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

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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 things such as degradation of internal components over time, and response to ambient stimulus.

The tests that will be detailed later in this report will be 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 the 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.

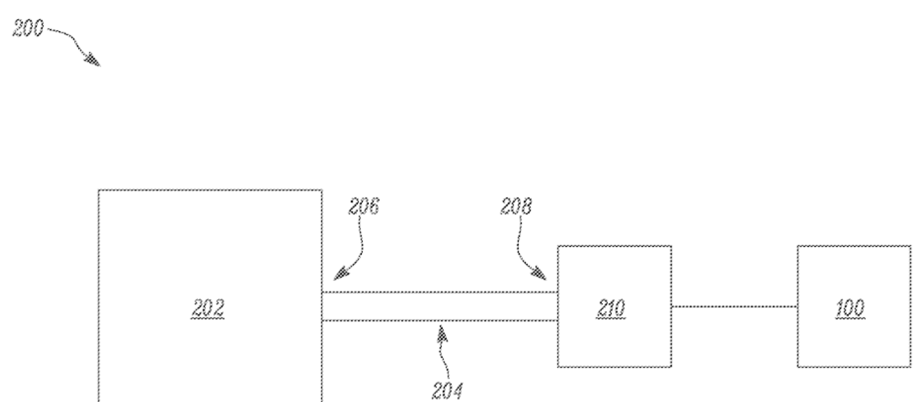

FIG. 2

2.1.2 Mechanical Assembly

Charging connector 210 can be observed in more detail in the patent’s fig. 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.

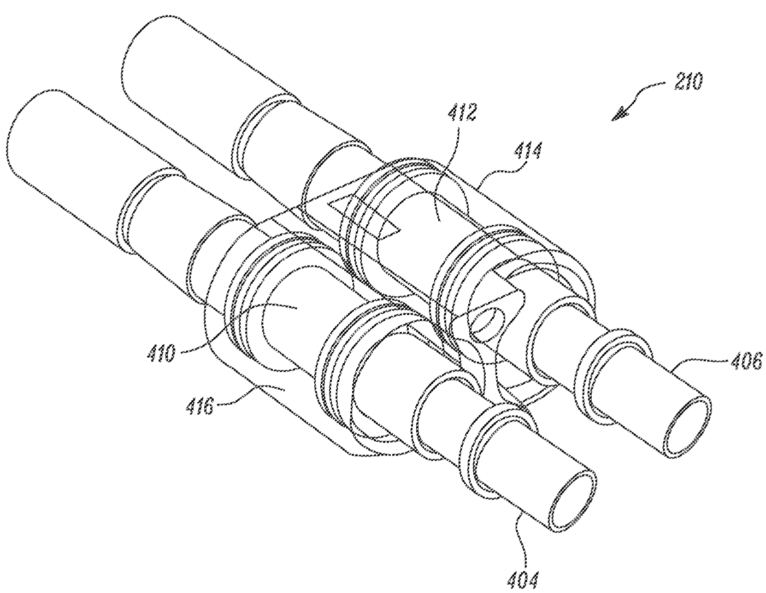

FIG. 4

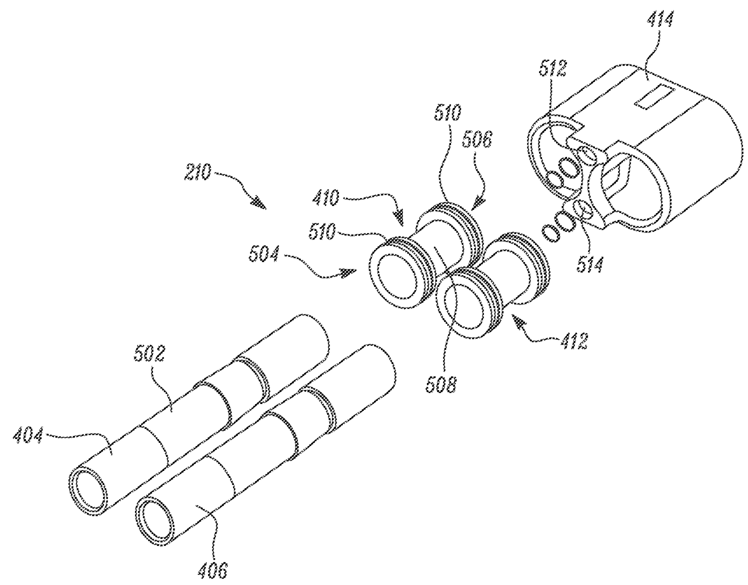
414
512
510
506
210
410
510
504
514
412
502
508
404
406

FIG. 5

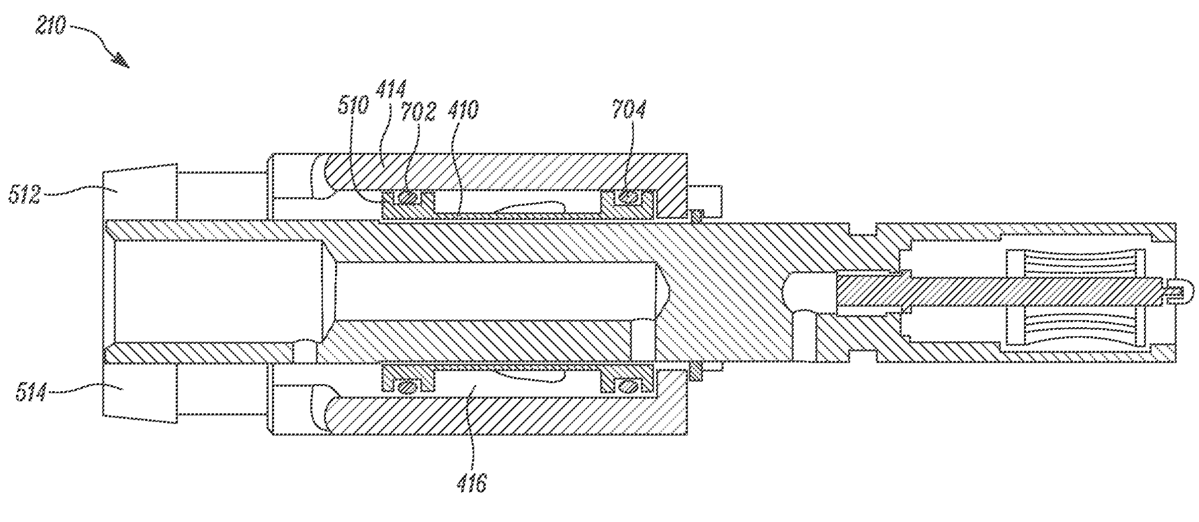
210
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FIG. 7

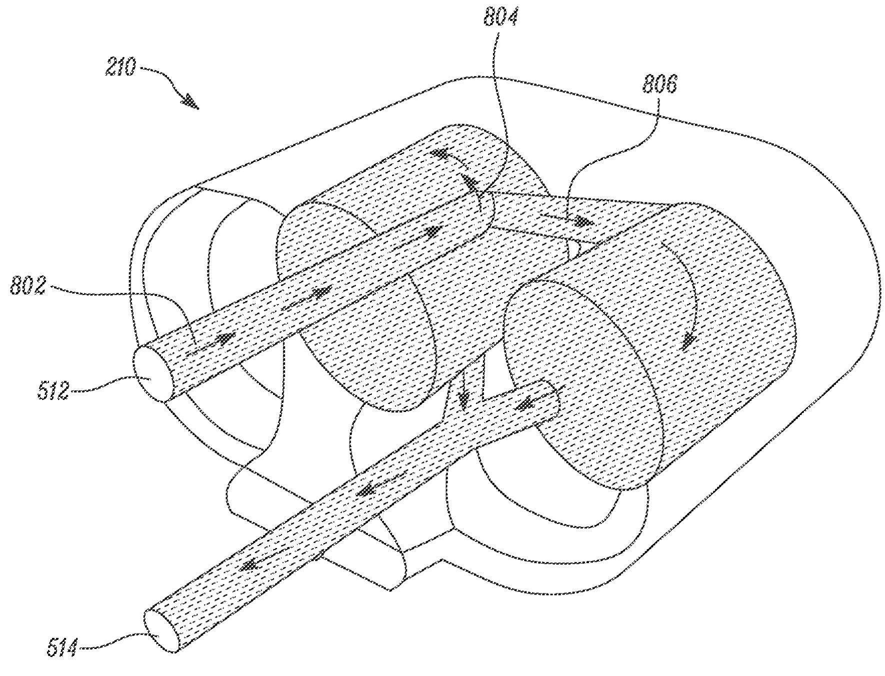


FIG. 8

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.

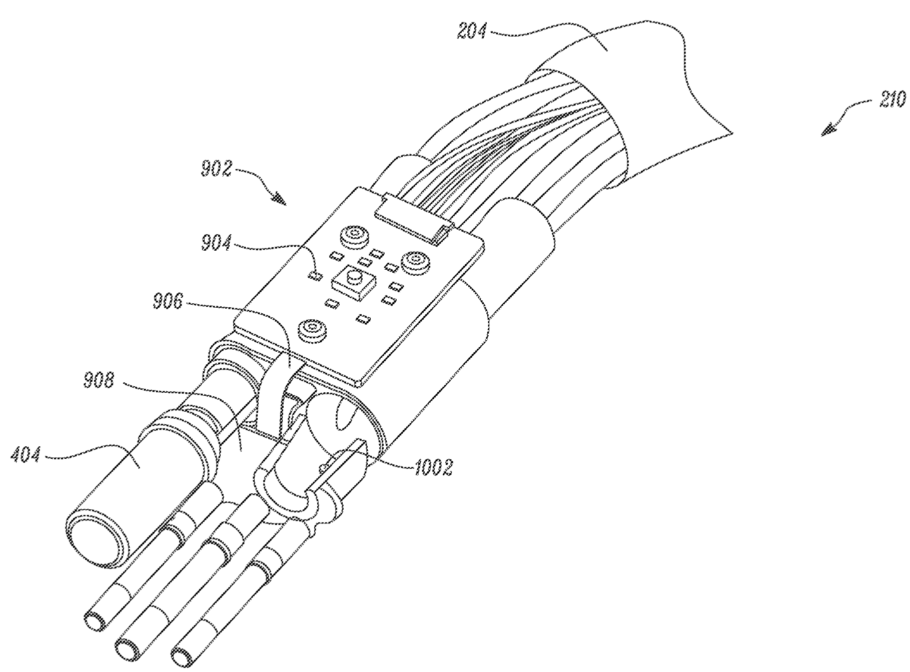


FIG. 10

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 things like 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 things like 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 from thermal stress

During the vehicle's charge cycle, the high voltage crimp is undergoing large thermal swings, some almost as large 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 chance that we may experience a chance 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 whole 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 water 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, I propose that a limited field test be conducted. The different ways that a human can incorrectly insert the socket into the vehicle are so numerous and random that it is very difficult, and bordering on impossible to accurately model this behavior with an automated system. A field test would be ideal since it would allow the very humans that stress the sockets to do the stressing, and would thus yield the best data we could possibly obtain. From this data, we will be tasked with calculating the expected life of the sockets based on the times that others failed during the limited field tests being conducted. We also have temperature data for the sockets, and can associate that with this collected data as well to further enhance the results that we will get from this field testing.

To gain enough data for this testing, I propose the installation of this new charging technology at four or five charging stations that are relatively spread out, but frequently visited. Once installed, an integrated computer system of some sort can be introduced temporarily to the system to monitor any errors that may be encountered during the duration of testing, which can go on for as long as needed, until enough failures to accurately map the data to a function are experienced. If no failures are experienced in the first six months of testing, It can be considered that this element of the new supercharger is reliable enough to install at the rest of the superchargers in the world.

3.1.3 Stress Conditions

The stress conditions for this test will be the induced stress that a human operator will naturally cause to the socket during operation, and the innate thermal stress that may possibly accelerate the rate of degradation. The time of failure of the handle as well as the temperature right before the start of charging and right before disengagement of the handle will be recorded. The number of times that the handle was inserted and removed will also be recorded.

3.2 Button testing

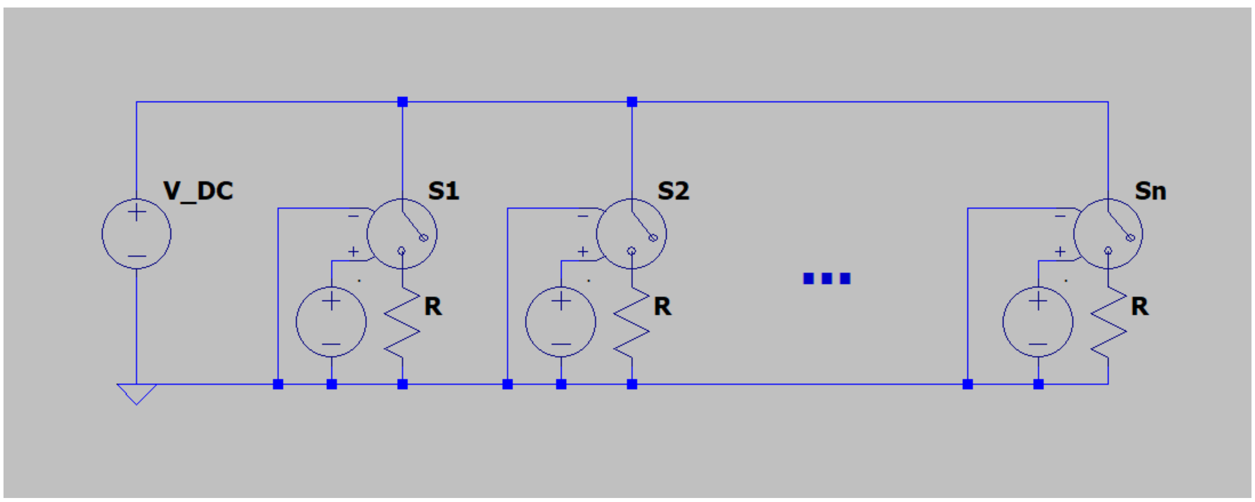
3.2.1 Component detail

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 stress test in a lab must be conducted. Since button presses in the field will not be experienced by the handle too frequently, an accelerated life test will not be necessary since it is possible to emulate a whole two years and more of button presses in the span of a few days at most. For this specific test, the time of failure of multiple buttons will be collected.

The test will be conducted as follows. An arrangement of about 100 buttons will be set up in a lab setting. These buttons will be repeatedly pressed and held for three seconds with a force of about twice the activation force needed to press the button. The buttons will be pressed by a mechanical arrangement of rods that will be pushed down by a hydraulic system calibrated to generate a pulse of force with a period of four seconds and a duty cycle of 75%. An integrated computer system would be connected to each button to monitor time of failure as shown in the figure below:



The voltage drop will be measured over the resistors R to detect if the button has failed. If the voltage of V_DC is not being measured with the same 4 second period with 75% duty cycle cycling as the buttons are experiencing, the button's time of failure will then be recorded for later analysis.

Enough cycles to emulate the total number of button presses that the most trafficked pump would experience in two years will be completed in about 25 hours of testing, so if there are no failures experienced within a day of testing, It can be considered that this element of the new supercharger is reliable enough to install at the rest of the superchargers in the world.

3.2.3 Stress conditions

The only stress conditions that should be present in this test is the mechanical stress of the button presses. We want to isolate specifically just the effect that pressing the button has on the life of the button. If there are any other stresses in play, it will negatively affect our results.

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 simulate all two years of thermal fatigue that the crimp experiences in a short amount of time like the button testing that was outlined in section 3.2. 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 calculate a that makes sense to run a test with, we need to first come up with a few test durations that we would like to run the test for. Just as baselines, I chose durations of one day, one week (7 days), and one month (28 days). Since the specifications of the thermal cycler that we will be using aren't available, I will be using the time it takes to complete a full charge (35 minutes and 44 seconds) as the theoretical time it takes to complete one full temperature cycle. This means that in one day 41 cycles can be completed, in one week 293 cycles can be completed, and in one month 1172 cycles can be completed. The number of cycles that will be experienced in the field over a span of two years is being assumed as 22512. We are getting this number by multiplying the most visits that any pump in Southern California experienced in 2019 by two. So now, to find a satisfactory range of temperatures to cycle between in the lab, we must divide this theoretical number of cycles over two years (22512) by the AF that we will get as a result of our test specifications as follows:

$$\Delta T_{test} = 62.488\sqrt{\frac{22512}{(\#\ of\ cycles)}}$$

For our three proposed numbers of cycles, we get the following results:

$$\Delta T_{test} \text{ for one day (41 cycles)} = 1464^{o}C$$

$$\Delta T_{test} \text{ for one week (293 cycles)} = 548^{o}C$$

$$\Delta T_{test} \text{ for one month (1172 cycles)} = 244^{o}C$$

A temperature cycle over 1464 or 548 degrees Celsius in just over a half hour of cycle time seems highly improbable. However, the 244 degree cycle seems to be a lot more doable, and assuming that the thermal cycler that is going to be used can handle that kind of change in as little as a half hour, we will have to end up running the test nonstop for a whole month while cycling our crimp in between two temperatures with a difference of 244 degrees Celsius.

If it is possible to constantly and safely monitor a current flowing through the crimp during the test, it should be done so that in case no failure is experienced, degradation data can be collected and used to model the life of the crimp over time. Otherwise, an integrated computer system can be set up to send a current through the crimp every time the thermal cycler reaches room temperature to ensure the safety of the cycler during measurement.

Enough accelerated cycles to emulate the total amount of thermal stress that the most trafficked pump would experience in two years will be completed in about one month of testing, so if there are no failures experienced within that time, It can be considered that this element of the new supercharger is reliable enough to install at the rest of the superchargers in the world.

3.3.3 Stress conditions

The stress only conditions for this test will be the temperature cycling. 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