University of Cincinnati

Date: 11/10/2021

I, Logan A Tipton, hereby submit this original work as part of the requirements for the degree of Master of Science in Industrial Hygiene (Environmental Health).

It is entitled:

Welding Fume Particle Emissions from Pulsed Gas Tungsten Arc Welding (GTAW-P)

Student's name: **Logan A Tipton**

This work and its defense approved by:

Committee chair: Jun Wang, Ph.D.

Committee member: Sergey Grinshpun, Ph.D.

Committee member: Marepalli Rao, Ph.D.

UNIVERSITY OF Cincinnati

41611

Welding Fume Particle Emissions from Pulsed Gas Tungsten Arc Welding (GTAW-P)

A thesis submitted to the
Graduate School
of the University of Cincinnati
in partial fulfillment of the
requirements for the degree of

Master of Science

in the Department of Environmental and Public Health Sciences
of the College of Medicine

by

Logan A. Tipton

B.S. Eastern Kentucky University
December 2018

Committee Chair: Jun Wang, Ph.D.

ABSTRACT

According to the American Welding Society (AWS), *welding* is defined as a joining process producing coalescence of materials by heating them to the welding temperature, with or without the application of pressure or by the application of pressure or by the application of pressure alone, and with or without the use of filler metal. The purpose of this study is to determine the particle size distribution of welding fume particles produced during the Pulsed Gas Tungsten Arc Welding (GTAW-P) process. A GTAW-P/shielded metal arc welding (SMAW) TIG welder (PowerTIG 200 DV) was used to produce welding fume emissions in the alternating current (AC) mode at various amperages and pulsing frequencies upon aluminum material within a stainless-steel conical test chamber. Welding currents were found to be the only statistically significant variable affecting particle concentration ($p<0.001$) for particles in size range of 0.3 - 10 µm. The highest current values produced the largest mean concentrations (particles/cm^3). All variables produced significance for geometric mean diameter for particles in the size range of 10 - 420 nm: pulse condition ($p=0.008$), current ($p=0.046$), and a combination of pulse condition and current (pulse condition * current) (0.005). The post-hoc pulse condition * current comparison determined that current provided the most statistical significance upon geometric mean diameter. Only the pulse condition ($p=0.025$) provided statistical significance for the geometric mean diameter of particles in size range of 0.3 -10 µm. Upon further investigation, it was determined that high pulse (HP) was the most significant ($p=0.042$). While pulsed conditions produced significant results, it was determined that current amperage still plays a more pivotal role in particle size distribution measurements. The study findings should be used in unison with future research to fully determine GTAW-P effect upon welding fume emissions as the process is incorporated more into industrial or manufacturing settings.

TABLE OF CONTENTS

INTRODUCTION

According to the American Welding Society (AWS), *welding* is defined as a joining process producing coalescence of materials by heating them to the welding temperature, with or without the application of pressure or by the application of pressure or by the application of pressure alone, and with or without the use of filler metal [1]. Numerous types of welding processes are practiced within manufacturing, construction, and other sectors. Common types of welding include gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), flux-cored arc welding (FCAW), etc. with a focus on different applications. According to the AWS, the GTAW welding application, also known as tungsten inert gas (TIG) welding, utilizes an arc amid a tungsten electrode (non-consumable) and the molten metal pool (weld pool) via shielding gas to create a weld bead[2]. This process is used when it is crucial to manipulate the weld pool of the molten bead to better suit the weld[3]. Additionally, GTAW is often used with thin pieces of ferrous (stainless steel) and non-ferrous metals (aluminum), given these materials are susceptible to heating temperature and GTAW is better at managing heat output[4]. For instance, a material may experience distortions resulting from excessive heat output.

Since aluminum has a low melting point (1220°F) compared to stainless steel (2750°F), it is critical to maintain the welding arc zone at lower temperatures with just enough energy feed. However, lower current or voltage will not work in specific applications since the weld bead cannot penetrate the base metal plate. The pulsed current process (GTAW-P) was introduced to arc welding as an alternative way to allow medium to high current usage while keeping the process at cooler temperatures. To be more specific, the GTAW-P process allows the operator to produce precision welds with maximum penetration by controlling the pulsing frequency of the

electrical current to fluctuate between peak current, where heating and fusion occurs, and background current levels, where solidification occurs[4,5]. However, it is essential to note that the GTAW-P process has been identified as one, if not the most, of the more complex processes within the industry. Occasionally, making it less attractive in terms of production when compared to other welding processes.

Regardless, human exposure to the generation of welding fumes may result in an onset of numerous health effects. In recent years, the International Agency for Research on Cancer (IARC) categorized welding fumes as a known human carcinogen, dismissing it as a possible human carcinogen[6]. According to the United States Occupational Safety and Health Organization (U.S. OSHA), acute exposure to welding fumes can cause dizziness, nausea, and irritation to the eyes, nose, and throat regions. Chronic exposures are associated with lung damage and cancer to the following regions: lung, larynx, and urinary tract[7]. However, U.S. OSHA has not determined an appropriate, permissible exposure limit (PEL) regarding welding fumes.

A previous study has identified welding fume emission rates from the GTAW process and high concentrations of ultrafine particles in the fume. Sims[9] found that welding currents were statistically significant ($p=0.001$) for fume generation rates. The highest current was found to generate the most fume emissions (3.19 mg/min^{-1}, 120 amps). Coincidentally, particle concentrations were highest when using higher currents ($p=0.014$). However, the frequency was found to be not statistically significant for the following parameters: fume generation rates ($p=0.681$), particle concentration ($p=0.14$), and geometric mean diameter ($p=0.91$). The average particle count concentration was found to be statistically greater at 120 amps (5.5 x106 cm^{-3}) than 90 amps (4.9 x106 cm^{-3}, $p=0.03$) or 60 amps (4.8 x106 cm^{-3}, $p=0.02$). However, the process

studied was not using pulse. Currently, it is unclear regarding the nature of fume generation rates and particle size distributions of fume emissions from the GTAW-P process.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the particle size distribution of welding fume particle emissions from the GTAW-P process.

SPECIFIC AIMS AND HYPOTHESES

The specific aims are to evaluate the particle size distributions of welding fume emissions produced from aluminum alloy plates and aluminum filler consumables during the GTAW-P process at various amperages and pulsing modes and identify how results compare to current relative literature.

The following hypotheses were evaluated during the study:

- H_1: There is a decrease in fume emissions from the GTAW-P process compared to the GTAW process with the same welding currents.
- H_2: Particle size distributions will be different with different pulsing frequencies.
- H_3: Difference amongst particle size distributions with various combinations of welding currents and pulsing frequencies.

MATERIALS AND METHODS

Part I. Equipment

A GTAW-P/shielded metal arc welding (SMAW) TIG welder (PowerTIG 200 DV, Everlast Power Equipment, San Francisco, CA) was utilized in the alternating current (AC) mode to complete welding applications upon aluminum material. The PowerTIG 200 DV TIG welder was chosen for being economically beneficial while still exceeding the operating functions needed to perform efficiently. Relevant operating functions included 120V/240V input, pulse frequency (0.5-150 Hz), pre/post gas flow control, and AC cleaning range. Argon shielding gas was used at an airflow rate of approximately 17 cubic feet per hour (CFH).

Welding applications were performed on ER6061 aluminum plates (6 x 12 x 1/4) via 2% lanthanated tungsten electrode (Midwest Tungsten Service, 3.2 millimeters, Willowbrook, Illinois) and ER4043 (5% silicon) aluminum rod (1/8) using the foot pedal (2T). The ER6061 aluminum plates were chosen for being one of the industry's most commonly used heat treatable alloy materials. Tungsten electrodes were sharpened following the recommendations via the 3Mirrors tungsten electrode sharpener rotary tool. Tungsten electrodes needed to be sharpened appropriately; if not, the weld bead was subject to becoming polluted.

A conical welding test chamber was manufactured using the AWS Laboratory Method for Measuring Fume Generation Rates and Total Fume Emission of Welding and Allied Processes (F1.2:2013)[8] suggested specifications (see Figure 1). A high-volume air pump (3420 CFM) (General Metal Works Inc., Model 2000, Cleves, Ohio) was installed atop the test chamber to evacuate aerosolized particles from the chamber to the exterior of the building using the exhaust system via duct hose. Test chamber leveling bolts were measured to a gap allowing adequate airflow to enter the space. Two sampling inlet ports were installed upon the test

chamber and connected via Tygon tubing to the inlet ports of the following instruments:

NanoScan Scanning Mobility Particle Sizer spectrometer (NanoScan SMPS) (TSI Industries,

Model 391000, Shoreview, Minnesota) and Optical Particle Sizer (OPS) (TSI Industries, Model

3330, Shoreview, Minnesota). Both instruments were recently calibrated within the

recommendations and connected to an appropriate computer utilizing the following software

programs: NanoScan Manager Software (TSI Industries, Version 1.0.0, Shoreview, Minnesota)

and Aerosol Instrument Manager Software (TSI Industries, Version 9.0.0, Shoreview,

Minnesota). See Figure 2 for welding set-up.

Figure 1. Conical Test Chamber
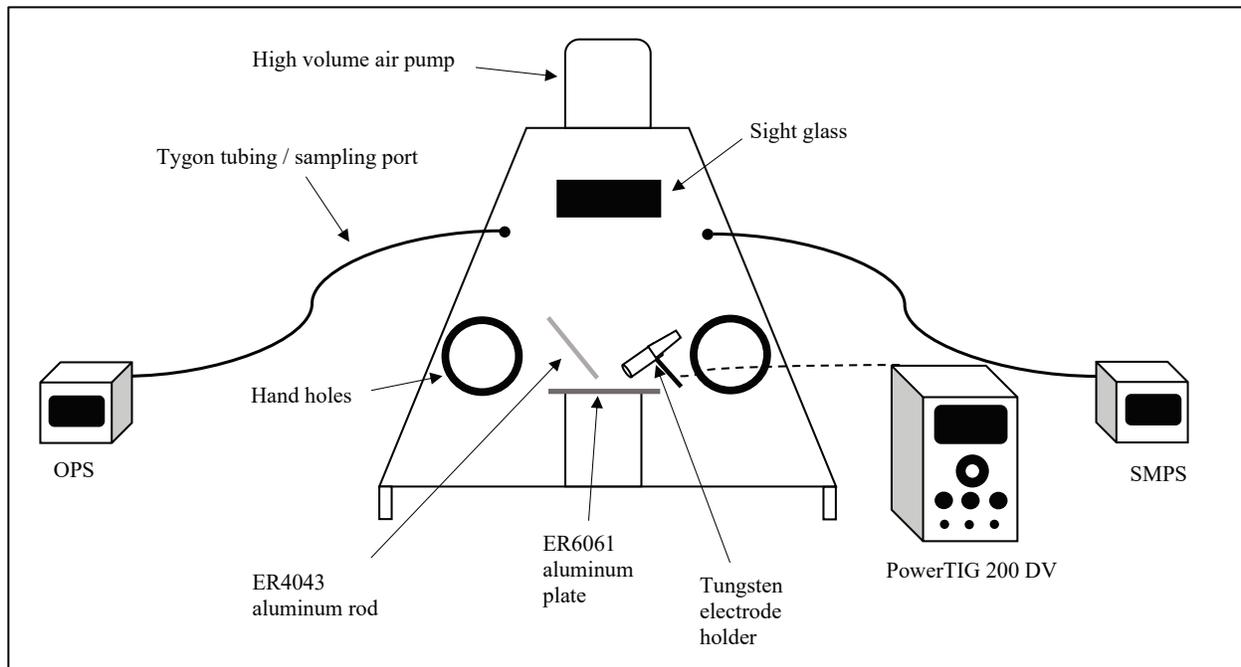
Figure 2. Welding Set-up

The NanoScan SMPS was used to allow the real-time measurement of nanoparticles in size ranges of 10 - 420 nanometers (nm). The NanoScan SMPS utilizes isopropyl alcohol within its internal condensation particle counter (CPC) to record low to high aerosolized concentrations (1,000,000 particles/cm^3) accurately. Listed are the following airflow rates for the NanoScan SMPS: sheath (0.75 liters per minute (L/min)), inlet (0.6 L/min), and CPC (0.25 L/min).

The OPS was used in unison with the NanoScan SMPS to allow a broader nanoparticle detection and measurement range. The sixteen size channels allowed researchers to measure particle sizes from 0.3 to 10 micrometers (μm). Therefore, giving researchers the ability to measure particles in size range of 10 nm to 10 μm with both instruments. The OPS allows concentrations of up to 3,000 particles/cm^3. The sample flow rate was 0.94 L/min, and the sheath flow rate was 0.25 L/min.

<u>Part II. Sampling</u>

It is important to note that the operator conducted a manual process rather than an automatic or semi-automatic process. Meaning no turntable or fixed torch process was used. Prior to sampling exercises, the NanoScan SMPS and OPS were allowed a 15-minute warm-up period. During this time, a stainless-steel wire brush was used to clean surface oxides from aluminum plates to ensure ease of arc start.

A total of twenty-seven samples were collected. Prior to each sample, a 5-minute background was taken. For example, the operator would perform arcing for 1-minute, rest for 1-minute, perform arcing for 1-minute, rest for 1-minute, perform arcing for 30-seconds, and then rest for the remaining 30-seconds. Following each sample, the high-volume air pump installed atop the test chamber was run for 10-minutes to ensure an evacuation of aerosol particles from the chamber. Sampling times were completed in 5-minute intervals with a total of 2.5 minutes welding/arching time and a 2.5-minute rest period. The following nine parameters were tested (see Table 1), with each exercise replicated three times. Amperage settings (120, 140, and 160 A) and pulse modes (no pulse, low pulse, and high pulse) were the main parameters subject to change (see Table 2).

Table 1. Exercise Acronyms

LPLC→ Low Pulse Low Current
LPMC→ … Medium Current
LPHC→… High Current
HPLC → High Pulse Low Current
HPMC→… Medium Current
HPHC→ … High Current
NPLC → No Pulse Low Current
NPMC → … Medium Current
NPHC → … High Current

Table 2. Sample Parameters

Variable	Amps	Pulse Mode	Pulse Frequency (Hz)	Pulse Amps Ratio	Pulse Time On Balance	AC Frequency (Hz)	Cleaning Balance
LPLC	120	Low	25	50%	75%	100	30%
LPMC	140	-	-	-	-	-	-
LPHC	160	-	-	-	-	-	-
HPLC	120	High	85	50%	75%	100	30%
HPMC	140	-	-	-	-	-	-
HPHC	160	-	-	-	-	-	-
NPLC	120	No Pulse	N/A	N/A	N/A	100	30%
NPMC	140	-	-	-	-	-	-
NPHC	160	-	-	-	-	-	-

Part III. Statistical Analysis

Statistical analysis was performed using the JASP Team (Version 0.15). A two-way and one-way analysis of variance (ANOVA) was completed to analyze variances in the data set collected from the welding fume emissions. If the p-value was found to be <0.05, the variances were determined to be significant. The significant values were then run through the post-hoc test to compare multiple variable conditions to determine which specific conditions attributed to the statistical significance. Background data was subtracted from concentration only.

RESULTS

Part I. Concentration

No statistical significance was detected using ANOVA comparison tests for particle concentration using SMPS data. However, the ANOVA test for OPS data found that current was significant ($p<0.001$). Next, the post-hoc test then showed that the following was significant: low current (LC) compared to high current (HC) ($p<0.001$) and medium current (MC) compared to

HC ($p<0.001$). Mean concentrations can be seen in Table 3. Mean concentration without background concentrations of pulse condition*current can be seen in Figure 3.

Table 3.Concentration w/o Background

Variable		SMPS Mean Concentration (particles/cm³)	OPS Mean Concentration (particles/cm³)
NP			
	LC	4.640e +6	574.413
	MC	5.138e +6	821.245
	HC	5.017e +6	1304.793
LP			
	LC	4.792e +6	222.715
	MC	4.609e +6	458.872
	HC	4.219e +6	1773.581
HP			
	LC	4.591e +6	656.718
	MC	4.118e +6	537.426
	HC	4.857e +6	1279.690

Figure 3. OPS Particle Concentrations

However, it is essential to note that the ANOVA test found that the combination of pulse condition and current (pulse condition *current) was relatively close to significance ($p= 0.076$). A post-hoc test found several parameters to be statistically significant (see Table 4).

Table 4. OPS Tukey's Post-Hoc Comparison for Pulse Condition*Current

Parameter(s)		p_{tukey}
NPLC		
	LPHC	<0.001
HPLC		
	LPHC	0.002
LPLC		
	NPHC	0.004
	HPHC	0.005
	LPHC	<0.001
NPMC		
	LPHC	0.018
HPMC		
	LPHC	<0.001
LPMC		
	LPHC	<0.001

Part II. Geometric Mean Diameter

Utilizing the ANOVA test for SMPS data, it was found that the geometric mean diameter of SMPS data was statistically significant ($p<0.05$) for all conditions: pulse condition ($p= 0.008$), current ($p=0.046$), and pulse condition*current ($p= 0.005$). Geometric mean diameters can be seen in Table 5. Mean geometric standard deviation of pulse condition*current can be seen in Figure 4.

Table 5. Geometric Mean Diameter

Variable		SMPS Mean Diameter (nm)	OPS Mean Diameter (µm)
NP			
	LC	65.920	0.374
	MC	69.634	0.374
	HC	62.234	0.383
LP			
	LC	58.628	0.367
	MC	59.314	0.369
	HC	61.401	0.392
HP			
	LC	57.527	0.372
	MC	67.404	0.369
	HC	75.003	0.392
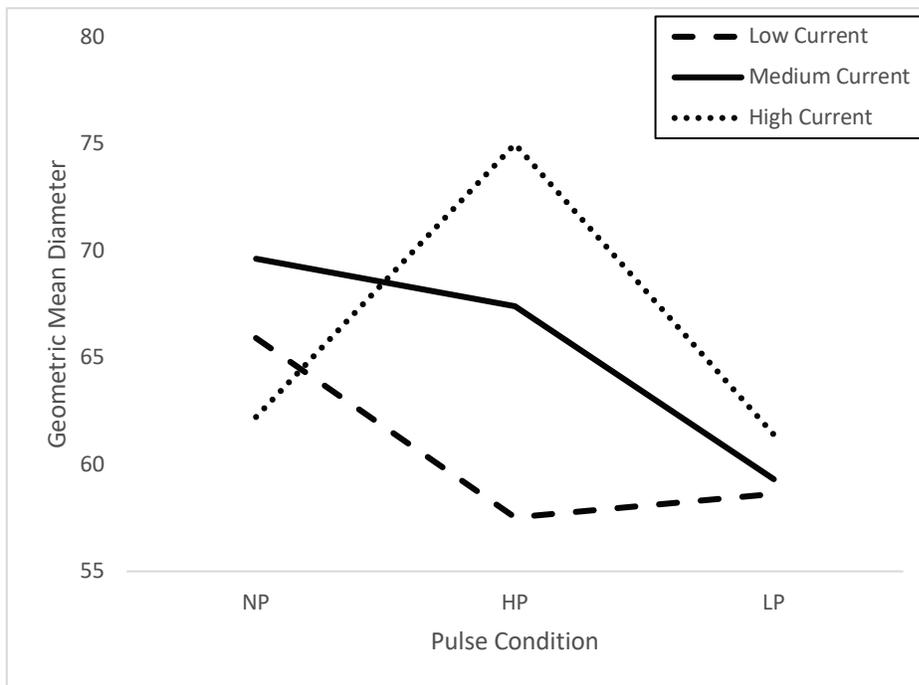
Figure 4. SMPS Geometric Mean Diameter

The post-hoc comparison test for pulse condition showed that NP; LP (p=0.029) and HP; LP (p=0.013) were significant. Current showed no significance; however, pulse condition*current had several parameters that expressed significance (see Table 6).

Table 6. SMPS Tukey's Post-Hoc Comparison for Geometric Mean Diameter

Parameter(s)		p_{tukey}
Pulse Condition		
NP		
	LP	0.029
HP		
	LP	0.013
Pulse Condition * Current		
HPLC		
	HPHC	0.001
LPLC		
	HPHC	0.004
LPMC		
	HPHC	0.007
HPHC		
	LPHC	0.033

Next, the OPS data and the ANOVA test for geometric mean diameter found that the pulse condition was statistically significant (*p*= 0.025). Using the post-hoc test for pulse condition, we determined that there was a significance when comparing HP; LP (*p*=0.042). The post-hoc test for pulse condition*current determined that only LPMC; HPHC was significant (*p*= 0.020). Mean geometric standard deviation of pulse condition*current can be seen in Figure 5.
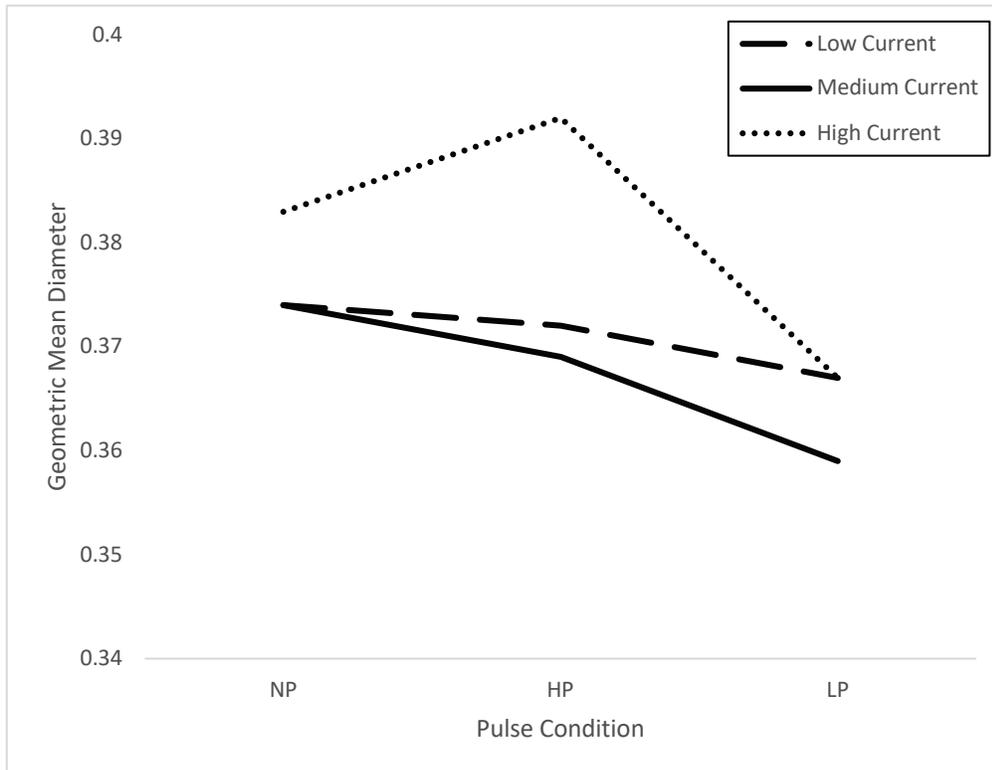
Figure 5. OPS. Geometric Mean Diameter

Part III. Geometric Standard Deviation

No statistically significant results were found for SMPS data regarding geometric standard deviation. However, using the OPS data and ANOVA tests, it was found that the pulse condition was significant ($p= 0.004$). The post-hoc test for pulse condition determined that NP; LP ($p= 0.009$) and HP; LP ($p=0.015$) were significant. The mean geometric standard deviations can be seen in Table 7.

Table 7. Mean Geometric Standard Deviation

Variable		Mean Geo. Standard Deviation (SMPS)	Mean Geo. Standard Deviation (OPS)
NP			
	LC	2.069	1.251
	MC	2.049	1.247
	HC	2.007	1.253
LP			
	LC	1.836	1.249
	MC	2.004	1.185
	HC	1.982	1.183
HP			
	LC	1.797	1.245
	MC	1.832	1.242
	HC	2.212	1.257

DISCUSSION

Part I. Concentration

To begin, it is essential to remember the particle size differences between SMPS (10 - 420 nm) and OPS (0.3 - 10 μm) datasets. No variables (pulse condition, current, or pulse condition * current) had statistical significance upon concentration retrieved from the SMPS (10 - 420 nm). The NPMC variable produced the highest mean concentration (5.017e +6 particle/cm^3). It is slightly surprising that NPMC produced the greatest mean concentration level (5.138e +6 particles/cm^3), without background concentration, compared to NPHC (5.017e +6 particles/cm^3).

Only current ($p<.001$) provided significance upon concentration for OPS (0.3 - 10 μm) data. The post-hoc comparisons LC; HC ($p<0.001$) and MC; HC ($p<0.001$) express that higher current results in a significant concentration difference when compared to the remaining lower current values. For example, high current variables produced the following highest mean

concentrations: NPHC (1304.793 particle/cm^3), LPHC (1773.581 particle/cm^3), and HPHC (1279.690 particle/cm^3).

Part II. Geometric Mean Diameter

All variables for geometric mean diameter were found significant for SMPS data: pulse condition (p= 0.008), current (p=0.046), and pulse condition*current (p= 0.005). The highest average geometric mean diameter was HPHC (75.003 nm). The post-hoc comparison test showed HPLC and HPHC (p=0.001) had the greatest significance of all variables. However, it is interesting to note that HPHC and LPHC were also significant (p= 0.033). This shows that the pulsing condition does create a significant difference amongst geometric mean diameter measurements. However, it is still the current amperage that accounts for the most statistical significance.

Only pulse condition was found to be significant (p=0.025) for OPS data. The post-hoc comparison test showed significant differences between HP;LP (p=0.042) and LPMC;HPHC (p=0.020). The largest geometric mean diameter was shared between LPHC and HPHC (0.392 μm).

Part III. Geometric Standard Deviation

As previously mentioned, only the pulse condition (p=0.004) was significant for geometric standard deviation (σ_g) for OPS data. Further analysis showed that NP; LP (p= 0.009) and HP; LP (p=0.015) were significant. The lowest mean geometric standard deviation was HPLC (1.797) for SMPS data and LPHC (1.183) for OPS data. This is important because *monodisperse particles* are defined as $\sigma_g \leq 1.1$, while polydisperse particles are $\sigma_g > 1.1$. Showing that all mean geometric standard deviations exhibit polydisperse particles. This comes

as no surprise since the mass of occupational aerosol-generating actions produces polydisperse emissions[11].

Part IV. Weld Appearance

It is worth noting the differences in weld appearance between the different welding exercises (see Appendix C). The LC exercises were more difficult for the operator to start an efficient arc when compared to HC exercises, regardless of pulse condition. It is important to note that the operator elected to start a new bead in select welding exercises rather than continue with the same bead once a break period was reached during the process. It is unknown whether this contributed to the results gathered during this experiment.

CONCLUSION

Welding currents were found to be the only statistically significant variable affecting particle concentration ($p<0.001$) for particles in size range of 0.3 -10 µm. The highest current values produced the largest mean concentrations (particles/cm3). All variables produced significance for geometric mean diameter for particles in the size range of 10 – 420 nm: pulse condition ($p=0.008$), current ($p=0.046$), and pulse condition * current (0.005). The post-hoc pulse condition * current comparison determined that current provided the most statistical significance upon geometric mean diameter. Only the pulse condition ($p=0.025$) provided statistical significance for the geometric mean diameter of particles in size range of 0.3 -10 µm. Upon further investigation, it was determined that HP was the most significant ($p=0.042$). While pulsed conditions produce significant results, it was determined that current amperage still plays a more pivotal role in particle size distribution measurements. The findings of this study should

be used in unison with future research to fully determine GTAW-P effect upon welding fume

emissions as the process is incorporated more into industrial or manufacturing settings.

BIBLIOGRAPHY

1. AWS Learning. (2021). American Welding Society. Welding.

2. AWS Learning. (2021). American Welding Society. Gas Tungsten Arc Welding (GTAW).

3. Modenesi, P. J., Apolinario, E. R., & Pereira, I. M. (2000). TIG welding with single-component fluxes. *Journal of materials processing technology*, *99*(1-3), 260-265.

4. Baghel, P. K., & Nagesh, D. S. (2017). Pulse TIG welding: Process, Automation and Control. *Journal of Welding and Joining*, *35*(1), 43-48.

5. Indira Rani, M., & Marpu, R. N. (2012). Effect of pulsed current TIG welding parameters on mechanical properties of J-joint strength of Aa6351. *The International Journal of Engineering and Science (IJES)*, *1*(1), 1-5.

6. Zeidler-Erdely, P. C., Falcone, L. M., & Antonini, J. M. (2019). Influence of welding fume metal composition on lung toxicity and tumor formation in experimental animal models. *Journal of occupational and environmental hygiene*, *16*(6), 372–377.

7. Occupational Safety and Health Administration. (2013). Controlling Hazardous Fume and Gases during Welding. *OSHA FactSheet*.

8. AWS Project Committee on Fumes and Gases. (2013). *Laboratory Method for Measuring Fume Generation Rates and Total Fume Emission of Welding and Allied Processes*. American Welding Society.

9. Sims, S. (2018). *Ultrafine Particles and Oxidative Gases Emission from Alternating Current Aluminum Tungsten Inert Gas Welding*. The University of Oklahoma Health Sciences Center.

10. TSI Incorporated (2012). Aerosol Statistics LOGNORMAL Distributions and dN/dlogDp. Application Note PR-001.

11. Plog, B. A., Niland, J., & Quinlan, P. (1996). *Fundamentals of industrial hygiene* (pp. 1-7). Ithaca, NY: National Safety Council.

APPENDICES

Appendix A. SMPS Data Analysis

Results

ANOVA
ANOVA - Concentration w/o Background

Cases	Sum of Squares	df	Mean Square	F	p	η²
Pulse condition	4.831e +12	2	2.415e +12	1.846	0.162	0.027
Current	1.364e +11	2	6.822e +10	0.052	0.949	7.642e -4
Pulse condition ✲ Current	8.668e +12	4	2.167e +12	1.656	0.164	0.049
Residuals	1.649e +14	126	1.309e +12			

Note. Type III Sum of Squares

Descriptives
Descriptives - Concentration w/o Background

Pulse condition	Current	Mean	SD	N
NP	1 Low	4.640e +6	943803.995	15
	2 Medium	5.138e +6	907502.949	15
	3 High	5.017e +6	1.073e +6	15
PH	1 Low	4.591e +6	1.427e +6	15
	2 Medium	4.118e +6	1.271e +6	15
	3 High	4.857e +6	761231.396	15
PL	1 Low	4.792e +6	1.094e +6	15
	2 Medium	4.609e +6	845095.807	15
	3 High	4.219e +6	1.664e +6	15

Descriptives plots
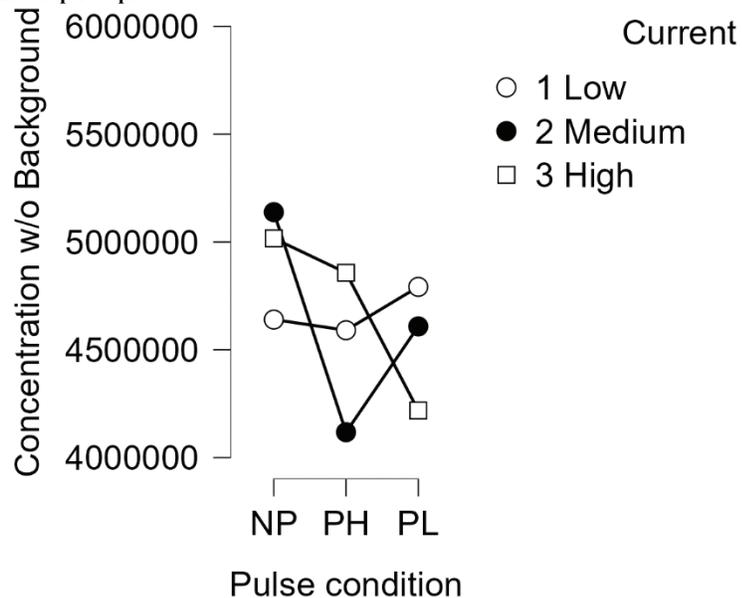
Post Hoc Tests

Standard

Post Hoc Comparisons - Pulse condition

		Mean Difference	95% CI for Mean Difference		SE	t	Cohen's d	p tukey
			Lower	Upper				
NP	PH	409845.844	-162161.905	981853.593	241177.229	1.699	0.374	0.209
	PL	392113.918	-179893.831	964121.667	241177.229	1.626	0.350	0.239
PH	PL	-17731.926	-589739.675	554275.822	241177.229	-0.074	-0.015	0.997

Note. Cohen's d does not correct for multiple comparisons.
Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).
Note. Results are averaged over the levels of: Current

Post Hoc Comparisons - Current

		Mean Difference	95% CI for Mean Difference		SE	t	Cohen's d	p tukey
			Lower	Upper				
1 Low	2 Medium	52745.532	-519262.217	624753.281	241177.229	0.219	0.047	0.974
	3 High	-23237.295	-595245.044	548770.453	241177.229	-0.096	-0.019	0.995
2 Medium	3 High	-75982.827	-647990.576	496024.921	241177.229	-0.315	-0.065	0.947

Note. Cohen's d does not correct for multiple comparisons.
Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).
Note. Results are averaged over the levels of: Pulse condition

Post Hoc Comparisons - Pulse condition ✻ Current

		Mean Difference	95% CI for Mean Difference		SE	t	p tukey
			Lower	Upper			
NP 1 Low	PH 1 Low	49451.211	-1.269e +6	1.368e +6	417731.214	0.118	1.000
	PL 1 Low	-151689.686	-1.470e +6	1.167e +6	417731.214	-0.363	1.000
	NP 2 Medium	-498146.667	-1.817e +6	820395.073	417731.214	-1.193	0.957
	PH 2 Medium	522482.122	-796059.618	1.841e +6	417731.214	1.251	0.943
	PL 2 Medium	31662.667	-1.287e +6	1.350e +6	417731.214	0.076	1.000
	NP 3 High	-376543.333	-1.695e +6	941998.406	417731.214	-0.901	0.993
	PH 3 High	-217085.800	-1.536e +6	1.101e +6	417731.214	-0.520	1.000
	PL 3 High	421678.773	-896862.967	1.740e +6	417731.214	1.009	0.984
PH 1 Low	PL 1 Low	-201140.897	-1.520e +6	1.117e +6	417731.214	-0.482	1.000
	NP 2 Medium	-547597.878	-1.866e +6	770943.862	417731.214	-1.311	0.926
	PH 2 Medium	473030.911	-845510.829	1.792e +6	417731.214	1.132	0.968
	PL 2 Medium	-17788.544	-1.336e +6	1.301e +6	417731.214	-0.043	1.000
	NP 3 High	-425994.544	-1.745e +6	892547.195	417731.214	-1.020	0.983
	PH 3 High	-266537.011	-1.585e +6	1.052e +6	417731.214	-0.638	0.999
	PL 3 High	372227.562	-946314.178	1.691e +6	417731.214	0.891	0.993
PL 1 Low	NP 2 Medium	-346456.981	-1.665e +6	972084.759	417731.214	-0.829	0.996
	PH 2 Medium	674171.807	-644369.932	1.993e +6	417731.214	1.614	0.796
	PL 2 Medium	183352.352	-1.135e +6	1.502e +6	417731.214	0.439	1.000
	NP 3 High	-224853.648	-1.543e +6	1.094e +6	417731.214	-0.538	1.000
	PH 3 High	-65396.114	-1.384e +6	1.253e +6	417731.214	-0.157	1.000
	PL 3 High	573368.458	-745173.281	1.892e +6	417731.214	1.373	0.906
NP 2 Medium	PH 2 Medium	1.021e +6	-297912.951	2.339e +6	417731.214	2.443	0.270
	PL 2 Medium	529809.333	-788732.406	1.848e +6	417731.214	1.268	0.939
	NP 3 High	121603.333	-1.197e +6	1.440e +6	417731.214	0.291	1.000
	PH 3 High	281060.867	-1.037e +6	1.600e +6	417731.214	0.673	0.999
	PL 3 High	919825.439	-398716.300	2.238e +6	417731.214	2.202	0.411
PH 2 Medium	PL 2 Medium	-490819.455	-1.809e +6	827722.285	417731.214	-1.175	0.960
	NP 3 High	-899025.455	-2.218e +6	419516.285	417731.214	-2.152	0.443
	PH 3 High	-739567.922	-2.058e +6	578973.818	417731.214	-1.770	0.701
	PL 3 High	-100803.349	-1.419e +6	1.218e +6	417731.214	-0.241	1.000
PL 2 Medium	NP 3 High	-408206.000	-1.727e +6	910335.740	417731.214	-0.977	0.987
	PH 3 High	-248748.467	-1.567e +6	1.070e +6	417731.214	-0.595	1.000
	PL 3 High	390016.106	-928525.634	1.709e +6	417731.214	0.934	0.991
NP 3 High	PH 3 High	159457.533	-1.159e +6	1.478e +6	417731.214	0.382	1.000
	PL 3 High	798222.106	-520319.634	2.117e +6	417731.214	1.911	0.608
PH 3 High	PL 3 High	638764.573	-679777.167	1.957e +6	417731.214	1.529	0.840

Note. P-value and confidence intervals adjusted for comparing a family of 9 estimates (confidence intervals corrected using the tukey method).

SMPS Geometric Mean Diameter

Results

ANOVA
ANOVA - Geo. Mean. Diameter

Cases	Sum of Squares	df	Mean Square	F	p	η²
Pulse condition	1281.362	2	640.681	5.021	0.008	0.064
Current	805.553	2	402.776	3.157	0.046	0.040
Pulse condition ✷ Current	1971.099	4	492.775	3.862	0.005	0.098
Residuals	16076.460	126	127.591			

Note. Type III Sum of Squares

Descriptives
Descriptives - Geo. Mean. Diameter

Pulse condition	Current	Mean	SD	N
NP	1 Low	65.920	10.729	15
	2 Medium	69.634	15.150	15
	3 High	62.234	10.813	15
PH	1 Low	57.527	10.651	15
	2 Medium	67.404	12.095	15
	3 High	75.003	7.633	15
PL	1 Low	58.628	12.576	15
	2 Medium	59.314	9.643	15
	3 High	61.401	10.844	15

Descriptives plots
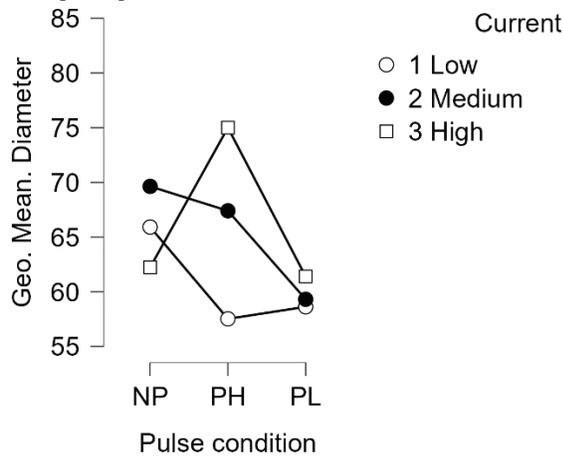
Post Hoc Tests

Standard
Post Hoc Comparisons - Pulse condition

			95% CI for Mean Difference					
		Mean Difference	Lower	Upper	SE	t	Cohen's d	p tukey
NP	PH	-0.715	-6.363	4.933	2.381	-0.300	-0.057	0.952
	PL	6.148	0.501	11.796	2.381	2.582	0.524	0.029 *
PH	PL	6.864	1.216	12.512	2.381	2.882	0.588	0.013 *

* p < .05
Note. Cohen's d does not correct for multiple comparisons.

Post Hoc Comparisons - Pulse condition

	Mean Difference	95% CI for Mean Difference		SE	t	Cohen's d	p tukey
		Lower	Upper				

Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).
Note. Results are averaged over the levels of: Current

Post Hoc Comparisons - Current

		Mean Difference	95% CI for Mean Difference		SE	t	Cohen's d	p tukey
			Lower	Upper				
1 Low	2 Medium	-4.759	-10.407	0.889	2.381	-1.998	-0.384	0.117
	3 High	-5.521	-11.168	0.127	2.381	-2.318	-0.475	0.057
2 Medium	3 High	-0.762	-6.410	4.886	2.381	-0.320	-0.062	0.945

Note. Cohen's d does not correct for multiple comparisons.
Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).
Note. Results are averaged over the levels of: Pulse condition

Post Hoc Comparisons - Pulse condition ∗ Current

		Mean Difference	95% CI for Mean Difference		SE	t	p tukey
			Lower	Upper			
NP 1 Low	PH 1 Low	8.393	-4.626	21.412	4.125	2.035	0.522
	PL 1 Low	7.292	-5.727	20.311	4.125	1.768	0.703
	NP 2 Medium	-3.714	-16.733	9.305	4.125	-0.900	0.993
	PH 2 Medium	-1.483	-14.502	11.536	4.125	-0.360	1.000
	PL 2 Medium	6.606	-6.413	19.625	4.125	1.602	0.802
	NP 3 High	3.686	-9.332	16.705	4.125	0.894	0.993
	PH 3 High	-9.082	-22.101	3.936	4.125	-2.202	0.411
	PL 3 High	4.519	-8.499	17.538	4.125	1.096	0.974
PH 1 Low	PL 1 Low	-1.100	-14.119	11.919	4.125	-0.267	1.000
	NP 2 Medium	-12.107	-25.126	0.912	4.125	-2.935	0.090
	PH 2 Medium	-9.876	-22.895	3.143	4.125	-2.394	0.296
	PL 2 Medium	-1.787	-14.806	11.232	4.125	-0.433	1.000
	NP 3 High	-4.706	-17.725	8.313	4.125	-1.141	0.967
	PH 3 High	-17.475	-30.494	-4.456	4.125	-4.237	0.001 **
	PL 3 High	-3.873	-16.892	9.146	4.125	-0.939	0.990
PL 1 Low	NP 2 Medium	-11.006	-24.025	2.013	4.125	-2.668	0.170
	PH 2 Medium	-8.776	-21.795	4.243	4.125	-2.128	0.460
	PL 2 Medium	-0.686	-13.705	12.332	4.125	-0.166	1.000
	NP 3 High	-3.606	-16.625	9.413	4.125	-0.874	0.994
	PH 3 High	-16.375	-29.394	-3.356	4.125	-3.970	0.004 **
	PL 3 High	-2.773	-15.792	10.246	4.125	-0.672	0.999
NP 2 Medium	PH 2 Medium	2.230	-10.789	15.249	4.125	0.541	1.000
	PL 2 Medium	10.320	-2.699	23.339	4.125	2.502	0.241
	NP 3 High	7.400	-5.619	20.419	4.125	1.794	0.686
	PH 3 High	-5.369	-18.388	7.650	4.125	-1.302	0.929
	PL 3 High	8.233	-4.786	21.252	4.125	1.996	0.549
PH 2 Medium	PL 2 Medium	8.089	-4.930	21.108	4.125	1.961	0.573
	NP 3 High	5.170	-7.849	18.189	4.125	1.253	0.943
	PH 3 High	-7.599	-20.618	5.420	4.125	-1.842	0.654
	PL 3 High	6.003	-7.016	19.022	4.125	1.455	0.874
PL 2 Medium	NP 3 High	-2.919	-15.938	10.099	4.125	-0.708	0.999
	PH 3 High	-15.688	-28.707	-2.669	4.125	-3.804	0.007 **
	PL 3 High	-2.086	-15.105	10.932	4.125	-0.506	1.000
NP 3 High	PH 3 High	-12.769	-25.788	0.250	4.125	-3.096	0.059
	PL 3 High	0.833	-12.186	13.852	4.125	0.202	1.000
PH 3 High	PL 3 High	13.602	0.583	26.621	4.125	3.298	0.033 *

 * p < .05, ** p < .01

Note. P-value and confidence intervals adjusted for comparing a family of 9 estimates (confidence intervals corrected using the tukey method).

SMPS Geometric Standard Deviation

Results

ANOVA
ANOVA - Geo. Std. Dev.

Cases	Sum of Squares	df	Mean Square	F	p	η²
Pulse condition	0.290	2	0.145	0.932	0.396	0.013
Current	0.639	2	0.320	2.055	0.132	0.029
Pulse condition ✳ Current	1.232	4	0.308	1.982	0.101	0.057
Residuals	19.587	126	0.155			

Note. Type III Sum of Squares

Descriptives
Descriptives - Geo. Std. Dev.

Pulse condition	Current	Mean	SD	N
NP	1 Low	2.069	0.503	15
	2 Medium	2.049	0.498	15
	3 High	2.007	0.401	15
PH	1 Low	1.797	0.246	15
	2 Medium	1.832	0.350	15
	3 High	2.212	0.452	15
PL	1 Low	1.836	0.311	15
	2 Medium	2.004	0.401	15
	3 High	1.982	0.306	15

Descriptives plots
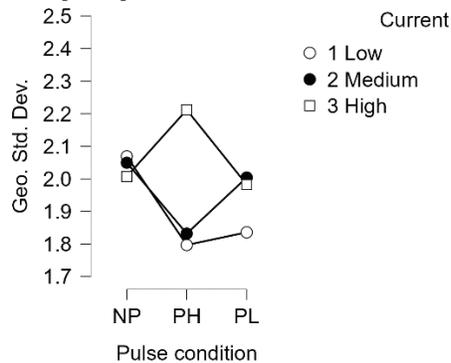
Post Hoc Tests

Standard
Post Hoc Comparisons - Pulse condition

		Mean Difference	95% CI for Mean Difference		SE	t	Cohen's d	p tukey
			Lower	Upper				
NP	PH	0.095	-0.102	0.292	0.083	1.143	0.221	0.489
	PL	0.101	-0.096	0.298	0.083	1.218	0.250	0.445
PH	PL	0.006	-0.191	0.203	0.083	0.075	0.017	0.997

Note. Cohen's d does not correct for multiple comparisons.
Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).
Note. Results are averaged over the levels of: Current

Post Hoc Comparisons - Current

		Mean Difference	95% CI for Mean Difference		SE	t	Cohen's d	p tukey
			Lower	Upper				
1 Low	2 Medium	-0.061	-0.258	0.136	0.083	-0.738	-0.153	0.741
	3 High	-0.167	-0.364	0.031	0.083	-2.004	-0.429	0.115
2 Medium	3 High	-0.105	-0.302	0.092	0.083	-1.267	-0.257	0.417

Note. Cohen's d does not correct for multiple comparisons.

Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).

Note. Results are averaged over the levels of: Pulse condition

Post Hoc Comparisons - Pulse condition ✳ Current

		Mean Difference	95% CI for Mean Difference		SE	t	p tukey
			Lower	Upper			
NP 1 Low	PH 1 Low	0.272	-0.182	0.727	0.144	1.892	0.621
	PL 1 Low	0.233	-0.221	0.688	0.144	1.621	0.792
	NP 2 Medium	0.020	-0.435	0.474	0.144	0.136	1.000
	PH 2 Medium	0.237	-0.217	0.692	0.144	1.647	0.777
	PL 2 Medium	0.065	-0.389	0.519	0.144	0.452	1.000
	NP 3 High	0.062	-0.392	0.516	0.144	0.430	1.000
	PH 3 High	-0.143	-0.597	0.312	0.144	-0.992	0.986
	PL 3 High	0.087	-0.368	0.541	0.144	0.603	1.000
PH 1 Low	PL 1 Low	-0.039	-0.493	0.415	0.144	-0.271	1.000
	NP 2 Medium	-0.253	-0.707	0.202	0.144	-1.756	0.711
	PH 2 Medium	-0.035	-0.490	0.419	0.144	-0.245	1.000
	PL 2 Medium	-0.207	-0.662	0.247	0.144	-1.440	0.880
	NP 3 High	-0.210	-0.665	0.244	0.144	-1.461	0.871
	PH 3 High	-0.415	-0.870	0.039	0.144	-2.884	0.103
	PL 3 High	-0.186	-0.640	0.269	0.144	-1.289	0.933
PL 1 Low	NP 2 Medium	-0.214	-0.668	0.241	0.144	-1.485	0.860
	PH 2 Medium	0.004	-0.451	0.458	0.144	0.026	1.000
	PL 2 Medium	-0.168	-0.623	0.286	0.144	-1.169	0.961
	NP 3 High	-0.171	-0.626	0.283	0.144	-1.191	0.957
	PH 3 High	-0.376	-0.831	0.078	0.144	-2.613	0.192
	PL 3 High	-0.147	-0.601	0.308	0.144	-1.018	0.983
NP 2 Medium	PH 2 Medium	0.218	-0.237	0.672	0.144	1.511	0.848
	PL 2 Medium	0.045	-0.409	0.500	0.144	0.316	1.000
	NP 3 High	0.042	-0.412	0.497	0.144	0.294	1.000
	PH 3 High	-0.162	-0.617	0.292	0.144	-1.128	0.969
	PL 3 High	0.067	-0.387	0.522	0.144	0.467	1.000
PH 2 Medium	PL 2 Medium	-0.172	-0.626	0.282	0.144	-1.195	0.956
	NP 3 High	-0.175	-0.630	0.279	0.144	-1.217	0.951
	PH 3 High	-0.380	-0.834	0.074	0.144	-2.639	0.181
	PL 3 High	-0.150	-0.605	0.304	0.144	-1.044	0.981
PL 2 Medium	NP 3 High	-0.003	-0.458	0.451	0.144	-0.022	1.000
	PH 3 High	-0.208	-0.662	0.247	0.144	-1.444	0.878
	PL 3 High	0.022	-0.433	0.476	0.144	0.151	1.000
NP 3 High	PH 3 High	-0.205	-0.659	0.250	0.144	-1.422	0.887
	PL 3 High	0.025	-0.430	0.479	0.144	0.173	1.000
PH 3 High	PL 3 High	0.230	-0.225	0.684	0.144	1.595	0.806

Note. P-value and confidence intervals adjusted for comparing a family of 9 estimates (confidence intervals corrected using the tukey method).

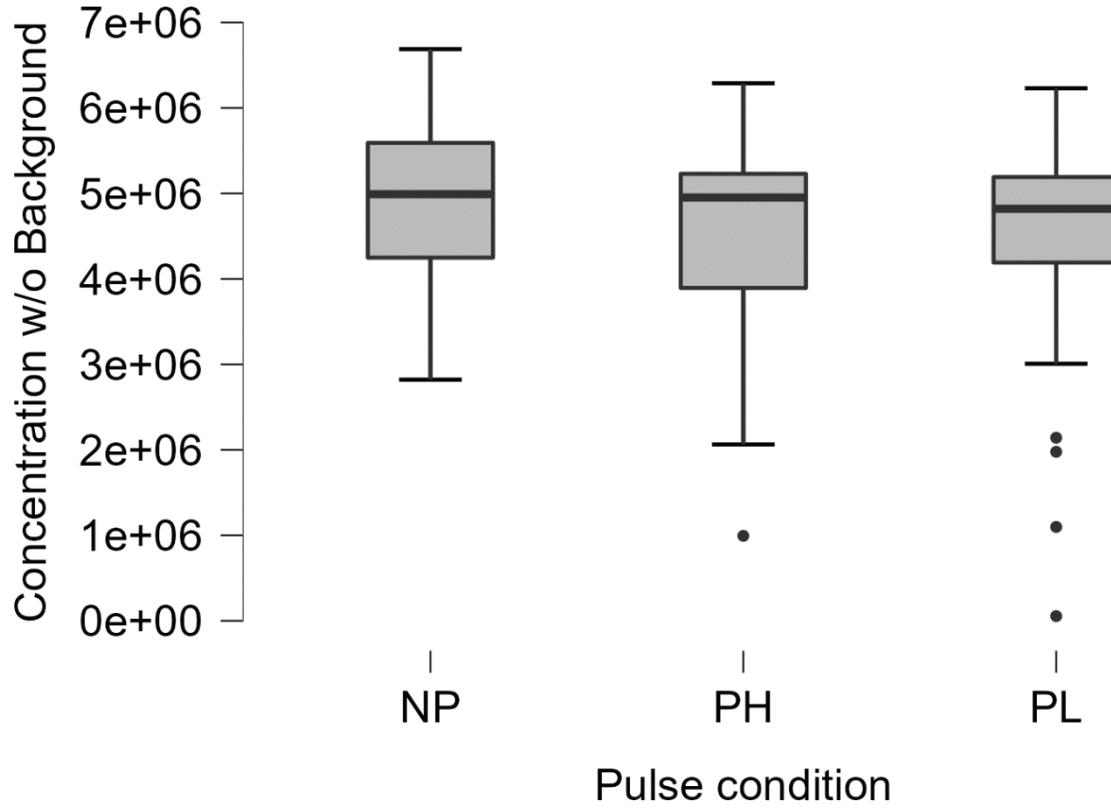**Results**
Descriptive Statistics
Descriptive Statistics

	Concentration w/o Background			Geo. Mean. Diameter			Geo. Std. Dev.		
	NP	PH	PL	NP	PH	PL	NP	PH	PL
Valid	45	45	45	45	45	45	45	45	45
Missing	0	0	0	0	0	0	0	0	0
Mean	4.932e +6	4.522e +6	4.540e +6	65.929	66.644	59.781	2.042	1.947	1.941
Std. Deviation	978653.654	1.201e +6	1.244e +6	12.498	12.391	10.897	0.459	0.399	0.342

Descriptive Statistics

	Concentration w/o Background			Geo. Mean. Diameter			Geo. Std. Dev.		
	NP	PH	PL	NP	PH	PL	NP	PH	PL
Minimum	2.822e +6	994458.967	54795.000	44.505	38.555	34.026	1.499	1.449	1.514
Maximum	6.689e +6	6.289e +6	6.231e +6	101.730	99.292	83.291	2.808	2.976	2.609

Boxplots
Concentration w/o Background

Geo. Mean. Diameter

Results
Descriptive Statistics
Descriptive Statistics

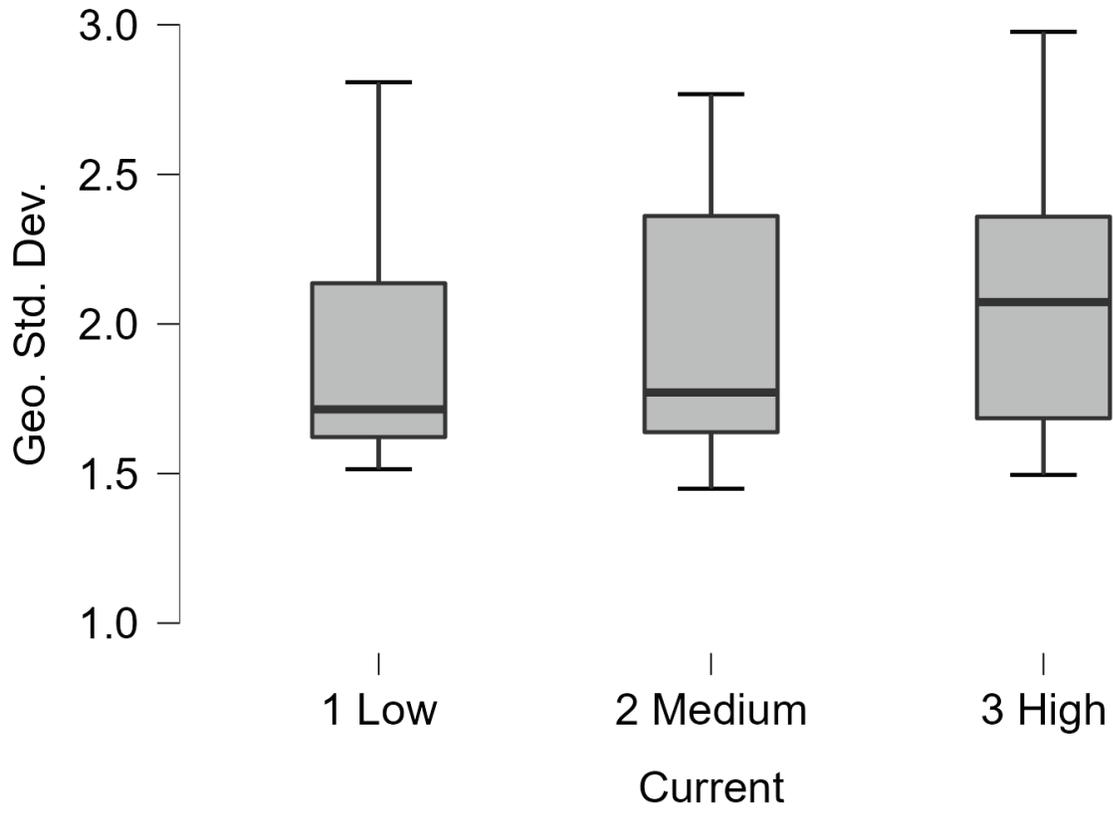|	Concentration w/o Background			Geo. Mean. Diameter			Geo. Std. Dev.		
	1 Low	2 Medium	3 High	1 Low	2 Medium	3 High	1 Low	2 Medium	3 High
Valid	45	45	45	45	45	45	45	45	45
Missing	0	0	0	0	0	0	0	0	0
Mean	4.674e +6	4.622e +6	4.698e +6	60.692	65.451	66.212	1.900	1.962	2.067
Std. Deviation	1.149e +6	1.087e +6	1.246e +6	11.715	13.010	11.524	0.381	0.422	0.396
Minimum	994458.967	1.977e +6	54795.000	34.026	43.769	42.634	1.514	1.449	1.496
Maximum	6.231e +6	6.689e +6	6.595e +6	83.494	101.730	93.828	2.808	2.768	2.976

Boxplots
Concentration w/o Background

Geo. Mean. Diameter
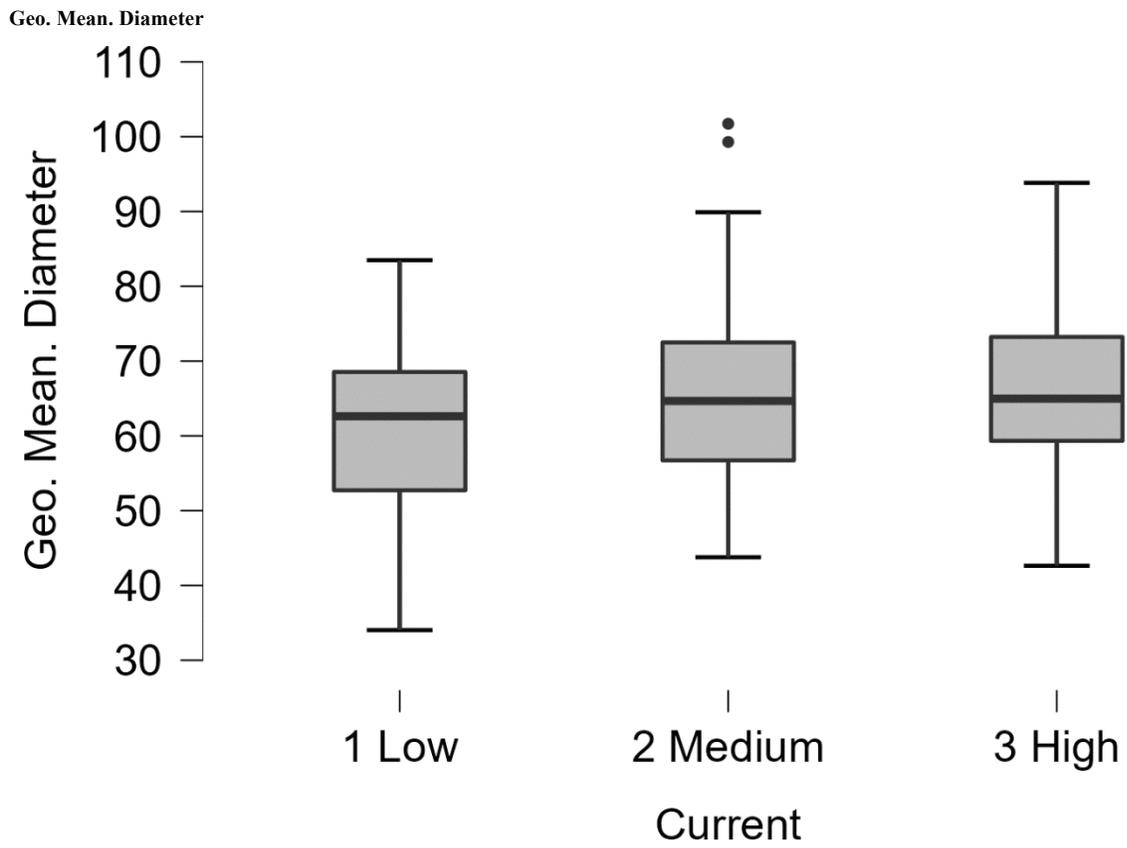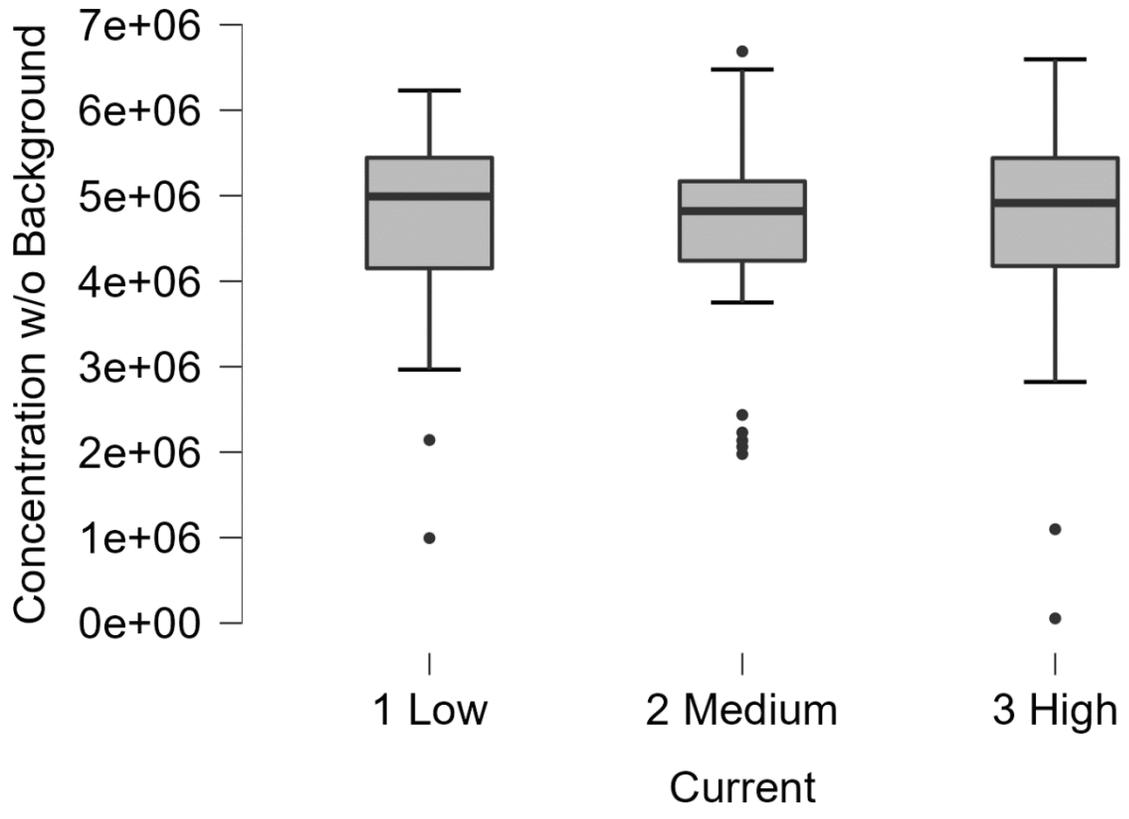
Geo. Std. Dev.
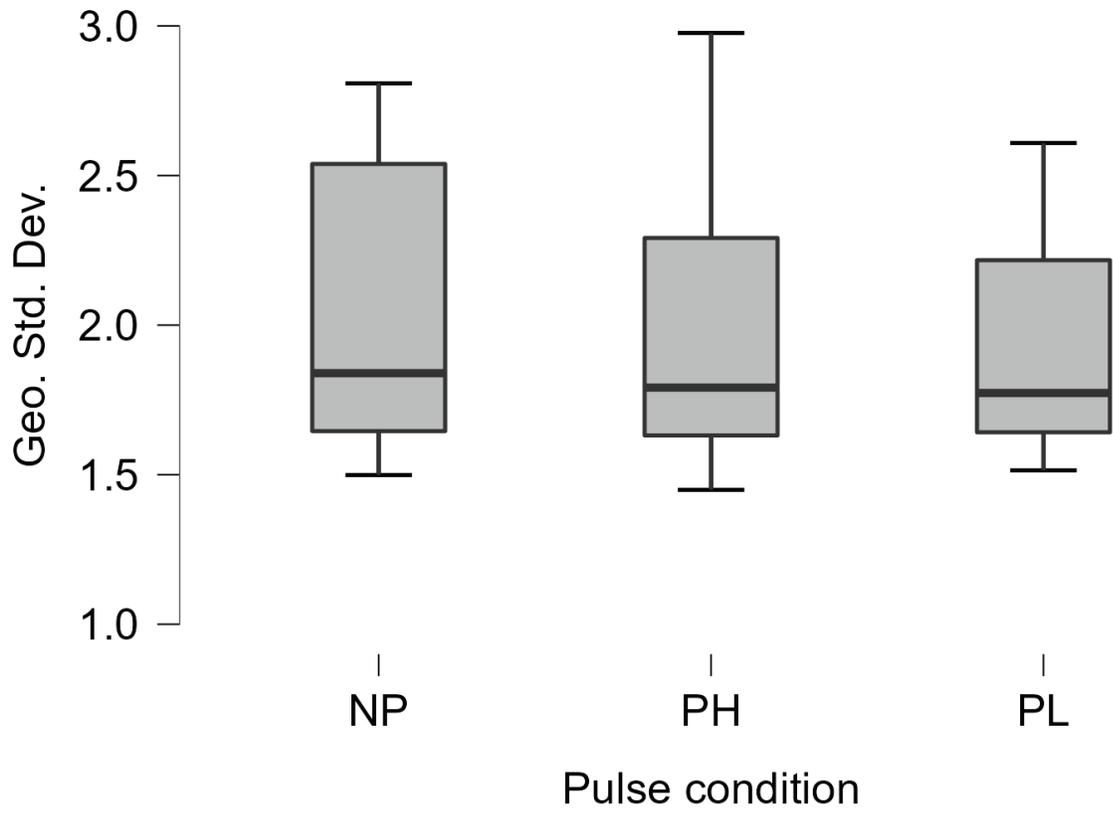
Appendix B. OPS Data Analysis

OPS DATA CONCENTRATION

Results

ANOVA

ANOVA - Concentration w/o Background

Cases	Sum of Squares	df	Mean Square	F	p	η²
Pulse condition	186446.742	2	93223.371	0.168	0.845	0.002
Current	2.503e +7	2	1.252e +7	22.597	< .001	0.251
Pulse condition ✳ Current	4.819e +6	4	1.205e +6	2.175	0.076	0.048
Residuals	6.980e +7	126	553957.203			

Note. Type III Sum of Squares

Descriptives

Descriptives - Concentration w/o Background

Pulse condition	Current	Mean	SD	N
NP	1 Low	574.413	343.337	15
	2 Medium	821.245	633.038	15
	3 High	1304.793	958.969	15
PH	1 Low	656.718	424.625	15
	2 Medium	537.426	594.590	15
	3 High	1279.690	1023.963	15
PL	1 Low	222.715	218.556	15
	2 Medium	458.872	424.848	15
	3 High	1773.581	1317.866	15

Descriptives plots
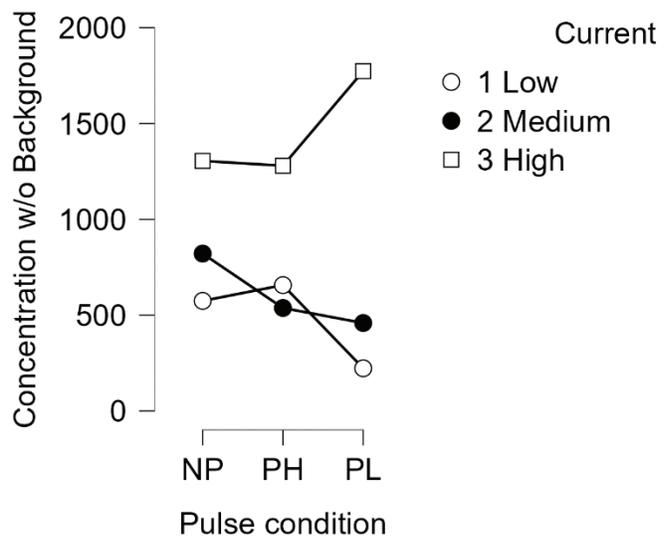
Post Hoc Tests

Standard

Post Hoc Comparisons - Pulse condition

		Mean Difference	95% CI for Mean Difference		SE	t	Cohen's d	p tukey
			Lower	Upper				
NP	PH	75.539	-296.606	447.684	156.909	0.481	0.099	0.880
	PL	81.761	-290.384	453.906	156.909	0.521	0.090	0.861
PH	PL	6.222	-365.923	378.367	156.909	0.040	0.007	0.999

Note. Cohen's d does not correct for multiple comparisons.
Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).
Note. Results are averaged over the levels of: Current

Post Hoc Comparisons - Current

		Mean Difference	95% CI for Mean Difference		SE	t	Cohen's d	p tukey
			Lower	Upper				
1 Low	2 Medium	-121.233	-493.378	250.913	156.909	-0.773	-0.250	0.720
	3 High	-968.072	-1340.218	-595.927	156.909	-6.170	-1.166	< .001 ***
2 Medium	3 High	-846.840	-1218.985	-474.695	156.909	-5.397	-0.961	< .001 ***

*** p < .001
Note. Cohen's d does not correct for multiple comparisons.
Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).
Note. Results are averaged over the levels of: Pulse condition

Post Hoc Comparisons - Pulse condition ✱ Current

		Mean Difference	95% CI for Mean Difference		SE	t	p tukey
			Lower	Upper			
NP 1 Low	PH 1 Low	-82.304	-940.141	775.532	271.774	-0.303	1.000
	PL 1 Low	351.699	-506.138	1209.535	271.774	1.294	0.931
	NP 2 Medium	-246.832	-1104.668	611.004	271.774	-0.908	0.992
	PH 2 Medium	36.987	-820.849	894.824	271.774	0.136	1.000
	PL 2 Medium	115.541	-742.295	973.378	271.774	0.425	1.000
	NP 3 High	-730.379	-1588.215	127.457	271.774	-2.687	0.163
	PH 3 High	-705.276	-1563.112	152.560	271.774	-2.595	0.199
	PL 3 High	-1199.168	-2057.004	-341.331	271.774	-4.412	< .001 ***
PH 1 Low	PL 1 Low	434.003	-423.833	1291.839	271.774	1.597	0.805
	NP 2 Medium	-164.528	-1022.364	693.309	271.774	-0.605	1.000
	PH 2 Medium	119.292	-738.545	977.128	271.774	0.439	1.000
	PL 2 Medium	197.846	-659.991	1055.682	271.774	0.728	0.998
	NP 3 High	-648.075	-1505.911	209.762	271.774	-2.385	0.302
	PH 3 High	-622.972	-1480.808	234.865	271.774	-2.292	0.355
	PL 3 High	-1116.863	-1974.700	-259.027	271.774	-4.110	0.002 **
PL 1 Low	NP 2 Medium	-598.531	-1456.367	259.306	271.774	-2.202	0.411
	PH 2 Medium	-314.711	-1172.548	543.125	271.774	-1.158	0.964
	PL 2 Medium	-236.157	-1093.994	621.679	271.774	-0.869	0.994
	NP 3 High	-1082.078	-1939.914	-224.242	271.774	-3.982	0.004 **
	PH 3 High	-1056.975	-1914.811	-199.139	271.774	-3.889	0.005 **
	PL 3 High	-1550.866	-2408.703	-693.030	271.774	-5.706	< .001 ***
NP 2 Medium	PH 2 Medium	283.819	-574.017	1141.656	271.774	1.044	0.981
	PL 2 Medium	362.373	-495.463	1220.210	271.774	1.333	0.919
	NP 3 High	-483.547	-1341.384	374.289	271.774	-1.779	0.696
	PH 3 High	-458.444	-1316.281	399.392	271.774	-1.687	0.753
	PL 3 High	-952.336	-1810.172	-94.499	271.774	-3.504	0.018 *
PH 2 Medium	PL 2 Medium	78.554	-779.282	936.390	271.774	0.289	1.000
	NP 3 High	-767.366	-1625.203	90.470	271.774	-2.824	0.119
	PH 3 High	-742.263	-1600.100	115.573	271.774	-2.731	0.148
	PL 3 High	-1236.155	-2093.991	-378.319	271.774	-4.548	< .001 ***

Post Hoc Comparisons - Pulse condition ✻ Current

			95% CI for Mean Difference				
		Mean Difference	Lower	Upper	SE	t	p tukey
PL 2 Medium	NP 3 High	-845.921	-1703.757	11.916	271.774	-3.113	0.056
	PH 3 High	-820.818	-1678.654	37.019	271.774	-3.020	0.072
	PL 3 High	-1314.709	-2172.545	-456.873	271.774	-4.838	< .001 ***
NP 3 High	PH 3 High	25.103	-832.733	882.939	271.774	0.092	1.000
	PL 3 High	-468.788	-1326.625	389.048	271.774	-1.725	0.730
PH 3 High	PL 3 High	-493.891	-1351.728	363.945	271.774	-1.817	0.671

Note. P-value and confidence intervals adjusted for comparing a family of 9 estimates (confidence intervals corrected using the tukey method).
 * p < .05, ** p < .01, *** p < .001

OPS DATA Geometric Mean Diameter

Results

ANOVA

ANOVA - Geo. Mean. Diameter

Cases	Sum of Squares	df	Mean Square	F	p	η²
Pulse condition	0.005	2	0.003	3.802	0.025	0.053
Current	0.004	2	0.002	3.051	0.051	0.043
Pulse condition ✻ Current	0.002	4	4.784e -4	0.684	0.605	0.019
Residuals	0.088	126	6.998e -4			

Note. Type III Sum of Squares

Descriptives

Descriptives - Geo. Mean. Diameter

Pulse condition	Current	Mean	SD	N
NP	1 Low	0.374	0.013	15
	2 Medium	0.374	0.028	15
	3 High	0.383	0.029	15
PH	1 Low	0.372	0.014	15
	2 Medium	0.369	0.008	15
	3 High	0.392	0.063	15
PL	1 Low	0.367	0.008	15
	2 Medium	0.359	0.006	15
	3 High	0.367	0.015	15

Descriptives plots
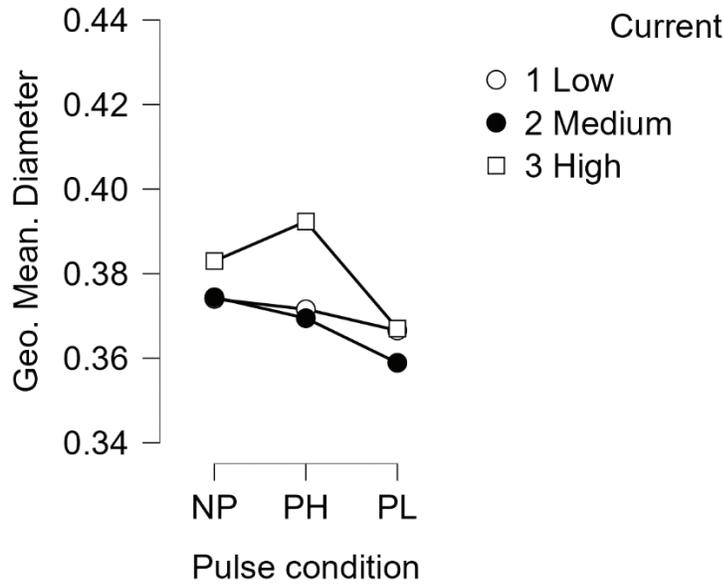
Post Hoc Tests

Standard

Post Hoc Comparisons - Pulse condition

			95% CI for Mean Difference					
		Mean Difference	Lower	Upper	SE	t	Cohen's d	p tukey
NP	PH	-6.472e -4	-0.014	0.013	0.006	-0.116	-0.020	0.993
	PL	0.013	-2.441e -4	0.026	0.006	2.328	0.687	0.056
PH	PL	0.014	4.031e -4	0.027	0.006	2.444	0.490	0.042 *

*p < .05

Note. Cohen's d does not correct for multiple comparisons.

Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).

Note. Results are averaged over the levels of: Current

Post Hoc Comparisons - Current

			95% CI for Mean Difference					
		Mean Difference	Lower	Upper	SE	t	Cohen's d	p tukey
1 Low	2 Medium	0.003	-0.010	0.016	0.006	0.560	0.203	0.842
	3 High	-0.010	-0.023	0.003	0.006	-1.804	-0.331	0.173
2 Medium	3 High	-0.013	-0.026	4.538e -5	0.006	-2.364	-0.414	0.051

Note. Cohen's d does not correct for multiple comparisons.

Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).

Note. Results are averaged over the levels of: Pulse condition

Post Hoc Comparisons - Pulse condition ✳ Current

			95% CI for Mean Difference				
		Mean Difference	Lower	Upper	SE	t	p tukey
NP 1 Low	PH 1 Low	0.002	-0.028	0.033	0.010	0.253	1.000
	PL 1 Low	0.007	-0.023	0.038	0.010	0.773	0.997
	NP 2 Medium	-3.948e -4	-0.031	0.030	0.010	-0.041	1.000
	PH 2 Medium	0.005	-0.026	0.035	0.010	0.472	1.000
	PL 2 Medium	0.015	-0.015	0.046	0.010	1.564	0.822
	NP 3 High	-0.009	-0.039	0.022	0.010	-0.928	0.991
	PH 3 High	-0.018	-0.049	0.012	0.010	-1.896	0.618

Post Hoc Comparisons - Pulse condition ✲ Current

		Mean Difference	95% CI for Mean Difference		SE	t	p tukey
			Lower	Upper			
	PL 3 High	0.007	-0.023	0.038	0.010	0.726	0.998
PH 1 Low	PL 1 Low	0.005	-0.025	0.036	0.010	0.520	1.000
	NP 2 Medium	-0.003	-0.033	0.028	0.010	-0.294	1.000
	PH 2 Medium	0.002	-0.028	0.033	0.010	0.219	1.000
	PL 2 Medium	0.013	-0.018	0.043	0.010	1.311	0.926
	NP 3 High	-0.011	-0.042	0.019	0.010	-1.181	0.959
	PH 3 High	-0.021	-0.051	0.010	0.010	-2.149	0.445
	PL 3 High	0.005	-0.026	0.035	0.010	0.473	1.000
PL 1 Low	NP 2 Medium	-0.008	-0.038	0.023	0.010	-0.814	0.996
	PH 2 Medium	-0.003	-0.033	0.028	0.010	-0.301	1.000
	PL 2 Medium	0.008	-0.023	0.038	0.010	0.791	0.997
	NP 3 High	-0.016	-0.047	0.014	0.010	-1.701	0.745
	PH 3 High	-0.026	-0.056	0.005	0.010	-2.669	0.170
	PL 3 High	-4.551e -4	-0.031	0.030	0.010	-0.047	1.000
NP 2 Medium	PH 2 Medium	0.005	-0.026	0.035	0.010	0.513	1.000
	PL 2 Medium	0.016	-0.015	0.046	0.010	1.605	0.800
	NP 3 High	-0.009	-0.039	0.022	0.010	-0.887	0.993
	PH 3 High	-0.018	-0.048	0.013	0.010	-1.855	0.646
	PL 3 High	0.007	-0.023	0.038	0.010	0.767	0.998
PH 2 Medium	PL 2 Medium	0.011	-0.020	0.041	0.010	1.092	0.974
	NP 3 High	-0.014	-0.044	0.017	0.010	-1.401	0.896
	PH 3 High	-0.023	-0.053	0.008	0.010	-2.368	0.311
	PL 3 High	0.002	-0.028	0.033	0.010	0.253	1.000
PL 2 Medium	NP 3 High	-0.024	-0.055	0.006	0.010	-2.492	0.246
	PH 3 High	-0.033	-0.064	-0.003	0.010	-3.460	0.020 *
	PL 3 High	-0.008	-0.039	0.022	0.010	-0.839	0.995
NP 3 High	PH 3 High	-0.009	-0.040	0.021	0.010	-0.968	0.988
	PL 3 High	0.016	-0.015	0.046	0.010	1.654	0.773
PH 3 High	PL 3 High	0.025	-0.005	0.056	0.010	2.621	0.188

* p < .05

Note. P-value and confidence intervals adjusted for comparing a family of 9 estimates (confidence intervals corrected using the tukey method).

OPS DATA Geometric Standard Deviation

Results

ANOVA

ANOVA - Geo. Std. Dev.

Cases	Sum of Squares	df	Mean Square	F	p	η²
Pulse condition	0.057	2	0.028	5.687	0.004	0.078
Current	0.014	2	0.007	1.360	0.260	0.019
Pulse condition ✲ Current	0.032	4	0.008	1.592	0.180	0.043
Residuals	0.630	126	0.005			

Note. Type III Sum of Squares

Descriptives

Descriptives - Geo. Std. Dev.

Pulse condition	Current	Mean	SD	N
NP	1 Low	1.251	0.070	15
	2 Medium	1.247	0.073	15
	3 High	1.253	0.064	15
PH	1 Low	1.245	0.052	15

Descriptives - Geo. Std. Dev.

Pulse condition	Current	Mean	SD	N
	2 Medium	1.242	0.066	15
	3 High	1.257	0.132	15
PL	1 Low	1.249	0.056	15
	2 Medium	1.185	0.042	15
	3 High	1.183	0.037	15

Descriptives plots
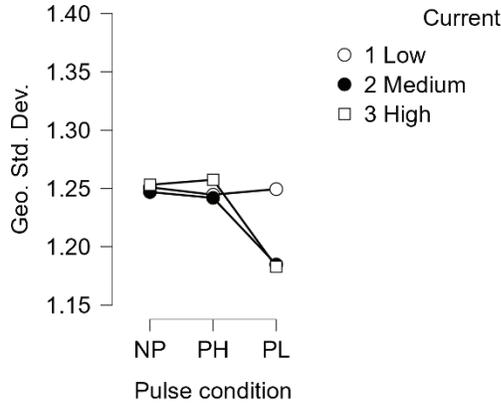
Post Hoc Tests

Standard

Post Hoc Comparisons - Pulse condition

		Mean Difference	95% CI for Mean Difference		SE	t	Cohen's d	p tukey
			Lower	Upper				
NP	PH	0.002	-0.033	0.038	0.015	0.158	0.030	0.986
	PL	0.045	0.009	0.080	0.015	2.996	0.729	0.009 **
PH	PL	0.042	0.007	0.078	0.015	2.839	0.576	0.015 *

* p < .05, ** p < .01
Note. Cohen's d does not correct for multiple comparisons.
Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).
Note. Results are averaged over the levels of: Current

Post Hoc Comparisons - Current

		Mean Difference	95% CI for Mean Difference		SE	t	Cohen's d	p tukey
			Lower	Upper				
1 Low	2 Medium	0.024	-0.012	0.059	0.015	1.597	0.380	0.251
	3 High	0.017	-0.018	0.053	0.015	1.155	0.223	0.482
2 Medium	3 High	-0.007	-0.042	0.029	0.015	-0.442	-0.082	0.898

Note. Cohen's d does not correct for multiple comparisons.
Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the tukey method).
Note. Results are averaged over the levels of: Pulse condition

Post Hoc Comparisons - Pulse condition ✼ Current

		Mean Difference	95% CI for Mean Difference		SE	t	p tukey
			Lower	Upper			
NP 1 Low	PH 1 Low	0.006	-0.075	0.088	0.026	0.246	1.000
	PL 1 Low	0.002	-0.080	0.083	0.026	0.061	1.000

Post Hoc Comparisons - Pulse condition ✳ Current

		Mean Difference	95% CI for Mean Difference		SE	t	p tukey
			Lower	Upper			
	NP 2 Medium	0.004	-0.077	0.086	0.026	0.158	1.000
	PH 2 Medium	0.009	-0.072	0.091	0.026	0.352	1.000
	PL 2 Medium	0.066	-0.015	0.148	0.026	2.563	0.213
	NP 3 High	-0.002	-0.084	0.079	0.026	-0.083	1.000
	PH 3 High	-0.006	-0.088	0.075	0.026	-0.250	1.000
	PL 3 High	0.068	-0.013	0.150	0.026	2.640	0.181
PH 1 Low	PL 1 Low	-0.005	-0.086	0.077	0.026	-0.185	1.000
	NP 2 Medium	-0.002	-0.084	0.079	0.026	-0.088	1.000
	PH 2 Medium	0.003	-0.079	0.084	0.026	0.106	1.000
	PL 2 Medium	0.060	-0.022	0.141	0.026	2.317	0.340
	NP 3 High	-0.009	-0.090	0.073	0.026	-0.329	1.000
	PH 3 High	-0.013	-0.094	0.069	0.026	-0.496	1.000
	PL 3 High	0.062	-0.020	0.143	0.026	2.394	0.296
PL 1 Low	NP 2 Medium	0.003	-0.079	0.084	0.026	0.097	1.000
	PH 2 Medium	0.008	-0.074	0.089	0.026	0.291	1.000
	PL 2 Medium	0.065	-0.017	0.146	0.026	2.503	0.241
	NP 3 High	-0.004	-0.085	0.078	0.026	-0.144	1.000
	PH 3 High	-0.008	-0.090	0.073	0.026	-0.311	1.000
	PL 3 High	0.067	-0.015	0.148	0.026	2.580	0.206
NP 2 Medium	PH 2 Medium	0.005	-0.077	0.087	0.026	0.194	1.000
	PL 2 Medium	0.062	-0.019	0.144	0.026	2.405	0.290
	NP 3 High	-0.006	-0.088	0.075	0.026	-0.241	1.000
	PH 3 High	-0.011	-0.092	0.071	0.026	-0.408	1.000
	PL 3 High	0.064	-0.017	0.146	0.026	2.482	0.251
PH 2 Medium	PL 2 Medium	0.057	-0.024	0.139	0.026	2.212	0.405
	NP 3 High	-0.011	-0.093	0.070	0.026	-0.435	1.000
	PH 3 High	-0.016	-0.097	0.066	0.026	-0.602	1.000
	PL 3 High	0.059	-0.022	0.141	0.026	2.289	0.357
PL 2 Medium	NP 3 High	-0.068	-0.150	0.013	0.026	-2.647	0.178
	PH 3 High	-0.073	-0.154	0.009	0.026	-2.813	0.122
	PL 3 High	0.002	-0.080	0.083	0.026	0.077	1.000
NP 3 High	PH 3 High	-0.004	-0.086	0.077	0.026	-0.167	1.000
	PL 3 High	0.070	-0.011	0.152	0.026	2.724	0.150
PH 3 High	PL 3 High	0.075	-0.007	0.156	0.026	2.890	0.101

Note. P-value and confidence intervals adjusted for comparing a family of 9 estimates (confidence intervals corrected using the tukey method).
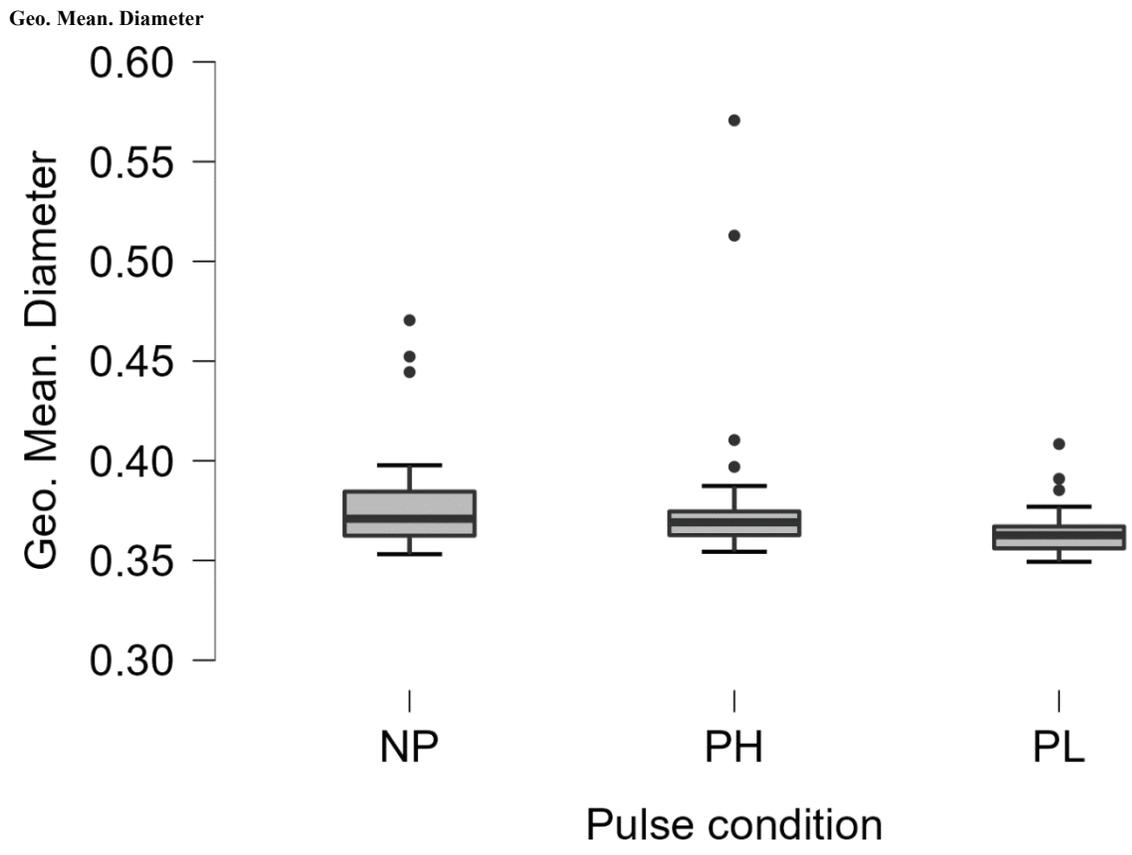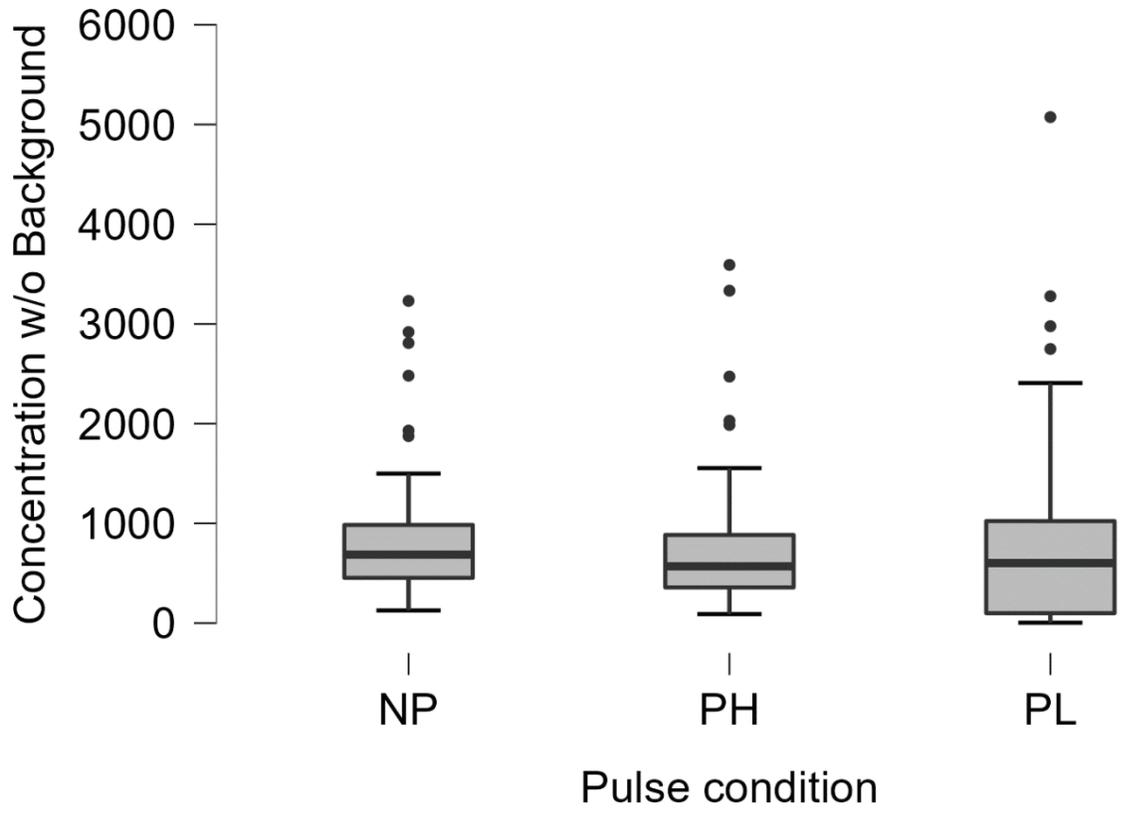
Results
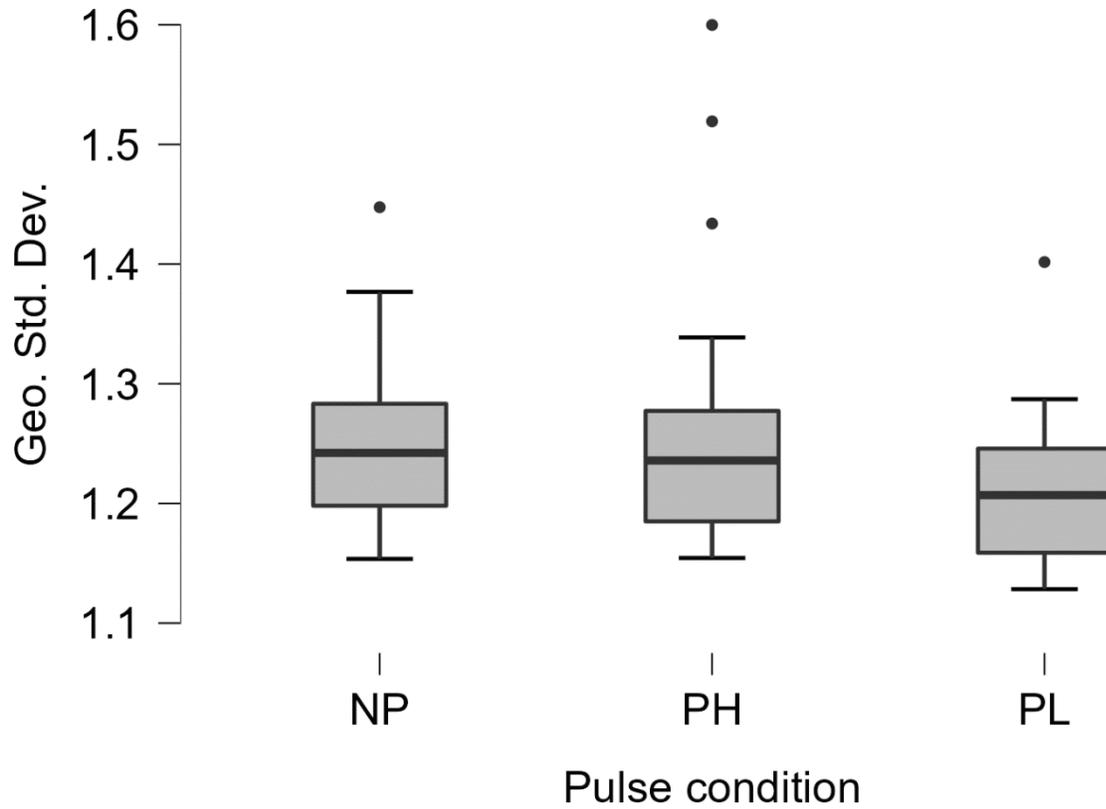**Descriptive Statistics**
Descriptive Statistics

	Concentration w/o Background			Geo. Mean. Diameter			Geo. Std. Dev.		
	NP	PH	PL	NP	PH	PL	NP	PH	PL
Valid	45	45	45	45	45	45	45	45	45
Missing	0	0	0	0	0	0	0	0	0
Mean	900.150	824.611	818.389	0.377	0.378	0.364	1.250	1.248	1.206
Std. Deviation	742.788	782.176	1049.432	0.024	0.038	0.011	0.068	0.089	0.054
Minimum	126.839	89.994	4.205	0.353	0.354	0.349	1.154	1.154	1.128
Maximum	3230.867	3591.589	5073.859	0.470	0.571	0.408	1.448	1.600	1.402

Boxplots
Concentration w/o Background

Geo. Mean. Diameter

Geo. Std. Dev.

Results
Descriptive Statistics
Descriptive Statistics

	Concentration w/o Background			Geo. Mean. Diameter			Geo. Std. Dev.		
	1 Low	2 Medium	3 High	1 Low	2 Medium	3 High	1 Low	2 Medium	3 High
Valid	45	45	45	45	45	45	45	45	45
Missing	0	0	0	0	0	0	0	0	0
Mean	484.615	605.848	1452.688	0.371	0.368	0.381	1.248	1.225	1.231
Std. Deviation	382.500	567.630	1109.772	0.012	0.018	0.041	0.058	0.067	0.092
Minimum	4.205	5.676	99.098	0.353	0.349	0.354	1.163	1.128	1.147
Maximum	1554.501	2918.386	5073.859	0.410	0.470	0.571	1.402	1.448	1.600

Boxplots
Concentration w/o Background

Geo. Mean. Diameter
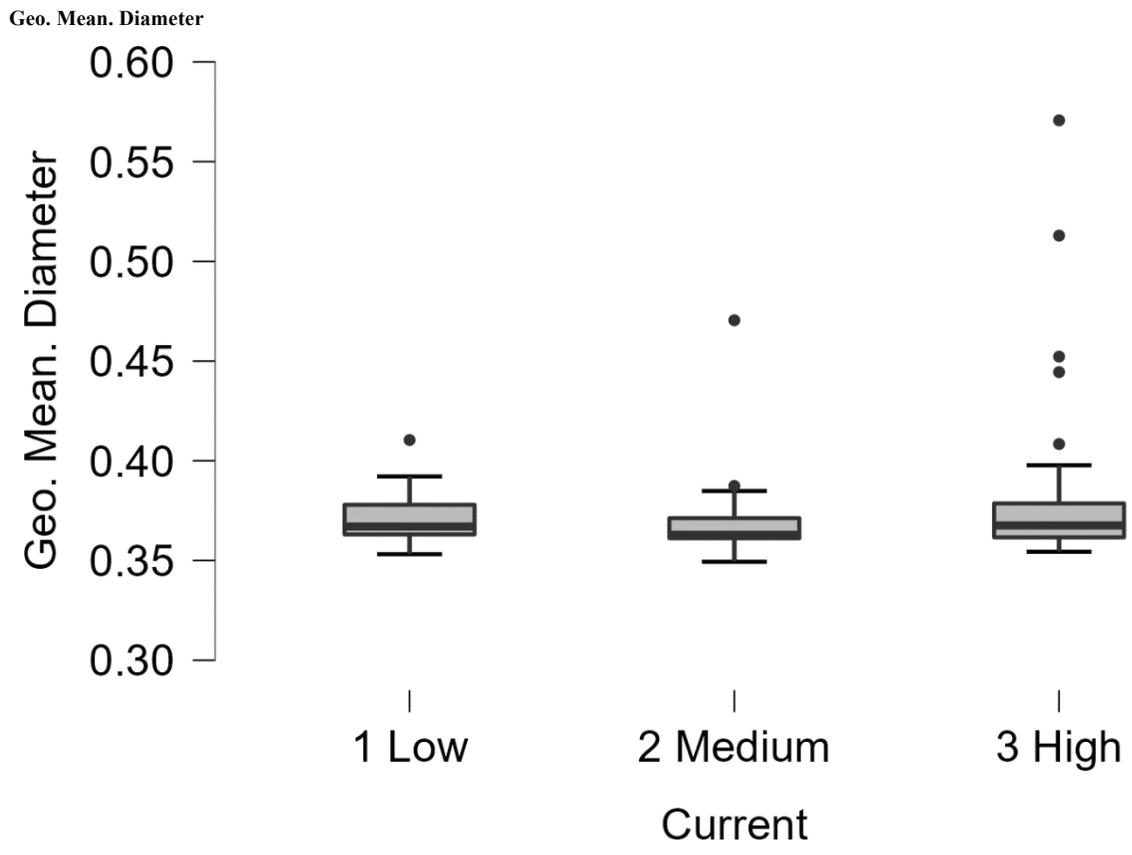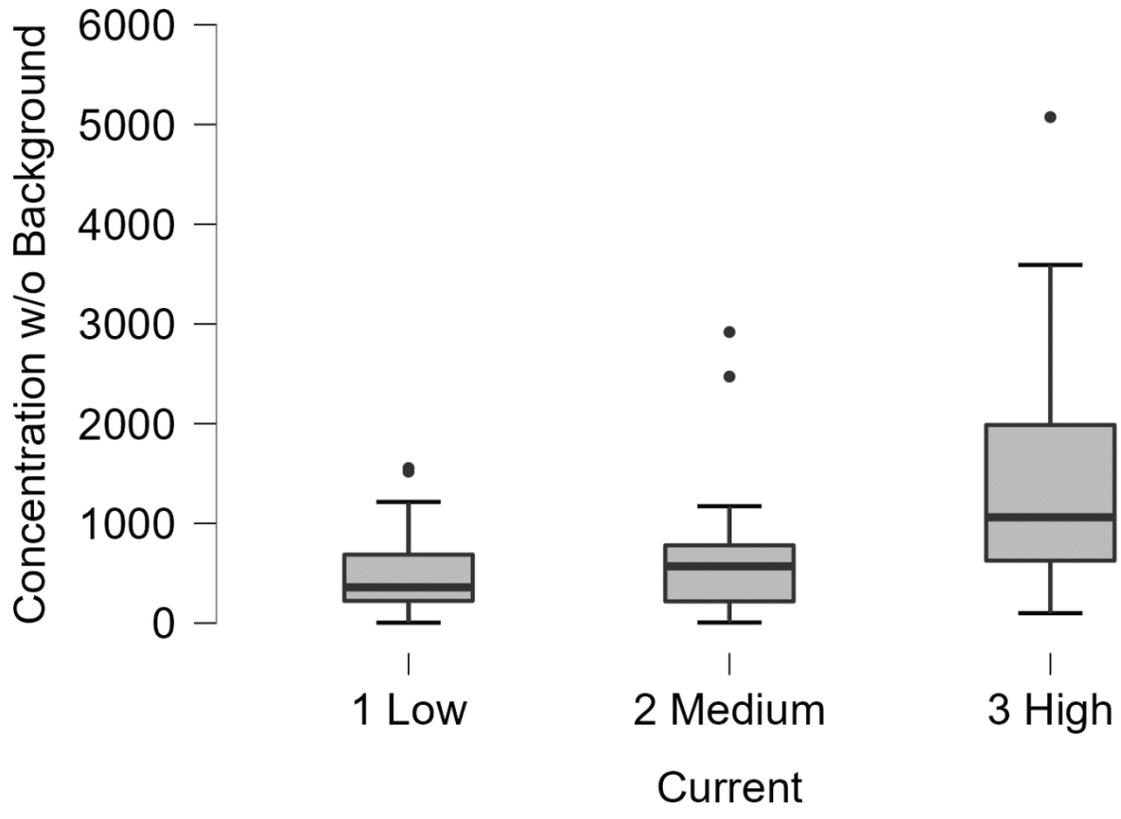
Geo. Std. Dev.
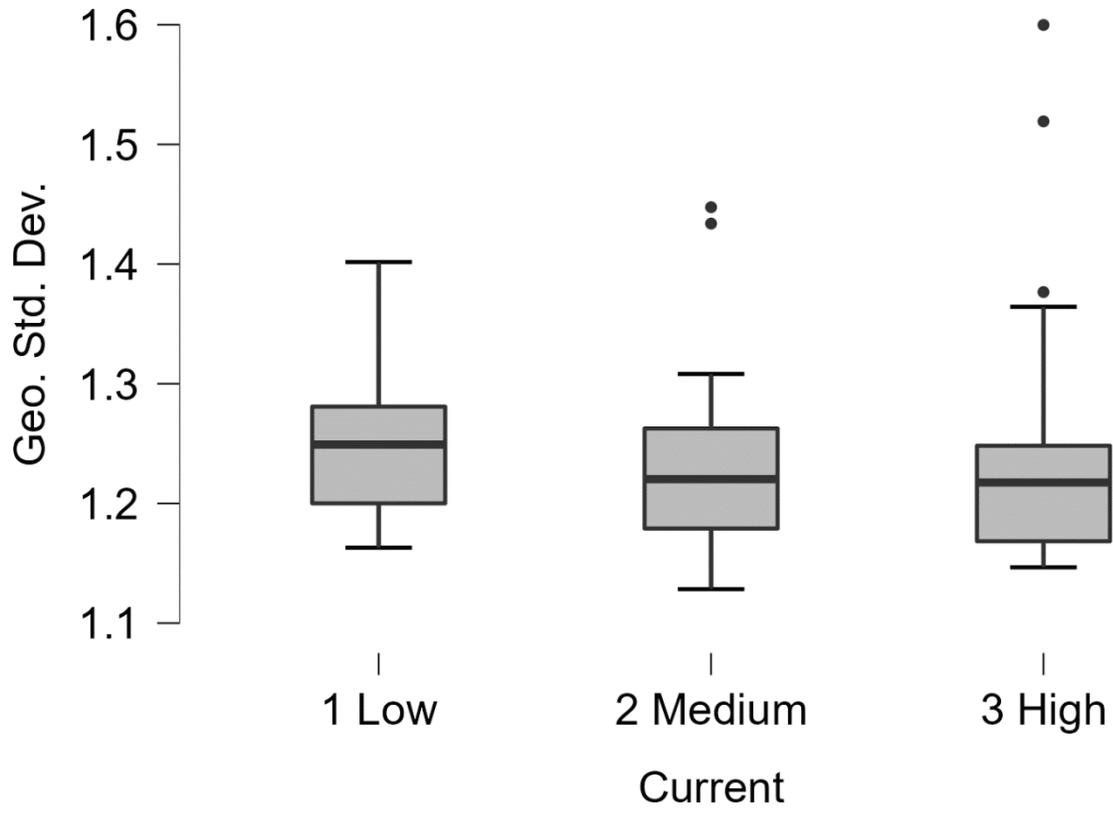
Appendix C. Weld Appearance
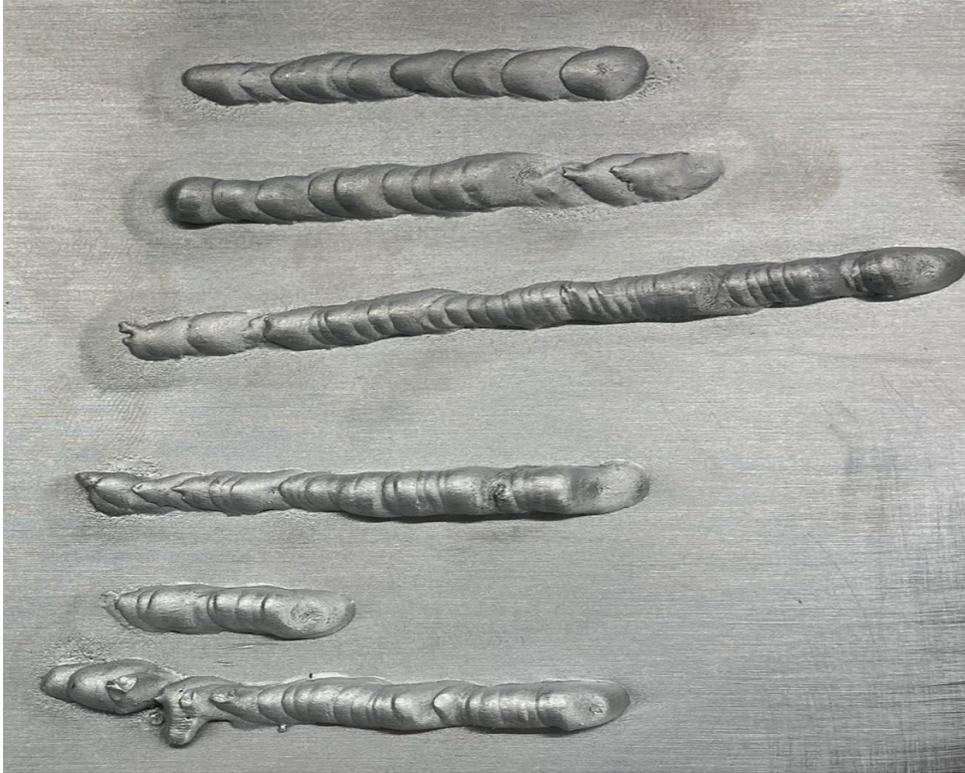
Figure 6. NPLC Welds
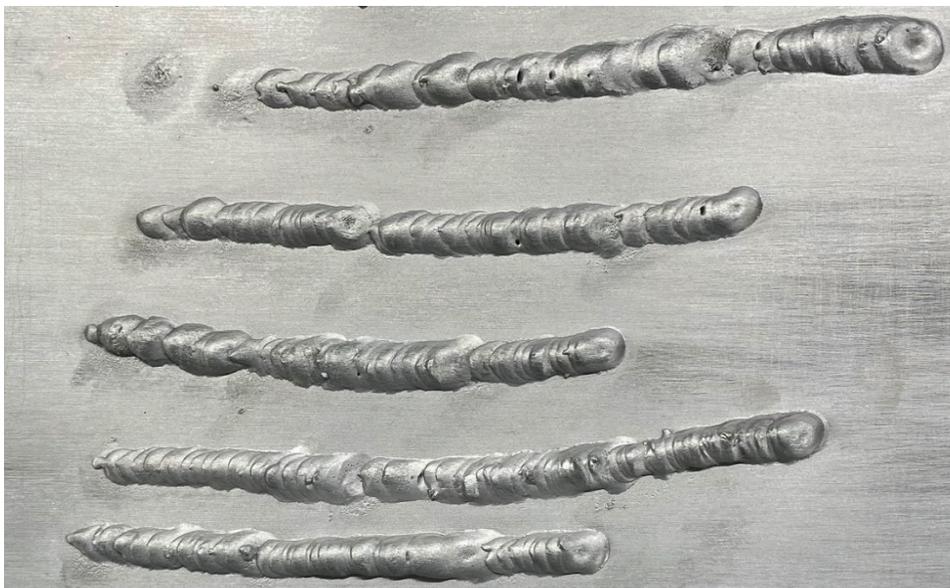
Figure 7. NPMC Welds
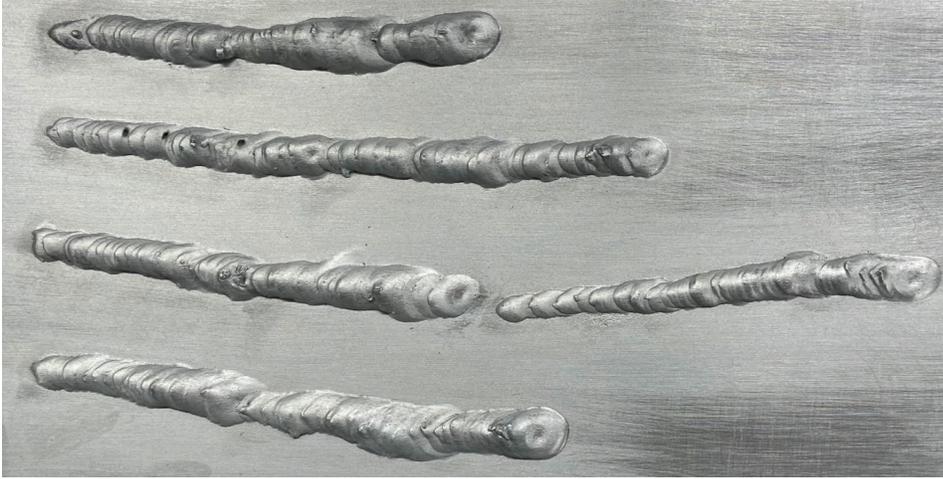
Figure 8. NPHC Welds
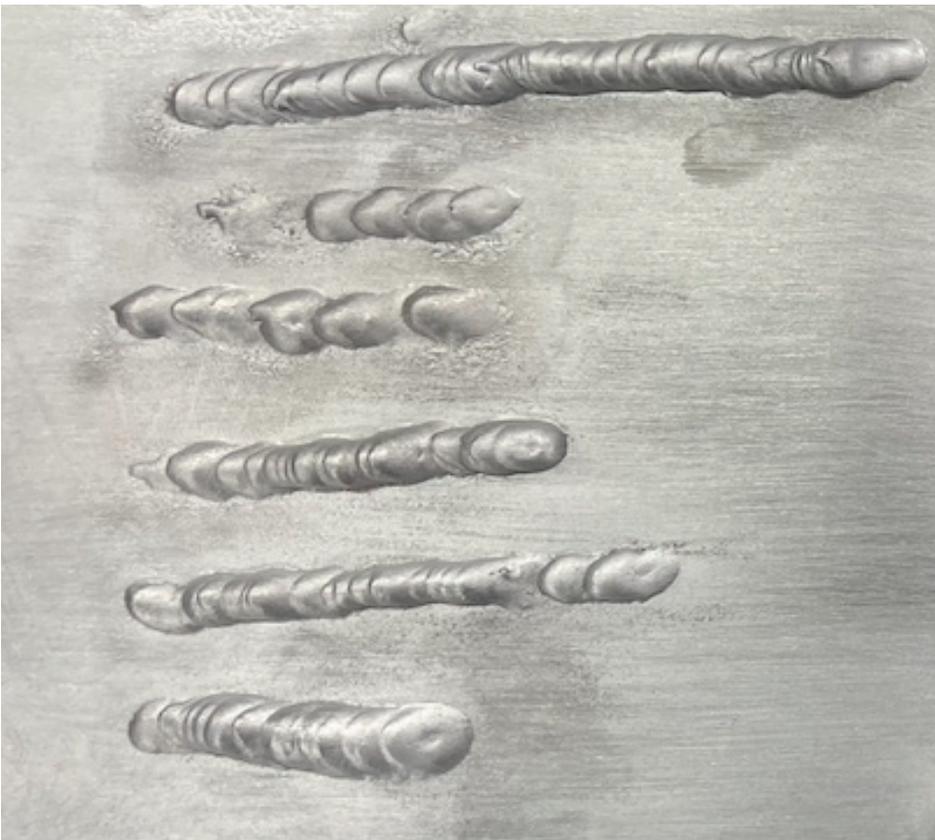
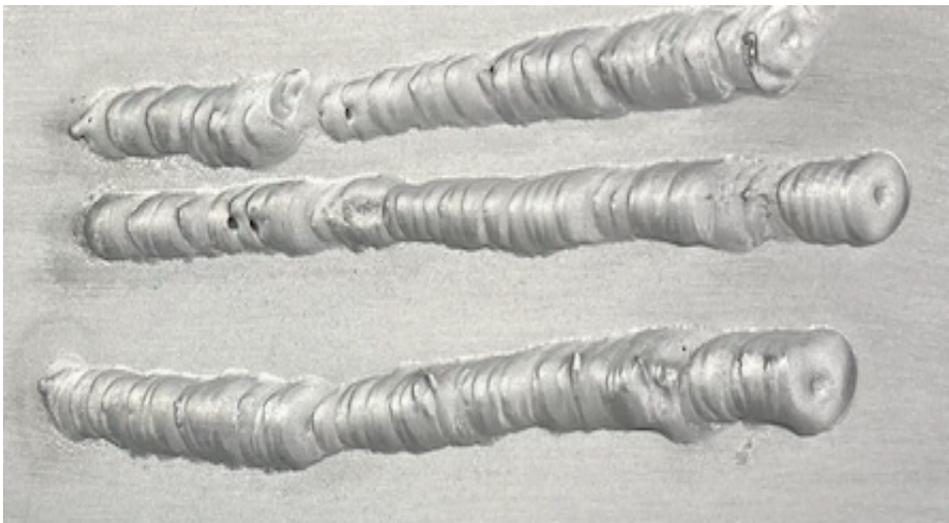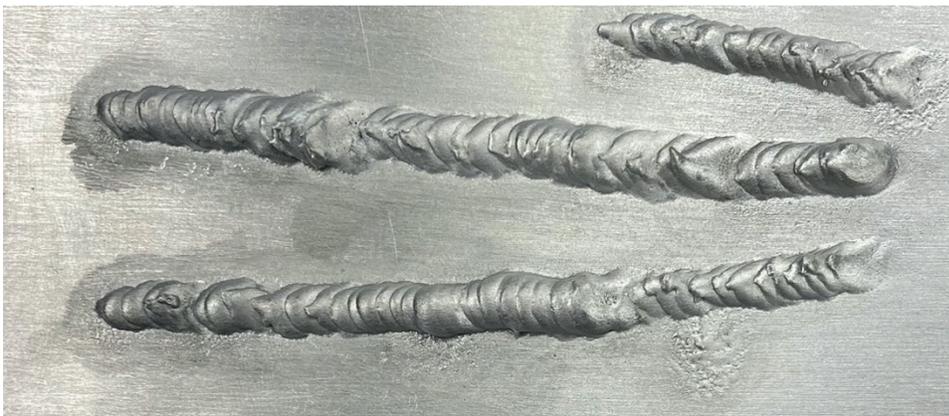*Figure 8. LPLC Welds*
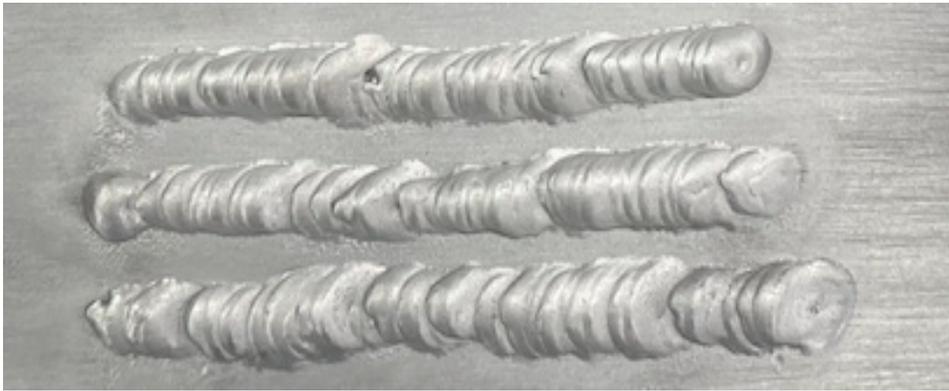
Figure 9. LPMC Welds
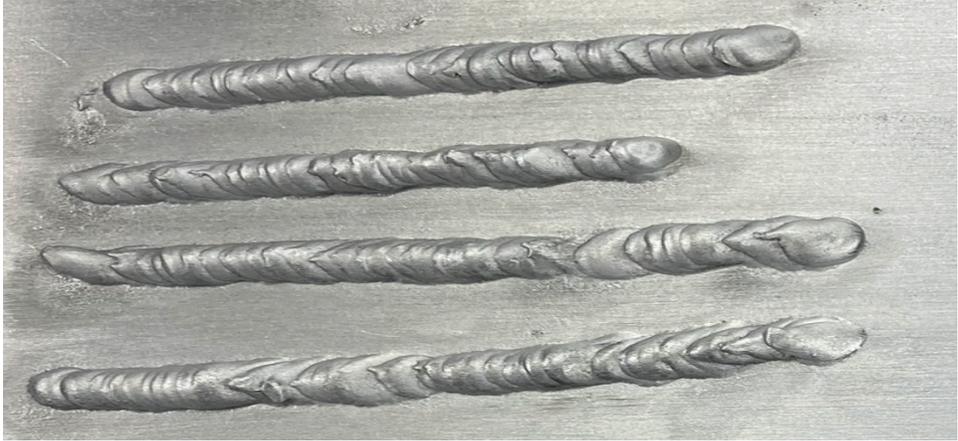

Figure 10. LPHC Welds

Figure 11. HPLC Welds

Figure 12. HPMC Welds

Figure 13. HPHC Welds