Characterization and Detection of the Deterioration of Electrical Connectors in a Flash-lamp System

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Abstract

In the OMEGA and OMEGA EP high-energy pulsed laser systems, high-intensity flash lamps are used to excite the laser glass amplifier medium to increase the energy of laser beams for experiments. This amplification system includes a continuous flow of high-resistance deionized water around the flash lamp. This keeps the lamps cool to decrease required laser-glass cool-down time and maximize the frequency of shot operations. When electrical current travels through the flash-lamp connections, a small amount of metal is displaced into the cooling water which causes the resistance of the cooling water to decrease. The metal components in the flash-lamp connector system undergo degradation over time due to repeated displacement of metal debris. Replacing the damaged connectors after a failure occurs is a costly process. Failures also interrupt laser experiment shot operations. To remedy the problem, the concept of a non-invasive process in detecting the levels of flash-lamp connector deterioration was developed and tested. This involves analyzing changes in the resistance of the water flowing through the flash-lamp cooling system. Both cooling-water and flash-lamp systems at different stages of degradation were tested. It was found that the transient change in water resistance is correlated with the level of deterioration in flash-lamp connectors. The minimum current needed to detect a resistance change was determined. Results from this research will allow for non-invasive detection of deteriorated flash-lamp connectors in the amplification system before failure. Implementation of this technique will decrease the risk of failed laser amplifier operation during a laser shot, thereby increasing the reliability of the amplifier system.

1. Introduction

In the 1990s, the Laboratory for Laser Energetics (LLE) Flash-lamp Test Facility was carrying out life expectancy testing on flash lamps to test the maximum number of shots the lamps could undergo before failure. Investigators observed that deionized water coming from the system momentarily dropped in resistance due to metal displacement from the connectors after each operation. Cleveland et al. provide data that supports this observation [1]. It was suspected that electrical arcing, as seen in Figure 1, caused this metal displacement in the connectors. The research described in this report aims to create a system to detect transient changes in water resistance and develop a method to characterize the properties of the changes. In turn, this characterization will assist lab operators in determining when maintenance is required on a flash-lamp system before an imminent failure occurs. A lab setup was developed to execute a proof of concept. This setup contained a deionized cooling-water system, a pulse forming network, and the flash-lamp system. Three flash-lamp systems were examined. Each had a different set of connectors. New (never used), slightly used (just burned-in but not worn-out), and used (ready to be replaced) sets of connectors were tested. Figure 2 shows connectors from a new set and a used set in comparison to a failed connector.

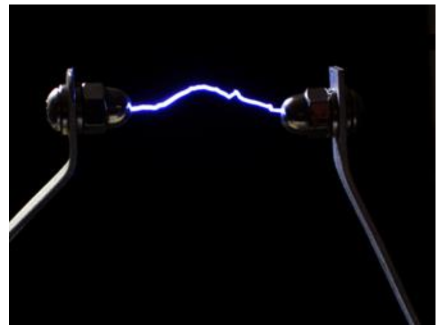


Figure 1: Electrical arcing between two electrodes.

Figure 2: Progression of flash-lamp connectors from new, used, to failed.

The amount of metal displacement at different currents was detected via changes in the deionized cooling-water resistance. The amount of metal displaced after a test was found to be correlated to the level of connector degradation. Tests were conducted to measure the minimum amount of current that could yield a detectable change in water resistance. Experiments at different resistances were also conducted. The development of this work will provide a flash-lamp system maintenance indicator to avoid failures caused by end-life flash-lamp connectors**.**

Connectors were inspected after testing was completed. The connectors in Figure 3 are from a used set of connectors. For this set of connectors, alternate sides of the same connector displayed different degrees of deterioration. Figures 3(a) and 3(b) show opposite views of the connector at one end of a flash lamp. A large difference in the degree of deterioration is clearly seen. Opposite views of the connector at the other end (Figures 3(c) and 3(d)) show the same trend. This is caused by the flash-lamp system sitting horizontally, as has been demonstrated by the flash-lamp maintenance team at LLE [2]. Varying degrees of deterioration on the same connector side are common on the OMEGA and OMEGA EP lasers at LLE.

Figure 3(a)

Figure 3(b)

Figure 3(c)

Figure 3(d)

Figure 3: Side comparison of connectors used on the flash-lamp system. Figures 3(a) and 3(b) show the connector at one end of a flash lamp and Figures 3(c) and 3(d) the connector at the other end. Figures (a) and (c) view from the opposite side of (b) and (d).

2. Experimental Setup

Figures 4(a), (b), and (c) show the layout of the experimental setup. Figure 4(a) displays the flash-lamp system energy storage, which powers the flash-lamp system. The silicon-controlled rectifier momentarily allows the energy in the flash-lamp system energy storage to flow through the flash-lamp system. Deionized cooling water and energy from the pulse forming network (PFN) interact with the flash-lamp system. In Figure 4(b), the variable power supply charges the flash-lamp system energy storage. On the oscilloscope, there is a nominal graph of current with respect to time after a test. The energy-storage dump stick discharges the flash-lamp system energy storage to ensure safe conditions for handling components in the test bed after experiments. The flash-lamp system trigger box connects to the silicon-controlled rectifier. When the trigger box is pressed, the silicon-controlled rectifier allows the flash-lamp system energy to be released. Figure 4(c) shows the connections of the pump to the resistance sensors and flash-lamp system. The resistance sensors measure the resistivity of the cooling water before and after passage through the connectors.

Figure 4(a)

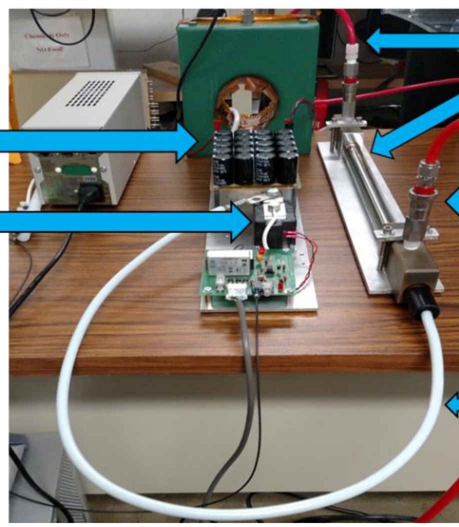
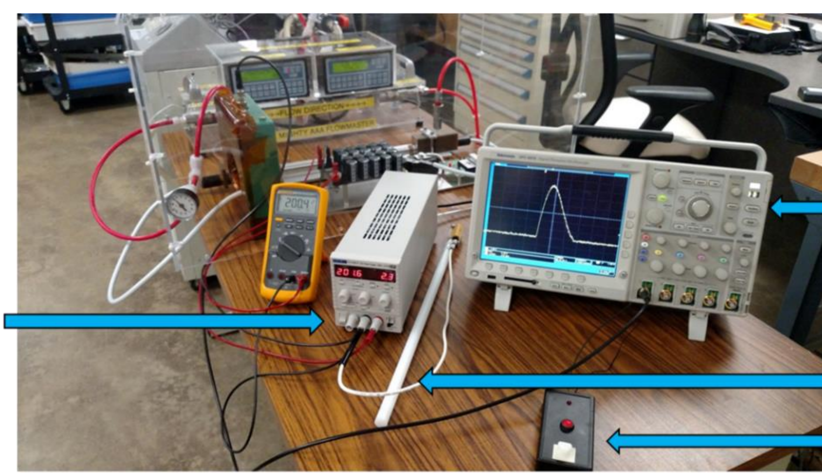


Figure 4(b)



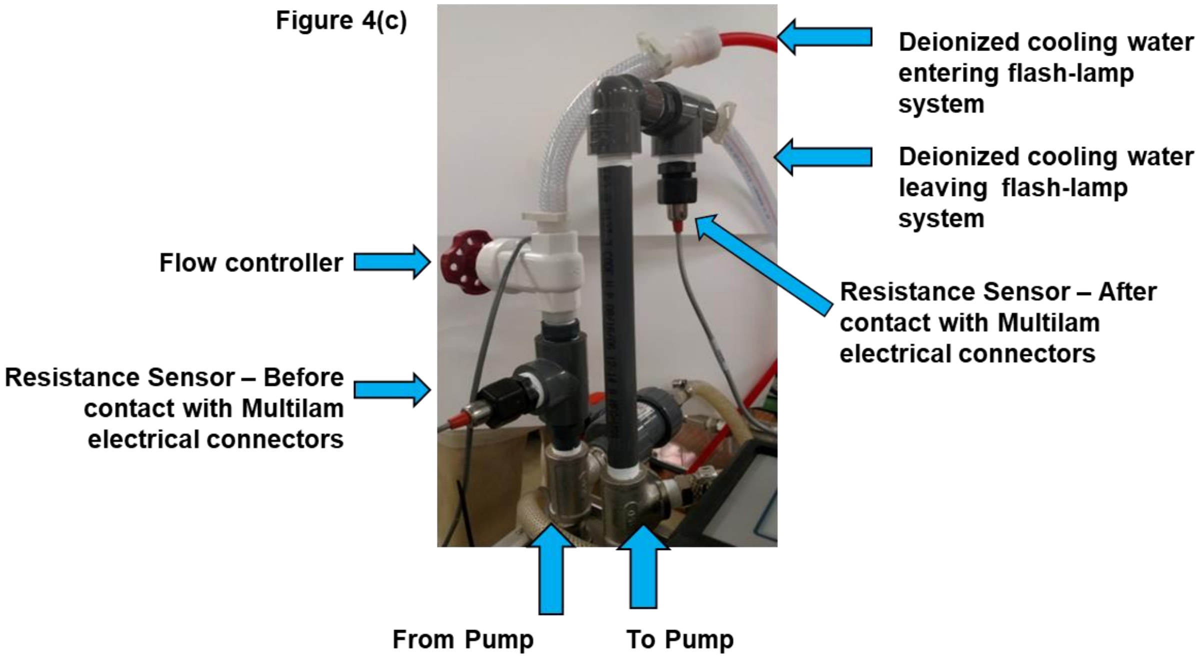


Figure 4: The entire experimental layout. (a) View showing the flash-lamp system. PFN: pulse forming network. (b) View showing auxiliary instruments of the PFN. (c) View showing the resistance sensors.

2.1 Flash-Lamp System

The flash-lamp system contained the connectors that were tested. A modified flash-lamp setup (Fig. 5) was used to optimize the compactness of the proof-of-concept testing. Brick ends, where the connectors are housed, from 52” flash lamps were combined with a metal rod surrogate of 10” arc lamp distance. Figure 5 shows a metal rod used as a surrogate for an arc lamp on the modified setup to decrease the voltage required to reach the standard current simulating OMEGA and OMEGA EP laser flash-lamp operation.

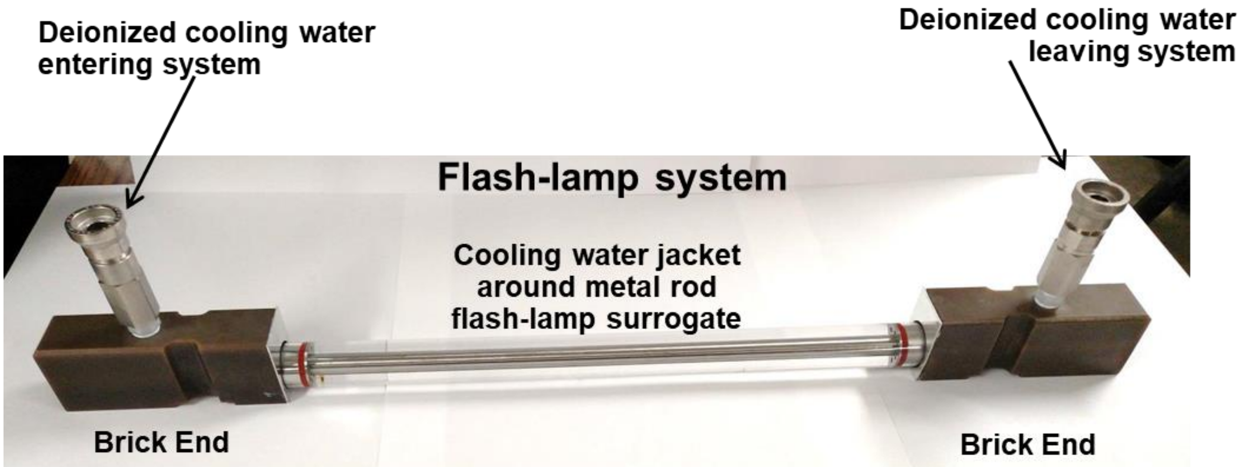


Figure 5: Modified flash-lamp system. The metal rod surrogate is between two brick ends from a 52” flash lamp. The flow of deionized cooling water through the system is shown.

The metal displacement that is captured on the sensors originates from inside the brick ends. The electric arcing that causes this deterioration occurs mainly at connections with Stäubli Multilam contact bands. Figure 6 shows where these Multilam contact band connections are placed on the flash lamp [3].

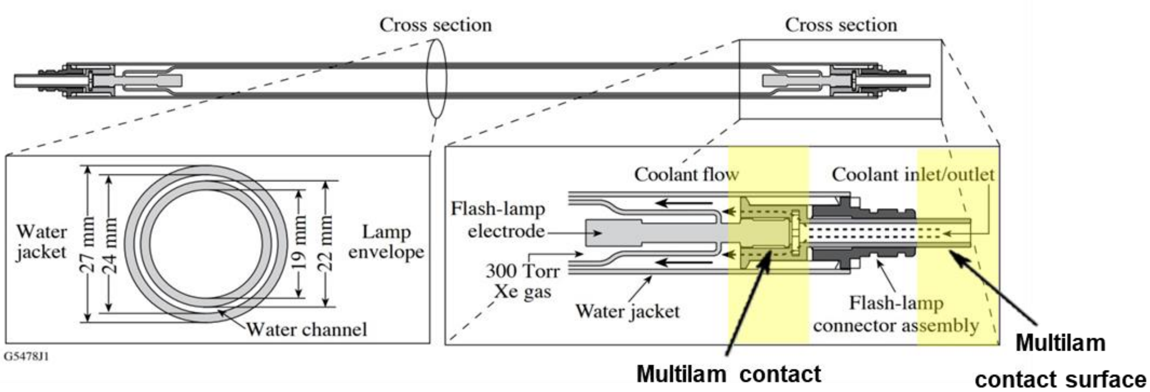


Figure 6: Cross sections of a flash lamp and its connector assembly. Highlighted yellow areas show Multilam contacts where deterioration in the flow of deionized cooling water can occur. Multilam bands are inside the female parts of connections. The male parts at these points, seen in the highlighted areas, incur deterioration.

2.2 Deionized Water System

The setup of the deionized water system is displayed in Figure 7.

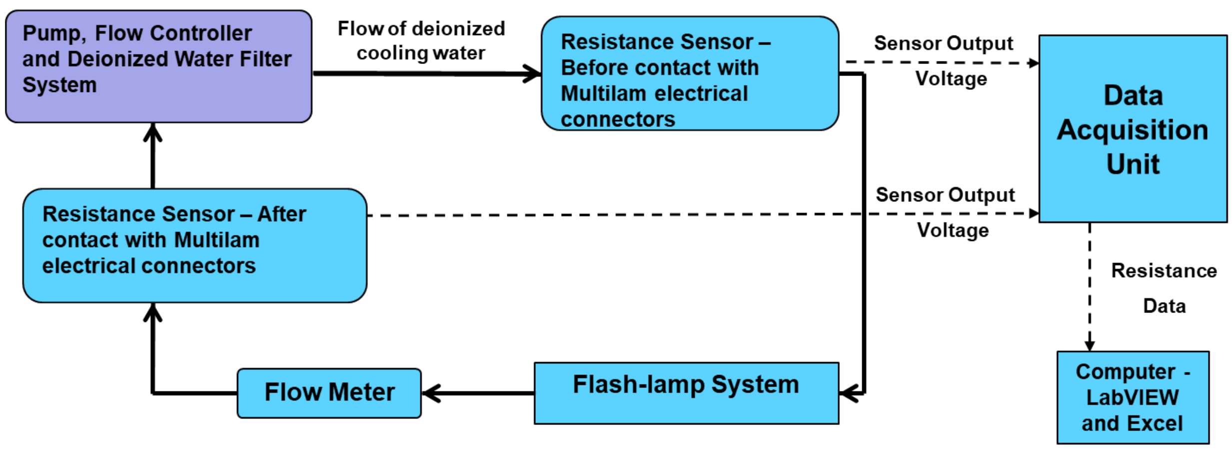


Figure 7: A block diagram of the deionized water system. Black lines indicate the flow of deionized cooling-water. Dashed lines signify the resistance data.

An FTS Systems Maxicool Recirculating Chiller, model # RC-00263-A is used to pump the deionized cooling-water through the system. The deionized cooling-water follows the same path during each experimental procedure. A flow controller is connected in the stream of water to control the velocity of the water. From the pump, the water moves to a resistance sensor. The deionized water goes through the flash-lamp system and acquires metal by the degradation at Multilam connections. The contaminated water then travels through a flow meter and reaches a second resistance sensor. It is sent back into the pump, where the water is purified through the deionized water filter system. The tubing which connected the deionized water system together is 3/8” in diameter. The resistance monitor resolution is approximately 0.02 Megaohms-cm. The average water velocity is 0.5 gal/min as detected by the flow meter. This matches the flow rate used on OMEGA and OMEGA EP. Resistance sensors were used to diagnose contaminated water from connectors. These sensors are easily attachable to the lab setup and are compact for implementation into OMEGA and OMEGA EP. Myron L CS-10 resistivity sensors were inserted into the flow of water before and after contact with the flash-lamp system. The sensors delivered resistance data to a Myron L 750 Series II resistivity monitor. This data was then converted to a voltage and sent to a data acquisition unit. The acquisition unit data was read by a LabVIEW application. The values were collected in an Excel file, where data reduction could occur.

2.3 Pulse Forming Network (PFN)

The pulse forming network used in this experiment simulated one found on OMEGA or OMEGA EP. A block diagram of the PFN can be seen in Figure 8. The variable power supply controls how much energy is stored in the flash-lamp system energy storage. Once the trigger is pressed on the flash-lamp system trigger box, the silicon-controlled rectifier allows the energy to flow through the flash-lamp system and back to ground. The network had the capacity to reach 7000 A to cover the range of the amplifiers used on OMEGA and OMEGA EP. Twenty 470-microfarad capacitors were used in parallel for energy storage. Capacitors were charged to a set voltage for the experiments. For different tests, the set voltage could be adjusted. The oscilloscope was used to monitor the pulse current on the PFN. Maximum currents ranged up to 6600 Amperes with a current pulse width of 500-600 microseconds.

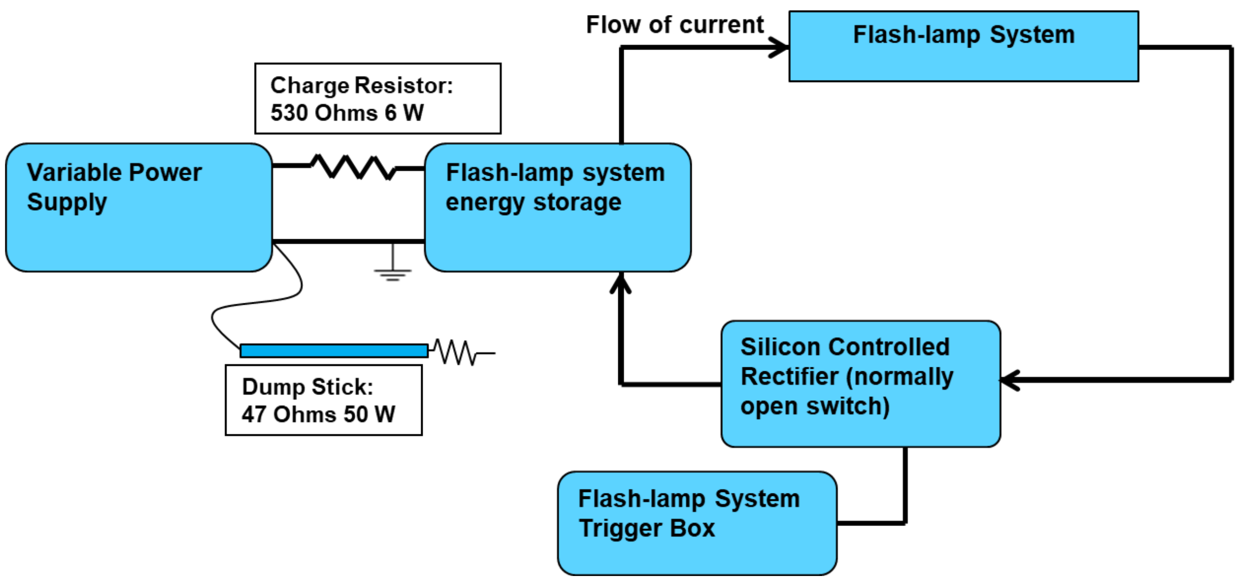


Figure 8: A block diagram of the pulse forming network which supplied current to the flash-lamp system

3. Experimental Data

The test procedure began with a charge of the flash-lamp system energy-storage capacitors. As the energy was stored, a LabVIEW program began recording data on the resistivity of the water. When the appropriate energy storage voltage was reached, the energy was released through the silicon-controlled rectifier into the flash-lamp system. The time of discharge relative to the start of the program's data collection was recorded in the LabVIEW data. This fundamental procedure was repeated for all tests.

Figure 9 shows a typical plot of a new flash-lamp system test. The starting resistance of the transient change of the water resistance was determined by the falling edge of the resistance drop. The time at which this drop occurred was usually between five and eight seconds after the PFN trigger. This matches the expected time the water takes to reach the sensor from the flash-lamp system. Approximately 8 oz of deionized cooling water separates the end of the flash-lamp system and the resistance sensor after contact with Multilam connections. At a flow rate of 64 oz per 60 sec (0.5 gal/min), the drop theoretically would begin at approximately eight seconds from the pulse.

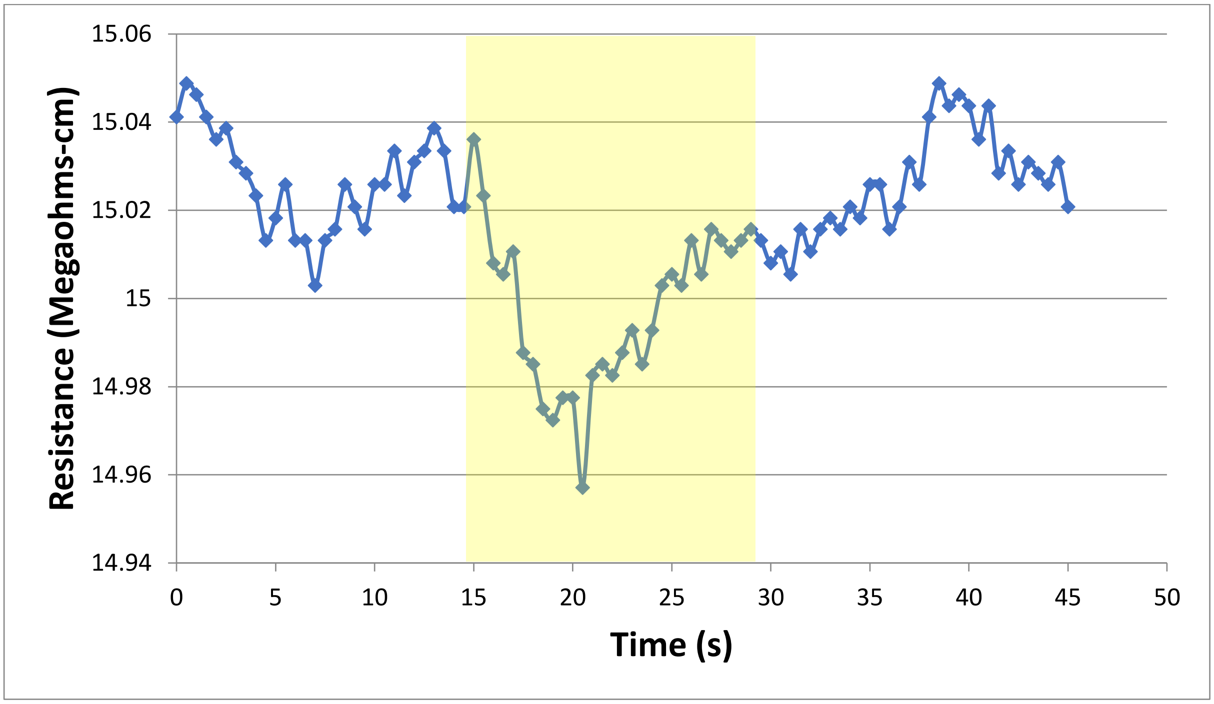


Figure 9: Typical plot of the cooling-water resistance as a function of time during a new flash-lamp system test. The current is 6700 A. The voltage is 210 V. A maximum drop of 0.061 Megaohms-cm was observed ten seconds after the pulse forming network trigger occurred. The yellow area highlights the drop induced by the pulse.

The resolution of the Myron L 750 Series II Resistivity Monitor is approximately 0.02 Megaohms-cm. If the resistance change of the test was within 0.02 Megaohms-cm, the flash-lamp system was deemed to effectively have no change.

Each new connector system test was done with the same flash-lamp system. Table 1 provides data for tests done with the new flash-lamp system. The transient change in water resistance is shown. The average change in resistance for each voltage is shown at the bottom of the respective column. Table 1 shows that as the peak current of the pulse increased the transient change in water resistivity increased as well.

Table 1: Maximum change in water resistance from the new connector flash-lamp system. Values are in Megaohms-cm.

Capacitor Charge Voltage Peak PFN Current	175 V 5200 A	200 V 6400 A	210 V 6700 A
Shot 1	0.056	0.0433	0.051
Shot 2	0.040	0.079	0.0554
Shot 3	0.043	0.060	0.061
Shot 4		0.0404	0.056
Shot 5		0.054	
Shot 6		0.0458	
Average	0.046	0.053	0.056

The transient changes in water resistance for slightly used flash-lamp system tests are displayed in Table 2. Again, the data shows that as the peak current of the pulse increased the transient change in water resistivity increased. Figure 10 shows a typical plot of a test done on the slightly used flash-lamp system.

Table 2: Maximum change in water resistance from the slightly used connector flash-lamp system. Values are in Megaohms-cm.

Capacitor Charge Voltage Peak PFN Current	175 V 5670 A	200 V 6400 A	210 V 6700 A
Shot 1	0.021	0.021	0.036
Shot 2	0.025	0.028	0.076
Shot 3		0.02	0.058
Shot 4			0.025
Average	0.023	0.023	0.049

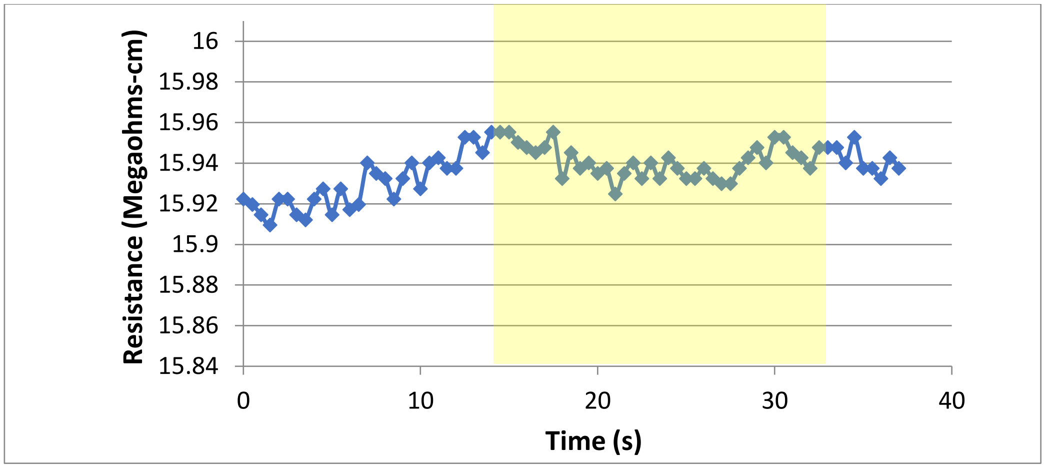


Figure 10: Typical plot of slightly used flash-lamp system test. The current is 5670 A. The voltage is 175 V. The graph illustrates a small change in resistance of approximately 0.02 Megaohms-cm. The pulse forming network trigger occurred at ten seconds. The yellow area highlights the drop induced by the pulse.

Used flash-lamp system data is shown in Table 3. The transient change in water resistance is listed. Figure 11 shows a typical plot of a used connectors test.

Table 3: Maximum change in water resistance from the used connector flash-lamp system. Values are in Megaohms-cm.

Capacitor Charge Voltage Peak PFN Current	175 V 5500 A	200 V 6300 A	210 V 6600 A
Shot 1	0.071	0.059	0.179
Shot 2	0.058	0.114	0.168
Shot 3	0.033	0.059	0.091
Shot 4	0.084	0.048	0.117
Shot 5		0.097	
Shot 6		0.038	
Shot 7		0.051	
Shot 8		0.194	
Average	0.062	0.083	0.139

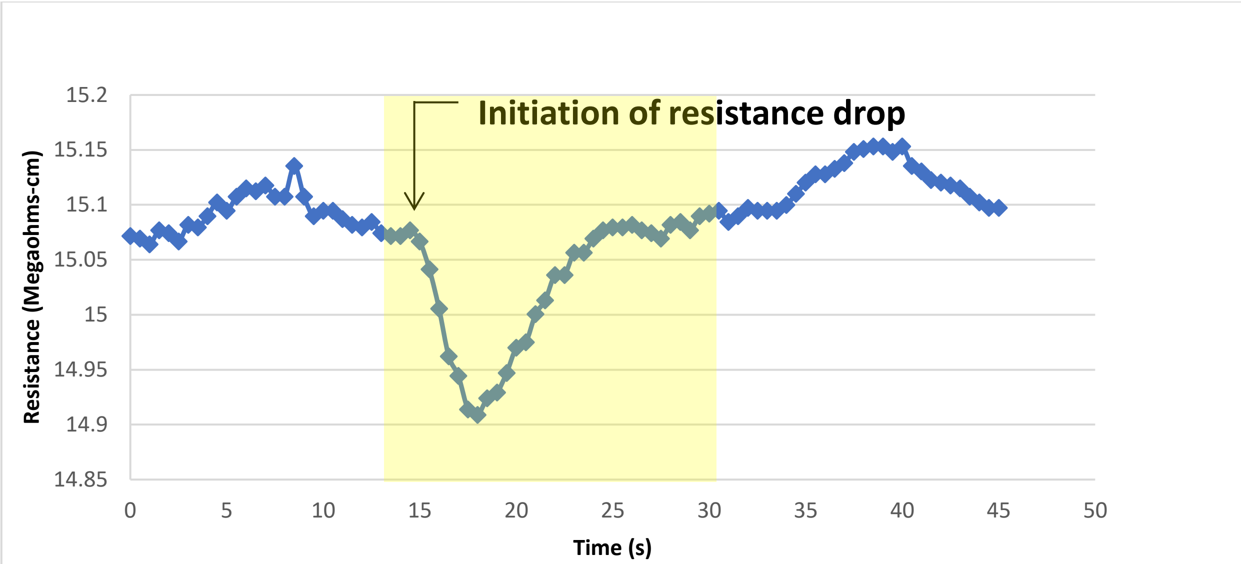


Figure 11: Typical plot of a used flash-lamp system test. The current is 6600 A. The voltage is 210 V. The plot illustrates a drop of approximately 0.16 Megaohms-cm. The pulse forming network trigger occurred at ten seconds. The yellow area highlights the drop induced by the pulse.

At an energy storage voltage of 210 V, the used flash-lamp system produced the greatest average change in water resistance, and therefore the highest amount of metal displacement from its connectors. The new and slightly used flash-lamp systems both exhibited similar magnitudes of water resistance change at 210 V.

Oils and scratches from manufacturing are found on the surface of the new connectors. The process of the male connector seating with the Multilam connections causes metal deterioration. As electricity passes through the slightly used connectors, the connection gets stronger and incurs spots of welding. Over time, this welding and repeated use causes the used connector to deteriorate and large amounts of metal debris release. This explains the counterintuitive observation that the slightly used set of flash-lamp connectors has a lower average change in deionized cooling-water resistance than the new set of flash-lamp connectors.

At all energy storage voltages, the used flash-lamp system produced the highest average change in water resistance, significantly above the other two flash-lamp systems tested.

4. Low Voltage Tests

Tests were conducted to measure the minimum amount of current that could be pulsed into the flash-lamp test system with a detectable change in cooling-water resistance. The minimum current was determined when the change in water resistance dropped consistently at or less than 0.02 Megaohms-cm. Figures 12, 13, and 14 shows tests done at decreasing energy storage voltages, corresponding to decreasing peak current. The change in deionized cooling-water resistance for the slightly used flash-lamp system was below the resistivity monitor threshold of 0.02 Megaohms-cm in a range from 4700 A to 5100 A. The change in deionized cooling-water resistance was below the resistivity monitor threshold for the new and used flash-lamp system in ranges from 4400 A to 4500 A and 4060 A to 4460 A, respectively. The minimum current necessary to release detectable metal particulate was lowest for the used flash-lamp system. This system also produced the highest average change in water resistance. The minimum current range was highest for the slightly used flash-lamp system, which exhibited the lowest average change in water resistance. The minimum energy needed for a flash-lamp system to release metal debris is related to the system's average change in water resistance. As the average change in water resistance and the level of released metal particulate increases, the energy needed to cause a change in water resistance decreases. As the set of flash-lamp connectors increases in deterioration, the amount of debris that is released after a pulse will also increase.

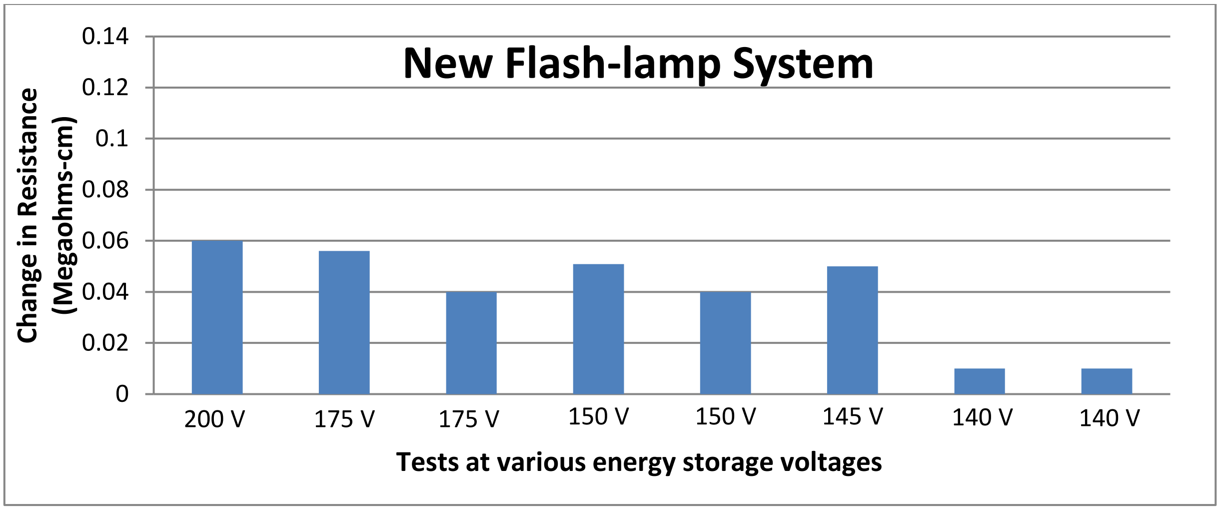


Figure 12: Changes in resistance at decreasing voltages on the new flash-lamp system. The peak current at 140 V was between 4500 A and 4400 A.

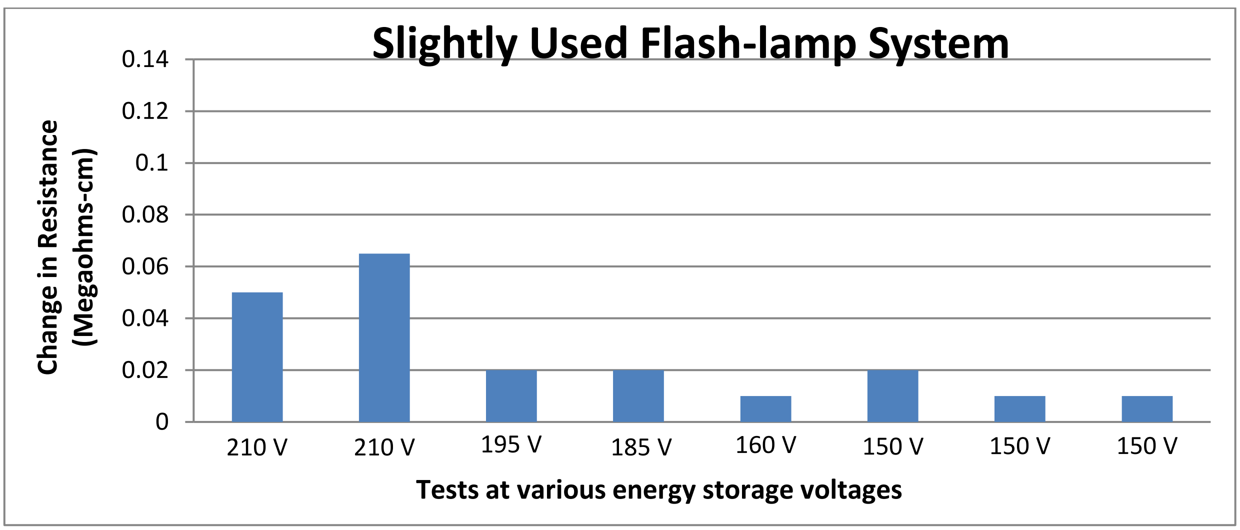


Figure 13: Changes in resistance at decreasing voltages on the slightly used flash-lamp system.

The peak currents at 160 V and 150 V were 5100 A and 4700 A, respectively.

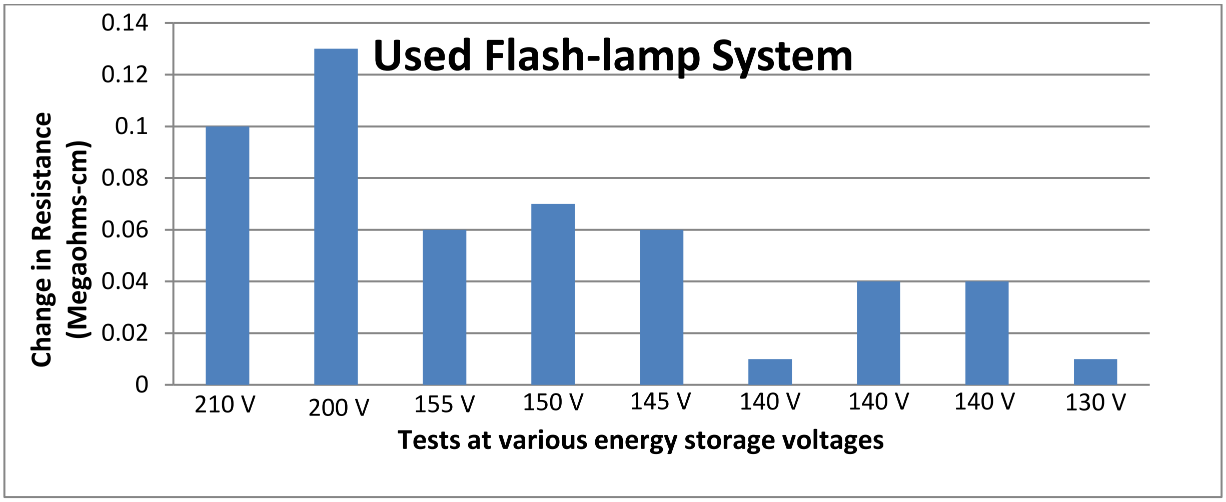


Figure 14: Changes in resistance at decreasing voltages on the used flash-lamp system. The peak currents at 140 V and 130 V were 4460 A and 4060 A, respectively.

5. Low Resistance Testing

Experiments at different deionized cooling-water resistances were conducted. Figure 15 shows these test results. The goal of these tests was to determine if the starting resistance of the cooling water would affect the magnitude and detectability of changes in water resistance. The flow controllers to the water reservoir filters were changed before using the fundamental procedure. This changed the percentage of contaminant which was filtered from the water. This gave control over the starting resistance of the cooling water. Each of these tests was conducted at the same energy storage voltage of 200 V, corresponding to a peak current of 6300 A, with the used flash-lamp system. The initial water resistance was determined by the monitor on the resistance sensor before contact with the flash-lamp system. As the starting resistance went down, the amount of change detected during flash-lamp testing also decreased. Below an initial starting point of 10 Megaohms-cm, the change in water resistance during flash-lamp tests was less than the resistance monitor resolution.

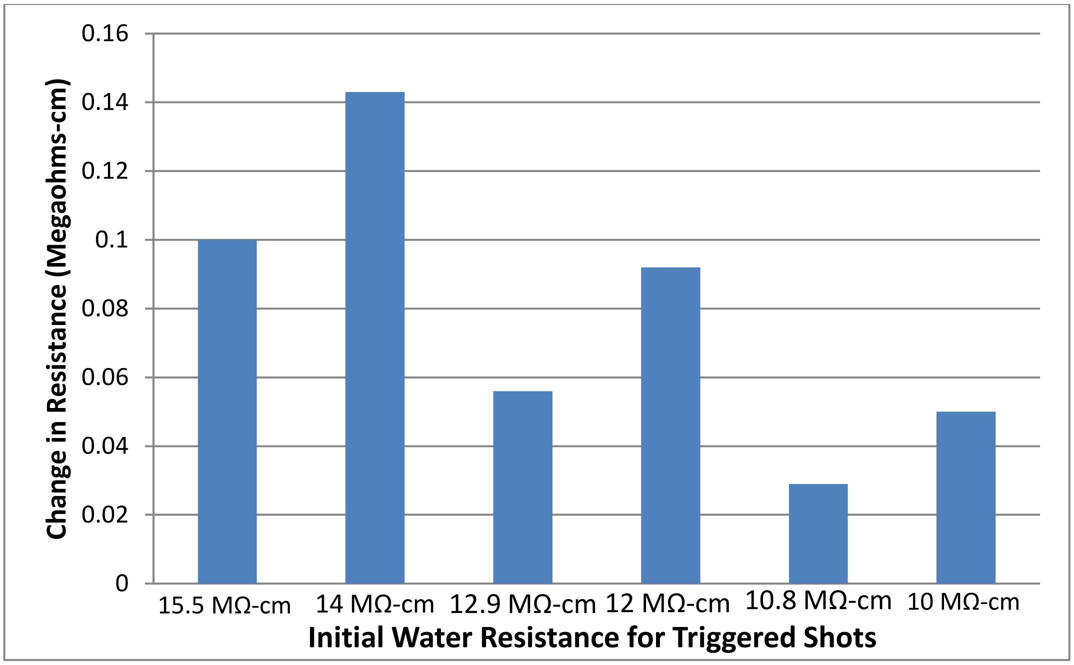


Figure 15: Changes in water resistance at decreasing starting resistances

6. Consecutive Drops

On some of the flash-lamp tests, a secondary drop in water resistance was detected after the first drop produced by a single current pulse. Figure 16 shows an exemplary graph with two consecutive drops in water resistance. This second drop was consistently smaller than the first drop and ranged from 0.07 Megaohms-cm to 0.02 Megaohms-cm in magnitude. The used lamp had the highest average discernible second drop. As the energy storage voltage increased, the frequency of secondary drops above the 0.02 Megaohms-cm benchmark increased. It was theorized that this double drop was produced by displaced metal from the second connector. This theory is supported by the secondary drop coming approximately 16 seconds after the pulse. The inside of the flash-lamp system, where the surrogate metal rod was housed, is 8 oz in volume. 16 oz of deionized cooling water separates the resistance sensor after contact with Multilam bands and the second connector in the flash-lamp system. At a flow rate of 64 oz per 60 sec, the second drop should arrive at the sensor approximately 16 seconds after the pulse forming network trigger.

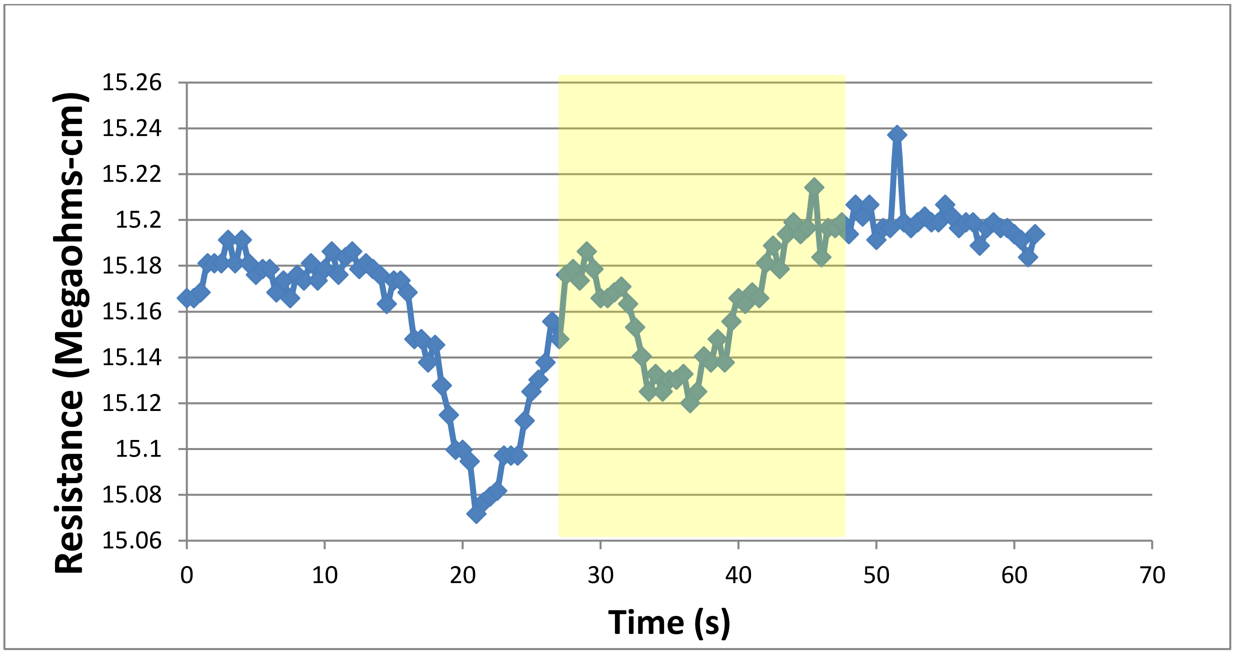


Figure 16: Data from sensor after contact with used flash-lamp system. There is a drop at 15.5 seconds followed by a second drop at 29 seconds. This test was conducted at 200 V. The Pulse Forming Network trigger occurred at ten seconds. The yellow area highlights the second drop induced by the pulse.

A possible explanation for the inconsistency of the appearance of the second drop under very similar conditions to Fig. 11 is that the released flash-lamp connector particulate varies in size. When relatively large particulate flows through the system, it requires a longer time for the debris to reach the sensor after contact with Multilam bands. If the amounts of debris for tests are approximately the same, the composition of the debris may be dissimilar. On tests where the flash-lamp connector releases particulate of a larger average size, the drop is longer in time and therefore has a lower magnitude. This explains why some tests, such as Fig. 11, show second drops with a change in resistance close to or below the resistance monitor threshold, while others, such as Fig. 16, show a change in resistance that exceeds the threshold. For more deteriorated flash-lamp connector sets, the amount of debris is great enough that a drop above 0.02 Megaohms-cm can still be recorded over a longer time. This effect of particulate size is compounded by the second connector because the holes which allow deionized water to enter the flash-lamp reservoir are higher than the base of the flash lamp. This could affect both the characteristics and timing of the second drop. Experiments that involve introducing different particulate of known sizes will help to understand the effect that particulate size has on how the release of flash-lamp connector debris is recorded on the graph.

7. Different Flow Rates

Different flow rates were explored and tested to see if any characteristics of resistance drops changed. With the new flash-lamp system, the flow rate was increased from 0.5 to 0.9 gal/min. Figure 17 shows a data set resulting from this faster flow rate. The flow rate had no effect on the magnitude of the drop. The resistance change did come earlier. At a flow rate of 115 oz per 60 sec (0.9 gal/min), the resistance drop should theoretically arrive at approximately four seconds after the trigger is initiated.

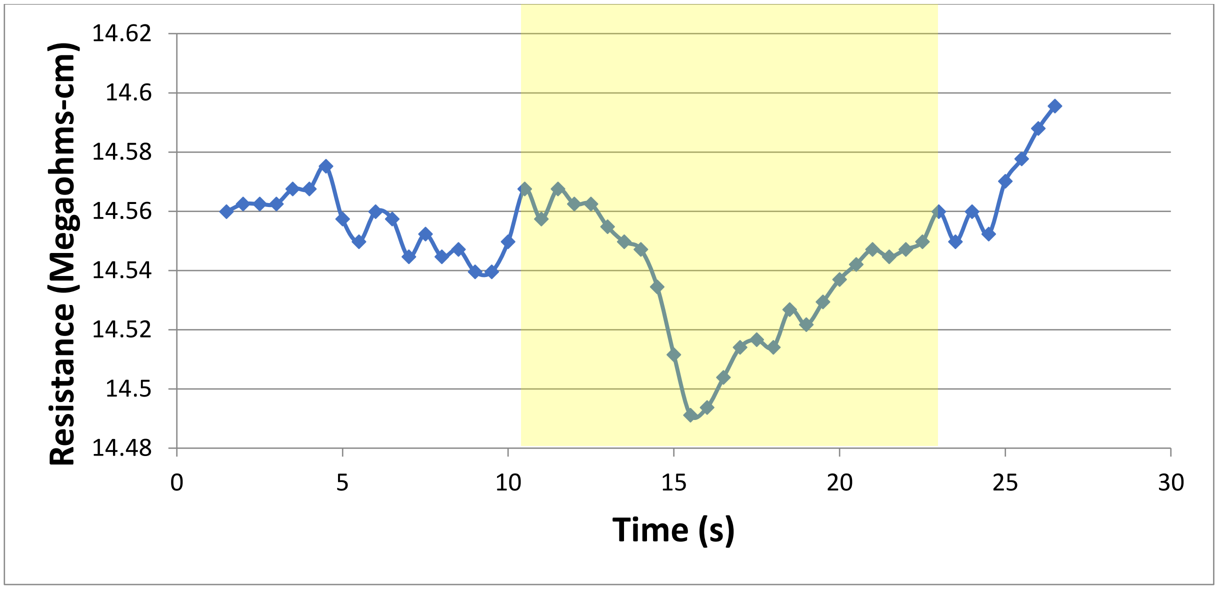


Figure 17: A graph of resistance with a flow rate of 0.9 gal/min. The change occurs at 12.5 seconds. The new flash-lamp system at 200 V was used to conduct this test. The Pulse Forming Network trigger occurred at ten seconds. The yellow area highlights the drop induced by the pulse.

8. Conclusion

Several conclusions can be drawn from these tests. The transient change in water resistance after a release of energy through the flash-lamp system can be reliably measured. As the current that flows through the flash-lamp system increases, the amount of metal displacement that occurs increases, thus the larger the resistance change. The used flash-lamp system consistently delivered the largest change in water resistance at all currents.

As a proposed future application, a surveillance system can be created to alert when the change in resistance after a laser shot exceeds a benchmark level. This will signify that the flash-lamp system, from which the large drop originated, needs to be serviced due to deteriorated connectors. Preemptive replacement of the flash-lamp connectors will avoid a flash-lamp system connector failure and laser shot failure.

Automation of the test used for this work may allow an insight into how many triggered shots it takes for a new flash-lamp system to produce resistance-change readings comparable to the used flash-lamp system.

The flash lamps on OMEGA and OMEGA EP that amplify the laser are connected in series-parallel. Analysis of flash lamps in series and series-parallel jacket connections is important for implementation into the OMEGA and OMEGA EP lasers.

Further research of the second connector in the flash-lamp system will increase the understanding of the water resistance graphs and increase accuracy in identifying flash-lamp connectors that need replacement.

On the experimental lab setup, debubbling can be tested. The process of removing dissolved gas bubbles in the water can decrease the amount of metal displacement and therefore increase the longevity of the flash-lamp systems. Results of the low resistance tests indicate that a lower resistance of the deionized cooling water negatively affects the accuracy of the change in resistance. For future implementation on OMEGA, the average starting point resistance would have to increase above 11 Megaohms-cm to be effective.

9. Acknowledgements

I would like to acknowledge Dr. Stephen Craxton and the Laboratory for Laser Energetics for giving me the opportunity to do this research. The internship was a fantastic experience. Special thanks to my advisors, Troy Walker and Greg Brent. They were instrumental in the growth of my knowledge in science and the success of this project.

10. References

[1] C. Cleveland, S. Moghaddam, and M. Orazem, “Nanometer-Scale Corrosion of Copper in De-Aerated Deionized Water,” *Journal of the Electrochemical Society,* vol. 161, pp. C107-C114, Dec. 31, 2013.

[2] Mike Scipione, Private Communication

[3] “Chapter 3: Laser Amplifiers,” *OMEGA EP System Operations Manual Volume VII–System Description*, pp. 17, August 2005.