

# Simulated Propellant Loading System: Testbed for cryogenic component and control systems research & development

J Toro Medina<sup>1</sup>, J Sass<sup>2</sup>, J Youney<sup>3</sup> and W Schmitz<sup>4</sup>

<sup>1</sup>Research and Development Engineer, Cryogenic Test Laboratory, NASA Kennedy Space Center Mail Stop: NE-M5-C Kennedy Space Center FL 32899, USA

<sup>2</sup>Laboratory Manager, Cryogenic Test Laboratory, NASA Kennedy Space Center Mail Stop: NE-L1-G Kennedy Space Center FL 32899, USA

<sup>3</sup>Controls and Electrical Engineer, Cryogenic Test Laboratory, NASA Kennedy Space Center Mail Stop: NE-L1-G Kennedy Space Center FL 32899, USA

<sup>4</sup>Fluid and Test Engineer, Cryogenic Test Laboratory, NASA Kennedy Space Center Mail Stop: NE-M5-C Kennedy Space Center FL 32899, USA

E-mail: jaime.a.toromedina@nasa.gov

**Abstract.** Technologies in the fields of cryogenic components and control systems are constantly evolving to advance the state of current cryogenic operations that will support future space exploration missions. To meet new demanding requirements, these missions will increasingly rely upon research and development in energy-efficient storage, transfer and use of cryogenics and cryogenic propellants on Earth and in space. The capability to test these technologies is sometimes limited to isolated subsystems with a narrow application spectrum. The initiative to develop the Simulated Propellant Loading System (SPLS) is to provide an integrated multipurpose generic testbed to allow dedicated test and evaluation of new technologies in a field environment on a scale that is relevant to launch facility propellant systems. The Cryogenic Test Laboratory (CTL) at the Kennedy Space Center has more than two years of operational experience of using the SPLS to support independent and integrated technology maturation. This paper presents the development of a highly repeatable automated cold flow test sequence that was used in the evaluation and advancement of autonomous control system technologies. A range of other recent applications and capabilities of the SPLS will also be presented in this paper.

## 1 Introduction

The use of experimental testing facilities for cryogenic applications are part of the validation and verification process for maturing technologies being used for supporting cryogenic related missions on Earth and in space. Such experimental facilities applications, ranges from testing high performance insulation materials [1-2] to testing a rocket engine component for hot-fire tests [3-4]. Other

<sup>1</sup>To whom any correspondence should be addressed.



experimental testing articles focus their goal on improving the cryogenic commodity management for storage, transfer and conservation [5-6]. As part of NASA's vision aimed at exploring far and beyond, experimental facilities that can support testing of cryogenic application articles must be developed. Some of the limiting factors on developing such experimental facilities are the safety factors and procedural overhead required to manage cryogenic propellant such as liquid oxygen, liquid methane and/or liquid hydrogen. Cryogenics itself is the study of the behavior of materials at low temperatures (-321°F for liquid nitrogen under atmospheric pressure). Liquid nitrogen as a simulated cryogenic propellant provides the desired temperature range for testing without increasing the safety and overhead complexities of managing cryogenic propellant used on combustion processes. The use of liquid nitrogen as a simulated propellant, provides the complexity of two-phase flow phenomena observed during heat transfer processes.

Storage, transfer and loading operations with cryogenic propellant requires complexity on command, control and cryogenic commodity management system in hardware and software [7-8]. A rocket engine system can be composed of several valves, supplies subsystems, and pipelines, but such complexity is not required to simulate a cryogenic propellant transfer to a vehicle. However, a rocket engine system can be analogously replaced by a main engine valve that opens at a terminal count on a launch sequence. Similarly, a vehicle interface can be represented by a main remote operated valve that can control the flow for slow or fast fill operations on a vehicle tank.

The details of a complex cryogenic propellant system can be concatenated into simpler analogous set of components, which subsequently, can be a scaled representation of a real complex cryogenic propellant system. Under the direction of NASA Kennedy Space Center, the Cryogenic Test Laboratory has developed the Simulated Propellant Loading System (SPLS) with the purpose of testing new technologies aimed to improve integrated ground support systems for cryogenic propellant loading operations. An iterative testing process has yielded a highly reliable repeatable simulated cryogenic propellant loading sequence capable of supporting the evaluation and advancement of autonomous control system technologies as well as validating the use of ground breaking technologies under cryogenic environment.

## **2 Experimental Setup**

As a complete simulated launch platform system, several elements were developed and matured to support the testing of new technologies. As part of the simulated propellant launching system (SPLS) several subsystems were developed.

### *2.1 Propellant Transfer Lines*

The SPLS (see Figure 1) consists of a 6000 gallon storage tank, a 2000 gallon vehicle simulator tank, and four distinct "skids" (Pump Skid, Valve Control Skid, Vehicle Interface Skid, and the Variable Frequency Drive (VFD) Skid). All cryogenic components within the SPLS are liquid nitrogen (LN2) cryogenic rated. All gaseous nitrogen (GN2) gas components are rated for the anticipated temperatures and system test and operating pressures.

- The Pump Skid is supplied by a 6 inch LN2 line. The cryogenic pump, currently in use, is capable of 70 gallons per minute (GPM) flow. There are chilldown/drain valves provided for each pipe section and shutoff valves on the upstream and downstream of the pump. The discharge of the pump is directed to the Valve Control Skid.
- The Valve Control Skid has a 1.5 inch LN2 line from the pump plumbed into a 4 inch supply line. Downstream of the 1.5" feed, the 4" line contains a tee; one leg continues to the Vehicle Interface skid, the remaining leg returns to the storage tank. Thus, flow from the 4 inch line can

be directed to any or all of three locations when the pumps are running: to the “flight” tank, back to the storage tank, or to the dump/drain line.

- The Vehicle interface skid has a 4 inch line with additional valves to supply the vehicle tank or to return LN2 to the drain/vent line.
- The VFD skid has equipment to control the pump speed and rate of LN2 flow from the Storage tank. The VFD equipment also monitors the pump speed and motor condition.

As part of the development of SPLS, a generic transfer line was developed to support simulated propellant transfer between storage and vehicle tanks with liquid nitrogen as the simulated propellant commodity. The mobile launcher area contains main solenoid and control valves which provides flow control of simulated propellant incoming from the cross country line. The vehicle interphase area contains the control valves for main and replenish flow into the vehicle tank. The simulated vehicle tank represents a section of the test bed dedicated to support various vehicle tank technologies including composite tanks single stage and multiple stages vehicles tanks. This section also contains pressure, temperature and level sensors as well as a vent line to relieve control simulated vehicle pressure and tank boil off gas.

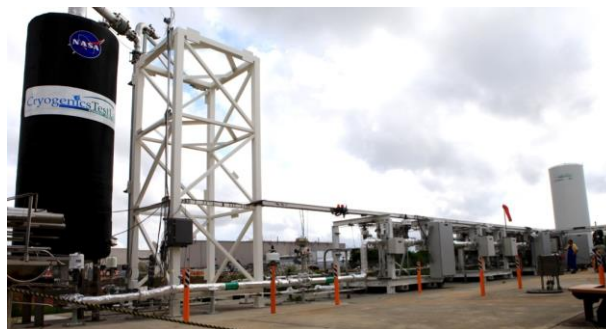


**Figure 1.** Simulated Propellant Loading System.

## 2.2 Storage Tank

The storage area is composed of a main liquid nitrogen supply tank (6000 gallon storage tank), which provides the simulated propellant (see Figure 1). This tank is well instrumented with temperature, pressure and liquid level transducer to provide telemetry of the tank during any phase of the cryogenic test. The SPLS is equipped with a pneumatic system that provides control of valve supply pressure, storage and vehicle tanks ullage pressurant gas, purging systems and pump system.

## 2.3 Single Stage Vehicle Tank

Testing with the SPLS have been performed with a 2000 gallon vehicle simulator tank (see Figure 1). The article is a vertical cylindrical tank approximately of 20-feet overall height (including stand) and 5-feet in diameter. The material of construction is stainless steel. The tank is designed for up to 75 psig operating pressure and liquid nitrogen temperature (-321 °F). The cylindrical side (barrel) of the tank is fairly unobstructed and ports are concentrated on the upper and lower domes. The barrel section is approximately 14-feet tall and the domes are each approximately 1-foot tall. A state of the art insulation technology referred to as Layered Composite Insulation for Extreme Conditions, or LCX, has been used to insulate the simulated vehicle tank [9].

## 2.4 Instrumentation

Several sensing technologies have been used and tested in the SPLS for validation, health monitoring, research, and innovation purposes. Currently, pressure (PT) and temperature transducers (TT) are being

used to monitor testing operations for the SPLS. These sensors are used to monitor the propellant thermodynamic state, maximum allowable working pressure and flow conditions for pump operations. In addition, these sensors are used as trigger points to advance the propellant transfer phases in the system. Capacitance probes (LT) and silicone diode (ECO) transducer technologies have been used to measure liquid levels in the simulated vehicle tank and storage tank.

As part of the valve monitoring and control system, the SPLS is composed of remote operated valves as well as manual valves for flow control. The remote operated (RO) and control valves (CV) are monitored via discrete or analog position sensor (POS) to indicate the state of the valve during the various phases of a simulated propellant transfer process. Solenoid valves (SV) are another type of valve which are remote operated valve and do not contain a position sensor.

### 2.5 Data Acquisition, Command and Control System

Data acquisition and control systems are widely used on cryogenic test facilities for commanding, controlling and real-time monitoring tests as well as past test data review [4]. A programmable logic controller (PLC) has been configured and integrated to command, control and health monitor of the SPLS loading sequence operations. This control system includes a command and control human-machine interface (HMI) panel that reflects temperatures, pressures, liquid levels and position sensors. The control system has the capability of commanding and controlling valves by manual signal input and/or by executing a pre-programmed sequence of steps initiated by feedback data. A proportional-integral-derivative (PID) control loop feedback mechanism, incorporated into the control system, is used to control valve commands to valves with position indicator to achieve a desired commanded state. The SPLS control system is also capable of executing automated pre-programmed sequences to control the cryogenic loading operations. The PLC also manages the control of several auxiliary sub-systems and provides a real time monitoring of all sensors of the SPLS.

## 3 Test Results

### 3.1 Loading Sequence Development

The primary purpose of the development of the SPLS is to become an experimental testbed to improve technologies being used on ground support systems. In order to prove these technologies, a reliable and repeatable testing sequence was developed as a baseline for future testing. The full repeatable sequence is composed of several phases:

#### 3.1.1 Chillydown

During the chillydown phase, liquid nitrogen is used to decrease the temperature of the system to a cryogenic nitrogen temperature range (-321 °F). During this phase, liquid nitrogen is transferred from the storage tank to the vehicle interface valve. Boil-off gas generated during the cool down process is relieved through valves that are redirected to the exhaust line on the system ("Dump Area").

This phase is divided between suction and discharge line chillydown. During the suction line chillydown, the main block valve of the storage tank is opened allowing cryogenic liquid to flow across the suction line. Figure 2 shows a decrease in temperature for all temperature sensor in the suction line. Due to the difference in pipe diameter and distance from source, all the sensors exhibit a lag and a dynamic behavior on temperature decrease rate. The closest sensor to the cryogenic storage tank discharge (TT202) shows an immediate decrease in temperature at the beginning of the test. The tank-pump suction sensor (TT105) shows a dynamic temperature decrease behavior. The change in the temperature decrease rate is due to the rapid exposure of saturated liquid followed by a rapid release of boiling commodity. Similar behavior can be observed for the temperature sensors located at the pump suction (TT162) and pump discharge (TT174). Several exhaust valves ("bleed" valves) are located along this section of the pipeline dedicated to discharge boil-off gas to atmosphere. A noticeable behavior can

be observed for TT174. This temperature sensor is located at the end of the first chilldown portion of the system. Several pipe diameter transitions occurs between the source tank and TT174, being TT174 a located in a smaller pipe diameter (from 3 inches to 1.5 inches). As observed in the temperature sensors TT105, TT202, and TT162, a gradual decrease in temperature occurs until a drastic drop to cryogenic temperatures (approximately  $-321^{\circ}\text{F}$ ) is observed. The temperature sensor TT174 shows a faster transition to a cryogenic temperature due to the effects pipe size on nucleate boiling phenomena. Complexities and dynamic behaviors are observed during the progression of the cryogenic transfer process. This fluid flow behavior is an inherent dynamic of the two phase flow phenomena.

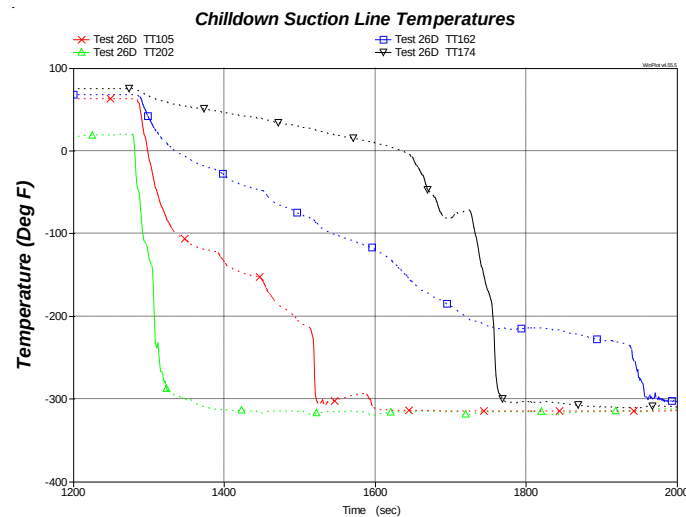


**Figure 2.** Chilledown Suction Line Temperature.

During the development of the simulated propellant transfer sequence, several iterations took place in order to achieve repeatability of results. Figure 3 shows the overall temperature results of the chilledown phase for 4 repeatable tests. These results show a reliable simulated propellant chilledown sequence yielding results on repeatability for Test 26 A, Test 26 B, Test 26 C, and Test 26 D. Variations on tests results were due to a higher initial atmospheric temperature on different days the tests were performed. Behaviors on temperature decrease rate and final temperature states were found to be similar during the repeatable tests.

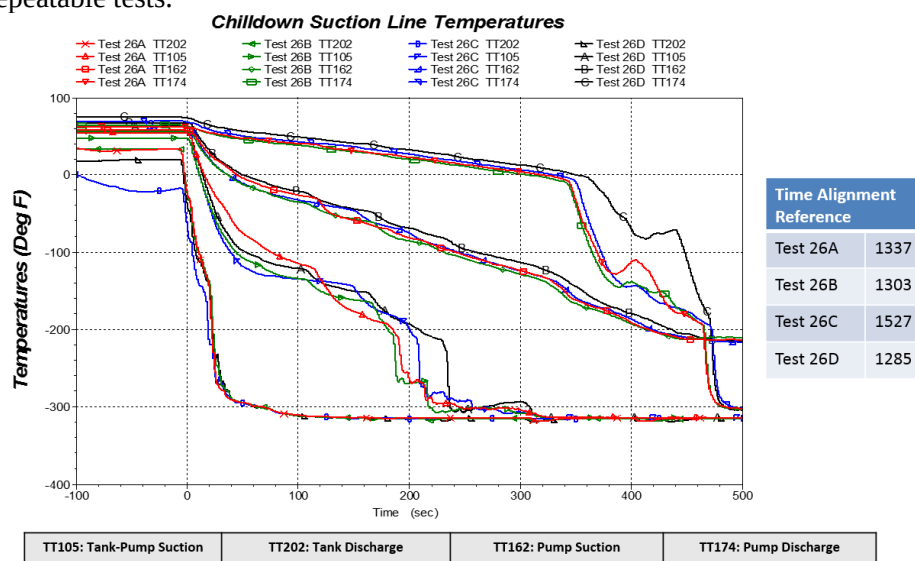


**Figure 3.** Repeatability results for Chilledown.

### 3.1.2 Slow and Fast Fill

During this phase, the cryogenic pump speed is increased to produce a flow rate of 70 GPM. The flow provided, produced a faster increase rate of LN2 liquid level in the simulated vehicle tank. Modifications to the flow rate during this phase were intended to produce a duration of approximately 30 minutes. The purpose of the extended duration of this phase was to allow a steady condition of the overall SPLS for additional testing purposes. A steady increase in tank liquid level (%) was observed by LT504 in Figure 4. During this phase, all the bleed and exhaust valves remained closed and saturated conditions on the system were maintained with a fast flow rate generated by the cryogenic pump.

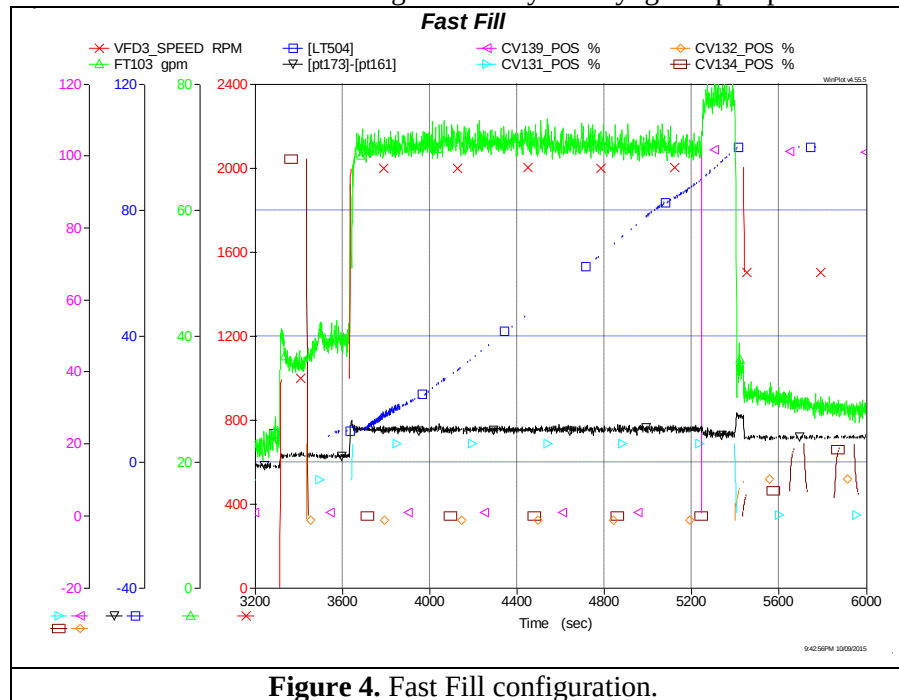


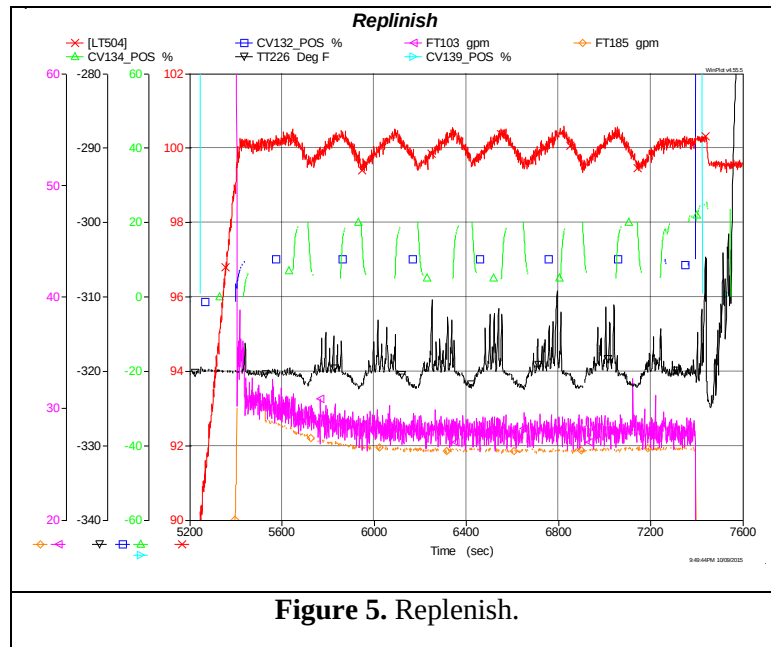
**Figure 4. Fast Fill configuration.**

### 3.1.3 Replenish

During this phase, a maximum tank fill level was achieved by the cryogenic commodity and a replenish algorithm was enabled (see Figure 5). This replenish algorithm monitored the tank level and commanded a exhaust valve (CV134) to either allow flow commodity into the tank (if tank level falls below a minimum threshold) or prevent an overfill on the vehicle tank. This is why if the vehicle tank liquid level LT504 falls below 99.5% then the exhaust valve CV134 closes to 5% to allow more commodity into the tank. If the vehicle tank liquid level LT504 rises above 100.5% then the exhaust valve CV134 opens to 20% to exhaust commodity into the atmosphere. During the replenish process, a constant flow rate of approximately 26 GPM (FT185) is provided by the replenish valve CV139 on the vehicle interface skid. This process mimics a real launch operations where a real vehicle might stay in the launching platform for hours while maintaining liquid level conditions until vehicle launch.

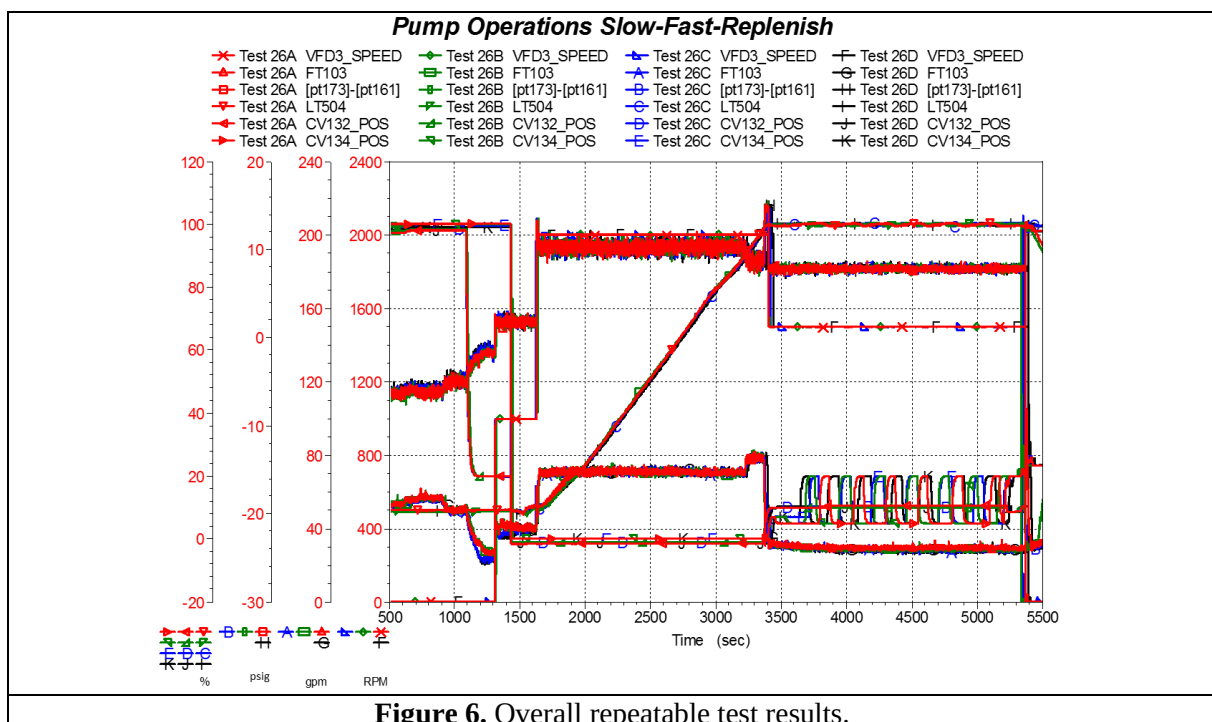
During the replenish phase, a commodity was provided to the piping system. Initial testing operations of the SPLS showed that low flow rates in the transfer line, during replenish phase, lead to decrease in commodity quality and temperature rise on the system. Modifications on the sequence were incorporated to maintain saturated commodity quality during this low flow rate phase. During the replenish phase, an exhaust (“bleed”) valve (CV132) was partially open to allow for a continuous removal of warm liquid and thus maintaining a cooler liquid temperature on the pump and vehicle control skid. A minimum flow rate of approximately 28 GPM (FT185) was supplied to the vehicle interface skid to maintain commodity quality in the transfer line prior to this location. This active thermal control procedure

provided improvements to the propellant transfer sequence and prevented redline violations on the system by maintaining operational flow conditions.



### 3.2 Overall Repeatable Results

Overall testing results over Test 26A, Test 26B, Test 26C, and Test 26D showed that the SPLS was capable of producing a reliable repeatable test sequences capable of simulating propellant transfer operations using analogous elements from a real launching platform (see Figure 6). Variations on repeatable results were inherited from the complexities of a two-phase flow phenomena and were expected to occur within an acceptable threshold.



#### 4 Conclusion

Repeatability tests results of the SPLS testing have been presented in this paper. An iteration process of several testing sequences, with different configurations, was conducted in order to achieve a final set of four (4) tests, with same configuration, that can validate the reliability of a system. This validation assures the capability of the SPLS in repeating a simulated propellant loading sequence. The outcome of this capability opens the door, as a testbed, for being part of the validation and verification testing of other technologies that requires a cryogenic propellant loading environment for their maturation cycle. The SPLS full configuration has proven to be a reliable testbed capable of supporting technologies on the need of a testing cryogenic environment as well as technologies aimed to improve processes and operations of cryogenic ground support systems.

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