Proposed Reliability Test Plan for Tesla's Liquid Cooled Supercharger Handles

Submitted by:

Darshan Singh

Submitted to:

James Wong

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1. Introduction

Tesla motors are the owners of the largest and most widespread network of electrical superchargers in the United States today. This is largely in part because every single car in Tesla's fleet is fully powered by electricity. In a stark contrast to the world's auto industry, which has been completely reliant on organic fuels as a power source for their cars since Carl Benz invented the first ever gasoline-powered car in 1879[1], Tesla cannot rely on the immense number of gasoline stations that litter the earth to serve as a location for a Tesla automobile to charge up. For this reason, Tesla had to develop their own supercharger technology in an effort to develop a similarly expansive network of superchargers so that Tesla owners could drive wherever they needed without fear that they would get stranded due to a lack of nearby superchargers.

In an effort to make the experience of charging your car similar to filling it at a traditional pump, Tesla needs to achieve charging speeds that are capable of rivaling the speed that is usually associated with filling up a gas-powered vehicle. Intuitively, it follows that the way to achieve a charging speed of 2-3 minutes for an electric car is done by pumping an incredibly high volume of charge into the car's internal battery at a breakneck pace. High charge flow means that the cables that are delivering the charge will be carrying very high currents, and high currents usually cause an incredible amount power dissipation when traveling through a resistance. In fact, power dissipated increases exponentially with respect to an increase in current. This means that the rate of charge being delivered by Tesla's superchargers is limited by how much power dissipation the electrical components and the actual housing can handle. In an effort to increase the maximum charge that their superchargers can deliver, the engineers at Tesla have recently created a variant of the original supercharger which is liquid cooled. This means that some of the power that the supercharger is going to generate in the form of heat will now be carried out of the system by a thermally conductive fluid which will eventually be recycled after it is cooled. On the surface, this design seems like an incredible innovation that needs to be released for public use as soon as possible,but that thought could not be farther from the truth. The introduction of a fluid system alongside an electrical system almost always spells disaster for the user if it isn’t properly tested beforehand for indicators of failure such as degradation of internal components over time, and response to ambient stimulus.

The tests detailed later in this report are focused mainly on socket wear out, button wear out, and HV crimp thermal fatigue. These three tests are going to test the most error-prone elements of the supercharger, and will aim to create a model that can accurately predict time to failure and expected life so that when they do eventually fail, a replacement or repair will already be on standby to remedy the failure.

2. Patent WO/2019/180622

2.1 Function

2.1.1 Overall System

The system as a whole can be simplified into a two-part assembly as illustrated in Fig. 2 of the patent. Charging system 200 is comprised of power supply 202 and charging connector 210. The power supply is connected to the charging connector through charging cable 204, whose ends 204 and 208 are coupled to power supply 202 and charging connector 210, respectively. This overall assembly has been recycled from previous supercharger designs, so there is no need to test it further. However, the design for charging connector 210 has been updated and will be explored further in the next sections.

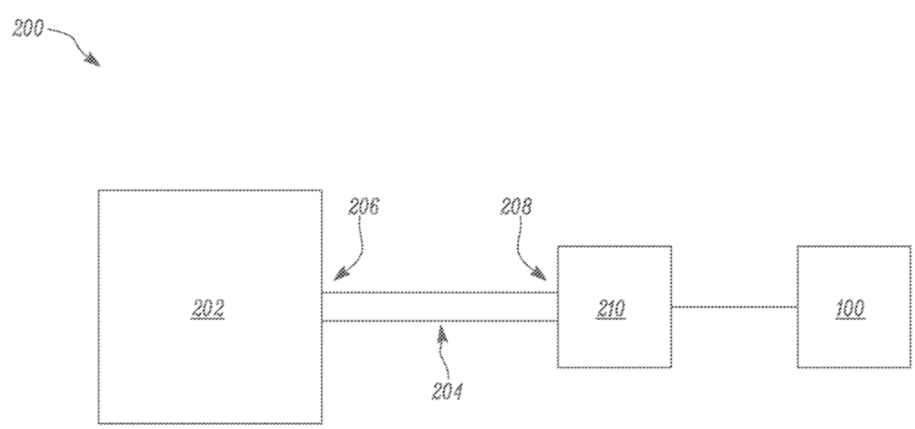

FIG. 2

2.1.2 Mechanical Assembly

Charging connector 210 can be observed in more detail in the patent'sFig. 4. When stripped of its handle housing (not shown), charging connector 210 is composed of two electrical sockets 404 and 406. These electrical sockets are concentrically coupled with socket sleeves 410 and 412, respectively. There also exists a manifold assembly 414 which encloses both sockets 404 and 406, along with socket sleeves 410 and 412. When assembled, there exists a hollow space 416 between manifold assembly 414 and socket sleeves 410 and 412 through which liquid will be flowing in an effort to try and cool down charging connector 210 when it is in use.

In fig. 5, The inlet conduit 512 and outlet conduit 514 for this liquid flow are shown. The liquid will flow through inlet conduit 512 and into hollow space 416, where the liquid will sink some of the heat generated by electrical sockets 404 and 406. Then that liquid will flow out of hollow space 416 and into outlet conduit 514.

To prevent fluid leakage, the cross-section illustrated in fig.7 shows that socket sleeve 410 is coupled to the manifold assembly 414 using O-rings 702 and 704. When coupled, O-rings 702 and 704 create a tightly sealed hollow space 416 where liquid can flow through without leaking.There are two more O-rings (not pictured) which will also be coupling socket sleeve 412 to manifold assembly 414 to seal the other end of hollow space 414. Although it is a bit difficult to see, both conduits 512 and 514 are placed in between socket sleeves 410 and 412 at the top and bottom of the manifold assembly 414.

The actual fluid flow path 802 is more explicitly illustrated in fig. 8. The fluid flows through input conduit 512 and bifurcates into two smaller streams 804 and 806, which flow around socket sleeves 410 and 412 respectively. While flowing around socket sleeves 410 and

412 in hollow space 416, Heat from electrical sockets 404 and 406 is being transferred to the liquid through thermally conducting sleeves 410 and 412. Streams 804 and 806 are then combined upstream of output conduit 514 on the other side of manifold assembly 414. The fluid which is flowing out of hollow space 416 and through output conduit 514 can then be routed to an on-site reservoir which can reject the absorbed heat of the liquid and recycle the liquid back into the flow path as specified above.

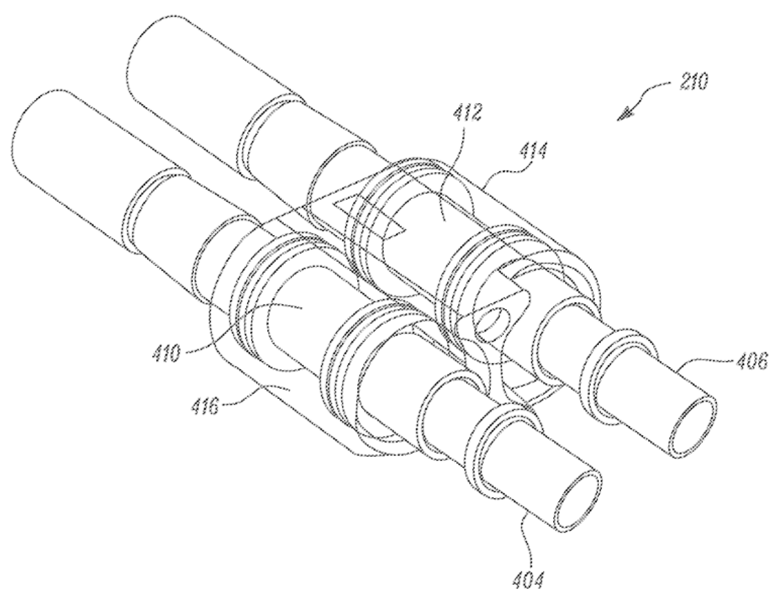

FIG. 4

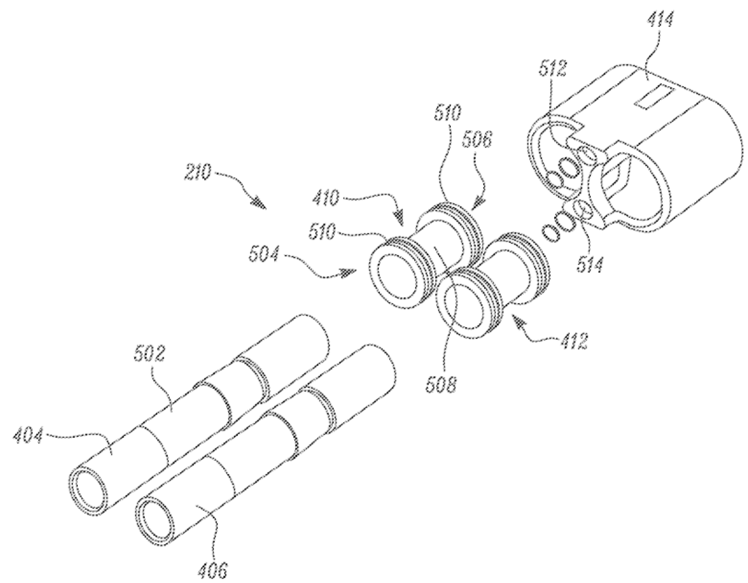
414
512
510
506
210
410
510
504
514
412
502
508
404
406

FIG. 5

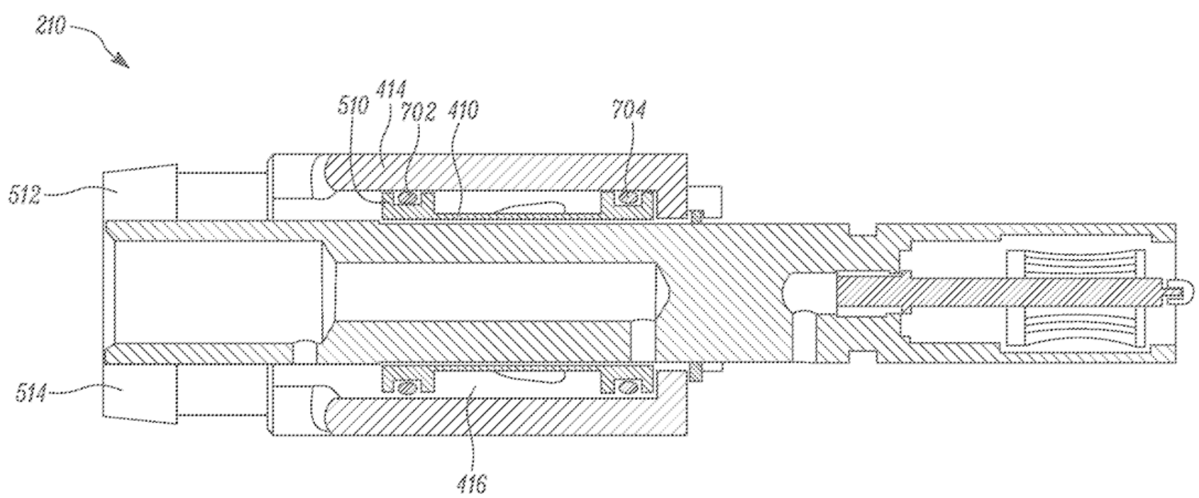
210
510
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FIG. 7

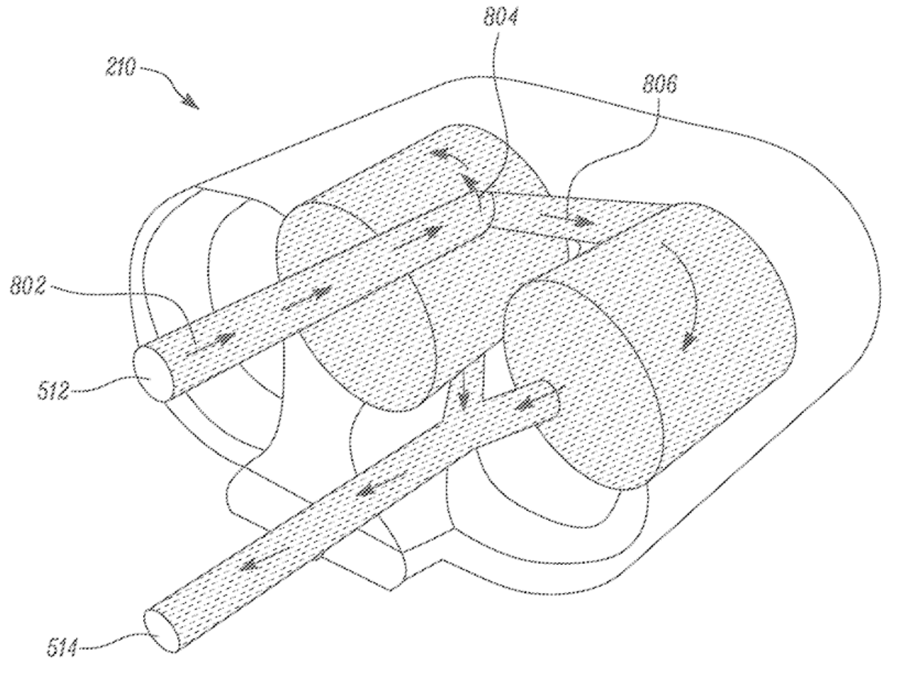


FIG. 8

2.1.3 Electrical Assembly

Relative to the Mechanical assembly, the electrical assembly is quite simple, as shown in fig. 10 of the patent. The only electrical component, Printed Circuit Board Assembly 902 (PCBA), is thermally coupled to charging connector 210. However, PCBA 902 is actually a two part system in that it is comprised of two separate boards 904 and 908, which are interconnected through a rigid-flex PCB construction. This two-part construction allows for the charger to have a smaller form factor than it would have otherwise. Also shown is temperature sensor 1002, which is thermally coupled to the inside of electrical socket 406 to provide accurate temperature readings, which can be used to regulate flow of coolant and provide data that may indicate imminent failure. There is also another temperature sensor coupled on the inside of electrical socket 404, but it is not shown in fig. 10.

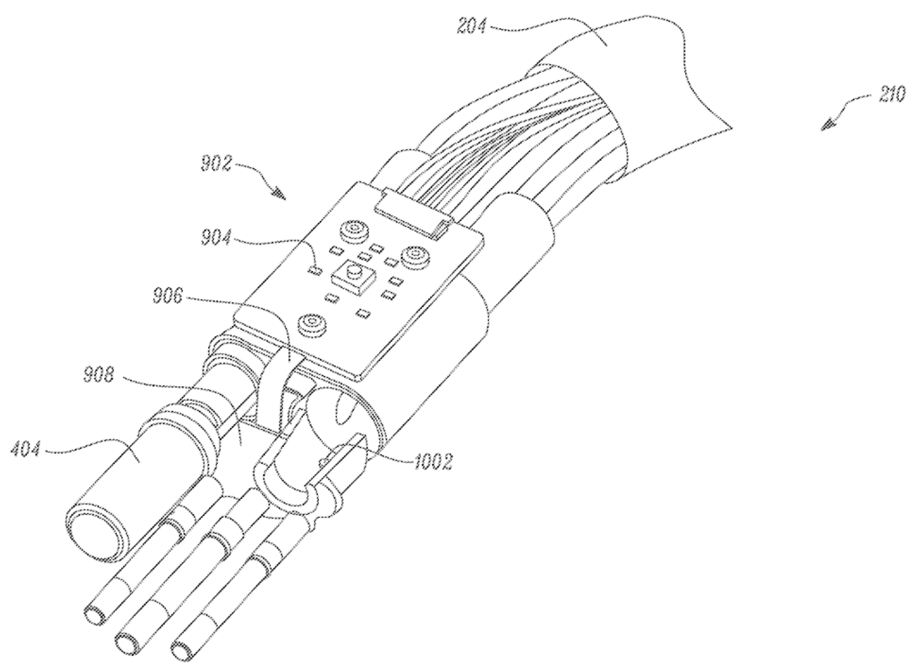


FIG. 10

2.2 Failure Modes Analysis

2.2.1 Failures from Wear

When a user is operating a supercharger in an attempt to charge their car, they need to interact with the charging connector that will be plugged into the charge port of the car. During this process, the user will be pressing the UHF button on the handle to open the charge port, and to disengage the connector from the port when charging is complete. The main failure mode of this button is purely mechanical and will occur as a result of repeated button presses. Other failure modes may include failures caused by targeted abuse or vandalism. However, we cannot set up tests for these sorts of failure modes since these events happen at random and are unpredictable.

When operating the supercharger, the user will also be interacting with the electrical socket in an indirect way. The user will be controlling stresses such as the force of entry and the angle of entry of the socket into the vehicle's charge port. These specific stresses are related somewhat to the height and the distractedness of the user, as well as their state of physical fitness. As such, we cannot set this kind of test up in a lab since we do not have any way of predicting what kind of people will be visiting our superchargers and at what frequency they may be visiting. However, it is possible to conduct field testing for this sort of stress which will provide effective data to create a model to give us a time to failure and an expected life.

2.2.2 Failures due to Thermal Stress

During the vehicle's charge cycle, the high voltage crimp is undergoing large thermal swings, some almost as high as 70 degrees Celsius. We know this because there are temperature sensors thermally coupled to the interior walls of the electrical sockets of the charging handle. This thermal stress over thousands of potential cycles yields a high probability of failure at this point. Since these handles are expected to have a two year lifetime, we have to conduct an accelerated life test to prove that the handles will indeed be operational for at least two years.

2.2.3 Other Failure Modes not being Tested

There are many other failure modes that we must take into consideration, but do not fall under the scope of this specific round of testing. Some other failure modes include the following but are not limited to:

- Coolant leakage as a result of cracked O-rings
- Internal breakage of the power cord, which may result to sporadic charging rates
- Forced ejection of the charging handle without disengaging the lock mechanism
- Inclement weather causing adverse effects to the internal mechanical and electrical hardware
- Internal damage from repeated dropping of the charging handle

3. Experimental Design

3.1 Socket Testing

3.1.1 Component Detail

The socket is visible in detail in fig. 10 as shown in section 2.1.3. The socket is comprised of an outer covering, an interior pin, and uses thermally conductive plastics and liquid cooling to reduce the temperature.

3.1.2 Data Acquisition

To acquire the data necessary to fit the operational life of the socket to a mathematical function, a time compression test should be conducted. The most used pump at any station in Southern California in 2019 was used a total of 11256 times. This means that there were at least 11256 inserts of the socket into vehicles, and 11256 extractions of the socket from vehicles. Since the lifetime of the charging connector is meant to be at least two years, we will need to simulate 22512 uses of the charging connector. Since these handles are only used a little more than 100 times a day at most, it is possible to greatly compress the time necessary to simulate 22512 uses of the socket.

The test will be conducted as follows. An elliptical cam will be set up which will be converting rotational motion into transversal motion. This transversal motion will be used to insert the socket and extract the socket from a charging port. There will be a small charge flowing from the socket into the charging port to provide data that will show degradation if there is any, and will be helpful when calculating time to failure and expected life functions with respect to time. This charge will be measured by an integrated computer system capable of monitoring current and storing large amounts of information. It will be set up to collect data constantly in the background while the test is run. At the end of the test, the data stored in this computer system will be examined and mined for data. In an effort to collect more accurate data, multiple sockets will be tested at the same time using this same method, and the data from each will be considered in the final calculations for product life, unless some unexpected failure mode is experienced. The temperature will be kept at room temperature in an effort to isolate the degradation that the mechanical stress of inserting and removing a socket from the port causes. Assuming that each cycle of the cam takes around one second to complete, all testing and measurement will conclude in under 16 hours. If no failures are experienced during testing, the socket of the charging connector can be considered fit for production and subsequent distribution.

When this socket is being inserted at a charging station by the average consumer, there is no guarantee that the socket will be inserted with the perfect angle of attack to ensure that the port and socket will experience the least mechanical fatigue possible. Every person that uses the supercharger will insert the connector with a different angle of attack from the other. So, to simulate this variation of stress, the charging port will be placed on a tilt table capable of tilting an object from side to side and from front to back. This table will be tilted a small amount from a completely flat state at random right before each cycle of the cam to more accurately reflect the operational life of the socket.

3.1.3 Stress Conditions

The stress condition for this test will be the repeated insertion and removal of the socket from a charging port. There will also be added mechanical stress caused by a tilt table which controls the angle of attack of the socket.

3.2 Button Testing

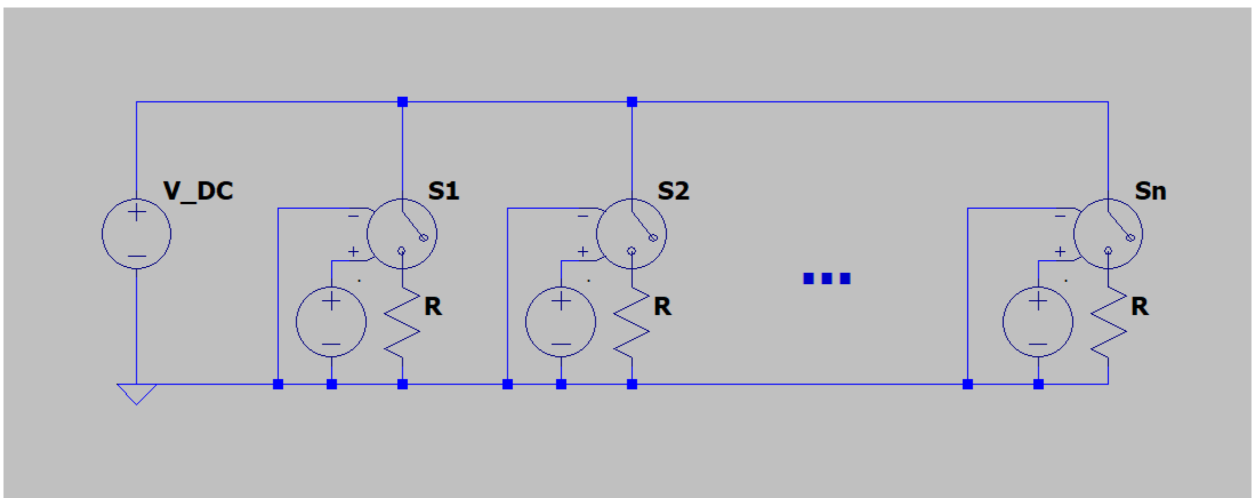
3.2.1 Component Detail

The button that will be present on the supercharger's handle is a two-state button that is being used solely to initiate charging and to disengage the handle from the vehicle at the end of charging. It will be pressed and held many times over its lifetime.

3.2.2 Data Acquisition

To acquire data necessary to fit the operational life of this button to a mathematical function, a time compression test should be conducted. Button presses are not experienced very often daily, so since it is possible to emulate a whole two years and more of button presses in the span of a few days, an accelerated life test will not be necessary. We suggest instead an accelerated time under the same normal operating conditions. For this specific test, the time of failure of multiple buttons placed on the same test bed will be collected.

The test will be conducted as follows. A quick-return mechanism will be set up in such a way that an appendage will extend much faster than it will reset. This transversal motion of this appendage will be split into many smaller appendages which will all concurrently press different buttons. Each of these appendages will be used to simulate a button press by exerting a force similar to that of a human's finger. An arrangement of about 100 buttons will be set up in a lab setting. These buttons will be repeatedly pressed and released with a frequency of one button press per second and a duty cycle of 50%. An integrated computer system will be connected to each button's output to monitor time of failure. Time of failure will be determined by measuring the voltage drop of a resistance that will be in series with the button's output signal as shown in the figure below:



The voltage drop of each resistor will be measured constantly by the integrated computer system during testing, and will be saved into its onboard memory. At the end of the test, the data stored in this computer system will be examined and mined for data. Assuming that each cycle of the mechanical mechanism takes about one second, all testing and measurement can conclude in under 16 hours, just like the socket testing that was detailed earlier in section 3.1.2.

3.2.3 Stress Conditions

In this test, the main stress will be coming from the repeated button presses that are simulated by the quick return mechanism as specified in section 3.2.2. This repeated periodic stress will cause the spring that makes the button pop back up to become weaker and possibly even crack. This degradation of the button will eventually lead to the failure of the button.

3.3 HV Crimp Testing

3.3.1 Component Detail

The HV crimp is one of the most essential elements of the handle in that it is quite literally the link between the vehicle and the supercharger that pumps charge into the batteries of the vehicle. Due to the very nature of the function that it fulfills, the crimp undergoes many large temperature cycles in a year. If the crimp were to fail even slightly, It would greatly hamper the blazing fast charging rates expected from this system, and could very possibly break the whole system until a repair can be arranged. The crimp exists inside the socket of the supercharger handle and is physically crushed and yielded to the socket during fabrication in order to establish an electrical connection.

3.3.2 Data Acquisition

Since temperature cycling of an object takes a very long time, It is not possible to conduct a time compression test. Thus, it is necessary to conduct an accelerated life test on the crimp.

To determine the cycles necessary to accelerate the operational life to a small enough period of time, we must utilize the Coffin Manson equation[2] to calculate a satisfactory acceleration factor (AF). The equation is as follows:

$$AF = \left(\frac{\Delta T_{test}}{\Delta T_{field}}\right)^n,$$

where ΔT_{test} is the range of the temperature cycle during our test, ΔT_{field} is the range of temperatures typically experienced in the field during operation. n is a constant which is reliant on the material in question. For this test, we need to find the ΔT_{test} necessary to accelerate the life to a small enough number of cycles where this test doesn't end up delaying the deployment of this system for too long. Our ΔT_{field} for this test is going to be 62.488 degrees Celsius since that is the largest range of temperatures that is expected from the new pumps when they are being charged from 0% to 90% based on collected data. Our function to find the acceleration factor is as follows:

$$AF(\Delta T_{test}) = \left(\frac{\Delta T_{test}}{62.488}\right)^2$$

To finally calculate an appropriate acceleration factor for our testing, we need to decide on a suitable range of temperatures to cycle between. In the United States of America, the hottest and coldest recorded temperatures on record are 56.7 ºC[3] and -56.7 ºC[4] respectively. By rounding these temperatures to their nearest multiple of ten, a range of temperatures spanning 120 ºC from -60 ºC to 60 ºC can be used the range of the thermal cycler. With ΔT_{test} now equalling 120, the number of cycles necessary to simulate two years of thermal stress can be found by solving the following equation:

$$\#\ of\ test\ cycles\ necessary = \frac{22512}{AF(120)},$$

where 22512 double of the most visits that any one pump had in 2019. It is solved like this:

$$\#\ of\ test\ cycles\ necessary\ =\ \frac{22512}{(\frac{120}{62.488})^2}$$

$$\#\ of\ test\ cycles\ necessary\ =\ \frac{22512}{3.687815985390742}\ \approx 6105\ cycles$$

So, just about 6105 cycles of the thermal cycler would be necessary to simulate two years of thermal fatigue on the HV crimp. To measure the effect of the thermal cycling, a small electric current can be put through the crimp and the cable that it's attached to. The current that travels through the crimp will be constantly measured during the whole duration of the testing by an integrated computer system that is capable of measuring current and storing large amounts of data. At the conclusion of testing, the data stored onboard the integrated computer system will be examined and mined for data.

3.3.3 Stress Conditions

The stress condition for this test is the thermal cycle. The current flowing through the crimp during testing will be large enough that it will change as the crimp degrades, but it will also be small enough so that its effect on the degradation of the crimp is minimal. We are trying to isolate the effect of the temperature cycling on the crimp, so any degradation caused by a current will negatively affect our results.

3.4 Other Proposed Tests

3.4.1 O-ring Testing

Rubber is known to become very brittle when exposed to stimuli such as ultraviolet rays or high temperatures, among others. Since these O-rings are the sole reason why the coolant isn't flooding the rest of the handle, and since they are being exposed to large temperature cycles on a daily basis, I feel that reliability testing should be done on these in a similar fashion to how testing is going to be done on the socket crimp. These O-rings are arguably more important to the function of the pump as compared to the crimp, so it’s an absolute priority that these rings don’t fail before the expected life of the pump is reached.

3.4.2 Humidity cycling

I also feel that the unit as a whole should go through some humidity cycling tests as a way to measure how waterproof the whole system is. By inserting indicator strips in various cavities of the handle, including the hollow space where the coolant cools the sockets, when the humidity is cycled, if all of the strips remain dry, then you can be fairly confident that no fluid will leak out of the handle in the event that a system may fail or malfunction. This will also test the tolerances of all the parts that are being used in the fabrication of this charging connector as well as the reliability of the handle in wetter climates. Even if this test may not return any viable reliability data, it should still be conducted just to test the overall quality of the product.

6. References

[1] “Benz Patent Motor Car. The first automobile (1885–1886)”, Daimler, 2020

[2] J. W. McPherson, Reliability Physics and Engineering, Springer, 2010

[3] Christopher C. Burt, (22 July 2016). "Hottest Reliably Measured Air Temperatures on Earth", Weather Underground, 2016

[4] "Top Ten Montana Weather Events of the 20th Century", National Weather Service, 2007