-07	0.927076	-0.105000	-0.288500	0.060661
60	Neodymium	Nd	8.89E-09	1.073453	-0.409000	-0.141900	0.055051
62	Samarium	Sm	9.97E-10	1.034525	-0.568000	-0.061000	0.059701
64	Gadolinium	Gd	1.27E-09	1.035985	-0.554000	-0.078900	0.059834
66	Dysprosium	Dy	1.02E-09	1.034973	-0.571000	-0.065500	0.059872
68	Erbium	Er	1.13E-09	1.034196	-0.566000	-0.070400	0.059845
70	Ytterbium	Yb	4.09E-09	1.013804	-0.468000	-0.107500	0.058403
71	Lutetium	Lu	1.07E-09	1.031798	-0.571000	-0.076900	0.060453
74	Tungsten	W	8.16E-09	1.063054	-0.428000	-0.139000	0.053829
78	Platinum	Pt	4.95E-08	1.034838	-0.292000	-0.214900	0.056376
79	Gold	Au	5.18E-08	0.984589	-0.244000	-0.191700	0.058617
81	Thallium	Tl	5.18E-08	0.971936	-0.237000	-0.195100	0.060038

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Table A.7 (continued)

Z	Name	Symbol	a	b	c	d	e
82	Lead	Pb	5.18E-08	1.007406	-0.262000	-0.145700	0.050672
83	Bismuth	Bi	5.18E-08	0.981046	-0.265000	-0.198600	0.059545
Formula	**Name**		**a**	**b**	**c**	**d**	**e**
C16H14O3	Lexan		3.28E-10	1.124096	-0.525000	-0.200800	0.063841
C2F4	Teflon		6.23E-10	1.190579	-0.577000	-0.186400	0.063726

A.5 Pressure

Table A.8: Pressure Scaling Law Coefficients

Z	Name	Symbol	a	b	c	d	e
3	Lithium	Li	1.88E-06	0.721515	-3.092000	1.446500	0.005915
4	Beryllium	Be	1.81E-05	0.554999	-2.778000	1.320400	0.012433
5	Boron	B	3.00E-05	0.561398	-2.819000	1.272400	0.009463
6	Carbon	C	7.64E-06	0.511926	-2.854000	1.360300	0.009245
11	Sodium	Na	1.54E-05	0.316637	-2.840000	1.341200	0.008378
12	Magnesium	Mg	4.29E-06	0.204895	-2.813000	1.337600	0.018956
13	Aluminium	Al	1.65E-06	0.286723	-2.936000	1.381000	0.017545
14	Silicon	Si	4.44E-07	0.264113	-3.022000	1.431700	0.017499
19	Potassium	K	4.74E-04	0.113000	-2.431000	1.170600	0.020716
20	Calcium	Ca	2.82E-08	0.171264	-3.182000	1.569900	0.018651
21	Scandium	Sc	5.42E-08	0.135399	-3.179000	1.506900	0.018441
22	Titanium	Ti	4.21E-07	0.278789	-3.048000	1.403600	0.022191
23	Vanadium	V	1.02E-07	0.119355	-3.131000	1.463700	0.019576
24	Chromium	Cr	7.82E-07	0.152767	-2.990000	1.353000	0.023234
25	Manganese	Mn	1.80E-06	0.104221	-2.876000	1.336100	0.023981
26	Iron	Fe	3.48E-07	0.112772	-3.023000	1.396100	0.023373
27	Cobalt	Co	6.73E-07	0.098871	-2.964000	1.364600	0.024475
28	Nickel	Ni	9.23E-07	0.102653	-2.933000	1.354400	0.025298
29	Copper	Cu	5.99E-06	0.103661	-2.791000	1.271900	0.027353
30	Zinc	Zn	4.00E-04	0.091383	-2.454000	1.100500	0.030479
31	Gallium	Ga	4.59E-06	0.096971	-2.808000	1.287700	0.027404
32	Germanium	Ge	1.60E-06	0.095013	-2.894000	1.333300	0.024116
33	Arsenic	As	4.64E-05	0.110007	-2.634000	1.174900	0.030475
34	Selenium	Se	4.80E-04	0.113610	-2.441000	1.079300	0.036521

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Table A.8 (continued)

Z	Name	Symbol	a	b	c	d	e
37	Rubidium	Rb	6.46E-04	0.123189	-2.400000	1.103700	0.033471
38	Strontium	Sr	1.63E-08	0.111317	-3.217000	1.565500	0.023668
39	Yttrium	Y	1.01E-07	0.132237	-3.136000	1.441000	0.025442
40	Zirconium	Zr	6.73E-08	0.112781	-3.162000	1.461400	0.023722
41	Niobium	Nb	2.19E-08	0.094963	-3.251000	1.495400	0.024780
42	Molybdenum	Mo	4.14E-08	0.095224	-3.199000	1.456200	0.026757
43	Technetium	Tc	1.10E-07	0.095041	-3.120000	1.416800	0.026700
44	Ruthenium	Ru	2.00E-07	0.110623	-3.072000	1.390200	0.027780
45	Rhodium	Rh	4.18E-07	0.107569	-3.012000	1.354600	0.029498
46	Palladium	Pd	2.38E-06	0.101676	-2.858000	1.290200	0.031195
47	Silver	Ag	5.12E-06	0.096197	-2.748000	1.271500	0.035272
48	Cadmium	Cd	4.81E-04	0.121094	-2.411000	1.069300	0.040733
49	Indium	In	1.60E-06	0.105253	-2.905000	1.303400	0.031331
50	Tin	Sn	1.28E-06	0.114646	-2.914000	1.340000	0.025859
53	Iodine	I	1.44E-03	0.201560	-2.520000	0.896600	0.056150
55	Caesium	Cs	8.54E-05	0.196629	-2.587000	1.171400	0.034373
60	Neodymium	Nd	7.34E-08	0.179023	-3.173000	1.463600	0.026642
62	Samarium	Sm	1.80E-08	0.154383	-3.236000	1.533400	0.028010
64	Gadolinium	Gd	1.61E-08	0.135746	-3.277000	1.504600	0.029085
66	Dysprosium	Dy	1.69E-08	0.147130	-3.261000	1.515000	0.028974
68	Erbium	Er	1.59E-08	0.162620	-3.260000	1.519300	0.029295
70	Ytterbium	Yb	4.63E-08	0.189013	-3.171000	1.472300	0.030407
71	Lutetium	Lu	1.63E-08	0.158021	-3.313000	1.478500	0.030527
74	Tungsten	W	4.63E-08	0.127343	-3.201000	1.412200	0.033290
78	Platinum	Pt	1.41E-06	0.122625	-2.919000	1.262300	0.038782
79	Gold	Au	7.51E-06	0.131333	-2.765000	1.198300	0.043078
81	Thallium	Tl	7.51E-06	0.205467	-2.788000	1.221400	0.040114

Continued on next page

Table A.8 (continued)

Z	**Name**	**Symbol**	**a**	**b**	**c**	**d**	**e**
82	Lead	Pb	1.51E-06	0.201113	-2.913000	1.287400	0.037067
83	Bismuth	Bi	6.87E-06	0.173174	-2.780000	1.219700	0.039826
Formula	**Name**		**a**	**b**	**c**	**d**	**e**
C16H14O3	Lexan		7.51E-06	0.566800	-2.911000	1.317700	0.013332
C2F4	Teflon		7.51E-06	0.566292	-2.970000	1.303500	0.016965

Appendix B

Scaling Law sensitivity check lists comparison with code ETFLOW

B.1 Temperature

Table B.1: First Temperature Scaling Law Sensitivity Check List

Z	Name	Symbol	Max Error
3	Lithium	Li	0.48%
4	Beryllium	Be	0.57%
5	Boron	B	0.47%
6	Carbon	C	0.39%
11	Sodium	Na	0.97%
12	Magnesium	Mg	1.03%
13	Aluminium	Al	0.51%
14	Silicon	Si	0.40%

Continued on next page

Table B.1 (continued)

Z	Name	Symbol	Max Error
19	Potassium	K	3.04%
20	Calcium	Ca	0.79%
21	Scandium	Sc	0.86%
22	Titanium	Ti	1.89%
23	Vanadium	V	0.73%
24	Chromium	Cr	2.07%
25	Manganese	Mn	2.08%
26	Iron	Fe	0.37%
27	Cobalt	Co	1.75%
28	Nickel	Ni	1.58%
29	Copper	Cu	0.84%
30	Zinc	Zn	1.90%
31	Gallium	Ga	0.97%
32	Germanium	Ge	2.00%
33	Arsenic	As	1.13%
34	Selenium	Se	1.22%
37	Rubidium	Rb	2.33%
38	Strontium	Sr	0.86%
39	Yttrium	Y	1.75%
40	Zirconium	Zr	2.51%
41	Niobium	Nb	0.85%
42	Molybdenum	Mo	0.30%
43	Technetium	Tc	0.70%
44	Ruthenium	Ru	1.00%
45	Rhodium	Rh	0.91%
46	Palladium	Pd	2.04%
47	Silver	Ag	1.37%

Continued on next page

Table B.1 (continued)

Z	Name	Symbol	Max Error
48	Cadmium	Cd	1.74%
49	Indium	In	0.92%
50	Tin	Sn	2.16%
53	Iodine	I	1.90%
55	Caesium	Cs	2.43%
60	Neodymium	Nd	1.29%
62	Samarium	Sm	0.67%
64	Gadolinium	Gd	0.68%
66	Dysprosium	Dy	0.64%
68	Erbium	Er	0.64%
70	Ytterbium	Yb	0.58%
71	Lutetium	Lu	0.59%
74	Tungsten	W	0.38%
78	Platinum	Pt	0.64%
79	Gold	Au	1.05%
81	Thallium	Tl	1.47%
82	Lead	Pb	1.13%
83	Bismuth	Bi	1.29%
Formula	**Name**		
C16H14O3	Lexan		1.22%
C2F4	Teflon		0.39%
	Total max error		3.04%

Table B.2: Second Temperature Scaling Law Sensitivity Check List

Z	Name	Symbol	Max Error
3	Lithium	Li	2.66%
4	Beryllium	Be	3.95%
5	Boron	B	2.99%
6	Carbon	C	1.41%
11	Sodium	Na	9.32%
12	Magnesium	Mg	2.53%
13	Aluminium	Al	0.79%
14	Silicon	Si	3.14%
19	Potassium	K	9.46%
20	Calcium	Ca	2.73%
21	Scandium	Sc	6.97%
22	Titanium	Ti	9.40%
23	Vanadium	V	5.77%
24	Chromium	Cr	4.47%
25	Manganese	Mn	5.42%
26	Iron	Fe	2.53%
27	Cobalt	Co	1.89%
28	Nickel	Ni	1.59%
29	Copper	Cu	4.50%
30	Zinc	Zn	7.87%
31	Gallium	Ga	2.69%
32	Germanium	Ge	2.27%
33	Arsenic	As	2.75%
34	Selenium	Se	5.16%
37	Rubidium	Rb	9.22%
38	Strontium	Sr	3.25%

Continued on next page

Table B.2 (continued)

Z	Name	Symbol	Max Error
39	Yttrium	Y	5.82%
40	Zirconium	Zr	6.61%
41	Niobium	Nb	5.07%
42	Molybdenum	Mo	3.55%
43	Technetium	Tc	3.56%
44	Ruthenium	Ru	4.99%
45	Rhodium	Rh	4.41%
46	Palladium	Pd	4.90%
47	Silver	Ag	6.98%
48	Cadmium	Cd	8.34%
49	Indium	In	3.91%
50	Tin	Sn	3.90%
53	Iodine	I	11.30%
55	Caesium	Cs	8.47%
60	Neodymium	Nd	4.15%
62	Samarium	Sm	2.44%
64	Gadolinium	Gd	3.96%
66	Dysprosium	Dy	2.56%
68	Erbium	Er	2.62%
70	Ytterbium	Yb	5.52%
71	Lutetium	Lu	2.81%
74	Tungsten	W	5.28%
78	Platinum	Pt	3.78%
79	Gold	Au	8.46%
81	Thallium	Tl	6.67%
82	Lead	Pb	4.30%

Continued on next page

Table B.2 (continued)

Z	Name	Symbol	Max Error
83	Bismuth	Bi	2.28%
	Total max error		11.30%

Table B.3: Third Temperature Scaling Law Sensitivity Check List

Z	Name	Symbol	Max Error
3	Lithium	Li	11.10%
4	Beryllium	Be	1.35%
5	Boron	B	1.02%
6	Carbon	C	4.43%
11	Sodium	Na	12.58%
12	Magnesium	Mg	1.71%
13	Aluminium	Al	2.39%
14	Silicon	Si	6.34%
19	Potassium	K	11.06%
20	Calcium	Ca	3.12%
21	Scandium	Sc	8.03%
22	Titanium	Ti	11.90%
23	Vanadium	V	9.34%
24	Chromium	Cr	9.07%
25	Manganese	Mn	4.49%
26	Iron	Fe	7.06%
27	Cobalt	Co	6.67%
28	Nickel	Ni	6.08%
29	Copper	Cu	4.55%
30	Zinc	Zn	5.85%
31	Gallium	Ga	4.21%
32	Germanium	Ge	7.17%
33	Arsenic	As	4.77%
34	Selenium	Se	7.98%
37	Rubidium	Rb	8.44%
38	Strontium	Sr	4.80%

Continued on next page

Table B.3 (continued)

Z	Name	Symbol	Max Error
39	Yttrium	Y	11.08%
40	Zirconium	Zr	13.78%
41	Niobium	Nb	14.20%
42	Molybdenum	Mo	11.56%
43	Technetium	Tc	12.23%
44	Ruthenium	Ru	11.22%
45	Rhodium	Rh	9.34%
46	Palladium	Pd	6.97%
47	Silver	Ag	6.69%
48	Cadmium	Cd	4.58%
49	Indium	In	5.71%
50	Tin	Sn	8.35%
53	Iodine	I	13.64%
55	Caesium	Cs	6.65%
60	Neodymium	Nd	10.61%
62	Samarium	Sm	6.91%
64	Gadolinium	Gd	9.00%
66	Dysprosium	Dy	8.68%
68	Erbium	Er	9.25%
70	Ytterbium	Yb	6.76%
71	Lutetium	Lu	10.56%
74	Tungsten	W	15.48%
78	Platinum	Pt	10.67%
79	Gold	Au	7.44%
81	Thallium	Tl	7.12%
82	Lead	Pb	6.93%

Continued on next page

Table B.3 (continued)

Z	Name	Symbol	Max Error
83	Bismuth	Bi	6.60%
	Total max error		15.48%

B.2 Heat Flux

Table B.4: Heat Flux Scaling Law Sensitivity Check List

Z	Name	Symbol	Max Error
3	Lithium	Li	1.75%
4	Beryllium	Be	2.29%
5	Boron	B	2.86%
6	Carbon	C	2.80%
11	Sodium	Na	3.87%
12	Magnesium	Mg	4.28%
13	Aluminium	Al	1.88%
14	Silicon	Si	1.98%
19	Potassium	K	12.12%
20	Calcium	Ca	3.46%
21	Scandium	Sc	3.36%
22	Titanium	Ti	5.88%
23	Vanadium	V	3.10%
24	Chromium	Cr	8.53%
25	Manganese	Mn	5.75%
26	Iron	Fe	1.80%
27	Cobalt	Co	4.29%
28	Nickel	Ni	4.45%
29	Copper	Cu	2.88%
30	Zinc	Zn	7.10%
31	Gallium	Ga	3.17%
32	Germanium	Ge	6.67%
33	Arsenic	As	4.57%
34	Selenium	Se	4.86%

Continued on next page

Table B.4 (continued)

Z	Name	Symbol	Max Error
37	Rubidium	Rb	9.30%
38	Strontium	Sr	3.43%
39	Yttrium	Y	4.93%
40	Zirconium	Zr	4.61%
41	Niobium	Nb	3.40%
42	Molybdenum	Mo	1.19%
43	Technetium	Tc	2.94%
44	Ruthenium	Ru	3.95%
45	Rhodium	Rh	3.61%
46	Palladium	Pd	7.81%
47	Silver	Ag	4.17%
48	Cadmium	Cd	6.96%
49	Indium	In	4.01%
50	Tin	Sn	8.62%
53	Iodine	I	7.59%
55	Caesium	Cs	9.69%
60	Neodymium	Nd	4.70%
62	Samarium	Sm	2.67%
64	Gadolinium	Gd	2.73%
66	Dysprosium	Dy	2.55%
68	Erbium	Er	2.55%
70	Ytterbium	Yb	2.55%
71	Lutetium	Lu	2.35%
74	Tungsten	W	1.30%
78	Platinum	Pt	5.19%
79	Gold	Au	4.69%
81	Thallium	Tl	5.88%

Continued on next page

Table B.4 (continued)

Z	**Name**	**Symbol**	**Max Error**
82	Lead	Pb	6.59%
83	Bismuth	Bi	5.82%
Formula	**Name**		
C16H14O3	Lexan		5.47%
C2F4	Teflon		5.37%
	Total max error		12.12%

B.3 Bulk Velocity

Table B.5: Bulk Velocity Scaling Law Sensitivity Check List

Z	Name	Symbol	Max Error
3	Lithium	Li	1.41%
4	Beryllium	Be	0.46%
5	Boron	B	0.43%
6	Carbon	C	0.24%
11	Sodium	Na	1.41%
12	Magnesium	Mg	0.67%
13	Aluminium	Al	0.39%
14	Silicon	Si	0.53%
19	Potassium	K	3.07%
20	Calcium	Ca	1.83%
21	Scandium	Sc	3.16%
22	Titanium	Ti	3.23%
23	Vanadium	V	2.37%
24	Chromium	Cr	2.02%
25	Manganese	Mn	1.41%
26	Iron	Fe	0.67%
27	Cobalt	Co	1.34%
28	Nickel	Ni	1.13%
29	Copper	Cu	0.73%
30	Zinc	Zn	0.96%
31	Gallium	Ga	0.69%
32	Germanium	Ge	2.01%
33	Arsenic	As	0.96%
34	Selenium	Se	1.39%

Continued on next page

Table B.5 (continued)

Z	Name	Symbol	Max Error
37	Rubidium	Rb	2.73%
38	Strontium	Sr	2.64%
39	Yttrium	Y	3.76%
40	Zirconium	Zr	3.59%
41	Niobium	Nb	3.13%
42	Molybdenum	Mo	0.91%
43	Technetium	Tc	2.27%
44	Ruthenium	Ru	1.79%
45	Rhodium	Rh	1.42%
46	Palladium	Pd	1.59%
47	Silver	Ag	0.98%
48	Cadmium	Cd	1.65%
49	Indium	In	1.02%
50	Tin	Sn	2.42%
53	Iodine	I	1.24%
55	Caesium	Cs	2.16%
60	Neodymium	Nd	5.13%
62	Samarium	Sm	2.84%
64	Gadolinium	Gd	2.77%
66	Dysprosium	Dy	3.15%
68	Erbium	Er	3.03%
70	Ytterbium	Yb	2.77%
71	Lutetium	Lu	2.00%
74	Tungsten	W	1.09%
78	Platinum	Pt	1.19%
79	Gold	Au	1.46%
81	Thallium	Tl	1.80%

Continued on next page

Table B.5 (continued)

Z	**Name**	**Symbol**	**Max Error**
82	Lead	Pb	2.74%
83	Bismuth	Bi	2.73%
Formula	**Name**		
C16H14O3	Lexan		0.92%
C2F4	Teflon		0.25%
	Total max error		5.13%

B.4 Total Ablated Mass (MTOT)

Table B.6: Total Ablated Mass (MTOT) Scaling Law Sensitivity Check List

Z	Name	Symbol	Max Error
3	Lithium	Li	3.97%
4	Beryllium	Be	4.13%
5	Boron	B	4.49%
6	Carbon	C	4.05%
11	Sodium	Na	4.60%
12	Magnesium	Mg	5.95%
13	Aluminium	Al	4.23%
14	Silicon	Si	4.33%
19	Potassium	K	13.58%
20	Calcium	Ca	9.82%
21	Scandium	Sc	7.79%
22	Titanium	Ti	14.71%
23	Vanadium	V	7.62%
24	Chromium	Cr	19.41%
25	Manganese	Mn	9.88%
26	Iron	Fe	6.50%
27	Cobalt	Co	8.24%
28	Nickel	Ni	9.62%
29	Copper	Cu	5.65%
30	Zinc	Zn	16.95%
31	Gallium	Ga	7.72%
32	Germanium	Ge	12.21%
33	Arsenic	As	6.87%
34	Selenium	Se	8.04%

Continued on next page

Table B.6 (continued)

Z	Name	Symbol	Max Error
37	Rubidium	Rb	10.71%
38	Strontium	Sr	10.16%
39	Yttrium	Y	9.90%
40	Zirconium	Zr	15.86%
41	Niobium	Nb	8.81%
42	Molybdenum	Mo	4.56%
43	Technetium	Tc	9.63%
44	Ruthenium	Ru	9.97%
45	Rhodium	Rh	9.60%
46	Palladium	Pd	15.22%
47	Silver	Ag	8.05%
48	Cadmium	Cd	11.01%
49	Indium	In	11.75%
50	Tin	Sn	11.34%
53	Iodine	I	18.97%
55	Caesium	Cs	17.40%
60	Neodymium	Nd	12.55%
62	Samarium	Sm	9.81%
64	Gadolinium	Gd	10.60%
66	Dysprosium	Dy	10.05%
68	Erbium	Er	10.39%
70	Ytterbium	Yb	13.14%
71	Lutetium	Lu	10.44%
74	Tungsten	W	4.08%
78	Platinum	Pt	8.00%
79	Gold	Au	10.80%
81	Thallium	Tl	15.32%

Continued on next page

Table B.6 (continued)

Z	**Name**	**Symbol**	**Max Error**
82	Lead	Pb	12.13%
83	Bismuth	Bi	17.87%
Formula	**Name**		
C16H14O3	Lexan		4.36%
C2F4	Teflon		3.37%
	Total max error		19.41%

B.5 Pressure

Table B.7: Pressure Scaling Law Sensitivity Check List

Z	Name	Symbol	Max Error
3	Lithium	Li	6.73%
4	Beryllium	Be	11.74%
5	Boron	B	7.70%
6	Carbon	C	7.00%
11	Sodium	Na	15.47%
12	Magnesium	Mg	15.31%
13	Aluminium	Al	15.16%
14	Silicon	Si	14.15%
19	Potassium	K	16.04%
20	Calcium	Ca	13.33%
21	Scandium	Sc	11.72%
22	Titanium	Ti	19.40%
23	Vanadium	V	10.77%
24	Chromium	Cr	15.43%
25	Manganese	Mn	13.39%
26	Iron	Fe	13.11%
27	Cobalt	Co	13.64%
28	Nickel	Ni	15.06%
29	Copper	Cu	14.48%
30	Zinc	Zn	13.72%
31	Gallium	Ga	14.97%
32	Germanium	Ge	14.00%
33	Arsenic	As	11.02%
34	Selenium	Se	16.38%

Continued on next page

Table B.7 (continued)

Z	Name	Symbol	Max Error
37	Rubidium	Rb	17.48%
38	Strontium	Sr	11.51%
39	Yttrium	Y	13.69%
40	Zirconium	Zr	12.12%
41	Niobium	Nb	10.19%
42	Molybdenum	Mo	11.37%
43	Technetium	Tc	9.59%
44	Ruthenium	Ru	10.40%
45	Rhodium	Rh	12.29%
46	Palladium	Pd	15.56%
47	Silver	Ag	15.93%
48	Cadmium	Cd	15.30%
49	Indium	In	13.87%
50	Tin	Sn	15.35%
53	Iodine	I	22.08%
55	Caesium	Cs	18.50%
60	Neodymium	Nd	14.74%
62	Samarium	Sm	11.82%
64	Gadolinium	Gd	10.67%
66	Dysprosium	Dy	10.88%
68	Erbium	Er	10.83%
70	Ytterbium	Yb	10.35%
71	Lutetium	Lu	10.58%
74	Tungsten	W	10.15%
78	Platinum	Pt	12.14%
79	Gold	Au	13.11%
81	Thallium	Tl	16.80%

Continued on next page

Table B.7 (continued)

Z	**Name**	**Symbol**	**Max Error**
82	Lead	Pb	13.88%
83	Bismuth	Bi	14.44%
Formula	**Name**		
C16H14O3	Lexan		13.30%
C2F4	Teflon		12.79%
	Total max error		22.08%

Appendix C

autoPIPE Code

```
Sub autoPipe()
' autopipe Macro
' Made by Pedro P. Vergara
' Email: ppvergarag@gmail.com
Dim tempMaterial As Variant 'Temporary variable that holds the name of the material in
    current iteration
Dim tempRadius As Double 'Temporary variable that holds the value of the radius in
    current iteration
Dim tMaterialArray() As Variant 'array that holds all material for this run
Dim tMaterialName() As Variant 'array that holds all material for this run but change
    first letter to uppercase
Dim tRadiusArray() As Double 'array that holds all radius for this run
Dim tLengthArray() As Double 'array that holds all Length for this run
Dim tMaxCurrentsArray() As Double 'array that holds all maximum currents
Dim tWidthCurrentsArray() As Double 'array that holds all width of currents (at half
    the amplitud)
Dim tMaxHeatFluxArray() As Double ' multidimentional array The index is [(num of
    materials)*(num of radius), (number of currents)]
Dim tMaxTempArray() As Double ' multidimentional array The index is [(num of materials)
    *(num of radius), (number of currents)]
```

```
'parameters to save: "Total mass ablated", T, q'' , Total density, Total Preassure,
    Velocity (all at z11 (exit))
Dim tParametersArray() As Double ' multidimentional array The index is [(num of
    materials)*(num of radius)*(num of lengths), (number of currents)]
Dim tParamNameArray() As Variant
Dim tParamNameAbrev() As Variant
Dim Chart1Parameters() As Variant
Dim Chart2Parameters() As Variant
Dim ParamPos As Integer
Dim LastSumPos As Integer ' Last summary sheet position
Dim Found As Boolean
Dim tTimeEnd As Integer 'last row with time
Dim i, j, k, l, temp As Integer
Dim SheetName As Variant
Dim workFileName As Variant 'Name of the file that has the settings and currents used
    to iterate with "ETF27 PIPE.xls"
Dim NumberOfCurrents As Integer 'Take how many columns from "Currents" (starting from
    A1) it will be used in every iteration.
Dim RunETFlow As Variant 'Do we run ETFlow or it is just a test?. This variable shoud
    be set to yes.
Dim RunZNodeChoice As Variant 'Do we run ZnodeChoice or it is just a test? This
    variable shoud be set to yes.
Dim JustRunSummary As Variant
Dim JustRunPlotting As Variant
Dim PlotSummary As Variant
Dim ParamPosition() As Integer 'Is the position (cell where is the name of the material
    ) of the parameter in the SummaryName.
Dim ParamPosition2() As Integer 'Is the position (cell where is the name of the
    material) of the parameter2 in the SummaryPlots.
Dim ParamPosition3() As Integer 'Is the position (cell where is the name of the
    material) of the parameter3 in the SummaryPlots.
Dim ParamPositionConst() As Integer 'Is the position (cell where is the name of the
    material) of the parameter in the SummaryNameConstant.
Dim StefanBoltzmannConstant, KBoltzmann, amuTokg As Double
Dim SummaryName, SummaryPlots, SummaryConstants As String 'name of our sumary sheets

StefanBoltzmannConstant = 5.670373 * 10 ^ (-8) ' [W] / [m^2 K^4].
```

```
amuTokg = 1.66054E-27 ' 1 amu = nn kg
KBoltzmann = 1.38 * 10 ^ -23 '[J/K]



SummaryName = "Summary"
SummaryPlots = "SumPlots"
SummaryConstants = "SumCons"


   workFileName = ThisWorkbook.Name
   Windows(workFileName).Activate
   Sheets("Settings").Select

   i = 2
   NumberOfCurrents = ActiveSheet.Cells(2, 4) 'Take how many columns from "Currents" (
       starting from B1) it will be used in every iteration.

RunETFlow = ActiveSheet.Cells(2, 5)
RunZNodeChoice = ActiveSheet.Cells(4, 5)
JustRunSummary = ActiveSheet.Cells(6, 5)
'JustRunPlotting = ActiveSheet.Cells(8, 5)
   PlotSummary = ActiveSheet.Cells(8, 5)

    'Get all materials and radius and maximum currents, for this run
    '/-------------------------------------
        k = 0
        ReDim Preserve tMaterialArray(0)
        ReDim Preserve tMaterialName(0)
        ReDim Preserve tRadiusArray(0)
        ReDim Preserve tLengthArray(0)
        ReDim Preserve tMaxCurrentsArray(NumberOfCurrents - 1)
        ReDim Preserve tWidthCurrentsArray(NumberOfCurrents - 1)
        Dim WorkRange As Range
        Dim MaxValdiv2 As Double
        Dim CurrentWidth As Double
```

```
'get materials
Do While ActiveSheet.Cells(k + 2, 1) <> ""
    tMaterialArray(k) = ActiveSheet.Cells(k + 2, 1)
    tMaterialName(k) = ActiveSheet.Cells(k + 2, 1)
    k = k + 1

    If ActiveSheet.Cells(k + 2, 1) <> "" Then
    ReDim Preserve tMaterialArray(k)
    ReDim Preserve tMaterialName(k)
    End If
Loop
'get Radius
k = 0
Do While ActiveSheet.Cells(k + 2, 2) <> ""
    tRadiusArray(k) = ActiveSheet.Cells(k + 2, 2)
    k = k + 1

    If ActiveSheet.Cells(k + 2, 2) <> "" Then
    ReDim Preserve tRadiusArray(k)
    End If
Loop
'Get lengths
k = 0
Do While ActiveSheet.Cells(k + 2, 3) <> ""
    tLengthArray(k) = ActiveSheet.Cells(k + 2, 3)
    k = k + 1

    If ActiveSheet.Cells(k + 2, 3) <> "" Then
    ReDim Preserve tLengthArray(k)
    End If
Loop

'Get max current
Sheets("Currents").Select
ActiveSheet.Cells(2, 1).Select
Selection.End(xlDown).Select
time_end = Selection.Row + 1
```

```
        ActiveSheet.Cells(Selection.Row + 1, 1).Select


        ActiveCell.FormulaR1C1 = "=MAX(R[-" & (Selection.Row - 1) & "]C:R[-1]C)"
            If NumberOfCurrents > 1 Then
            Selection.AutoFill Destination:=Range(Cells(Selection.Row, 1), Cells(
                Selection.Row, NumberOfCurrents + 1)), Type:=xlFillDefault
            Range(Cells(Selection.Row, 1), Cells(Selection.Row, NumberOfCurrents + 1)).
                Select
            Else
            ActiveSheet.Cells(Selection.Row, 2).Select
            End If
        Selection.Copy

        ActiveSheet.Cells(Selection.Row + 2, 1).Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:=
            False, Transpose:=False 'paste just values

            If NumberOfCurrents > 1 Then
            Range(Cells(Selection.Row - 2, 1), Cells(Selection.Row - 2,
                NumberOfCurrents + 1)).Select
            Else
            ActiveSheet.Cells(Selection.Row - 2, 2).Select
            End If
        Selection.Clear

        For k = 0 To NumberOfCurrents - 1
        tMaxCurrentsArray(k) = ActiveSheet.Cells(Selection.Row + 2, k + 2) * 1000 'max
            current converted to amperes
        Next k

        'get current width
        For k = 0 To NumberOfCurrents - 1
            Set WorkRange = Range(ActiveSheet.Cells(2, k + 2), ActiveSheet.Cells(
                time_end, k + 2))
            MaxValdiv2 = Application.Max(WorkRange) / 2
            CurrentWidth = 0
```

```
            For nnn = 2 To time_end
                If (ActiveSheet.Cells(nnn, k + 2) > MaxValdiv2) Then
                CurrentWidth = CurrentWidth + 1
            End If
            Next nnn
        tWidthCurrentsArray(k) = CurrentWidth
    Next k

'/----------------------------------
'We are goning to use this later to store our max values
ReDim tMaxHeatFluxArray((UBound(tMaterialArray(), 1) + 1) * (UBound(tRadiusArray(),
     1) + 1) * (UBound(tLengthArray(), 1) + 1), NumberOfCurrents - 1)
ReDim tMaxTempArray((UBound(tMaterialArray(), 1) + 1) * (UBound(tRadiusArray(), 1)
    + 1) * (UBound(tLengthArray(), 1) + 1), NumberOfCurrents - 1)

'parameters to save: MTOT, T, q'' , Total Rho, Total P, V,Total number density
' Parameters(Material,Length,radius,parameter,currents)
ReDim tParametersArray((UBound(tMaterialArray(), 1) + 1), (UBound(tLengthArray(),
    1) + 1), (UBound(tRadiusArray(), 1) + 1), 6, NumberOfCurrents - 1)
ReDim tParamNameArray(6)
ReDim tParamNameAbrev(6)
tParamNameArray(0) = "MTOT [kg]"
tParamNameAbrev(0) = "MTOT"
tParamNameArray(1) = "Temperature [K]"
tParamNameAbrev(1) = "Temp"
tParamNameArray(2) = "Heat Flux [W/m^2]"
tParamNameAbrev(2) = "HF"
tParamNameArray(3) = "RHO [Kg/m^3]"
tParamNameAbrev(3) = "RHO"
tParamNameArray(4) = "Pressure [N/m^2]"
tParamNameAbrev(4) = "PRES"
tParamNameArray(5) = "Velocity [m/s]"
tParamNameAbrev(5) = "VEL"
tParamNameArray(6) = "NP [m^-3]"
tParamNameAbrev(6) = "NP"

ReDim Chart1Parameters(6, 2) 'Parameters, (type, order, intersection)
```

```
ReDim Chart2Parameters(6, 2) 'Parameters, (type, order, intersection)
'/-----------------------------------
For k = 0 To 6
Chart1Parameters(k, 0) = Workbooks(workFileName).Sheets("Settings").Cells(16 + k,
    5).Value
Chart1Parameters(k, 1) = Workbooks(workFileName).Sheets("Settings").Cells(16 + k,
    6).Value
Chart1Parameters(k, 2) = Workbooks(workFileName).Sheets("Settings").Cells(16 + k,
    7).Value
Chart2Parameters(k, 0) = Workbooks(workFileName).Sheets("Settings").Cells(16 + k,
    8).Value
Chart2Parameters(k, 1) = Workbooks(workFileName).Sheets("Settings").Cells(16 + k,
    9).Value
Chart2Parameters(k, 2) = Workbooks(workFileName).Sheets("Settings").Cells(16 + k,
    10).Value
Next k
'/-----------------------------------
''Are we just going to run the summary?
If JustRunSummary <> "no" And JustRunSummary <> "No" And JustRunSummary <> "NO" And
     JustRunSummary <> "nO" Then
GoTo Summary
End If
'/-----------------------------------

Windows(workFileName).Activate
Sheets("Settings").Select

Workbooks.Open ThisWorkbook.Path & "\ETF27 PIPE.xls", True, False

'for the selected materials listed in column A.
For m = 0 To UBound(tMaterialArray(), 1)

    For l = 0 To UBound(tLengthArray(), 1)

        Windows("ETF27 PIPE.xls").Activate
        Sheets("material").Select
```

```
'Search material row
For k = 21 To 218
    If ActiveSheet.Cells(k, 2) = tMaterialArray(m) Then
    Exit For
    End If
Next k
Windows("ETF27 PIPE.xls").Activate
Sheets("main").Select
ActiveSheet.Cells(17, 1) = k 'sleeve material setting
ActiveSheet.Range("E14") = tLengthArray(l)


    'loop for every radius
    For r = 0 To UBound(tRadiusArray(), 1)
        Windows("ETF27 PIPE.xls").Activate
        Sheets("main").Select
        ActiveSheet.Cells(14, 1) = tRadiusArray(r) 'plasma radius material
            setting

            'For every current
            For c = 1 To NumberOfCurrents
                'clear current in ETFLow
                Windows("ETF27 PIPE.xls").Activate
                Sheets("main").Select
                Range("B30:B1000").Clear
                Range("A30:A1000").Clear
                'copy current from file to "ETF27 PIPE"
                Windows(workFileName).Activate
                Sheets("Currents").Select
                ActiveSheet.Cells(2, c + 1).Select
                Range(ActiveSheet.Cells(2, c + 1), Selection.End(xlDown)).
                    Select
                Selection.Copy
                time_end = Selection.Count + 1

                'Paste current to "ETF27 PIPE"
                Windows("ETF27 PIPE.xls").Activate
```

```
                        Sheets("main").Select
                        'paste
                        Range("B30").Select
                        ActiveSheet.Paste
                        'Copy time
                        Windows(workFileName).Activate
                        Sheets("Currents").Select
                        ActiveSheet.Cells(2, 1).Select
                        Range(ActiveSheet.Cells(2, 1), ActiveSheet.Cells(time_end,
                            1)).Select
                        Selection.Copy
                        'Paste current to "ETF27 PIPE"
                        Windows("ETF27 PIPE.xls").Activate
                        Sheets("main").Select
                        'paste
                        Range("A30").Select
                        ActiveSheet.Paste

                        Range("C30").Select

'/----------------------------------
                        'Code to activate PIPE_Flow and Z_no_choice
'/----------------------------------
                        Application.ScreenUpdating = True
                            If RunETFlow <> "no" And RunETFlow <> "No" And
                                RunETFlow <> "NO" And RunETFlow <> "nO" Then
                            'Dim obj1 As Object
                            'Set obj1 = Application
                            'Application.Run "'ETF27 PIPE.xls'!ETFLOW.ET_FLOW"
                            'obj1.Run "'ETF27 PIPE.xls'!ETFLOW.ET_FLOW"
                            'Set obj1 = Nothing


                                Windows("ETF27 PIPE.xls").Activate
                                ActiveWorkbook.Save
                                ActiveWorkbook.Close ("ETF27 PIPE.xls")
```

```
                    Workbooks.Open ThisWorkbook.Path & "\ETF27 PIPE.xls
                        ", True, False
                    Application.Run "'ETF27 PIPE.xls'!ETFLOW.ET_FLOW"
                    Windows("ETF27 PIPE.xls").Activate
                    ActiveWorkbook.Save
                    ActiveWorkbook.Close

                    Workbooks.Open ThisWorkbook.Path & "\ETF27 PIPE.xls
                        ", True, False

                End If

                If ThenRunZNodeChoice <> "no" And ThenRunZNodeChoice <>
                     "No" And ThenRunZNodeChoice <> "NO" And
                    ThenRunZNodeChoice <> "nO" Then
                Application.Run "'ETF27 PIPE.xls'!Z_node_choice"
                End If

'/-----------------------------------
            'Code for Copying results
'/-----------------------------------
            Application.ScreenUpdating = False
'/-----------------------------------
             'sheet name
              Windows(workFileName).Activate
              'Material -Radius in [mm] -Length in [cm]

              If tMaterialArray(m) = "teflon (PTFE)(
                  polytetrafluoroethylene)" Then
              SheetName = "teflon" & "-R" & (tRadiusArray(r) *
                  1000) & "-L" & (tLengthArray(l) * 100)
              Else
              SheetName = tMaterialArray(m) & "-R" & (tRadiusArray(
                  r) * 1000) & "-L" & (tLengthArray(l) * 100)
              End If
             'see is sheet exist
```

```
                                Found = False

                                For w = 1 To Worksheets.Count
                                    If Sheets(w).Name = SheetName Then
                                    Found = True
                                    Exit For
                                    End If
                                Next

                                If Found = False Then
                                   Sheets.Add.Name = SheetName
                                   Sheets(SheetName).Select
                                   ActiveSheet.Move After:=Sheets(ActiveWorkbook.
                                       Sheets.Count) 'Move til the end
                                End If

                                Sheets(SheetName).Select
'/-----------------------------------
                                 Dim CollDist As Integer
                                 CollDist = NumberOfCurrents + 1

                                'Copy Time (running)
                                    Windows("ETF27 PIPE.xls").Activate
                                    Sheets("main").Select
                                    Range("D28").Select
                                    Range(Selection, Selection.End(xlDown)).Select
                                    Application.CutCopyMode = False
                                    Selection.Copy

                                    Windows(workFileName).Activate
                                    Sheets(SheetName).Select
                                    ActiveSheet.Cells(2, 1).Select
                                    ActiveSheet.Paste

                                'Copy MTOT
                                    Windows("ETF27 PIPE.xls").Activate
                                    Sheets("main").Select
```

```
            Range("O8").Select
            Application.CutCopyMode = False
            Selection.Copy

            Windows(workFileName).Activate
            Sheets(SheetName).Select
            ActiveSheet.Cells(2, c + 1).Select
            ActiveSheet.Cells(2, c + 1) = "MTOT"
            ActiveSheet.Cells(3, c + 1) = "kg"
            ActiveSheet.Cells(4, c + 1).Select
            ActiveSheet.Paste
            ActiveSheet.Cells(1, c + 1) = "Current" & c

        'Copy Temperature
            Windows("ETF27 PIPE.xls").Activate
            Sheets("main").Select
            Range("G28").Select
            Range(Selection, Selection.End(xlDown)).Select
            Application.CutCopyMode = False
            Selection.Copy

            Windows(workFileName).Activate
            Sheets(SheetName).Select
            ActiveSheet.Cells(2, c + CollDist).Select
            ActiveSheet.Paste

            ActiveSheet.Cells(1, c + CollDist) = "Current"
                & c

        'Copy Heat flux
            Windows("ETF27 PIPE.xls").Activate
            Sheets("main").Select
            Range("T28").Select
            Range(Selection, Selection.End(xlDown)).Select
            Application.CutCopyMode = False
            Selection.Copy
```

```
        Windows(workFileName).Activate
        Sheets(SheetName).Select
        ActiveSheet.Cells(2, CollDist * 2 + c).Select
        ActiveSheet.Paste

        ActiveSheet.Cells(1, CollDist * 2 + c) = "
            Current" & c

    'Copy Rho
        Windows("ETF27 PIPE.xls").Activate
        Sheets("main").Select
        Range("H28").Select
        Range(Selection, Selection.End(xlDown)).Select
        Application.CutCopyMode = False
        Selection.Copy

        Windows(workFileName).Activate
        Sheets(SheetName).Select
        ActiveSheet.Cells(2, CollDist * 3 + c).Select
        ActiveSheet.Paste

        ActiveSheet.Cells(1, CollDist * 3 + c) = "
            Current" & c

    'Copy Pressure
        Windows("ETF27 PIPE.xls").Activate
        Sheets("main").Select
        Range("J28").Select
        Range(Selection, Selection.End(xlDown)).Select
        Application.CutCopyMode = False
        Selection.Copy

        Windows(workFileName).Activate
        Sheets(SheetName).Select
        ActiveSheet.Cells(2, CollDist * 4 + c).Select
        ActiveSheet.Paste
```

```
                ActiveSheet.Cells(1, CollDist * 4 + c) = "
                    Current" & c

            'Copy Velocity
                Windows("ETF27 PIPE.xls").Activate
                Sheets("main").Select
                Range("AB28").Select
                Range(Selection, Selection.End(xlDown)).Select
                Application.CutCopyMode = False
                Selection.Copy

                Windows(workFileName).Activate
                Sheets(SheetName).Select
                ActiveSheet.Cells(2, CollDist * 5 + c).Select
                ActiveSheet.Paste

                ActiveSheet.Cells(1, CollDist * 5 + c) = "
                    Current" & c

             'Copy Total number density
                Windows("ETF27 PIPE.xls").Activate
                Sheets("main").Select
                Range("P28").Select
                Range(Selection, Selection.End(xlDown)).Select
                Application.CutCopyMode = False
                Selection.Copy

                Windows(workFileName).Activate
                Sheets(SheetName).Select
                ActiveSheet.Cells(2, CollDist * 6 + c).Select
                ActiveSheet.Paste

                ActiveSheet.Cells(1, CollDist * 6 + c) = "
                    Current" & c

'/---------------------------------
                    Windows("ETF27 PIPE.xls").Activate
```

```
                                Sheets("main").Select
                                Range("C30").Select

                                Windows(workFileName).Activate
                                ActiveWorkbook.Save
                                Sheets("Settings").Select
                                Range("D3").Select
                            Next c
                            'End For every current
                        Windows(workFileName).Activate
                        ActiveWorkbook.Save
                        Sheets("Settings").Select
                        Range("D3").Select
                    Next r
                    Windows(workFileName).Activate
                    ActiveWorkbook.Save
                    Sheets("Settings").Select
                    Range("D3").Select
                Next l
    Windows(workFileName).Activate
    ActiveWorkbook.Save
    Sheets("Settings").Select
    Range("D3").Select
    Next m
    'Finish collecting data



    '/---------------------------------
'Code for Summarize results
    '/---------------------------------
Summary:
Application.ScreenUpdating = True
Application.ScreenUpdating = False
Windows(workFileName).Activate
```

```
    '/----------------------------------
'Getting the data from the sheets (Max Temperature, Max Heat Flux)
    '/----------------------------------

'For all of our materials
For m = 0 To UBound(tMaterialArray, 1) 'upper boundary of array
 'For all of our length
    For l = 0 To UBound(tLengthArray, 1)
        'For all of our radius
        For r = 0 To UBound(tRadiusArray, 1) 'upper boundary of array
             'For all of our parameters
             ParamPos = 0
             For p = 0 To UBound(tParametersArray, 4)
            'Material -Radius in [mm] -Length in [cm]
            SheetName = tMaterialArray(m) & "-R" & (tRadiusArray(r) * 1000) & "-L" & (
                tLengthArray(l) * 100)
            Sheets(SheetName).Select

                'finding current 1 of Temperature
                    For ParamPos = 1 + ParamPos To 2000
                        If (ActiveSheet.Cells(1, ParamPos) = "Current1") Then
                        Exit For
                        End If
                    Next ParamPos
                    '////////////////////////////Getting Max Temp
                        ////////////////////////
                    ActiveSheet.Cells(2, 1).Select
                    Selection.End(xlDown).Select
                    tTimeEnd = Selection.Row + 1
                    ActiveSheet.Cells(Selection.Row + 1, ParamPos).Select
                    'get Maximum
                    ActiveCell.FormulaR1C1 = "=MAX(R[-" & (Selection.Row - 4) & "]C:R
                        [-1]C)"

                        If NumberOfCurrents > 1 Then
                        Selection.AutoFill Destination:=Range(Cells(Selection.Row,
                            ParamPos), Cells(Selection.Row, ParamPos + NumberOfCurrents
```

```
                        - 1)), Type:=xlFillDefault
                    Range(Cells(Selection.Row, ParamPos), Cells(Selection.Row,
                        ParamPos + NumberOfCurrents - 1)).Select
                    Else
                    ActiveSheet.Cells(Selection.Row, ParamPos).Select
                    End If
                Selection.Copy

                ActiveSheet.Cells(Selection.Row + 2, ParamPos).Select
                Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone,
                    SkipBlanks:=False, Transpose:=False 'paste just values

                    If NumberOfCurrents > 1 Then
                    Range(Cells(Selection.Row - 2, ParamPos), Cells(Selection.Row -
                         2, ParamPos + NumberOfCurrents - 1)).Select
                    Else
                    ActiveSheet.Cells(Selection.Row - 2, ParamPos).Select
                    End If
                Selection.Clear

                For c = 0 To NumberOfCurrents - 1
                'Arrays start at 0 so I'm change in it to the apropiate index
                tParametersArray(m, l, r, p, c) = ActiveSheet.Cells(Selection.Row +
                     2, ParamPos + c)
                Next c
            Next p
        Next r
    Next l
Next m

    '/---------------------------------
'Printing and Formating Summary
    '/---------------------------------
'we will have a summary for every length
Dim SummaryLengthName As String
```

```
ReDim ParamPosition(UBound(tMaterialArray, 1), UBound(tParametersArray, 4), UBound(
    tLengthArray(), 1), 1)
ReDim ParamPosition2(UBound(tMaterialArray, 1), UBound(tParametersArray, 4), UBound(
    tLengthArray(), 1), 1)
ReDim ParamPosition3(UBound(tMaterialArray, 1), UBound(tParametersArray, 4), UBound(
    tLengthArray(), 1), 1)

ReDim ParamPositionConst(UBound(tMaterialArray, 1), UBound(tParametersArray, 4), UBound
    (tParametersArray, 4), 2, UBound(tLengthArray(), 1), 1)

For l = 0 To UBound(tLengthArray(), 1)
    SummaryLengthName = SummaryName & "-L" & (tLengthArray(l) * 100)
    'checking sheet
    '/-----------------------------------
        'see if SummaryName sheet exist
            For w = 1 To Worksheets.Count
                If Sheets(w).Name = SummaryLengthName Then
                    Application.DisplayAlerts = False
                    Workbooks(workFileName).Sheets(w).Delete
                    Application.DisplayAlerts = True
                Exit For
                End If
            Next

               Sheets.Add.Name = SummaryLengthName
               Sheets(SummaryLengthName).Select
               ActiveSheet.Move After:=Sheets(5 + l) 'Move after Settings
               LastSumPos = 5 + l + 2

    '/-----------------------------------

    Dim sRow, sCol As Integer 'starting row and column
    sRow = 2
    sCol = 2

    'uppercase first letter materials
    Dim strg, str2 As String
```

```
For i = 0 To UBound(tMaterialArray, 1)
    strg = tMaterialArray(i)
    str2 = UCase(Mid(strg, 1, 1))
    strg = str2 & Mid(strg, 2, Len(strg))
    tMaterialName(i) = strg
Next i

Windows(workFileName).Activate
Sheets(SummaryLengthName).Select

'for all parameters
For p = 0 To UBound(tParametersArray, 4)
    'For all of our materials
    For m = 0 To UBound(tMaterialArray, 1) 'upper boundary of array
        PosParamCol = p * (UBound(tRadiusArray, 1) + 3)
        PosParamRow = (NumberOfCurrents + 3) * m

        'ParamPosition(i, p) = Cells(PosParamCol, PosParamRow)
        ParamPosition(m, p, 1, 0) = sRow + PosParamRow
        ParamPosition(m, p, 1, 1) = sCol + PosParamCol

        ActiveSheet.Cells(sRow + PosParamRow, sCol + PosParamCol) = tMaterialName(m
            )
        ActiveSheet.Cells(sRow + PosParamRow, sCol + PosParamCol).Select
            'Formatting
            Selection.Font.Bold = True
            With Selection.Font
                .Color = -16776961
                .TintAndShade = 0
            End With
            '///

        ActiveSheet.Cells(sRow + 1 + PosParamRow, sCol + PosParamCol) = "I [A] \ r
            [m]"
        ActiveSheet.Cells(sRow + PosParamRow, sCol + 1 + PosParamCol) =
            tParamNameArray(p)
```

```
            If UBound(tRadiusArray, 1) > 0 Then
                Range(Cells(sRow + PosParamRow, sCol + 1 + PosParamCol), Cells(sRow
                     + (NumberOfCurrents + 3) * m, sCol + 1 + UBound(tRadiusArray,
                    1) + PosParamCol)).Select
                Selection.Merge
            End If

            'Formatting
            '////
            Range(Cells(sRow + PosParamRow, sCol + PosParamCol), Cells(sRow +
                PosParamRow + (NumberOfCurrents + 1), sCol + 1 + UBound(
                tRadiusArray, 1) + PosParamCol)).Select
            With Selection.Borders
                .LineStyle = xlContinuous
                .Weight = xlThin
                .ColorIndex = xlAutomatic
            End With
            With Selection
                .HorizontalAlignment = xlCenter
                .VerticalAlignment = xlCenter
            End With

            Range(Cells(sRow + PosParamRow + 2, sCol + 1 + PosParamCol), Cells(sRow
                 + PosParamRow + (NumberOfCurrents + 1), sCol + 1 + UBound(
                tRadiusArray, 1) + PosParamCol)).Select
            Selection.NumberFormat = "0.0000E+00"
            '////
        'For all of our radius
        For r = 0 To UBound(tRadiusArray, 1) 'upper boundary of array
            ActiveSheet.Cells(sRow + 1 + PosParamRow, sCol + (r + 1) + PosParamCol)
                 = tRadiusArray(r)
                For c = 0 To NumberOfCurrents - 1
                ActiveSheet.Cells((sRow + 1 + PosParamRow + 1) + c, sCol +
                    PosParamCol) = tMaxCurrentsArray(c)
                ActiveSheet.Cells((sRow + 1 + PosParamRow + 1) + c, sCol + (r + 1)
                    + PosParamCol) = tParametersArray(m, l, r, p, c)
                Next c
```

```
            Next r
        Next m
    Next p
    Columns("A:ZZ").Select
    Selection.Columns.AutoFit
    Range("A1").Select
Next l
    '/-----------------------------------
'Summary Type 2
    '/-----------------------------------
For l = 0 To UBound(tLengthArray(), 1)
    SummaryLengthName = "T2-" & SummaryName & "-L" & (tLengthArray(l) * 100)
    'checking sheet
    '/-----------------------------------
        'see if SummaryName sheet exist
            For w = 1 To Worksheets.Count
                If Sheets(w).Name = SummaryLengthName Then
                    Application.DisplayAlerts = False
                    Workbooks(workFileName).Sheets(w).Delete
                    Application.DisplayAlerts = True
                Exit For
                End If
            Next
               Sheets.Add.Name = SummaryLengthName
               Sheets(SummaryLengthName).Select
               ActiveSheet.Move After:=Sheets(LastSumPos - 1 + l) 'Move after Settings

               If l = UBound(tLengthArray(), 1) Then
               LastSumPos = LastSumPos + l + 2
               End If
    '/-----------------------------------
    ''/Dim sRow, sCol As Integer 'starting row and column
    sRow = 2
    sCol = 2

    Windows(workFileName).Activate
    Sheets(SummaryLengthName).Select
```

```
    'for all parameters (Temperature,Heat flux)
    For p = 0 To UBound(tParametersArray, 4)
        'For all of our materials
        For m = 0 To UBound(tMaterialArray, 1) 'upper boundary of array
'            PosParamCol = p * (UBound(tRadiusArray, 1) + 3)
'            PosParamRow = (NumberOfCurrents + 3) * m

            PosParamCol = p * 4
            PosParamRow = (NumberOfCurrents * UBound(tRadiusArray, 1) + 3) * m

            'ParamPosition(i, p) = Cells(PosParamCol, PosParamRow)
            ParamPosition(m, p, 1, 0) = sRow + PosParamRow
            ParamPosition(m, p, 1, 1) = sCol + PosParamCol

            ActiveSheet.Cells(sRow + PosParamRow, sCol + PosParamCol) = tMaterialName(m
                )
            ActiveSheet.Cells(sRow + PosParamRow, sCol + PosParamCol).Select
                'Formatting
                Selection.Font.Bold = True
                With Selection.Font
                    .Color = -16776961
                    .TintAndShade = 0
                End With
                '///

            ActiveSheet.Cells(sRow + 1 + PosParamRow, sCol + PosParamCol) = "r [m]"
            ActiveSheet.Cells(sRow + 1 + PosParamRow, sCol + 1 + PosParamCol) = "I [A]"
            ActiveSheet.Cells(sRow + 1 + PosParamRow, sCol + 2 + PosParamCol) =
                tParamNameArray(p)

            'For all of our radius
            For r = 0 To UBound(tRadiusArray, 1) 'upper boundary of array


                For c = 0 To NumberOfCurrents - 1
```

```
                    ActiveSheet.Cells((sRow + 1 + PosParamRow + 1) + (r * (
                        NumberOfCurrents)) + c, sCol + PosParamCol) = tRadiusArray(r)

                    ActiveSheet.Cells((sRow + 1 + PosParamRow + 1) + (r * (
                        NumberOfCurrents)) + c, sCol + PosParamCol + 1) =
                        tMaxCurrentsArray(c)

                    ActiveSheet.Cells((sRow + 1 + PosParamRow + 1) + (r * (
                        NumberOfCurrents)) + c, sCol + PosParamCol + 2) =
                        tParametersArray(m, l, r, p, c)
                    Next c
            Next r
        Next m
    Next p
    Columns("A:ZZ").Select
    Selection.Columns.AutoFit
    Range("A1").Select
Next l
    '/---------------------------------
'Summary Type 3, TOTAL
    '/---------------------------------
    SummaryLengthName = "All-" & SummaryName
    'checking sheet
    '/---------------------------------
        'see if SummaryName sheet exist
            For w = 1 To Worksheets.Count
                If Sheets(w).Name = SummaryLengthName Then
                    Application.DisplayAlerts = False
                    Workbooks(workFileName).Sheets(w).Delete
                    Application.DisplayAlerts = True
                Exit For
                End If
            Next
               Sheets.Add.Name = SummaryLengthName
               Sheets(SummaryLengthName).Select
               ActiveSheet.Move After:=Sheets(4) 'Move after Settings
               LastSumPos = LastSumPos - 1
```

```
    Windows(workFileName).Activate
    Sheets(SummaryLengthName).Select
    sRow = 2
    sCol = 2

    'for all parameters (Temperature,Heat flux)
    For p = 0 To UBound(tParametersArray, 4)
        'For all of our materials
        For m = 0 To UBound(tMaterialArray, 1) 'upper boundary of array
'            PosParamCol = p * (UBound(tRadiusArray, 1) + 3)
'            PosParamRow = (NumberOfCurrents + 3) * m

            PosParamCol = p * 6
            If m = 0 Then
             PosParamRow = (NumberOfCurrents * (UBound(tRadiusArray, 1) + 1) * (UBound(
                 tLengthArray, 1) + 1)) * m 'Ncurrent * Nradius * Nlength * Nmaterials
            Else
             PosParamRow = (NumberOfCurrents * (UBound(tRadiusArray, 1) + 1) * (UBound(
                 tLengthArray, 1) + 1)) * m + 4 * m 'Ncurrent * Nradius * Nlength *
                 Nmaterials
            End If

            'ParamPosition(i, p) = Cells(PosParamCol, PosParamRow)
            ''ParamPosition(m, p, 1, 0) = sRow + PosParamRow
            ''ParamPosition(m, p, 1, 1) = sCol + PosParamCol

            ActiveSheet.Cells(sRow + PosParamRow, sCol + PosParamCol) = tMaterialName(m
                )
            ActiveSheet.Cells(sRow + PosParamRow, sCol + PosParamCol).Select
                'Formatting
                Selection.Font.Bold = True
                With Selection.Font
                    .Color = -16776961
                    .TintAndShade = 0
                End With
                '///
```

```
        ActiveSheet.Cells(sRow + 1 + PosParamRow, sCol + PosParamCol) = "L [m]"
        ActiveSheet.Cells(sRow + 1 + PosParamRow, sCol + 1 + PosParamCol) = "r [m]"
        ActiveSheet.Cells(sRow + 1 + PosParamRow, sCol + 2 + PosParamCol) = "I [us]
            "
        ActiveSheet.Cells(sRow + 1 + PosParamRow, sCol + 3 + PosParamCol) = "I [A]"
        ActiveSheet.Cells(sRow + 1 + PosParamRow, sCol + 4 + PosParamCol) =
            tParamNameArray(p)

        For l = 0 To UBound(tLengthArray(), 1)
            'For all of our radius
            For r = 0 To UBound(tRadiusArray, 1) 'upper boundary of array
                    For c = 0 To NumberOfCurrents - 1
                    ActiveSheet.Cells((sRow + 1 + PosParamRow + 1) + (l * (UBound(
                        tRadiusArray(), 1) + 1) * (NumberOfCurrents) + r * (
                        NumberOfCurrents)) + c, sCol + PosParamCol) = tLengthArray(
                        l)
                    ActiveSheet.Cells((sRow + 1 + PosParamRow + 1) + (l * (UBound(
                        tRadiusArray(), 1) + 1) * (NumberOfCurrents) + r * (
                        NumberOfCurrents)) + c, sCol + PosParamCol + 1) =
                        tRadiusArray(r)
                    ActiveSheet.Cells((sRow + 1 + PosParamRow + 1) + (l * (UBound(
                        tRadiusArray(), 1) + 1) * (NumberOfCurrents) + r * (
                        NumberOfCurrents)) + c, sCol + PosParamCol + 2) =
                        tWidthCurrentsArray(c)
                    ActiveSheet.Cells((sRow + 1 + PosParamRow + 1) + (l * (UBound(
                        tRadiusArray(), 1) + 1) * (NumberOfCurrents) + r * (
                        NumberOfCurrents)) + c, sCol + PosParamCol + 3) =
                        tMaxCurrentsArray(c)
                    ActiveSheet.Cells((sRow + 1 + PosParamRow + 1) + (l * (UBound(
                        tRadiusArray(), 1) + 1) * (NumberOfCurrents) + r * (
                        NumberOfCurrents)) + c, sCol + PosParamCol + 4) =
                        tParametersArray(m, l, r, p, c)
                    Next c
            Next r
        Next l
    Next m
    Columns("A:ZZ").Select
```

```
        Selection.Columns.AutoFit
        Range("A1").Select
    Next p
    '/---------------------------------
    '/---------------------------------
Application.ScreenUpdating = True
    '/---------------------------------
End Sub
 '/---------------------------------
Sub ClearResultsWorkbook()
' ClearResultsWorkbook Macro
'
Dim workFileName As Variant 'Name of the file that has the settings and currents used
    to iterate with "ETF27 PIPE.xls"
Dim i As Integer
workFileName = "autoPIPE V2.4.xlsm"
Windows(workFileName).Activate
Workbooks(workFileName).Activate
Response = MsgBox("You are about to delete all recolected data and summary, Are you
    sure?", 1, "DELETE ALERT")
If Response = 1 Then
    'Disable alerts so we dont have to accept every deleted sheet.
    Application.DisplayAlerts = False
        'Delete all sheets except the first 3
        i = 1
        Do While Workbooks(workFileName).Sheets.Count > 4
            If Workbooks(workFileName).Sheets(i).Name <> "Settings" And _
            Workbooks(workFileName).Sheets(i).Name <> "Currents" _
            And Workbooks(workFileName).Sheets(i).Name <> "Others" _
            And Workbooks(workFileName).Sheets(i).Name <> "material" _
            Then
            Workbooks(workFileName).Sheets(i).Delete
            i = 1
            End If
            i = i + 1
        Loop
End If
```

```
Application.DisplayAlerts = True
End Sub
```