Refurbishment of a Crawford Strand Burner and Procedures

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In the past, students in Sun Devil Rocketry, formerly Daedalus Astronautics, have utilized a Crawford Strand Burner to aid in the characterization of solid propellants. In recent years the Strand Burner has gone unused and neglected. Due to the growing need to mix and characterize propellants for internal club use, the members of the Solid Propellant Research Team will refurbish the Strand Burner for future testing and development of solid propellants. Updating the Strand Burner, along with the propellant mixing and testing procedures, will allow Sun Devil Rocketry to accurately and safely characterize different rocket propellant variants for future use in competitions. Through cumulative research since 2019, many updates have been made to the mixing and testing procedures which will be employed by Sun Devil Rocketry in subsequent years.

I. Nomenclature

ASU = Arizona State University
A_b = Burn Area
A_e = Exit Area
a = Regression Rate Coefficient
DAQ = Data Acquisition
F = Thrust
FOS = Factor of Safety
$\dot{m}$ = Mass Flow Rate
n = Regression Rate Exponent
P = Pressure
$\dot{r}$ = Regression Rate
ρ_b = Burning Density
V_e = Exit Velocity

II. Introduction

Solid rocket propellant is widely used for aerospace applications today, from missiles to space launch vehicles. Whether for massive aerospace corporations like Raytheon and Northrop Grumman, or amateur rocketry members in the Tripoli Rocket Association and the National Association of Rocketry, there is a need for rocket propellant research in order to support its varied applications. Up until 2015, Sun Devil Rocketry (formerly Daedalus Astronautics) developed and tested various solid rocket propellant mixtures. The Solids Research Group (SRG) has worked on projects such as designing a flight-ready O-class motor as well as investigating the effects of aging on solid propellants. The team did this while developing a Crawford Strand Burner to characterize different propellant formulations. The Strand Burner itself allowed for rapid prototyping of propellant mixtures as smaller batches of propellant could be mixed and evaluated for critical performance measures. This rapid approach helped to develop

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different propellants quickly and assisted in creating flight-ready variants. In 2012, the SRG ran into complications with a full motor test resulting in a catastrophic failure, in which a spacer was not properly implemented between propellant grains. Since that incident, the organization has been held to stringent safety standards and critical oversight. However, this incident did not stop the SRG from propellant development as there have been intermittent tests over the past few years. Unfortunately, there has not been a flight-ready motor fabricated by the SRG since 2015.

Now, seeing the need for more research in solids, the solid rocket propellant development process has been reborn at Sun Devil Rocketry. However, many of the systems that were previously used have gone untouched for several years. Since the Strand Burner system has been unused since 2015, it is necessary to review the design to ensure it is safe for further use. This review has included reading through the design paper, identifying the design tolerances and the overall strengths and weaknesses of the Strand Burner. The SDR testing and mixing procedures also required a significant update, as many of the documents were not well-kept and some of the alterations were not properly recorded over time. To ensure the safe development and testing of propellants, the structure and subsequent procedures must be updated to comply with current safety standards at ASU as well as the internal standards set by the club.

III. Crawford Strand Burner and Upgrades.

A. Solid Rocket Propellant Characterization

A big challenge for solid propellant development is the difficulty to predict the performance of a rocket motor through analytical equations. Therefore, it is necessary to characterize the propellant on a small scale before packing an entire motor. The fundamental science that drives solid propellants is called 'internal ballistics' [1]. This refers to many important parameters of solid propellant performance such as 'regression rate,' 'burn area' and 'combustion chamber pressure' to name a few. These parameters are the easiest to modify and test with quick, small-scale tests with a Strand Burner.

The primary goal of solid propellants characterization is to determine the 'regression rate.' The regression rate can be altered by adding burn rate modifiers or 'catalysts' that will increase the burn rate. The regression rate of a solid rocket motor is dependent on its chemical formula and chamber pressure; thus, an equation can be written to relate these characteristics to the burn rate of the propellant in order to predict performance parameters, including thrust and specific impulse. The mathematical relationship for the burn rate and pressure are defined by Saint Robert's Law seen in Eq. (1). The equation is made up of three terms: the chamber pressure, burn rate coefficient, and burn rate exponent. The burn rate coefficient *a* is also referred to as the temperature coefficient as it has a linear relationship to the initial propellant temperature. The burn rate exponent *n* is also denoted as the combustion index, as it is directly attributed to the influence of chamber pressure.

$$\dot{r} = aP^n \tag{1}$$

Since the values of *a* and *n* cannot be determined analytically, they must be found empirically by characterization tests. This can typically be achieved in a Strand Burner or small scale evaluation motors. Small scale tests such as these offer the advantage of a lower energy testing environment in the event of a failure. As can be seen by Eq. (1) the burn rate is very sensitive to the burn rate exponent *n*. Higher values of *n* can lead to rapid changes in burn rate with changes in chamber pressure. When the burn rate exponent becomes 1, small changes in pressure can lead to large spikes in regression rate and have unfavorable consequences. Along with the burn rate and pressure as mentioned previously, the burn area plays an important role in rocket motor performance. The area of burning propellant will determine the mass leaving the motor, and subsequently the thrust produced by the propellant. This is evident in Eq. (2), which describes the mass flow rate in terms of the regression rate, burn area and propellant density.

$$\dot{m} = A_b \dot{r} \rho_b \tag{2}$$

Being able to predict the mass flow rate has a large impact on predicting the flight performance of the motor. As seen in Eq. (3), the thrust is linearly dependent on the mass flow out of the rocket motor. The thrust can be expressed as a function with either the mass flow rate, or the regression rate as seen below.

$$F = \dot{m}V_e + \Delta P A_e = A_b \dot{r} \rho_b V_e + \Delta P A_e \tag{3}$$

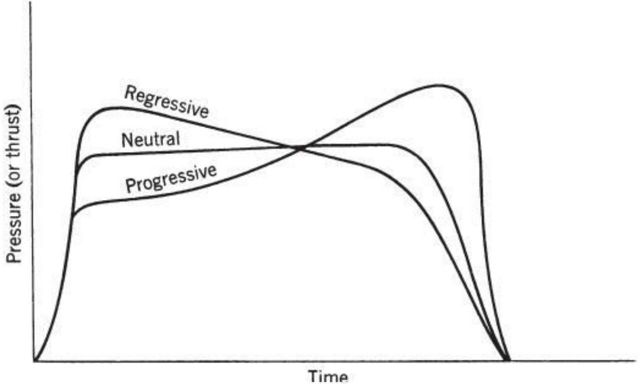

Figure 1: Thrust Curves of Various Burn Types[1]

Obtaining the values of *a* and *n* for a given propellant formula is critical for the prediction of performance, as it determines the regression rate. This allows for the thrust or chamber pressure to be characterized over the burn time of the motor. The thrust curve plot is critical in designing a flight-ready motor as it will detail the motor behavior throughout the boost phase of the flight. In order to calculate thrust, the regression rate and burn area are key parameters. There are three general burn rate types: progressive, regressive, and neutral. For progressive burn rates, the burn area will increase with time, and subsequently the thrust will too. For regressive burn rates, the motor will start with a large surface area burn and decrease over time. For neutral burning motors, the burning surface area will stay relatively constant, thus providing constant thrust throughout the boost phase. The different types of thrust curves can be seen in Fig. 1 [1]. For the purpose of Strand Burner testing, the burn area is kept constant, thus providing a relatively neutral burn. Being able to predict the regression rate, expected pressures and thrust helps determine the adequate structural requirements and failure modes to maintain a safe testing environment.

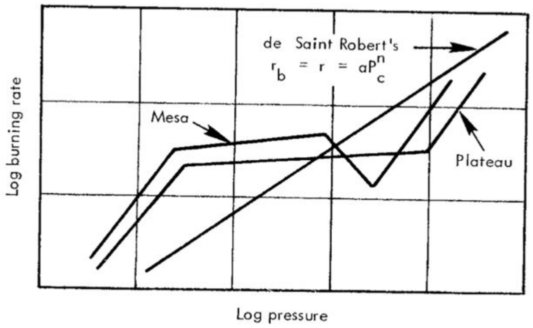

Figure 2: Log-Log Burn Rate vs Pressure[2]

Using the Strand Burner, the values of *a* and *n* are found by measuring the regression rate and pressure during each test. Since the regression rate is a function of pressure, a change in pressure results in a change in regression rate. This is necessary for determining performance characteristics based on chamber pressure but can create errors in burn rate measurements. When the data is processed by logarithmic scaling of each axis, the trend reveals a St. Robert's plot. This allows for a more complete analysis, as the relationship between pressure and regression rate would ideally be linearized [3]. However, this is usually not the case, as the propellant is not guaranteed to consistently follow one single trend line due to variations in ambient conditions during testing and other random factors.

B. Crawford Strand Burner Original Design

As solid rocket motors are commonly used in the defense industry, the Strand Burner was designed in accordance with a military standard. It was designed adhering to MIL-STD-286C for solid propellant testing [4]. One notable exception was the standard for temperature control, which was omitted due to time constraints at the time of its initial fabrication by former Solids Research Group members. According to these standards, the operating pressure of the Strand Burner casing is required to be at least 5,000 psi and hydrostatically tested to 10,000 psi. Other requirements, such as materials selection, internal volume, and piping selection were also incorporated into the design to the best attainable specifications [3].

Figure 3: SRG Entire Strand Burner Setup

The Strand Burner system is comprised of a pressure vessel that contains the combustion and a key that locks into the top of the vessel. This is connected to an overflow tank during the test, which keeps in accordance with MIL-STD-286C. According to calculations and analysis conducted at the time of fabrication, the key and vessel have factors of safety (FOS) approaching 30 and 50 respectively [3]. This is more than enough pressure for what could be reached with equipment available to Sun Devil Rocketry as of 2020. From the initial design a stress analysis determining the total displacement of parts in the system demonstrated that the casing would not suffer a fatigue failure for several years. Although it is assumed that there was a depressurization method, the details of this process cannot be determined with certainty based on the available documents.

Data acquisition (DAQ) was conducted using a computer and circuit box that has since been updated. Although the available documentation is unclear about the components and use of the DAQ system, it is known from the old testing procedures that one nichrome wire was placed on the strand for ignition and two others were embedded in the propellant strand to use as timers. These wires are connected to the strand burner key, which holds it in place inside the casing. It is presumed that a LabVIEW program checked for circuit continuity in the wires until they were severed by burning propellant. Meanwhile, another program measured the pressure in the casing during the test through a 7500 psi pressure transducer over the duration of the test. Data analysis was likely conducted by plotting Eq. (3) and fitting a linear regression to find the regression rate, then plotting regression rate against pressure and fitting an exponential regression to determine the values of a and n as in Eq. (1).

C. Refurbishment of Strand Burner

The first issue to tackle when updating the Strand Burner was to take the system apart to retroactively observe how the system was made. Each of the pipes and fittings were removed methodically and cleaned vigorously to remove old solid propellant residue and rust particles. There were several fittings and connections that needed to be rearranged to improve and ease the use of the system. Whilst some of the fittings only needed cleaning, one of the T-junctions needed to be entirely replaced. The replacement parts for the system were all sourced to the recommended FOS of 2. With the addition of two-way threaded pipe fittings and a four-way connector, the Strand Burner vessel can now be dismantled more efficiently. The incorporation of the four way connector also improves the functionality of the system as there is another location for DAQ equipment in the future.

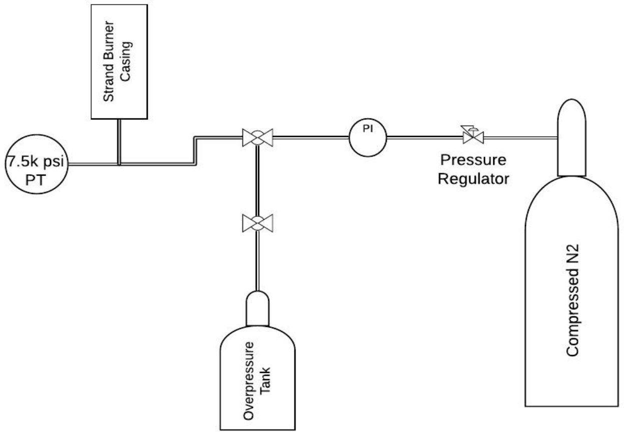

Figure 4: SRG Strand Burner Piping and Instrumentation Diagram

Unfortunately, among the documentation available on the system itself, there was no clear documentation of the piping or depressurization of the system. Consequently, this part of the system needed to be redesigned. From the limited pictures of the original system, it was clear that there was no obvious blowoff valve for depressurization. Therefore, it was up to the team to find a position to release the inert gas after a test. In the current piping design, the system will be depressurized by a braided pipe initially connected to the pressurized inert gas fill tank and expelled into the surrounding space. Fig. 4 shows the updated piping and instrumentation for the Strand Burner.

Due to the scant documentation of the original DAQ system, redesigning the DAQ was imperative. In the new DAQ system, the data collection is done using a microcontroller which sends data from the strand burner test stand to a mobile device application. The microcontroller is connected to two batteries, one for powering itself and the other for ignition, which is done by triggering a resistor that will in turn ignite either an electric match or a piece of nichrome wire. Nichrome timing wires are used in a similar way as the old design, except they are laced through the strand at the middle and end. The microcontroller program checks for voltage across each wire until the propellant burns through, when the time stamp is recorded and sent via Bluetooth to a mobile device application from the Strand Burner test stand, as well as saving the data to an SD card. Because the data is stored in two places, there is lower risk of losing data in the event of a testing failure. Further analysis of the data will be conducted by correlating values of pressure to time, then using the times at which the nichrome wire circuits broke to determine the regression rate, and finally fitting an exponential curve to obtain values of a and n as in Eq. (1).

IV. Mixing and Testing Procedures

The procedures for mixing and testing practices needed to be updated to better suit the safety guidelines defined by the organization as well as ASU. Although several updates had been made to the systems themselves, the procedures have not evolved with the system. A rewrite of the procedures was necessary in order to standardize nomenclature and ensure consistent, ordered steps for testing and mixing

A. Procedure for Mixing Solid Propellants

The mixing procedures that had been used previously were not thorough enough to ensure that safety measures and mixing practices were kept consistent. Following the old mixing procedures resulted in air bubbles and various other inconsistencies in the propellant after it had cured. Therefore, the mixing practices needed to be rewritten to ensure consistent usable propellant grains.

There are a few events that lead to the need for updated practices. Among them was an overpressurization event during a small scale 29mm test. The propellant was mixed following the outdated procedures. However, the vacuum seal did not pull a strong enough vacuum on the propellant after it had been cast. This resulted in a lower than predicted propellant density. Upon inspection of the remaining propellant grains post failure, there was a significant amount of air bubbles present throughout the grain. This was the primary reason for the spike in burn rate seen in the test, leading to the overpressurization of the system. The adjustment needed to be made to the vacuum system to ensure the seal was airtight. After applying this improvement, the propellant densities that have been measured since are closer to the predicted design density in PropEP [5].

Due to the length of the mixing procedures, they are presented in Appendix A.

B. Procedure for Operating the Crawford Strand Burner

Before operating the Strand Burner, ample care must be made to ensure the proper personal protective equipment (PPE) is worn to decrease the chances of chemical exposure. Care should also be taken to ensure that the gaseous byproducts are properly stored and accounted for in the appropriate high pressure vessels. Eye and ear protection are mandatory for operation of the Strand Burner due to the high pressure gasses which will leave the system during depressurization of the system as well as in the event of a failure, when particles or debris may also leave the system with enough energy to cause bodily harm to the testers. In the event in which the fuels are being handled directly, prior to sealant, protective hand-wear for the specific chemical is required. Before the handing of these chemicals, the respective Material Safety Data Sheet (MSDS) must be consulted to ensure proper handling procedures as well as to ensure the proper procedures are taken in the event of an exposure.

Operation of the Strand Burner takes place on a deserted lot on the Arizona State University West campus. Testing takes place 350 feet from the nearest buildings and other infrastructure. All tests take place in an open air environment with free ventilation. To mitigate risks, only the principal investigator and launch engineer will set up the stand as well as initiate the test.

Through the careful operation of these steps, risk to the individuals observing the test as well as the surrounding infrastructure can be minimized. These procedures are still active and as such they are prone to change as inconsistencies are discovered and better practices are learned.

Prior to testing, the strands need to be measured and categorized based upon their mass and dimensions. Ensure that the sample being tested is within the appropriate size for testing [3].

The testing procedures are presented in Appendix B.

V. Future Plans

The future plans for this project are to both fabricate and characterize the propellants for use within the club. Once the confidence interval for the propellant created is within a safe range, the propellant will be used in club designed rockets based upon the characterization they have. These rockets will include those built during the introductory design challenge for new club members, and prototypes for new fabrication methods and materials. After the motors have been tested in smaller rockets, the motors are intended to be used in rockets for the Intercollegiate Rocket Engineering Competition. In the more distant future, the fabrication of rocket motors that burn a certain color would be a much desired product for the organizations renowned Outreach program.

VI. Conclusion

Refurbishment of the Crawford Strand Burner is critical for ensuring the reliability and safety of solid rocket propellant research at ASU. Analyzing the old system and making necessary modifications allows for the development of new rocket propellants for extensive use in the organization. In addition to replacing parts of the system, findings from previous propellant production mishaps and gaps in the current knowledge motivated the team to update the mixing procedures. Given the lack of experience with testing live propellants, a rewrite of the testing procedure was also necessary in preparation of restarting more robust research and development. Updating these procedures allows for the learned experience to be applied in the field as new standard practice. This creates a safer testing environment and helps to mitigate risks inherent in propellant research.

Appendix

Appendix A

The following are mixing instructions for Mixing Space Shuttle Booster Propellant.

1. Place expected mix date and time warning sheets on laboratory door (48 hours prior to mixing)
2. Calculate required propellant mass for mix operations
3. Use percent mass formula to determine individual chemical masses
4. Fill out batch sheet with batch number, purpose for mixing (with grain serial numbers), date, and required chemical masses
5. Put disposable gloves, safety glasses, and ESD bracelets on and fireproof lab coats if necessary
6. Do not mix without closed toed shoes and cotton clothes with long sleeves
7. Prepare mandrel(s)
    a. Scrub clean with mineral spirits
    b. Let sit for 15 minutes
    c. Coal mandrel with thick layer of Mann Mold Release
    d. Mark casting tubes (if motors are being mixed) with grain serial number ad batch serial number
    e. Install casting tubes into mandrels
    f. Set aside
8. Assemble and prepare mix equipment
    a. Clean mixer with mineral spirits
    b. Check oil levels
    c. Check gasket integrity on vacuum plate
9. Put respirator masks on
10. Mass out liquid chemicals
    a. Mark individual cup with chemical label
    b. Place cup on the scale
    c. Tare the Scale
    d. Pour chemical into cup
    e. Ensure final mass of chemical is +/- 5% from required mass
    f. Record final mass on batch sheet
    g. Set aside
    h. Repeat for all liquid chemicals
11. Mass out solid chemicals
    a. Mark individual cup with chemical label
    b. Place cup on scale
    c. Tare the scale
    d. Pour chemical into cup slowly, to avoid making a dust cloud
    e. Ensure final mass of chemical is +/- 5% from required mass
    f. Record final mass on batch sheet
    g. Set aside
    h. Repeat for all solid chemicals

12. Mix liquid chemicals
    a. Pour HTPB and DOA into mixing bowl
    b. Install mixing bowl into mixer
    c. Mix at low speed for 20minutes
    d. Start timer
    e. Every 10 minutes, lower the bowl and manually scrape the bowl's sides
    f. Record actual time of mix on batch sheet
13. Mixing in Metal Powders
    a. Detach mixing bowl from mixing stand
    b. Slowly pour aluminum into the mixing bowl
    c. Avoid making dust
    d. Slowly mix (by hand) all of the aluminum into the liquid
    e. Once the aluminum cannot form dust, re-install the mixing bowl into the mixer
    f. Mix on low speed for 10 minutes
    g. Record actual mix time on batch sheet
    h. Remove mixing bowl and scrape bowl walls clean
    i. Pour in iron oxide powder slowly
    j. Slowly mix (by hand) all of the iron oxide into the mixture
    k. Once the iron oxide cannot form dust, re-install the mixing bowl into the mixer
    l. Mix on low speed for 10 minutes
    m. Record actual mix time one batch sheet
14. Mixing in Ammonium Perchlorate
    a. Detach mixing bowl from mixing stand
    b. Slowly pour in ammonium perchlorate (AP) powder into mixing bowl\
    c. Avoid making dust
    d. Slowly mix (by hand) all of the AP into the mixture
    e. When it cannot form a dust cloud again, reinstall mixing bowl on mixer
15. General Mixing
    a. Turn the mixer on low setting
    b. Let mixer run for 60 minutes
    c. At this point, the particulate masks are no longer necessary
    d. While mixer is running, clean mix area and mark hazardous waste for chemical disposal
    e. Every 5 minutes, lower the mixing bowl and scrape the walls clean
    f. Be sure the mixer is not overheating
    g. If it is, let the mixer cool before continuing
    h. Record actual mix time on batch sheet
16. Vacuum
    a. Remove mixing bowl from mixer
    b. Install vacuum plate on bowl
    c. Pull vacuum on propellant for 20 minutes
    d. Record actual vacuum time on batch sheet
17. Curative mixing
    a. Stop pulling vacuum on propellant
    b. Remove vacuum plate
    c. Pour curative into mixture
    d. There is now a three hour time limit on the propellant
    e. Install mixing bowl into the mixer
    f. Mix at low speed for 20 minutes
    g. Every 5 minutes, lower the mixing bowl and scrape the walls clean
    h. Record actual mix time on batch sheet
18. Casting
    a. Remove mixing bowl from mixer
    b. Place mandrels near mixing bowl
    c. Roll propellant into small cylinders or balls

    d. Drop propellant evenly into mandrel
    e. Firmly tamp propellant down with wooden dowel to remove air pockets
    f. Continue this process until all the propellant is cast
    g. Avoid spilling propellant onto the exterior of the mold
    h. Despite there being a time limit, move deliberately and slowly with the casting process
19. Curing
    a. Once all propellant has been cast, store mandrels in a thermally stable and safe location
    b. Place warning sign on container holding curing propellant
    c. Record total time of mix and any pertinent notes
    d. Store batch sheet in solids propellant team binder
20. Clean up
    a. Clean the entire work area
    b. Use mineral spirits to clean mixing equipment
    c. Mark used cleaning supplies for hazardous waste disposal
    d. Use EH&S website (https://cfo.asu.edu/ehs-environmentalaffairs?destination+node%2F955) to request hazardous waste disposal

Appendix B

The following is the testing procedure for the Crawford Strand Burner.

Strand Preparation

1. Cast propellant into strand curing mold.
2. Measure density and record with batch number.
3. Pierce strand for timer wires.
4. Install nichrome timer and ignition wires.
5. Coat each strand individually with epoxy and let dry vertically.
6. Repeat step 5 for a second coat of epoxy.
7. Record three length measurements between wires in SI units.
8. Record strand cross sectional area.
9. Store in a temperature and humidity controlled location.

Test Procedures

1. Measure and categorize propellant strands by mass and length. Select a sample that is 6” to 7” in length, and 1/8” to 3/8” in diameter.
2. Measure the position of each wire within the strand three times from one end of the strand and between the wires to ensure the measurement is accurate.
3. Assemble all pipe fittings between the reservoir, strand burner, and inlet/outlet.
    a. Use two to three wraps of PTFE tape for non-NPT fittings.
    b. Ensure inlet/outlet is easily accessible and pointed outward from the test setup.
4. Press grease into the pressure transducer (this is to protect the transducer circuitry from flame damage; ensure there are no air pockets to prevent water hammer).
5. Install the pressure transducer into the test stand.
6. Hook Arduino microcontroller up to the test stand.
7. Ensure connections of sensors to the test stand and data acquisition system are functional and continuity has been met.
8. Verify that the Strand Burner is fully assembled and completely sealed.
    a. Ensure cables, piping, and reservoir tank are properly connected and tightly sealed, using PTFE tape as needed.
    b. Verify that the bulkheads, continuity wires, and ignition wire are correctly tightened and positioned before installation.
9. Verify seals inside the Strand Burner before inserting the sample strand into the system.
10. Install O-ring seals on the casing key slot.
11. Lightly grease the casing key slot.
12. Scrub ends of the copper key wires until the metal is exposed.

13. Insert the key into the casing to seal the casing.
    a. Press key in firmly until teeth reach the ledge of the casing
    b. Twist key until teeth are aligned in the slots
14. Attach the pressurized nitrogen gas cylinder.
15. Open the reservoir tank valve.
16. Fill system to initial testing pressure.
17. Check for leaks at pipe and tank connections.
    a. Monitor the pressure transducer for one to two minutes after the system has been pressurized and ensure the seal is maintained.
    b. Remove the nitrogen cylinder and purge the system through the severed connection before fixing leaks.
    c. Repeat until seal is maintained
18. Separate the key and casing, then connect the data wires feeding through the key and the continuity wires in the propellant strand.
19. Place ignition wire on the open face of the sample.
20. Feed continuity wires, ignition wires, data rails, and the fuel sample into the casing.

Note: system is pressurized from this point on

21. Reconnect nitrogen tank and raise the system to an operational pressure of 2000 psi.
22. Close seal ball valve after pressurization and remove nitrogen cylinder.
23. Check for continuity across all measurement wires.
    a. If the measurement readings indicate a discrepancy, the overall system must be purged and verified as in steps 7 through 16.
24. After the system has been verified, clear the testing area. A maximum of two individuals, who were decided upon before the test, (in general, the principal investigator and launch engineer) may remain inside of the bunker. All other personnel must remain 300 feet beyond the bunker with the safety officer.
25. Connect the ignition lines as well as the timing wires to the Arduino microcontroller.
26. When the system is safe, continuity has been met and the area is all clear, start the testing sequence.
    a. Turn on hazard lights.
    b. Identify to the safety officer that the test is about to commence.
    c. Turn on the siren to notify bystanders of testing in progress.
    d. Once given the ‘OK’ from the safety officer step 28 may commence.
27. Ignite propellant.
28. If the propellant does not ignite, immediately remove the power source from the ignition line and continuity wires.
    a. Turn off the Arduino microcontroller.
    b. Purge the system using the bleed valve.
    c. Verify the system once again as in steps 7 through 16.
29. After the propellant is done burning, stop data acquisition equipment.
30. Allow a minimum of 5 minutes for the system to cool and settle.
31. When the system is safe to handle, the test engineers may approach the system with PPE to begin depressurization procedures.
32. Seal off the reservoir tank.
33. Stand behind the opening of the depressurization ball valve.
34. Slowly crack open the ball valve and let the pressure equalize with the ambient air.
    a. It is critical to remember that the reservoir tank still holds pressure.
35. Once the system has returned to ambient pressure, disassemble the key and pressure vessel and remove any leftover debris from the burn.
    a. Check the integrity of the sealant components.
    b. Replace O-rings every 50 tests if no damage is observed.
36. After every 5 tests, remove the pressure transducer and check grease level.
    a. Grease can be vaporized during testing.
    b. Refill as necessary.

37. Regrease key slot as necessary.
38. If conducting more tests, thoroughly clean the system and verify the system as in steps 7 through 16 before continuing.
39. After testing, remove parts and clean system
    a. Clean small parts such as fittings using baking soda solution or acetone baths.
    b. Thoroughly scrub all strand burner parts.
    c. Failure to adequately clean parts can result in parts being damaged and buildup of particulates in the system. This can result in the failure of fittings at high pressures.

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