Contact-Tube Temperature During GMAW

G. Adam, T. A. Siewert, T. P. Quinn, and D. P. Vigliotti, NIST, Boulder, CO

Abstract

The rate of heating and the maximum temperature reached by the contact tube during gas-metal-arc welding (GMAW) is quantified. We studied the effect of changes in the contact-tube-to-work distance (CTWD), voltage, welding wire feed speed, gas-flow rate, composition of the shielding gas, welding speed, and radiation shielding of the contact tube on the final temperature. Also, models were developed that simulate the heating curve of the contact. We found that the major sources of heating were resistance (from the voltage drop between the contact tube and electrode) and radiation (from the arc), with the major heat loss occurring through conduction to the gun body. The contact tubes often reached 300 °C with the air-cooled gun that we used for our tests, and the temperatures reached a plateau in about 50 s. To lengthen contact-tube life, the tube temperature can be minimized by increasing the CTWD, decreasing the current, or decreasing the arc length.

Keywords

GMAW, contact tube, contact-tube temperature, heating model, welding

Introduction

This paper investigates the heating of the contact tube in gas-metal-arc welding (GMAW). In GMAW, a welding electrode (wire) is continuously fed from a spool through the contact tube. The contact tube serves both to position the electrode and to transfer current to the electrode. The contact tube is usually made from an alloy of copper because of the combination of good thermal and electrical conductivity. The contact tube fails when (1) the tube hole grows to where the tube can no longer direct the electrode accurately, (2) the tube provides intermittent or no current to the electrode, or (3) the tube-electrode interface causes the electrode velocity to fluctuate (or stop). Failure modes 1 and 2 occur when the sliding contact causes wear of the contact tube. In this case, the hole in the contact tube increases in size, often forming an oval shape. Failure mode 3 occurs when debris build up on the interior of the tube, until the mechanical interference between the electrode and tube hinders the electrode feed and causes the arc to become unstable. In both cases, stick-slip mechanisms can cause variations in the electrode's feed speed, which makes the arc unstable (Refs. 1, 2).

As the hole in the contact tube is enlarged from wear, the electrode can suddenly shift contact points, causing at least intermittent contact, and at worst, arcing inside the contact tube. Arcing in the contact tube could weld the electrode to the tube, causing the electrode to stop, in turn, causing the arc length to increase until the contact tube

---

melts. If wear debris or dirt should accumulate in the contact tube, the wire's feed speed could fluctuate, resulting in arc instability. Another common cause of failure is spatter accumulating on the face of the contact tube and narrowing or closing the hole for the electrode.

Each of the mechanisms that cause contact-tube failure gets worse as the temperature goes up. The wear of the contact tube increases with temperature. Reference 3 is an example of the dependence of wear coefficient on the temperature and Reference 4 reports recrystallization (softening) of the microstructure and the reduction in the conductivity with temperature. When a piece of spatter lands on the contact tube, it may raise the local temperature of the tube to the point where a metallurgical bond can form. If the spatter does not have enough thermal mass to raise the local temperature of the tube sufficiently, it is less likely to stick. Therefore, the higher the operating temperature of the contact tube, the easier it is for spatter to accumulate.

The object of this paper is to understand the important heating and cooling mechanisms of the contact tube. Experimental studies of the key variables (CTWD, voltage, arc length, gas-flow rate, and gas type) were undertaken. Models of the major heating and cooling mechanisms were used to understand the important factors.

Heat Flux

The heat input to the tube arises principally from the following sources:

a) Radiation from the arc and weld pool.
   This source is approximately constant in time (as long as the arc is stable) and depends mainly on the CTWD and to some extent on the arc’s length. This is best estimated as an expanding cone of radiation extending outward from the arc plasma. The solid angle intersected by the contact tube is the fraction that contributes to tube heating. This source also includes radiation from the weld pool, but as the radiated heat scales as the 4th power of temperature, the contribution of the pool is relatively small.

b) Resistive heating at the interface as current is transferred between the contact tube and welding electrode.
   The heating power is the product of the welding current and the potential drop between the contact tube and the welding electrode. The rapid fluctuations in the welding current and in the potential due to droplet-transfer events can be ignored because the time constant of the heating is on the order of seconds.

c) Ohmic heating due to the current flowing through the contact tube.
   The resistance of a typical contact tube is relatively low, so this is a small source of heat (Refs. 4, 5).

d) Heat flowing upwards through the welding electrode from the weld to the contact tube.
   As reported in Reference 3, little heat flows up the electrode by conduction, so the heat input from this source is negligible, even for a short electrode extension.

The contact tube is cooled during welding by the following processes:
a) Conduction of heat to the upper parts of the gun (and then to the surroundings).
b) Cooling by convection via the shielding gas.
c) Radiative losses (which becomes important only for very high temperatures of the contact tube).

Quantitative estimates for these heat sources and sinks (and the assumptions used to develop them) are shown in Table 1. This is based on a contact tube with an outer diameter of 6 mm, an inner diameter of 1.6 mm, and a length of 30 mm. The gas cup has an inner diameter of 15 mm.

Table 1. Approximate heat transferred to and from the contact tube at equilibrium.

Mechanism	Assumptions	Heat Transfer
Resistive heating from voltage drop at interface between electrode and contact tube	Half of the heat generated goes into the contact tube. I = 200 to 450 A, voltage drop at interface is 0.5 V	50 to 110 W
Ohmic heating from the current as it passes the length of the contact tube	Pure copper contact tube at 669 K I = 365 A	6 W
Radiative heating on the face of the contact tube	The contact tube is a gray-body emitter/ absorber at 667 K. The arc is a black- body emitter at 13437 K (Ref. 6). The arc is modeled as a disk 32 mm to 19 mm away from the contact tube with a diameter of 9 mm (Ref. 6).	21 to 68 W
Convective cooling of the contact tube as the argon flows along its length	Constant heat flux from the contact tube, which is at a uniform temperature of 667 K. The argon enters at a temperature of 294 K and has a Prandtl Number of 0.7 and a thermal conductivity of 0.018 W/(m K) (Ref. 7). The thermal properties for the argon are taken at the average temperature. No heat transfer to the gas cup.	-6 W
Conduction of heat along the contact tube into the rest of the gun	The contact tube transfers heat to the gun body, which is maintained at 290 K. The tip of the contact tube is at 460 to 670 K.	-65 to -130 W

These estimates were developed for thermal equilibrium (after the temperature has stabilized), and balanced to within 10 percent of the experimental values. The radiation model considers the arc as a planar disk of constant temperature. The temperature used for the disk was calculated as the average temperature over the volume of a 350 A arc as calculated in Ref. 8. Radiative transfer is considered only on the face of the contact tube. The model for the convection heat transfer is for not yet fully developed flow along a cylinder either thermally or hydrodynamically. Changing any of the conditions (e.g. current, voltage, or CTWD) will change the magnitude of these values, but the estimates do serve to illustrate the relative effects of the various terms. The conductive terms are nearly linear with temperature and so can be scaled to estimate the relative thermal flows for other conditions.

These estimates predict that resistive heating and radiation dominate over the other sources of heating, and balance with cooling by conduction. The ratio between resistive and radiation is determined by the specific welding parameters that are used. Thus, the maximum temperature reached by the contact tube can be controlled by the gun designers, as well as by the welding engineers and operators.

Experiments

The experimental setup used a commercial air-cooled gun. The welds were bead-on-plate made on 10 mm thick by 50 mm wide plates using an inverter power source and matching electrode feeder. The power source had pulsing capabilities, but we selected the "constant current" mode to eliminate the complexities of pulse parameters. Older power sources for GMAW often have a constant-voltage characteristic, and so a different response.

The electrode was AWS type E70S-3, and the shielding gas was a mixture of argon and 5 % carbon dioxide, flowing at a rate of 18 l/min (40 cfh). We did make one weld with 100 % carbon dioxide to allow an estimate of the effect of our choice of shielding gas. The welding gun was an air-cooled unit, rated at 400 A for carbon dioxide shielding gas and derated by the manufacturer to a 60 % duty cycle for shielding-gas mixtures. The gun was fixed perpendicular to the welded plate, which was moved underneath it at a constant speed of 7.75 mm/s (0.3 in./s). This speed was maintained during the whole set of experiments, except for one test to examine the speed effect. All weld runs lasted about 150 seconds, a time found to be sufficient to reach thermal stability in the contact tube. The welding current and voltage were measured with a pair of isolated transducers to an absolute accuracy of 1 % and 0.5 % respectively and recorded on a personal computer. The contact-tube's temperature was measured with a K-type thermocouple that was inserted into a small hole at the side of the tube. The thermocouple was secured in the hole with the aid of a center punch. The thermocouple's output was fed to a cold-junction-compensated linear amplifier that gave an analog output of 1.6 mV/°C. This output was also recorded on the computer. The sampling rate was 100 Hz.

To learn more about the contribution of radiation to the heating of the contact tube, a number of welds were made with a ceramic radiation shield introduced between the contact tube and the workpiece. In this setup, a square of machinable ceramic (40 mm by 40 mm by 5 mm) was placed just below the contact tube. The welding electrode was fed through the ceramic square via a small hole drilled in the center of the square. To eliminate any conduction between the ceramic radiation shield and the contact tube, three layers of ceramic cloth were placed between them. In this setup, we could not use a standard gas cup, so the shielding gas was delivered to the weld area by an external tube.

To demonstrate that shielding can also be achieved with more realistic welding conditions, we made some welds with a gas cup and a ceramic shield narrow enough so that it will shield the contact tube from direct radiation while allowing gas flow to the weld area.

The experimental design was a full factorial matrix. Three contact-tube-to-work-distances (CTWDs) were used: 19 mm (0.75 in.), 25 mm (1 in.) and 32 mm (1.25 in.). We were unable to investigate shorter CTWDs because we needed to allow room for the ceramic radiation shield between the arc and the contact tube. Four welding-wire feed speeds (WFSs) were used: 110 mm/s (260 in./min), 120 mm/s (285 in./min), 130 mm/s (305 in./min) and 140 mm/s (330 in./min). The voltages at the power supply were 27 V, 30 V, and 33 V. These voltages correspond to arc lengths of about 2, 4, and 6 mm, respectively. Some combinations of these parameters are well outside the parameters used in normal welding, but the aim of this work was to analyze the contact tube's temperature over the widest possible range, which required a complete experimental matrix. To check the influence of the gas flow rate on the contact tube's temperature, two additional welds were made with gas flow rate values of 14 l/min (30 cfh) and 23.6 l/min (50 cfh). To check the influence of welding travel speed on the contact tube's temperature, one weld was made at a speed of 15.5 mm/s (0.6 in./s).

The contact tube had a mass of 9.5 grams and a heat capacity of 2.4 J/K. This means that a net heat input of about 100 watts would produce an initial heating rate of 40 degrees per second.

Heating Model

A simple model was developed to simulate the contact tube's temperature rise with time. We assumed that the contact tube heats from a constant heat input (producing linear heating initially), and cools at a rate that is proportional to its temperature. The differential equation that describes such behavior is

$$(1)\quad \frac{dT}{dt} = k - \alpha T \ ,$$

where T is the temperature (°C), t the time (s) and k and α are constants.

Solving eq. (1) gives:

$$(2)\quad T(t) = \frac{k}{\alpha} + \left(T(0) - \frac{k}{\alpha} \right) e^{-\alpha t} \ .$$

$\frac{k}{\alpha}$ is, according to this model, the temperature of the contact tube at very long times. In this work, we took $T(t=0)$ to be 24 °C, which is the ambient temperature in the lab. We waited a minimum of 2.5 hours between welds to let the gun return to room temperature. We varied k and α to minimize the sum of the squares of the difference between the measurements and the calculated curve. The R^2 of the fit was typically 0.94.

Results and discussion

A typical result of the contact tube's temperature measurements during a weld is presented in Figure 1. These 15,000 measurements (100 Hz for 150 s) show a band of data with a standard deviation of about 14 °C wide. Since the mass of the contact tube is sufficient to damp small thermal fluctuations, the band's width is due mainly to electrical noise that could not be filtered from the millivolt-scale thermocouple signal. Still, the temperature trend is quite clear. The band is wide enough to hide the model's prediction on this figure, which fits nicely down the center of the band. Table 2 lists the main parameters and results for the welds that were performed. For the entire matrix, the final temperatures ranged from 200 to 550 °C (390 to 1000 °F), and the temperature reached about 90 % of the final value within 50 s. The initial heating rates (measured over the first 5 s of the weld) ranged from 6.6 to 40 °C /s. At the high end of the temperature range, the gas cup and contact tube were discolored. As expected, the low temperatures and low heating rates were obtained while welding with combinations of low WFS, low voltage (short arc length) and high CTWD, whereas the high temperature and high heating rate values were obtained for combinations of high voltage setting, high WFS and low CTWD. For α, we found an average value of 0.059 s^{-1} with a standard deviation of 0.012 s^{-1}. Since the changes in α were not correlated to the changes in any of the welding parameters, we fixed α at 0.059 s^{-1}, and fitted the model to the data by varying just the final temperatures. The average effects of the CTWD, the voltage setting, and the WFS are presented in Figures 2 to 4 respectively. As these effects are in descending order, they suggest that the radiation is a major heat source, especially at low values of CTWD. This confirms the heat transfer model data in Table 1. Simple approximations of the slopes of these lines show the relative effects of the variables. Figure 2 shows that a reduction in radiation of 62 % (68 % increase in the CTWD) reduces the equilibrium temperature by 40 %. Figure 3 shows that an increase in voltage of 22 % increases the equilibrium temperature by 27 %. Figure 4 shows that a reduction in WFS of 21 % reduces the equilibrium temperature by 7 %.

Figure 5 shows the calculated final temperature as a function of the average power (calculated from the measured current and voltage) and CTWD. This effectively combines the trends of Figures 3 and 4 by expressing the heat input as power. As expected, lowering the CTWD increases the temperature of the contact tube for a given input power. Figure 6 shows the relation between the heating rate and the CTWD for three different WFSs. As expected, the heating rate is highest for the smallest CTWD. The wire feed speed did not affect the arc's length (and thus the radiation from the arc) in our tests, but did affect the current during the weld (and thus the resistive heating). Thus, the three WFSs result in almost parallel curves of heating rate vs. CTWD.

Figure 7 shows the heating curves from two welds that were made with the same welding parameters but with two different values of gas-flow rate. One flow rate was 25 % below the rate used for most of the test matrix, and the other was 25 % above. Even though the flow rate changed by 50 %, the heating curves are almost identical and reach the same final temperatures. This result is as predicted by the heat-transfer model, which indicates that the heat carried away by the gas is less than 10 % of the total heat. Even a 50 % change in the gas-flow rate has a very small effect on the heating curve.

Figure 8 shows the heating curves for two welds that were made with the same welding parameters but with different travel speeds. The weld denoted by “low speed” was made at a travel speed of 7.75 mm/s (the speed at which all the welds in the matrix were made). The second weld was made at 15.5 mm/s (twice the original speed). The heating curves for these two welds are practically the same. This is explained by the fact that the principal effect of the welding speed is on the size of the weld pool: the higher the travel speed, the smaller the weld pool. The weld pool contributes to the heating of the contact tube mainly by radiation. As it is further away from the tube than the arc, and as its temperature is only about 13 % of that of the arc, the contribution of this heating is small, and changes in the size of the pool have minimal effect on the tube’s heating curve.

Figure 9 demonstrates how the selection of the shielding gas can affect the heating of the contact tube. Curve 1 shows the temperature with Ar-5%CO_2, while curve 2 shows the temperature with CO_2, only produced with the same welding parameters. The differences between these two welds demonstrate that switching to CO_2 as a shielding gas results in a lower temperature of the contact tube, while depositing the same amount of metal in the weld (same wire feed speed of 140 mm/s). All the weld-parameter data for these welds are shown in Table 3. The changes between curve 1 and curve 2 can be explained as the effects of the change in shielding gas on the voltage and current (and the total weld power), as resolved by the power-source response characteristic. The model supports this result by indicating reductions in both the resistive and arc-radiation contributions to the contact-tube heating, although the radiation effect appears to dominate here. We did not try to quantify the effects of the higher particulate level in the CO_2 arc or the change in the arc spectrum.

Table 3. Effect of shielding gas on the contact-tube temperature

Curve	Shielding Gas	Voltage, V	WFS, mm/s	Current, A	Power, kW
1	Ar-5%CO_2	29	140	410	12
2	CO_2	27	140	415	11
3	Ar-5%CO_2	26	130	430	11

Curve 3 shows the temperature when the wire feed speed for the Ar-5%CO_2 weld was decreased until the arc power was the same as for the weld with CO_2 (curve 2). Here, the temperatures of the contact tubes with the two shielding gases follow nearly identical patterns. Thus, the lower tube temperature for the weld with CO_2 at the same power-source settings seems most related to the reduction in arc power. Since the current increased while the voltage decreased, the relative changes in the contributions from resistive heating and arc radiation seem to offset each other. We were unable to obtain good measurements of the arc lengths for the shielding gas tests, and so we cannot compare these changes to our heat estimates. In general, we see that using CO_2 as a shielding gas enables one to deposit more metal into the weld for a given temperature rise in the tube.

The welding gun was an air-cooled unit, rated at 400 A for CO_2 shielding gas and derated to a 60 % duty cycle for use with shielding-gas mixtures. The NEMA duty cycle is an industrial rating system used to avoid overheating of welding power supply components (Ref 9). The NEMA rating cycle is the ratio of the time that a device is used during a 10-minute interval. For example, a 60 % duty cycle means that a power supply can deliver its rated output for 6 minutes out of any 10-minute period without overheating. In this study, we found that the contact tube reached about 90 % of its equilibrium value within 50 s. Thus, a 10-minute duty cycle might be appropriate for components with high thermal mass, but it is too long for welding components with low thermal heat capacities, such as the contact tube in this air-cooled gun. In figure 9, the weld with mixed gas shielding (curve 1) nearly reaches the equilibrium temperature of the weld with CO_2 shielding (curve 2) in 20 seconds. A more appropriate duty cycle for a contact tube (and so for a low-mass welding gun) would seem to be 15 to 30 seconds. A time in this range would prevent the contact tube from reaching its equilibrium temperature during welding with shielding-gas mixtures.

Placing a solid ceramic radiation shield and a few layers of ceramic cloth between the arc and contact tube effectively eliminates radiative heating, separating this effect from the other heat sources. Note that the ceramic became red hot during even these short tests, and it often cracked during cooling. This further supports the intensity of the radiation from the arc. Figures 10 through 12 show the heating curves (with and without the heat shield in place) for CTWD values of 19, 25 and 32 mm, respectively. The contribution of radiation from the arc is very pronounced at a CTWD of 19 mm, and is much smaller at a CTWD of 32 mm. The significant drop in the relative contribution of radiation with distance for the three examples in Figures 10 to 12 confirms the trends shown in Figure 2 for the averages of the entire test matrix. Figure 10 shows a 33 % reduction in equilibrium temperature when the radiation contribution was eliminated by the ceramic shield, coming close to the 40 % reduction in equilibrium temperatures found for the test matrix averages in Figure 2. The exact ratios of the contributions of radiation and resistive heating obviously depend on the welding conditions; however, these tests show that these contributions can be similar in magnitude.

We had to remove the gas cup in order to fit the ceramic shield and cloth against the contact tube for the tests in Figures 10 to 12. This meant that we had to feed the shielding gas from the side, an arrangement that was convenient for our tests, but could be criticized as not accurately simulating the actual situation. To come closer to standard practice, we tried another weld with the gas cup in place and added a smaller (about 25 mm by 25 mm) ceramic shield just below it. This smaller shield had a series of holes for the usual axial flow of shielding gas, but these holes also allowed a small amount of the radiation to reach the contact tube. This compromise in the design meant that the tube was expected to heat a little faster than with the higher-quality radiation shielding used for Figures 10 to 12.

Figure 13 shows the heating curve for this test. We see that the curve starts out almost identically to the curve named “square shield”, which is the shielded curve from Figure 11. However, after a few seconds, the narrow shield started to melt. This is not surprising because, as it was mounted on the bottom of the gas cap, it was much nearer to the arc. As it melted, it allowed the radiation from the arc to reach the contact tube, so the heating curve slowly approaching the unshielded curve (which is again the unshielded curve from Figure 11). This experiment demonstrates that radiative shielding can be achieved under normal welding condition, but it is difficult to develop a shield that withstands the intense heat of the arc.

Summary

The contact tube in an air-cooled GMAW gun often reaches a temperature of 300 °C (570 °F) or higher for typical welding conditions, nearly halfway to the melting temperatures of many common copper alloys. The reduction in strength and wear resistance at these temperatures explains why water-cooled guns are necessary for long welds under conditions of higher radiation. The contact tube reaches about 90 % of its equilibrium temperature in about 50 s. This means that higher power inputs can be tolerated for short welds (10 to 20 s) because the contact tube never reaches the equilibrium temperature. Figures 2 to 4 confirm that the equilibrium temperature goes down with increasing CTWD, but goes up with WFS and with welding voltage. Over the measured range, WFS has the least influence on the final temperature. This means that, without overheating of the contact tube, the power input to the weld can be increased by increasing the voltage and the WFS, provided the CTWD is also increased. This is also demonstrated in Figure 5, which shows how to move along a constant temperature (horizontal) line by increasing the power and the CTWD at the same time.

Radiation from the arc and resistive heating from the electrode-contact tube interface are the two major sources of contact-tube heating. Shielding of the contact tube from the arc radiation can reduce its temperature significantly, especially at low CTWD values, thus lengthening its operational lifetime. The welding speed and the gas-flow rate have no significant influence on the heating of the contact tube. Conduction of heat into the gun body through the contact tube mount is the most important means of cooling the contact tube. Cooling from the shielding gas flowing around the contact tube provides only about 10 % of the conductive cooling effect.

References

1) Quinn, T. P., Madigan, R. B., Mornis, M. A., and Siewert, T. A. 1995. Contact Tube Wear Detection in Gas Metal Arc Welding. *Welding Journal* 74 (4): 115s-121s.

2) Quinn, T.P., Madigan, R.B., and Siewert, T.A., 1994. An Electrode Extension Model for Gas Metal Arc Welding. *Welding Journal* 73(10): 241-s to 248-s.

3) Rabinowicz, E., 1982. The Temperature Rise at Sliding Electrical Contacts. *Wear* 78, 29-37.

4) Villafuerte, J., 1999. Understanding Contact Tip Longevity for Gas Metal Arc Welding. *Welding Journal 78* (12): 29-35.

5) Yamada, T. and Tanaka, O., 1987. Fluctuation of the Wire Feed Rate in Gas Metal Arc Welding. *Welding Journal* 66(9): 35 to 42.

6) Sparrow, E. M., and Cess, R. D. 1978. *Radiation Heat Transfer*. p. 340, Hemisphere Publishing Corp., Washington.

7) Kays, W. M., and Perkins, H. C. 1985. In *Handbook of Heat Transfer Fundamentals*, edited by W. M. Rohsenow, J. P. Hartnett and E. N. Ganic. pp. 7-47 to 7-88. McGraw Hill, New York.

8) Jonsson, P.G., Szekely, J., Madigan, R.B., and Quinn, T.P., 1995. Power Characteristics in GMAW: Experimental and Numerical Investigation. *Welding Journal* 74(3): 93-s to 101-s.

9) Welding Handbook, Volume 2 (Welding Processes), 1991, p. 14. American Welding Society, Miami. Florida.

Figure captions

Fig 1 - A typical heating curve for a contact tube during a weld.

Fig 2 – Average (over all voltages and electrode feed speeds) equilibrium contact-tube temperature vs. CTWD.

Fig 3 - Average (over all CTWDs and electrode feed speeds) equilibrium temperature vs. voltage setting.

Fig 4 - Average (over all voltages and CTWDs) equilibrium temperature vs. WFS.

Fig 5 – Equilibrium temperature vs. power, for various CTWD values.

Fig 6 – Heating rate vs. CTWD for various WFS values.

Fig 7 – Effect of gas flow rate on the contact tube’s heating curve.

Fig 8 – Effect of welding speed on the contact tube’s heating curve.

Fig 9 – Effect of shielding gas composition on the contact tube’s heating curve. The welding parameters for each curve are detailed in Table 3.

Fig 10 – Effect of shielding on the contact tube’s heating curve for CTWD of 19 mm. The top curve is unshielded and the lower curve is shielded.

Fig 11 – Effect of shielding on the contact tube’s heating curve for CTWD of 25 mm. The top curve is unshielded and the lower curve is shielded.

Fig 12 – Effect of shielding on the contact tube’s heating curve for CTWD of 32 mm. The top curve is unshielded and the lower curve is shielded.

Fig 13 – Effect of shielding with a small shield, which melted away during welding: shielded (lower) and unshielded (upper) heating curves.

Table 2: The parameters and results for all welds.

CTWD (mm)	Arc Length (mm)	Voltage setting (V)	W. Speed (mm/s)	Average Voltage (V)	Average Current (A)	Final Temp.(°C)	Heating rate (°C/s)
19	2	27	110	20	350	319	17
19	2	27	120	22	340	340	20
19	2	27	130	24	331	336	20
19	2	27	140	27	323	322	22
19	4	30	110	21	391	408	24
19	4	30	120	24	381	455	32
19	4	30	130	26	372	427	22
19	4	30	140	28	365	396	25
19	6	33	110	22	436	544	36
19	6	33	120	24	429	461	29
19	6	33	130	26	419	466	28
19	6	33	140	29	410	544	40
25	2	27	110	18	356	265	15
25	2	27	120	21	346	309	19
25	2	27	130	22	339	316	20
25	2	27	140	24	332	318	21
25	4	30	110	19	398	347	20
25	4	30	120	21	390	364	22
25	4	30	130	23	382	372	24
25	4	30	140	25	375	398	25
25	6	33	110	19	446	355	16
25	6	33	120	22	436	323	22
25	6	33	130	23	431	349	20
25	6	33	140	25	423	367	24
32	2	27	110	16	365	195	7
32	2	27	120	18	358	236	12
32	2	27	130	20	348	256	14
32	2	27	140	21	347	239	14
32	4	30	110	16	409	225	11
32	4	30	120	18	402	245	12
32	4	30	130	21	394	269	14
32	4	30	140	22	388	293	16
32	6	33	110	17	454	244	12
32	6	33	120	19	447	251	15
32	6	33	130	21	439	273	13
32	6	33	140	23	433	289	16