

NSRP Panel Project Final Report **Nelson Test Report 2012-1**

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Green Stud Welding Technologies

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Executive Summary

This Panel Project primarily aims at quantifying electricity savings potential of modern stud welding power source technology in ship construction. The new inverter drawn arc power sources and the new switch-mode capacitor discharge (CD) power sources were compared with timer boxes and transformer-rectifier technology, both in controlled lab environment and in various shipyard productions. It was found that due to the low duty cycle typical of stud welding most of the energy is consumed during idle. Modern technology consumes 20X – 24X less power in idle. It is estimated that \$842 - \$1013 per power source per year or \$0.128 - \$0.154 per stud can be saved if old technology is replaced. Collectively \$589,000 - \$708,000 annual savings is projected if 700 old technology stud welders are upgraded in the NSRP member yards. Productivity and weld quality improvement and labor hour reduction from modern technology will realize additional savings which may be quantified by a future NSRP project.

It is also discovered that NSRP yards can benefit from the enhanced safety standard of modern stud welding equipment. It is recommended that trigger interlock on stud making contact with workpiece, ISO/EN14121-1 (or its predecessor EN1050) and RoHS compliance become part of the stud welder specification when procuring new welding equipment.

Additionally, a motorized gun was tested in welding 3/8" stainless studs with good weld quality; the switch-mode capacitor discharge power source was found to be light weight and portable in climbing decks and scaffolding; pecker mode was tested to overcome marginally conductive primer paint spots; and welding parameters were optimized to weld insulation pins on primer coated plate.

Every weld counts towards ship quality; every minute counts towards ship schedule; every watt counts towards utility bills; and every dollar counts towards total cost of ownership. This Panel Project demonstrates that modern stud welding technology cuts electricity, creates safer workplace, boosts productivity, and to top it all, leaves a greener planet to future generation shipbuilders.

1 Introduction

In the construction of U.S. naval ships, millions of studs are shot with stud welders that are not as energy-efficient as modern technology has enabled us to achieve. The utility bill of a shipyard due to the stud welder fleet amounts to hundreds of thousands to over millions of dollars per year. The cost of poor weld quality, predominantly from weld gun set-up and lack of dedicated and skilled operators due to the seasonal nature of the ship construction cycle, as well as worn gun, cable and connectors can be significant impediments to overall ship building production quality and construction schedules. Unlike the wide adoption of prefabrication weldable primers in European and Asian marine fabrication, most U.S. shipyards are less competitive from the extra labor and time of removing primer paint prior to stud welding and lack standard qualification procedures of welding on primer coated plates. Backside paint damage and repair can be a significant hidden cost to shipbuilders from the high heat input process of stud welding. Weld process monitoring along with statistical process control has been adopted in automotive industry for almost two decades, but was rarely seen in U.S. shipbuilding. Philip Crosby made the bold statement "Quality is free" over 30 years ago. The Lean Six Sigma wave has since spread to many industries, and with this green technologies proposal as a catalyst, it has the ability to spread to U.S. shipbuilding to reduce total ownership cost.

This project is built upon 6 years of research and development at Nelson Stud Welding to reduce operating cost of stud welding in shipyards, cutting utility usage, re-work, operations before and after welding, and down-time. The shipyard-specific technologies such as portable inverters, pulsed current waveform, plunge current control, constant energy, motorized gun and weld process monitor, weld gun, cable and connector monitor have shown great promise under lab conditions. For example, Austal is beginning to benefit from pulse technology in aluminum ship construction and Electric Boat with inverter with motorized gun technology. The inverter welder and motorized gun technology need to be extended to cover the larger range of studs shot in shipyards.

The portability and flexibility of compact inverter power sources have already benefited shipyards. The primary goal with this project and report is to evaluate the energy-efficiency of switch-mode power supply technology in electric energy consumption reduction in both drawn arc stud welding and in capacitor discharge stud welding in shipyard weld procedure qualifications. A second goal is to reduce labor costs associated with primer paint removal and backside paint repair by establishing welding procedures for plates coated with selected primers. A third objective is to evaluate the motorized gun technology available together with the energy-efficient inverters to eliminate operator error in gun setup. A stretch goal is to evaluate benefits of weld process monitor and equipment monitor in ship construction.

2 Welding Equipment and Energy and Production Monitor

There is a variety of equipment for stud welding currently in use in ship construction. For drawn arc welding they include timer boxes powered off a DC grid, transformer-rectifier machines and inverters. For capacitor discharge (CD) welding, it is transformer-rectifier type for charging capacitors. Nelson offers two inverters, N800i for ½” stud welding and N1500i for ¾” welding. The machines do not have internal data storage for recording production data. Additional hardware must be developed to monitor electricity consumption externally and to record production statistics internally.

2.1 Daughter Printed Circuit Board For Weld Data Storage

This custom designed hardware enabled storage of weld data to an SD card in the N800i. Software had to be written to interface the main control to this board’s components.



Figure 1. Daughter board for weld data storage in Nelson inverters

2.2 Weld Counter



Figure 2. Weld counter mounted on weld cable

A commercially available counter was used in conjunction with a magnetic reed switch to count the number of welds performed on any welder. The counter and reed switch were mounted in an enclosure and strapped to the weld cable for sensing current.

2.3 Weld Energy Meters

Three phase 480VAC energy usage was measured using a commercially available energy meter system. This consisted of a control box and CTs for measuring current. These devices were mounted in a larger enclosure to be installed in-line with each welder.



Figure 3. Inside view showing meter and CTs



Figure 4. Energy meter enclosure shown here with a pigtail cord

It was found during testing that fuses were needed inside the enclosure as field power can damage the meter. Later, a better, more available meter was found and used from www.ekmmetering.com.



Figure 5. Improved 3 phase energy meter from EKM

2.4 Motorized Gun

The motorized gun shown in Figure 6 uses a motor for stud lifting and plunging which was accomplished by spring and solenoid in a conventional gun. One benefit is that the stud motion (e.g. lift height and plunge depth) can be programmed into a preset and is controlled by the welding power source. This reduces the potential for variability by operators with different experience and skills in setting up the gun properly for a particular stud in production. The plunge speed can be also programmed to achieve the desired plunge dampening effect to minimize spatter and to optimize weld quality and appearance. The gun has two LEDs, one indicating the motor is ready and the other indicates a suspect weld after welding a stud controlled by the internal weld process monitor.

The motorized gun was improved for longer stroke to weld 5/8” diameter studs in the shipyard and better bearing for higher reliability.

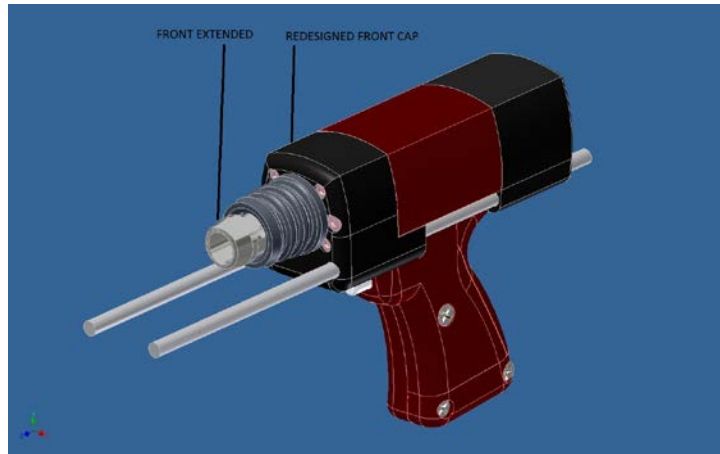


Figure 6. Motorized gun model with sliding legs

2.5 Power Analyzer

A power analyzer was used to measure power factor, efficiency, idle current draw, and energy usage for several different power units.



Figure 7. Power Analyzer from Fluke

3 Shipyard Testing

Testing was done at two shipyards: Ingalls Shipyard at Pascagoula, Mississippi and Bath Iron Works at Bath, Maine. Each shipyard used the equipment for 6-8 weeks on various applications. Nelson personnel made a trip to install the equipment and gather data. At Ingalls, drawn arc inverter technology is compared with transformer-rectifier technology in energy consumption.

At BIW, inverter is compared with timer box in energy consumption. A motorized gun was tested at Ingalls. A switch-mode capacitor discharge (CD) power source was tested at NNS.

3.1 Ingalls Shipyard

The applications were insulation pinning for energy metering and 3/8" stainless steel stud welding for motorized gun testing.

3.1.1 Energy Consumption Comparison at Ingalls

Power units compared were Series 4000 (transformer rectifier type) and N800i (inverter). Electrical supervisor Julius Randall assisted the testing in the yard. A light duty drawn-arc floating-lift gun (shown in Figure 9) was paired with the 40 lb N800i inverter (shown in Figure 10) to weld insulation pins.



Figure 8. Series 4000 with energy meter box at Ingalls



Figure 9. Insulation pinning at Ingalls



Figure 10. N800i with weld counter box at Ingalls

Ingalls energy metering	N800i Inverter	Series 4000 Transformer Rectifier
# studs shot	11,178	6,000 est
Total Energy	193 kWh	144 kWh
Energy per Weld	17 Wh	24 Wh

Table 1. Ingalls electrical energy consumption comparison

The Series 4000 consumed about 41% more energy than the inverter in this case, or the energy savings of the inverter is 29% on a per stud basis. However, the duration of the test was not captured to compare energy usage for a given amount of hours when the power sources were plugged in. The energy per weld is heavily dependent on number of welds and on the total hours a welding power source is plugged in.

3.1.2 Motorized Gun Test at Ingalls

A front end was designed for the purpose of extending the stroke on the motorized gun from 1/2” to 5/8” welding. A prototype was built, tested, and shipped to Ingalls shipyard for their evaluation. Ingalls found the motorized gun system to produce high quality welds. They also noted the need for higher reliability. The gun shaft design is currently being improved and it will be sent back to Ingalls for retest.



Figure 11. Motorized gun for 5/8" welding at Ingalls



Figure 12. Burn-off measurement on a stud welded by a motorized gun

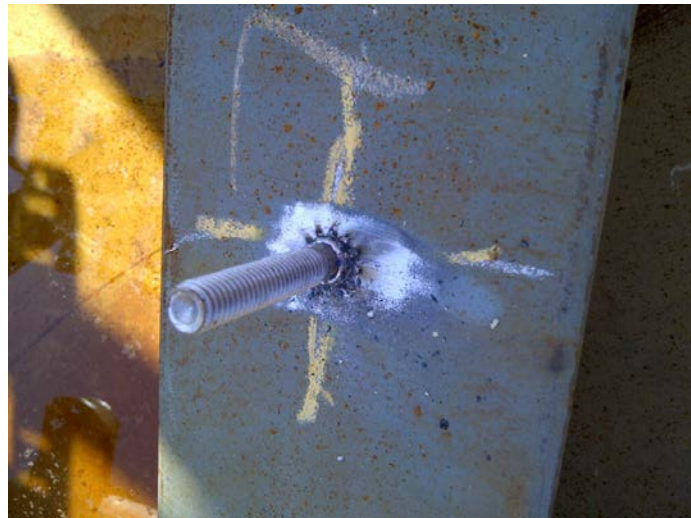


Figure 13. 3/8" Stainless Steel weld by a motorized gun at Ingalls



Figure 14. Motorized gun N1500i system on a mobile cart at Ingalls

According to Albert Williams:

“We appreciate Nelson Stud Welding posture of continued improvement of your products that we utilize for ship manufacturing. The quality of the weld produced from the motorized gun/machine meets the criteria of a high quality product for our customers and our craftsmen. I look forward to continuing the field trial of the motorized gun/machine for this NSRP project...as well as the continued interaction with Nelson Stud Welding.”

3.2 BIW Shipyard

3.2.1 Energy Consumption Comparison at BIW

BIW energy metering (reported on 4/23/12)	N800i Inverter	Timer Box on a DC grid
# studs shot	635	899
Total Energy	1.53 kWh	9 kWh
Energy per Weld	2.4 Wh	10 Wh

Table 2. BIW electrical energy consumption comparison

The N800i inverter consumed only 25% of the energy consumed by the timer boxes. In other words, the energy saving is 75%. Again, the total plug-in hours are not tracked to discern effect of idle power.



Figure 15. Pinning at BIW with N800i and energy monitor



Figure 16. Pinning at BIW with timer box (left) and grid load and energy monitor (right)

The inverter is used for pinning on primer painted plates. It was observed in about 1 in 20 welds that the arc won't take-off. Lab tests on the BIW coated plates confirmed that there is intermittent contact issue when there is no solid electrical continuity due to the heavy paint. The poor contact from heavy paint interlocks trigger as a safety feature in the inverter to prevent the output of high voltage or current without a solid contact between the stud and the workpiece. A "load bank" mode was used as a test to defeat the interlock allowing BIW to weld pins without having to move the gun to get arc ignition on heavy paint. A "peck mode" was also used to peck through the paint. This function lifts and plunges the pointed stud to peck through the paint and detects contact after each peck. After the contact is detected it stops pecking adaptively and goes immediately into welding. On average it was found 1 to 2 pecks are applied whenever heavy paint is encountered.

It was also noted that operators prefer the convenience of grid power without calling electricians for connecting to 480VAC.

3.2.2 Safety Feature of New Equipment

During equipment testing, it was noted that older equipment (i.e. timer boxes) has a much higher probability of operator shock since there is no logic that requires contact with the work material prior to delivering weld energy. This means that the operator could be holding on to the chuck while pulling the trigger and be exposed to voltages upwards of 80VDC. Newer equipment such as in the N1500i / N800i inverters and N4000 / N6000 does not expose the operator to such risks. They require solid electrical contact prior to allowing for welding after breaking contact from the previous weld (also known as Chuck Saver). It is recommended that shipyard specify “electrical shock prevention in checking stud-to-workpiece contact prior to welding each stud” in all new stud welder purchases. In addition, modern inverters are designed to comply with international safety standards ANSI / IEC/ EN 60974-1 on welding power sources and ISO/EN 14121-1 (or its predecessor EN1050) on machinery risk assessment.

Modern power sources are also designed to comply with the RoHS (Restriction of Hazardous Substances) directive which eliminates lead and 5 other hazardous substances in the welding equipment to protect the environment.

3.3 NNS Shipyard

Newport News Shipbuilding tested an industry-first switch-mode capacitor discharge (CD) welder NCD+1000 in welding 3/16” pins on Dry Dock 12 in the construction of USS Gerald Ford, CVN-78. The NCD+ 1000 has about half the weight (17lb) as the conventional CD-Lite welder, a feature much appreciated by the operators. It was also reported that several improvements are needed for compatibility with existing equipment and welding procedure.

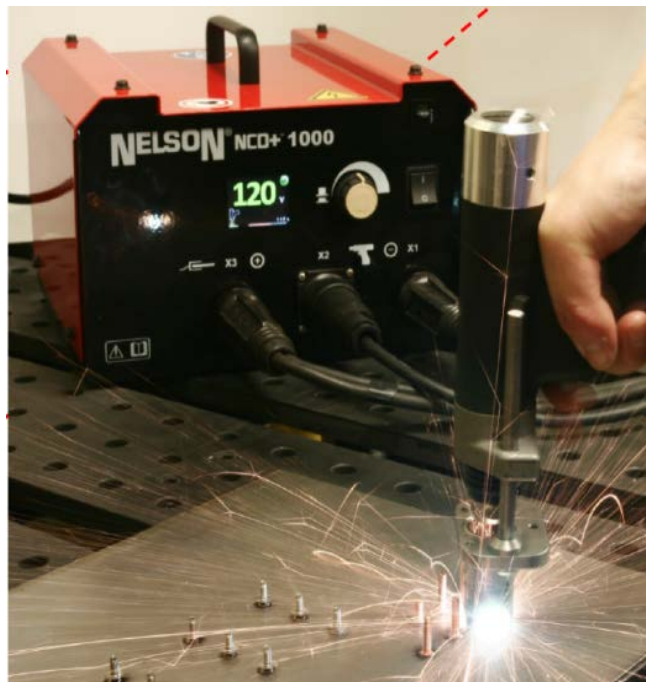


Figure 17. NCD+1000 switch-mode power supply for capacitor discharge welding

4 Lab Testing

4.1 Drawn Arc Welding and Idle Tests

Testing was done in the lab to measure energy differences in a more controlled environment. For the weld test, each power source was set to deliver 550A for 330ms at 12 studs per minute firing into a fixed resistive load. For an idle test, each power unit was set to do no welding for a fixed period of time. In each test, the input energy was measured and recorded. Equipment used were the Nelweld 6000 (Transformer-rectifier) and N1500i (inverter).

KWh	N1500i Inverter	N6000 Transformer Rectifier	Energy Savings
Welding 1335 studs in 112 minutes	2.45 KWh	13.06 kWh	81%
Idle 18.5 hours	1.16 kWh	81.2 kWh	99%

Table 3. BIW electrical energy consumption comparison

The idle energy draw of a transformer rectifier is significantly higher than that of the inverter because of the magnetizing current involved with such a large transformer. The inverter idle draw is from a small control transformer only used to power up the controls. The transformer rectifier system creates significant heat internally even while idle to trip a large fan that runs continuously.

From idle energy usage during the weld test, which lasted about 2 hours, one can find out the energy that went into the weld:

$$\begin{aligned} \text{N1500i used } & 1.16 \text{ kWh} \times 2/18.5 = 0.126 \text{ kWh} \\ 2.45\text{kWh} - & 0.126\text{kWh} = 2.32 \text{ kWh into the weld.} \end{aligned}$$

$$\begin{aligned} \text{Nelweld 6000 used } & 81.2 \text{ kWh} \times 2/18.5 = 8.78 \text{ kWh} \\ 13.0 \text{ kWh} - & 8.78 \text{ kWh} = 4.28 \text{ kWh into the weld.} \end{aligned}$$

Comparing the two, the N1500i uses about 54% of the energy used by the Nelweld while welding. In other words, N1500i saved 46% energy in comparison with the N6000.

4.2 Power Factor and Efficiency of Drawn Arc Welders

A Fluke 434 Power Analyzer was used to compare energy characteristics in another way, generating data such as usage (kW), power factor, and efficiency. Power sources compared were Nelweld 6000 and Series 5000 (transformer-rectifiers) and N1500i and N800i (inverters).



Figure 18. N800i with the Fluke Power Analyzer



Figure 19. Nelweld 6000 with the Fluke power analyzer

	N800i	N1500i	Nelweld 6000	Series 5000
kWatts idle	0.05	0.06	1.2	1.2
kVA idle	0.06	0.08	5.9	2.2
PF idle	0.4	0.3	0.2	0.5
Idle Amps A	0.1	0.3	8	3
B	0.2	0.2	7	4
C	0.2	0.3	7	2
Idle Amps Avg.	0.2	0.3	7.3	3.0
Volts A	475	475	478	483
B	482	482	485	483
C	478	478	484	477

Table 4. Idle power comparison in controlled test of drawn arc welders

	N800i	N1500i		Nelweld 6000		Series 5000	
Output load	800A / 27 V	800A/ 27 V	1200 A/ 42 V	800A/ 27 V	1200 A/ 42 V	800A/ 27 V	1200 A/ 42 V
kW w/load	29.2	28.4	64.6	31	63.2	35.6	77.2
kVA load	40	39	80	81	126.3	59.8	90
PF load	0.72	0.71	0.77	0.35	0.47	0.57	0.84
Output kW	21.6	21.6	50.4	21.6	50.4	21.6	50.4
Efficiency	0.74	0.76	0.78	0.70	0.80	0.61	0.65
Input Amps A	48	47	99	111	164	73	112
with load B	47	45	98	106	160	78.00	115
C	48	50	103	100	164	74	111
Loaded Amps Avg	47.7	47.3	100.0	105.7	162.7	75.0	112.7
Volts A	481	473	457	473	472	475	476
B	491	480	465	479	478	475	475
C	489	479	461	479	478	480	470

Table 5. Power comparison under load in controlled test of drawn arc welders

This data shows again that while idle, the kVA required for the Nelweld 6000 and Series 5000 is 27x – 98x that of the N800i and N1500i. The kW required for transformer-rectifier models is 20x – 24x that of inverters. 1.145 KW are saved in idle on average.

During the weld at 800A, N1500i takes only 50% of the kVA required by the N6000. 2.25 KW are saved by welding with inverter technology.

4.3 Power Factor and Efficiency of CD welders

Similar power analysis was done on 5 models of CD welders to compare switch-mode type (NCD+ 1600 and NCD+ 1000) vs. conventional transformer-rectifier type (CD Lite, CD 212 and NCD 60). The test was conducted with 115VAC input, charge voltage of 200V and a weld rate of 9 studs per minute.

	NCD+1600 (switch mode)	NCD+1000 (switch mode)	CD Lite (trans-rec)	CD 212 (trans-rec)	NCD60 (trans-rec)
mF	81	54	66	66	54
VA	278	210	559	528	560
PF	0.86	0.86	0.60	0.60	0.60
Output Power (W)	216	144	176	176	144
Input Power (W)	239	181	335	317	336
Efficiency	0.90	0.80	0.52	0.56	0.43

Table 6. Power comparison under load in controlled test of CD welders

It was found that NCD+ models save 43% energy in comparison with CD Lite with almost twice the efficiency and 43% improvement in power factor. Comparing NCD+1000 and NCD60 at the same output power of 144W, 155W are saved.

5 Energy Savings Estimates

Electricity rates vary in the country. BIW provided an electricity rate of \$0.0765 per kw-hour which can be used in the savings estimate. U.S. Energy Information Administration (EIA) published national average rate of 9.8 cents in 2010, and forecasted 9.2 cents in 2019 and 9.5 cents in 2035 in AEO2012 Reference case. The annual savings of replacing one transformer-rectifier power source with inverter can be estimated below based on the BIW rate:

- 100% idle: 8766 hours x 1.145 kW x \$0.0765 = \$768
- 100% welding: 8766 hours x 2.25 kW x \$0.0765 = \$1509
- 10% duty cycle: \$842 per stud welding power source per year

If the EIA 2019 outlook rate of 9.2 cents is used instead:

- 100% idle: 8766 hours x 1.145 kW x \$0.092 = \$923
- 100% welding: 8766 hours x 2.25 kW x \$0.092 = \$1815
- 10% duty cycle: \$1013 per stud welding power source per year

Alternatively, one can calculate based on per stud weld savings. At BIW it is estimated that one stud welding power source welds 6558 studs per year. When the old technology is replaced by modern energy efficient power sources, savings of \$0.128 can be realized per stud based on the BIW utility rate. Savings of \$0.154 can be realized per stud based on the EIA rate.

On a per yard basis, taking BIW as an example, if 45 old technology welders were to be upgraded to energy efficient inverters, \$38,000 can be saved annually in electricity cost. Collectively NSRP member yards have 700 old technology stud welders to be upgraded with potential savings of \$589,000 - \$708,000 annually in electricity. Based on savings per stud, an aircraft carrier with 10 million studs with 30% shot with old technology can potentially save \$384,000 - \$462,000 in electricity.

The energy savings should be an important factor in deciding yard welding equipment upgrades, retooling or expansion. Return on investment can be computed based on energy and labor savings estimated along with price of new equipment, cost of capital and time horizon. An online calculator can be used to estimate a shipbuilder's stud welding energy savings under specific application conditions with different power source technologies:

<http://www.nelsonstud.com/calculator/energy.html>

6 Designed Experiment in Welding Insulation Pins on Primer Painted Plate

Design of Experiment (DOE) tools were applied to develop surface response models (also known as weld lobes) of welding insulation pins on primer coated plate used in shipbuilding. TFNC 3/16" insulation pins conforming to MIL-S-24149 Type 3 Class 6 were used. It was reported that the paint is a low zinc silicate PPG coating or SigmaKalon MC7177 applied with 1 mil or less.

A light duty drawn arc floating lift gun and an N800i power source were used in the experiment. N800i short circuit on-time (F31) was set at 10 ms. Three numerical welding parameters were swept:

Arc current	100A-500A (100A increment)
Arc time	25ms – 150ms (25ms increment)
Lift	0 – 1.5 clicks (0.5 click increment, one click corresponds to 0.010 inch)

Two categorical factors are studied:

Polarity	straight/reverse
Coating	light/heavy

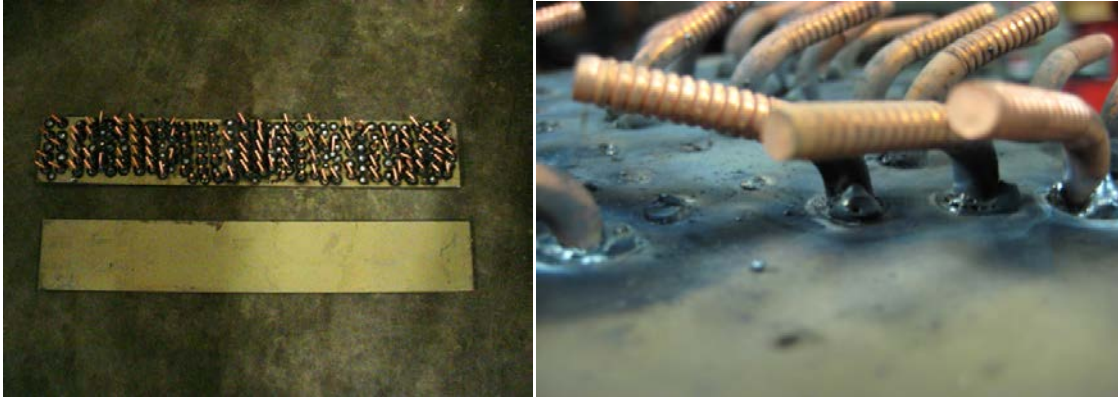


Figure 20. BIW primer coated plate as received (left bottom) and the welded plate

Three welds were made under each welding condition and were subject to bend test. The number of welds passing the bend test without failure is the DOE response, indicative of the weld strength or consistency. Thus an output of 3 means all 3 welds passed the bend test, and an output of 0 means all failed.

A surface response cubic model is established with an F value of 51 and p-value less than 0.0001, indicating the model is highly significant. The R-squared value of 0.84 and signal-to-noise ratio of 26 also indicate high reliability of the model.

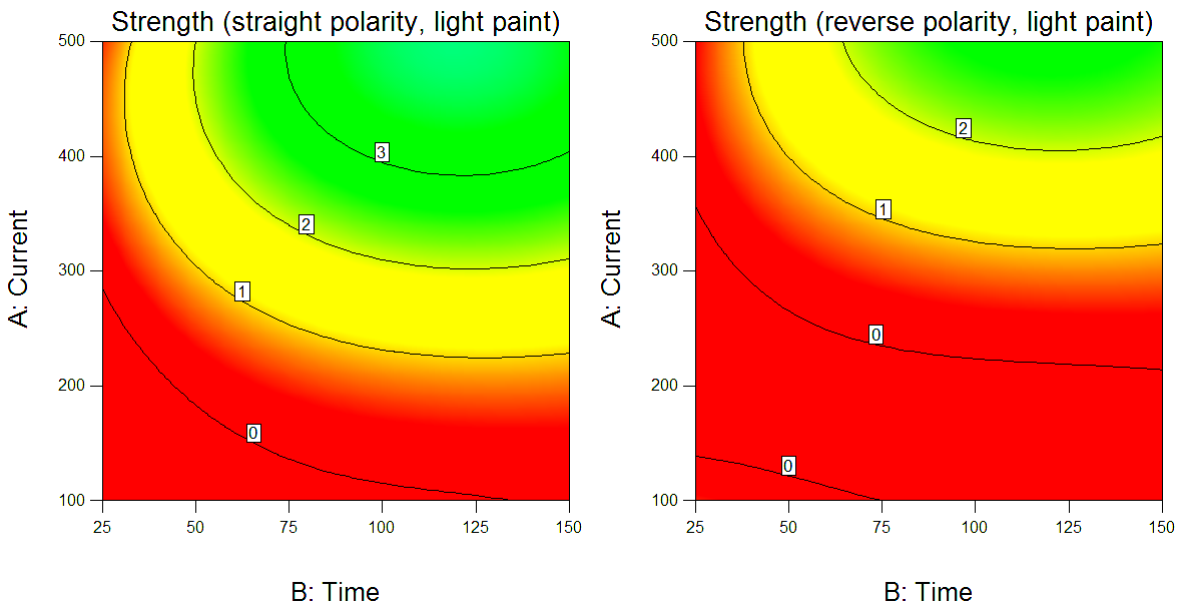


Figure 21. Number of successful bends as a proxy of weld consistency under light paint

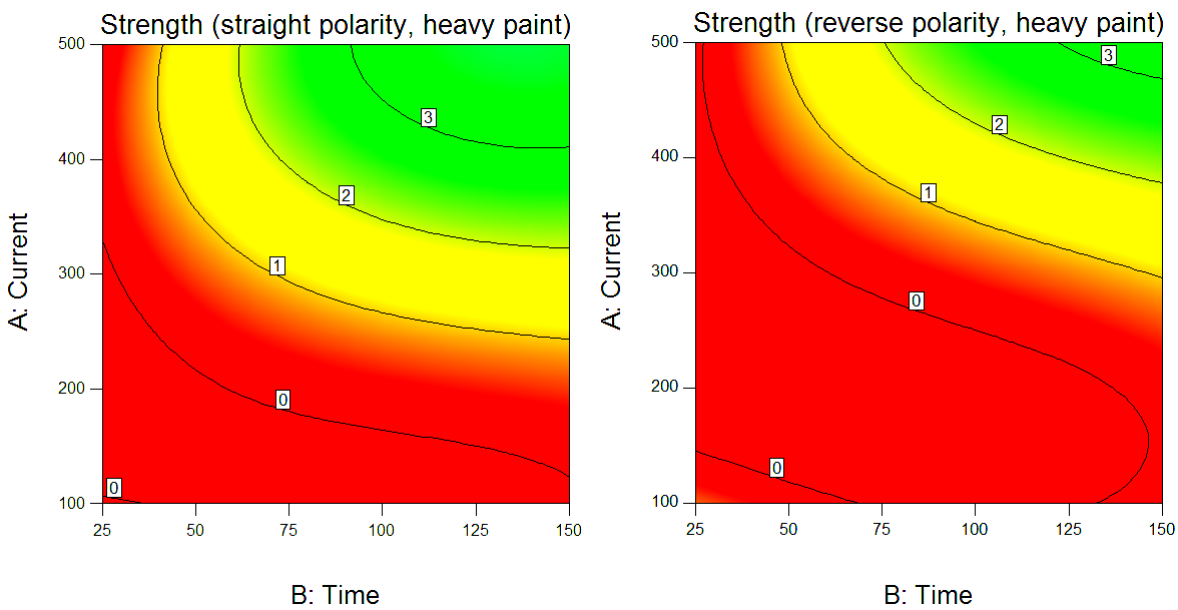


Figure 22. Number of successful bends as a proxy of weld consistency under heavy paint

It can be observed that in general, a higher energy procedure with higher current and lower weld time is preferred to weld insulation pins, as shown by the green zone in the upper right corner. Higher lifts result in larger green zones in both polarities and both paint thicknesses. The charts in the figures are made with a lift of 1 click. Under both paint thicknesses, reverse polarity results in smaller green zones. The reverse polarity puts more heat on the plate, burns more paint and likely engages more zinc, therefore requires more heat to make consistent welds. The statistical model can be used to predict weld strength and consistency with standard deviation and strength values under 95% confidence intervals (CI).

Paint	Current (A)	Time (ms)	Weld Strength	Std Dev	95% CI Low	95% CI High
Light	300	150	1.9	0.55	1.6	2.1
Heavy	300	150	1.8	0.55	1.5	2.1
Light	385	100	3.0	0.55	2.8	3.2
Heavy	385	100	2.5	0.55	2.3	2.8
Heavy	410	130	3.1	0.55	2.8	3.3

Table 7. Weld consistency prediction of conventional and hotter weld procedures of welding pins on primer coated plate under straight polarity (lift set at 1 click)

It can be predicted that the conventional setting (300A, 150ms) to weld primer coated plate results in a strength value of 1.8 to 1.9, or 1 in 3 welds will fail to bend. Higher current or hotter setting (385A and 100ms) is needed to burn through the light paint, and even higher current (410A, 130ms) is needed to burn through the heavy paint to ensure weld consistency.

7 Conclusions

Both field testing and lab testing were performed to compare energy usage of the old timer-box and transformer-rectifier welding power sources and the new switch-mode type power sources for stud welding in ship construction. New motorized gun technology was also enhanced and evaluated. Designed experiment was carried out to optimize welding parameters in welding insulation pins on primer coated plate. The findings are:

1. Energy usage in non-inverter based welding equipment far exceeds that of inverter based welding equipment. Older technology consumes 20 - 24X more power while sitting idle and 2X the energy while welding.
2. On average it is estimated \$842 - \$1013 annual savings per drawn arc stud welding power source can be realized from upgrading transformer-rectifier power source to inverter.
3. On average it is estimated that \$0.128 - \$0.154 per stud can be saved from upgrading to inverter technology.
4. Shipyards are advised to consider enhanced safety standards when procuring new stud welding equipment including trigger interlock on stud making contact with workpiece and ISO 14121-1 or equivalent. Shipyards are also advised to consider RoHS compliant welding equipment to protect the environment.
5. Motorized gun has demonstrated superior weld quality in 3/8" stainless steel stud welding.
6. Higher current is needed to ensure weld consistency in welding insulation pins on plates coated with primer paint.
7. Lower weight NCD+ capacitor discharge welder provides better portability in ship construction with multiple decks and scaffolding.
8. Inverter unit with pecker mode feature is tested to adaptively peck through and penetrate the insulating paint to establish a solid electrical contact prior to drawing an arc.

8 Future Work

During the one year time frame the project focus was placed on measureable “hard savings” in electricity costs. Labor cost reduction, downtime reduction, maintenance cost reduction and efficiency and productivity improvements are not measured. The full potential of modern stud welding equipment to reduce total cost of ownership of ship construction would require the evaluation of:

1. Motorized gun in improving weld repeatability and reducing inconsistent weld quality resulting from gun setup error or novice operators;
2. Weld process monitor in applying lean sigma and statistical process control principles in ship construction;
3. Weld equipment monitor (weld gun motion, chuck and weld cable and connector wear) in assisting preventative maintenance and ensure production uptime;
4. Pulse waveform in reducing heat input and distortion;
5. Pulse waveform and constant energy process control in welding primer coated steels;

9 References

1. Hsu, C. et al, Stud Welding Technologies for a Greener Future, AWS Welding Journal, October 2010 pp. 39-42.
2. Cooper R.B. et al, NSRP 0408 Fundamentals of Arc Stud Welding: An Interactive Multimedia lesson for Shipyard Training, U.S. Department of the Navy Carderock Division, Naval Surface Warfare Center, November 1993.
3. [U.S. Energy Information Administration AEO2012 Early Release Overview.](#)

10 Appendix – Experimental data of welding pins on primer coated plate

current	time	lift	polarity	paint	strength	current	time	lift	polarity	paint	strength
500	25	1.5	straight	light	0	500	25	1.5	straight	heavy	0
500	25	1	straight	light	0	500	25	1	straight	heavy	0
500	25	0.5	straight	light	0	500	25	0.5	straight	heavy	0
500	25	0	straight	light	0	500	25	0	straight	heavy	0
500	50	1.5	straight	light	3	500	50	1.5	straight	heavy	2
500	50	1	straight	light	3	500	50	1	straight	heavy	2
500	50	0.5	straight	light	3	500	50	0.5	straight	heavy	2
500	50	0	straight	light	3	500	50	0	straight	heavy	0
500	75	1.5	straight	light	3	500	75	1.5	straight	heavy	3
500	75	1	straight	light	3	500	75	1	straight	heavy	3
500	75	0.5	straight	light	3	500	75	0.5	straight	heavy	3
500	75	0	straight	light	3	500	75	0	straight	heavy	3
500	100	1.5	straight	light	3	500	100	1.5	straight	heavy	3
500	100	1	straight	light	3	500	100	1	straight	heavy	3
500	100	0.5	straight	light	3	500	100	0.5	straight	heavy	3
500	100	0	straight	light	3	500	100	0	straight	heavy	3
500	125	1.5	straight	light	3	500	125	1.5	straight	heavy	3
500	125	1	straight	light	3	500	125	1	straight	heavy	3
500	125	0.5	straight	light	3	500	125	0.5	straight	heavy	3
500	125	0	straight	light	3	500	125	0	straight	heavy	3
500	150	1.5	straight	light	3	500	150	1.5	straight	heavy	3
500	150	1	straight	light	3	500	150	1	straight	heavy	3
500	150	0.5	straight	light	3	500	150	0.5	straight	heavy	3
500	150	0	straight	light	3	500	150	0	straight	heavy	3
400	25	1.5	straight	light	0	400	25	1.5	straight	heavy	0
400	25	1	straight	light	0	400	25	1	straight	heavy	0
400	25	0.5	straight	light	0	400	25	0.5	straight	heavy	0
400	25	0	straight	light	0	400	25	0	straight	heavy	0
400	50	1.5	straight	light	3	400	50	1.5	straight	heavy	2
400	50	1	straight	light	3	400	50	1	straight	heavy	1

400	50	0.5	straight	light	1	400	50	0.5	straight	heavy	0
400	50	0	straight	light	2	400	50	0	straight	heavy	0
400	75	1.5	straight	light	3	400	75	1.5	straight	heavy	3
400	75	1	straight	light	3	400	75	1	straight	heavy	3
400	75	0.5	straight	light	3	400	75	0.5	straight	heavy	2
400	75	0	straight	light	2	400	75	0	straight	heavy	3
400	100	1.5	straight	light	3	400	100	1.5	straight	heavy	3
400	100	1	straight	light	3	400	100	1	straight	heavy	3
400	100	0.5	straight	light	3	400	100	0.5	straight	heavy	3
400	100	0	straight	light	3	400	100	0	straight	heavy	2.5
400	125	1.5	straight	light	3	400	125	1.5	straight	heavy	3
400	125	1	straight	light	3	400	125	1	straight	heavy	3
400	125	0.5	straight	light	3	400	125	0.5	straight	heavy	3
400	125	0	straight	light	3	400	125	0	straight	heavy	2
400	150	1.5	straight	light	3	400	150	1.5	straight	heavy	3
400	150	1	straight	light	3	400	150	1	straight	heavy	3
400	150	0.5	straight	light	3	400	150	0.5	straight	heavy	3
400	150	0	straight	light	3	400	150	0	straight	heavy	3
300	25	1.5	straight	light	0	300	25	1.5	straight	heavy	0
300	25	1	straight	light	0	300	25	1	straight	heavy	0
300	25	0.5	straight	light	0	300	25	0.5	straight	heavy	0
300	25	0	straight	light	0	300	25	0	straight	heavy	0
300	50	1.5	straight	light	0	300	50	1.5	straight	heavy	0
300	50	1	straight	light	0	300	50	1	straight	heavy	0
300	50	0.5	straight	light	0	300	50	0.5	straight	heavy	0
300	50	0	straight	light	0	300	50	0	straight	heavy	0
300	75	1.5	straight	light	3	300	75	1.5	straight	heavy	1
300	75	1	straight	light	2	300	75	1	straight	heavy	1
300	75	0.5	straight	light	1	300	75	0.5	straight	heavy	1
300	75	0	straight	light	0	300	75	0	straight	heavy	0
300	100	1.5	straight	light	3	300	100	1.5	straight	heavy	2
300	100	1	straight	light	2.5	300	100	1	straight	heavy	0.5
300	100	0.5	straight	light	2.5	300	100	0.5	straight	heavy	0.5
300	100	0	straight	light	1.5	300	100	0	straight	heavy	0
300	125	1.5	straight	light	3	300	125	1.5	straight	heavy	3
300	125	1	straight	light	3	300	125	1	straight	heavy	3
300	125	0.5	straight	light	3	300	125	0.5	straight	heavy	2
300	125	0	straight	light	3	300	125	0	straight	heavy	0
300	150	1.5	straight	light	3	300	150	1.5	straight	heavy	3
300	150	1	straight	light	3	300	150	1	straight	heavy	3
300	150	0.5	straight	light	3	300	150	0.5	straight	heavy	3
300	150	0	straight	light	2	300	150	0	straight	heavy	0
200	25	1.5	straight	light	0	200	25	1.5	straight	heavy	0
200	25	1	straight	light	0	200	25	1	straight	heavy	0
200	25	0.5	straight	light	0	200	25	0.5	straight	heavy	0
200	25	0	straight	light	0	200	25	0	straight	heavy	0
200	50	1.5	straight	light	0	200	50	1.5	straight	heavy	0
200	50	1	straight	light	0	200	50	1	straight	heavy	0
200	50	0.5	straight	light	0	200	50	0.5	straight	heavy	0
200	50	0	straight	light	0	200	50	0	straight	heavy	0
200	75	1.5	straight	light	0	200	75	1.5	straight	heavy	0
200	75	1	straight	light	0	200	75	1	straight	heavy	0
200	75	0.5	straight	light	0	200	75	0.5	straight	heavy	0
200	75	0	straight	light	0	200	75	0	straight	heavy	0
200	100	1.5	straight	light	0	200	100	1.5	straight	heavy	0
200	100	1	straight	light	0	200	100	1	straight	heavy	0
200	100	0.5	straight	light	0	200	100	0.5	straight	heavy	0
200	100	0	straight	light	0	200	100	0	straight	heavy	0
200	125	1.5	straight	light	0	200	125	1.5	straight	heavy	0
200	125	1	straight	light	0	200	125	1	straight	heavy	0
200	125	0.5	straight	light	0	200	125	0.5	straight	heavy	0
200	125	0	straight	light	0	200	125	0	straight	heavy	0
200	150	1.5	straight	light	0	200	150	1.5	straight	heavy	0
200	150	1	straight	light	0	200	150	1	straight	heavy	0
200	150	0.5	straight	light	0	200	150	0.5	straight	heavy	0
200	150	0	straight	light	0	200	150	0	straight	heavy	0
100	25	1.5	straight	light	0	100	25	1.5	straight	heavy	0
100	25	1	straight	light	0	100	25	1	straight	heavy	0
100	25	0.5	straight	light	0	100	25	0.5	straight	heavy	0
100	25	0	straight	light	0	100	25	0	straight	heavy	0
100	50	1.5	straight	light	0	100	50	1.5	straight	heavy	0
100	50	1	straight	light	0	100	50	1	straight	heavy	0
100	50	0.5	straight	light	0	100	50	0.5	straight	heavy	0
100	50	0	straight	light	0	100	50	0	straight	heavy	0



100	75	1.5	straight	light	0	100	75	1.5	straight	heavy	0
100	75	1	straight	light	0	100	75	1	straight	heavy	0
100	75	0.5	straight	light	0	100	75	0.5	straight	heavy	0
100	75	0	straight	light	0	100	75	0	straight	heavy	0
100	100	1.5	straight	light	0	100	100	1.5	straight	heavy	0
100	100	1	straight	light	0	100	100	1	straight	heavy	0
100	100	0.5	straight	light	0	100	100	0.5	straight	heavy	0
100	100	0	straight	light	0	100	100	0	straight	heavy	0
100	125	1.5	straight	light	0	100	125	1.5	straight	heavy	0
100	125	1	straight	light	0	100	125	1	straight	heavy	0
100	125	0.5	straight	light	0	100	125	0.5	straight	heavy	0
100	125	0	straight	light	0	100	125	0	straight	heavy	0
100	150	1.5	straight	light	0	100	150	1.5	straight	heavy	0
100	150	1	straight	light	0	100	150	1	straight	heavy	0
100	150	0.5	straight	light	0	100	150	0.5	straight	heavy	0
100	150	0	straight	light	0	100	150	0	straight	heavy	0
500	25	1.5	reverse	light	0	500	25	1.5	reverse	heavy	0
500	25	1	reverse	light	0	500	25	1	reverse	heavy	0
500	25	0.5	reverse	light	0	500	25	0.5	reverse	heavy	0
500	25	0	reverse	light	0	500	25	0	reverse	heavy	0
500	50	1.5	reverse	light	3	500	50	1.5	reverse	heavy	0
500	50	1	reverse	light	2	500	50	1	reverse	heavy	0
500	50	0.5	reverse	light	2	500	50	0.5	reverse	heavy	0
500	50	0	reverse	light	1	500	50	0	reverse	heavy	0
500	75	1.5	reverse	light	3	500	75	1.5	reverse	heavy	3
500	75	1	reverse	light	3	500	75	1	reverse	heavy	3
500	75	0.5	reverse	light	2	500	75	0.5	reverse	heavy	3
500	75	0	reverse	light	0	500	75	0	reverse	heavy	2
500	100	1.5	reverse	light	3	500	100	1.5	reverse	heavy	3
500	100	1	reverse	light	2.5	500	100	1	reverse	heavy	3
500	100	0.5	reverse	light	2.5	500	100	0.5	reverse	heavy	3
500	100	0	reverse	light	1.5	500	100	0	reverse	heavy	2.5
500	125	1.5	reverse	light	3	500	125	1.5	reverse	heavy	3
500	125	1	reverse	light	3	500	125	1	reverse	heavy	3
500	125	0.5	reverse	light	3	500	125	0.5	reverse	heavy	3
500	125	0	reverse	light	1	500	125	0	reverse	heavy	3
500	150	1.5	reverse	light	3	500	150	1.5	reverse	heavy	3
500	150	1	reverse	light	3	500	150	1	reverse	heavy	3
500	150	0.5	reverse	light	3	500	150	0.5	reverse	heavy	3
500	150	0	reverse	light	3	500	150	0	reverse	heavy	3
400	25	1.5	reverse	light	0	400	25	1.5	reverse	heavy	0
400	25	1	reverse	light	0	400	25	1	reverse	heavy	0
400	25	0.5	reverse	light	0	400	25	0.5	reverse	heavy	0
400	25	0	reverse	light	0	400	25	0	reverse	heavy	0
400	50	1.5	reverse	light	1	400	50	1.5	reverse	heavy	0
400	50	1	reverse	light	2	400	50	1	reverse	heavy	0
400	50	0.5	reverse	light	1	400	50	0.5	reverse	heavy	0
400	50	0	reverse	light	0	400	50	0	reverse	heavy	0
400	75	1.5	reverse	light	3	400	75	1.5	reverse	heavy	0
400	75	1	reverse	light	2	400	75	1	reverse	heavy	0
400	75	0.5	reverse	light	1	400	75	0.5	reverse	heavy	0
400	75	0	reverse	light	0	400	75	0	reverse	heavy	0
400	100	1.5	reverse	light	3	400	100	1.5	reverse	heavy	1.5
400	100	1	reverse	light	2.5	400	100	1	reverse	heavy	1.5
400	100	0.5	reverse	light	1	400	100	0.5	reverse	heavy	1.5
400	100	0	reverse	light	0.5	400	100	0	reverse	heavy	1
400	125	1.5	reverse	light	3	400	125	1.5	reverse	heavy	3
400	125	1	reverse	light	3	400	125	1	reverse	heavy	3
400	125	0.5	reverse	light	1	400	125	0.5	reverse	heavy	2
400	125	0	reverse	light	0	400	125	0	reverse	heavy	3
400	150	1.5	reverse	light	3	300	25	1.5	reverse	heavy	0
400	150	1	reverse	light	3	300	25	1	reverse	heavy	0
400	150	0.5	reverse	light	1	300	25	0.5	reverse	heavy	0
400	150	0	reverse	light	0	300	25	0	reverse	heavy	0
300	25	1.5	reverse	light	0	300	50	1.5	reverse	heavy	0
300	25	1	reverse	light	0	300	50	1	reverse	heavy	0
300	25	0.5	reverse	light	0	300	50	0.5	reverse	heavy	0
300	25	0	reverse	light	0	300	50	0	reverse	heavy	0
300	50	1.5	reverse	light	0	300	75	1.5	reverse	heavy	0
300	50	1	reverse	light	0	300	75	1	reverse	heavy	0
300	50	0.5	reverse	light	0	300	75	0.5	reverse	heavy	0
300	50	0	reverse	light	0	300	75	0	reverse	heavy	0
300	75	1.5	reverse	light	1	300	100	1.5	reverse	heavy	0
300	75	1	reverse	light	0	300	100	1	reverse	heavy	0

300	75	0.5	reverse	light	0	300	100	0.5	reverse	heavy	0
300	75	0	reverse	light	0	300	100	0	reverse	heavy	0
300	100	1.5	reverse	light	1	300	125	1.5	reverse	heavy	1
300	100	1	reverse	light	1.5	300	125	1	reverse	heavy	0
300	100	0.5	reverse	light	0.5	300	125	0.5	reverse	heavy	0
300	100	0	reverse	light	0	300	125	0	reverse	heavy	0
300	125	1.5	reverse	light	0	200	25	1.5	reverse	heavy	0
300	125	1	reverse	light	0	200	25	1	reverse	heavy	0
300	125	0.5	reverse	light	0	200	25	0.5	reverse	heavy	0
300	125	0	reverse	light	0	200	25	0	reverse	heavy	0
300	150	1.5	reverse	light	0	200	50	1.5	reverse	heavy	0
300	150	1	reverse	light	0	200	50	1	reverse	heavy	0
300	150	0.5	reverse	light	0	200	50	0.5	reverse	heavy	0
300	150	0	reverse	light	0	200	50	0	reverse	heavy	0
200	25	1.5	reverse	light	0	200	75	1.5	reverse	heavy	0
200	25	1	reverse	light	0	200	75	1	reverse	heavy	0
200	25	0.5	reverse	light	0	200	75	0.5	reverse	heavy	0
200	25	0	reverse	light	0	200	75	0	reverse	heavy	0
200	50	1.5	reverse	light	0	200	100	1.5	reverse	heavy	0
200	50	1	reverse	light	0	200	100	1	reverse	heavy	0
200	50	0.5	reverse	light	0	200	100	0.5	reverse	heavy	0
200	50	0	reverse	light	0	200	100	0	reverse	heavy	0
200	75	1.5	reverse	light	0	200	125	1.5	reverse	heavy	0
200	75	1	reverse	light	0	200	125	1	reverse	heavy	0
200	75	0.5	reverse	light	0	200	125	0.5	reverse	heavy	0
200	75	0	reverse	light	0	200	125	0	reverse	heavy	0
200	100	1.5	reverse	light	0	200	150	1.5	reverse	heavy	0
200	100	1	reverse	light	0	200	150	1	reverse	heavy	0
200	100	0.5	reverse	light	0	200	150	0.5	reverse	heavy	0
200	100	0	reverse	light	0	200	150	0	reverse	heavy	0
200	125	1.5	reverse	light	0	100	25	1.5	reverse	heavy	0
200	125	1	reverse	light	0	100	25	1	reverse	heavy	0
200	125	0.5	reverse	light	0	100	25	0.5	reverse	heavy	0
200	125	0	reverse	light	0	100	25	0	reverse	heavy	0
200	150	1.5	reverse	light	0	100	50	1.5	reverse	heavy	0
200	150	1	reverse	light	0	100	50	1	reverse	heavy	0
200	150	0.5	reverse	light	0	100	50	0.5	reverse	heavy	0
200	150	0	reverse	light	0	100	50	0	reverse	heavy	0
100	25	1.5	reverse	light	0	100	75	1.5	reverse	heavy	0
100	25	1	reverse	light	0	100	75	1	reverse	heavy	0
100	25	0.5	reverse	light	0	100	75	0.5	reverse	heavy	0
100	25	0	reverse	light	0	100	75	0	reverse	heavy	0
100	50	1.5	reverse	light	0	100	100	1.5	reverse	heavy	0
100	50	1	reverse	light	0	100	100	1	reverse	heavy	0
100	50	0.5	reverse	light	0	100	100	0.5	reverse	heavy	0
100	50	0	reverse	light	0	100	100	0	reverse	heavy	0
100	75	1.5	reverse	light	0	100	125	1.5	reverse	heavy	0
100	75	1	reverse	light	0	100	125	1	reverse	heavy	0
100	75	0.5	reverse	light	0	100	125	0.5	reverse	heavy	0
100	75	0	reverse	light	0	100	125	0	reverse	heavy	0
100	100	1.5	reverse	light	0	100	150	1.5	reverse	heavy	0
100	100	1	reverse	light	0	100	150	1	reverse	heavy	0
100	100	0.5	reverse	light	0	100	150	0.5	reverse	heavy	0
100	100	0	reverse	light	0	100	150	0	reverse	heavy	0
100	125	1.5	reverse	light	0						
100	125	1	reverse	light	0						
100	125	0.5	reverse	light	0						
100	125	0	reverse	light	0						
100	150	1.5	reverse	light	0						
100	150	1	reverse	light	0						
100	150	0.5	reverse	light	0						
100	150	0	reverse	light	0						

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