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Mechanical Design and Operation of a Novel Lunar Environment Structural Test Rig (LESTR)

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Summary

The Lunar Environment Structural Test Rig (LESTR) was developed to address a critical gap in mechanical property data for metal alloy wire materials under lunar-relevant conditions down to 40 K. Conventional aerospace material databases provide thermophysical properties for bulk metals over a wide temperature range, but validated mechanical and physical property data below 77 K, particularly for small-diameter wires, remain limited and are generally the exception rather than the rule. These conditions are essential for Artemis mission hardware such as shape memory alloy (SMA) rover tires. LESTR's design requirements were to combine a high-stiffness electrodynamic load frame with closed-cycle cryogenic cooling, high-vacuum capability (10^{-6} torr), and noncontact optical strain measurement to enable tensile, four-point bend, and fatigue testing of wires or other materials and geometries at temperatures from 40 to 125 K. These considerable requirements were merged with the need to lower the barrier of testing for the end user as measured in terms of cost-per-test cycle, safety improvement, and reduction in upkeep costs associated with state-of-the-art solutions associated with cryomechanical material characterization. The system incorporates modular gripping and alignment fixtures; precision thermal management using cryocoolers and embedded heaters; and integrated instrumentation for displacement, load, temperature, and vacuum control. Calibration procedures establish correlations between tooling and specimen temperature, ensuring accurate thermal conditions across the design envelope unbound by cryofluid conditions in heritage immersion-based test systems. Initial validation tests using Inconel® (Special Metals Corp.) wire demonstrated accurate ultimate strength and post-yield behavior. The load frame operation was also verified under representative service conditions, including thermal cycling and prolonged fatigue loading. By generating mechanical property data at ultralow temperatures, LESTR fills a critical gap in existing materials databases and provides a scalable platform for iterative alloy development and durability assessment for planetary hardware. This capability supports NASA's long-term objectives for surface exploration by enabling design confidence for components operating in extreme cryogenic environments.

*Retired.

1.0 Introduction

Mechanical characterization of materials is critical for the design and development of innovative technologies to operate safely, reliably, and successfully. For space exploration, these materials must perform reliably under extreme conditions that depend on the destination, for example, on the Moon during the long lunar night, when temperatures drop significantly, or at the lunar south pole, where permanently shadowed regions can reach temperatures as low as 40 K or below. For Artemis missions, hardware such as shape memory alloy (SMA) rover tires must operate across a broad thermal range from 40 to 400 K (Refs. 1 and 2). Verifying mechanical performance under these conditions is essential for mission success.

Developing materials for such environments is inherently challenging, and current aerospace material property databases, including NASA's Materials and Processes Technical Information System (MAPTIS), NASA's Thermal Protection Systems Expert (TPSX) Material Property Database, the Metallic Materials Properties Development and Standardization (MMPDS) Handbook, and the National Institute of Standards and Technology (NIST) cryogenic repositories, provide scarce thermophysical data for bulk metals down to cryogenic temperatures and lack validated mechanical property data for fine wires below 77 K (Refs. 3 to 6). This gap is significant because SMA wires, a fundamental component of lunar tire designs, experience complex stress states and fatigue cycles in service that are further compounded within a challenging thermal environment. NASA Standard (STD) 6016C, Standard Materials and Processes Requirements for Spacecraft (Ref. 7), defines the minimum performance and characterization requirements that NASA and its providers must meet for a material to be approved for spaceflight use. Notable requirements (though not an exhaustive list) are summarized in Table 1.

Table 1. NASA-STD-6016C notable requirements

Requirement identifier	Requirement	Justification
4.a.	Materials shall meet the worst-case useful life requirements for the particular application.	Common-sense requirement that materials used in an application be assessed for all of the environmental extremes that the materials will encounter during the life cycle.
4.1.6b.	MUAs (Material Usage Agreements—Waivers by which a material that is nonconforming with NASA-STD-6016C may be permitted for use for a particular application) shall not be used to change the M&P (Materials and Processes) requirements for a nonconforming product.	The purpose of the MUA process is to justify the acceptance of specific material or material process design nonconformances, not the acceptance of a nonconforming product.
4.1.7a.	All parts or materials for spaceflight hardware that provides mission-critical functions shall be certified as to composition, properties, and requirements as identified by the procuring document.	Ensures that consistent and reliable materials are used in spaceflight hardware and further ensures that materials and their properties can be repeated from program to program and from company to company.
4.1.8.1b.	The sampling for other mechanical properties, such as dynamic properties like fatigue and fracture, and verification of design values shall be representative of the material, product form, and state used in the design.	Needed to ensure design values for other required mechanical properties are representative of the material, product form, and state used in the design.
4.2.3.5	All materials shall be selected to meet the useful life of the hardware with no maintenance or be identified as limited-life items requiring maintainability.	If a material cannot meet the useful life requirements of the hardware of which it is a part, then it must be identified as having limited-life and a maintenance plan identified to address its limited-life.

Existing cryogenic testing methods typically rely on large quantities of hazardous cryogenic fluids (e.g., LN_2 and LHe), which are costly, inefficient, and pose safety risks. To enable successful Artemis missions and future Mars exploration, NASA requires a test system capable of characterizing materials under lunar-relevant conditions, specifically, a rig that can replicate temperatures from 40 to 125 K in vacuum for long-duration durability testing.

This work addresses that gap by developing and documenting the Lunar Environment Structural Test Rig (LESTR), a modular system optimized for accurate uniaxial strain and four-point bend testing of fine wires across a wide thermal range. LESTR integrates a high-stiffness electrodynamic load frame with closed-cycle cryogenic cooling, high-vacuum capability (10^{-6} torr), and noncontact optical strain measurement. Unlike conventional cryogenic setups, LESTR eliminates consumable cryogens, enabling extended fatigue testing under stable conditions. The resulting data will populate the wire properties database, supporting alloy selection, processing optimization, and finite-element modeling of SMA rover tire structures.

This report focuses on the mechanical design and operational capabilities of LESTR Unit 01. A companion paper addressing the cryogenic system is currently in preparation.

2.0 Design Requirements and Constraints

LESTR was designed to meet several key requirements, including the following:

1. Axial loading: Axial load capacity in the tensile direction of no less than 800 lbf (3,559 N) with high force resolution
2. Displacement control: Submicron resolution for displacement-controlled loading
3. Interchangeable grips: Configurations for both tensile and four-point bend tests (like ASTM E8 and ASTM D-6272, respectively) for wire diameters between 0.050 and 0.085 in. (0.127 and 0.216 cm) (Refs. 8 and 9)
4. Thermal management: Efficient system minimizing hazardous consumables while maintaining precise temperature control across the entire test duration at any setpoints from 40 to 125 K
5. Vacuum environment: High-vacuum capability no greater than 10^{-6} torr while operating the cryocooler and pumps concurrently (the system benefits from cryopumping from the cold head in reaching high vacuum)
6. Optical compatibility: Accommodation for optical strain measurement techniques

The overarching goal was to develop a modular, scalable test rig architecture that supports the characterization of multiple materials. Future generations of LESTR will incorporate lessons learned from this design and will require facility-level planning for continuous operation exceeding 1 yr, enabling at least 60,000,000 cycles per test without maintenance. This level of reliability demands component redundancy for parts with annual maintenance and calibration schedules.

For the version described in this paper, LESTR Unit 01, the operational requirements were more modest:

1. Tensile tests: Fewer than 50 continuous cycles without maintenance
2. Four-point bend tests: Up to 100,000 cycles without maintenance

Additional detailed requirements for each subsystem are discussed in the following subsections.

2.1 Thermal Requirements

This project focuses on characterizing SMA wire performance between 40 and 125 K. Very few test rigs are capable of testing in this critical range of the temperature envelope. NASA's Extravehicular Activity and Human Surface Mobility Program (EHP) is developing a new class of SMAs to enable tire technologies for lunar and Martian missions (Refs. 10 and 11). Alloy development targets a broad temperature range of 40 to 400 K, covering the minimum and maximum thermal conditions of both environments. Test rigs with these thermal capabilities will be required for the development and verification of spaceflight hardware.

Three levels of thermal vacuum requirements were established for LESTR, as well as requirements specific to the thermal environment. These requirements are summarized in Table 2.

Table 2. Summary of thermal vacuum system requirements for LESTR

Level	Requirements Decomposition	ID no.
Level 1	LESTR Unit 01 shall be designed to accomplish the goal of maintaining lunar environment for the duration of the test with a design that is manufacturable and scalable for future needs and block improvements.	02
Level 2	The thermal management system, a combination of vacuum pumps, cryocooler/s, cold box, and insulation, shall function to maximize heat removal from the test system, minimize heat infiltration, and balance the temperature at a given setpoint.	024
Level 3	The system shall be capable of maintaining a minimum sample temperature no greater than 40 K.	0241
	The system shall be capable of maintaining a maximum sample temperature of no less than 125 K.	0242
	Number of temperature setpoints: The system shall be capable of supporting 4 to 5 discrete temperature setpoints between minimum and maximum temperature described in requirements 0241 and 0242.	0243
	Temperature variability: Wire dispersion less than 5 K.	0244
	The mechanical drive train shall provide mounting locations for thermal straps.	0245
	The span of the drive train as defined by the length between the vacuum-ambient flange interface to the thermal strap interface shall be designed to resist heat transfer through material and geometric design considerations.	0246
	The span of the drive train as defined by the length between the thermal strap and the interface to the sample fixtures shall be designed to maximize heat transfer through material and geometric design conditions.	0247
	A source of heat shall be built into the drivetrain as a counterweight to the cooling capacity of the cryocoolers to bring the temperature of the sample to the correct value.	0248
	The thermal control system shall cool the system conductively through the drivetrain and radiatively through the use of a cold box both of which shall be thermally linked to the cryocooler/s.	0249

2.2 Load Frame Requirements

Similarly, three levels of load requirements were levied on LESTR as summarized in Table 3. The load frame is among the most flexible elements an end-user can change to meet their requirements. Different load frames are optimized for different kinds of information gathering. The selection of the Instron® (Illinois Tool Works Inc.) ElectroPuls™ E10000 was made after a competitive bid process to find a solution that best suited the mission of the parent-project developing LESTR. Specifically, the load frame selection was driven by the requirements for high-cycle, very long duration (~2 yr continuous) testing and was not driven by cryogenic requirements. Any load frame with enough open volume and reasonable fixturing locations could theoretically be adapted to the LESTR standard.

2.3 Mechanical System Requirements

Requirements for the mechanical test system included providing precise control and measurement capabilities for both tensile and four-point bend tests under vacuum and cryogenic conditions. Requirements are summarized in Table 4 and Table 5.

Table 3. Summary of load frame requirements for LESTR

Level	Requirements Decomposition	ID no.
Level 1	LESTR Unit 01 shall be designed to accomplish the goal of maintaining lunar environment for the duration of the test with a design that is manufacturable and scalable for future needs and block improvements.	02
Level 2	The test rig shall meet requirements for integration of chamber and integration with facility infrastructure.	025
Level 3	The daylight opening as defined by the horizontal distance between the two pillars supporting the crosshead shall accommodate a vacuum chamber that is 17 in. (43 cm) wide.	0251
	The distance from the fully retracted load head to the table surface shall be no less than 35.5 in. (90.17 cm)	0252
	The load frame shall have electrical requirements no greater than 240 VAC at 40 A.	0253
	The load frame shall not weigh more than 3,000 lb (1,361 kg).	0254
	The mechanical drive train shall provide mounting locations for thermal straps.	0245
Level 2	The test rig shall possess mechanical properties that meet the requirements of both the slow-speed low-cycle tensile test and the relatively high-speed high-cycle four-point bend tests.	026
Level 3	The load frame piston shall be capable of displacement greater than or equal to 2.0 in. (5 cm) as defined from the position of maximum displacement to the position of minimum displacement.	0261
	The load frame shall be capable of maintenance-free operation of over 3 yr.	0262
	The load frame shall meet a minimum static load capacity of 1,500 lbf (6,672 N) and a minimum dynamic load capacity of 2,000 lbf (8,896 N).	0263
	The load frame shall be capable of supporting a minimum cyclic displacement rate of 0.25 in/s (0.64 cm/s), as determined by the primary investigator (PI).	0264
	The load frame shall be specifically qualified for cyclic fatigue testing equivalent or similar to the type desired for this experimentation.	0265
	The load frame shall be capable of low-cycle, low-rate quasistatic tensile testing in support of tensile wire testing.	0266
	The load cell resolution shall be under 0.1% of the minimum load capacity.	0267
	The load frame shall be compatible with load cell and alignment subsystems as needed to ensure successful data acquisition and construction.	0268
	From execution of the quote, delivery time shall be less than or equal to 12 weeks.	0269

2.3.1 Tensile Test Fixture Requirements

Table 4 lists requirements for the tensile text fixtures, including capstan or screw-actuated grips.

2.3.2 Four-Point Bend Fixture Requirements

Requirements for the four-point bend test fixtures are summarized in Table 5.

Table 4. Summary of tensile test fixture requirements for LESTR

Requirements Decomposition			ID no.
Level 1	The tests being run shall include four-point bend wire testing and tensile wire testing. Data collection systems shall be tailored to the unique load, environment, temperature, and duration requirements of these tests.		03
Level 2	The test rig shall support a cyclic tensile test.		031
Level 3		The tensile test shall support a maximum tensile load of at least 400 lbf (1,779 N).	0311
		The tensile test shall use fixtures such as capstan grips or screw-actuated grips capable of reliably applying load without inducing error into the system.	0312
		The test shall resemble ASTM E8 Standard Test Methods for Tension Testing of Metallic Materials.	0313
		The test fixture shall seek to induce the minimal amount of thermal resistance upon the cryocooled load train with the tradeoff of stiffness and thermal conductivity.	0314
		Tensile test fixtures shall be designed such that the size of the wire diameter is within their useful operational range.	0315
		If the tensile test fixture has a required wire length for the sample, that length shall be reported to the responsible engineer for sample specification and acquisition.	0316
		The tensile test fixtures shall be appropriately sized to integrate within the cold box.	0317
		Visual access through the use of a viewing glass on the vacuum chamber door and the cold box shall be provided to allow for optical strain data gathering.	0318

Table 5. Summary of four-point bend fixture requirements for LESTR

Requirements Decomposition			ID no.
Level 1	The tests being run shall include four-point bend wire testing and tensile wire testing. Data collection systems shall be tailored to the unique load, environment, temperature, and duration requirements of these tests.		03
Level 2	The test rig shall support a four-point durability test.		032
Level 3		The four-point bend test shall be designed and instrumented for a maximum load of 40 lbf (178 N).	0321
		The four-point bend fixture shall be designed specifically for consistency with test requirements as set out in ASTM D6272, with any reasonable adaptations as needed.	0322
		The four-point bend fatigue test shall resemble ASTM D6272 Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four-Point Bending.	0323
		The four-point bend test fixture shall be designed for at least 100,000 cycles of use at a rate of 1 Hz.	0324
		The four-point bend fixture shall be designed to accommodate as-manufactured sample dimensions.	0325
		The bounding box of the four-point bend fixture shall be reported to the engineer/s responsible for the design of the cold box as a requirement for the cold-box inner dimensions.	0326
		The four-point bend fixture shall seek to induce the minimal amount of thermal resistance upon the cryocooled load train with the tradeoff of stiffness and thermal conductivity.	0327
		The load frame shall be compatible with load cell and alignment subsystems as needed to ensure successful data acquisition and construction.	0328
		From execution of the quote, delivery time shall be less than or equal to 12 weeks.	0329

2.4 Instrumentation and Sensing Requirements

The requirements summarized in Table 6 were established for instrumentation and sensing.

2.5 Test Sample Size Requirements

Table 7 summarizes the size ranges of wire specimens the test rig was required to accommodate. These dimensions were determined by the parent project for its needs and goals. Appropriate fixturing expands the specimen range to include other sample types, such as dogbone and bowtie.

Table 6. Summary of instrumentation and sensing requirements for LESTR

Level	Requirements Decomposition	ID no.
Level 1	The tests being run shall include four-point bend wire testing and tensile wire testing. Data collection systems shall be tailored to the unique load, environment, temperature, and duration requirements of these tests.	03
Level 2	Instrumentation and data collection of the rig shall provide information for the PI to use in characterizing the desired material properties.	036
Level 3	During checkout testing, verify that temperature gradients of wire meet thermal requirements.	0361
	Test specimen sample temperature shall be indirectly derived through the use of sensors located on the drivetrain and cold box.	0362
Level 2	Instrumentation and data collection of the rig shall provide information for the technicians and engineers to use in operating the rig.	037
Level 3	A pressure transducer shall be built into the vacuum chamber so that soft vacuum conditions are verified prior to turning on the cryocooler.	0372
	Temperature sensors shall be used to provide data feedback for environmental monitoring and programming of software controls.	0373
Level 2	Instrumentation and data collection of the rig shall provide information for the thermal control system governing the operation of the cryocooler/s and heaters to balance their operation and achieve setpoint temperature.	038
Level 3	Instrumentation shall be capable of verifying specimen temperature at cryogenic setpoint.	0381

Table 7. Test sample size requirements for LESTR

Test type	Wire diameter, in. (cm)	Nominal wire length, in. (cm)	Gauge length, in. (cm)
Tensile test	0.050 to 0.085 (0.13 to 0.22)	33 to 38 (84 to 97)	4 to 5 (10 to 13)
Four-point bend	0.050 to 0.085 (0.13 to 0.22)	1 to 3 (3 to 8)	N/A

3.0 Mechanical Architecture

3.1 Overall Layout

LESTR Unit 01 consists of a vertical, high-stiffness, precision-aligned, dual-column Instron® ElectroPuls® E10000 electrodynamic load frame (Figure 1) (Ref. 12). This frame incorporates an adjustable-height crosshead and an integral T-slot base platen that provides flexibility for mounting fixtures and accessories. The actuators mounted on the crosshead operate in linear-only mode. A pair of nonrotating leadscrews positioned beside each column allows the crosshead to be driven by rotating nuts integrated into the crosshead assembly, ensuring precise vertical movement. Power is supplied to the linear actuator through a linear power amplifier, and an Instron® 8800MT controller manages closed-loop control for accurate application of load and displacement. Despite its robust design, the frame maintains a compact footprint relative to hydraulically actuated alternatives, requiring less than 8.6 ft^2 (0.80 m^2) of floor space, making it suitable for laboratory environments where space is limited.

3.1.1 Actuation System

Displacement in the LESTR load frame for both dynamic and static testing applications is accomplished using the actuation system. This actuation system delivers the high dynamic performance necessary to replicate the structural physics of a wheel in motion. The load frame is capable of steady operation at frequencies up to 100 Hz. The load frame provides a dynamic capacity of ±2,250 lbf (10,009 N) and a static load capacity of ±1,570 lbf (6,984 N), with a linear stroke of 2.36 in. (5.99 cm). These specifications enable precise control of displacement and force across a wide range of testing conditions, ensuring compatibility with both low-cycle quasistatic tensile tests and high-cycle fatigue tests.

3.1.2 Load Path and Force Measurement

The pressure vessel, which maintains the required vacuum environment, presented a significant design challenge for LESTR. The system required a method to transmit vertical motion from a crosshead located outside the pressure boundary to a load column inside the vessel while preserving the vacuum seal and applying an axial load to the test specimen within the pressure boundary. LESTR transmits these loads from the load piston into a plate mounted to compliant bellows (Figure 2).This plate is joined to the piston and the load train below it through blind tapped holes on either side, thus acting as a mobile atmosphere-vacuum boundary interface. These loads then feed through the plate into the connected upper pull rods linked to the upper sample grip, then through the test specimen, continuing through the lower grip and through the lower pull rods to an inline load cell mounted concentrically with the load axis (Figure 3).

The load cell is fixed to the static base of the load frame, making it a stationary component during testing (Figure 4). Two interchangeable load cells were selected based on the anticipated test capacities: Instron® Dynacell 2527 Series models were chosen for their precision and adaptability. Model number 2527-153 provides a ±1,125-lbf (5,004-N) capacity for the tensile tests, and model number 2527-131 offers a ±56-lbf (250-N) capacity for four-point bend tests (Ref. 13). Both load cells can measure forces as low as 1/250 of their rated capacity with an accuracy of 0.5%. For example, the 56-lbf load cell can accurately measure 0.2 lbf (0.9 N) within 0.001 lbf (0.004 N). Although these load cells are not formally vacuum rated, they were recommended by Instron® engineers based on proven performance history in vacuum environments and have not faced issues to date through operational use in LESTR Unit 01. Additionally, the design allows for substitution with any vacuum-compatible load cell that meets the size and interface requirements of the current LESTR configuration.

Figure 1. Rendering of LESTR Unit 01 test rig.

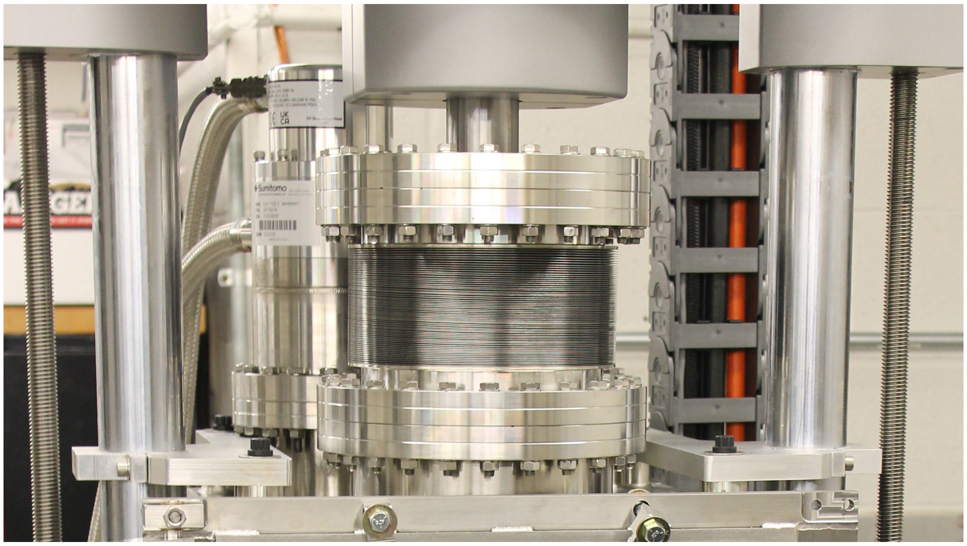

Figure 2. LESTR Unit 01 bellows in compressed state.

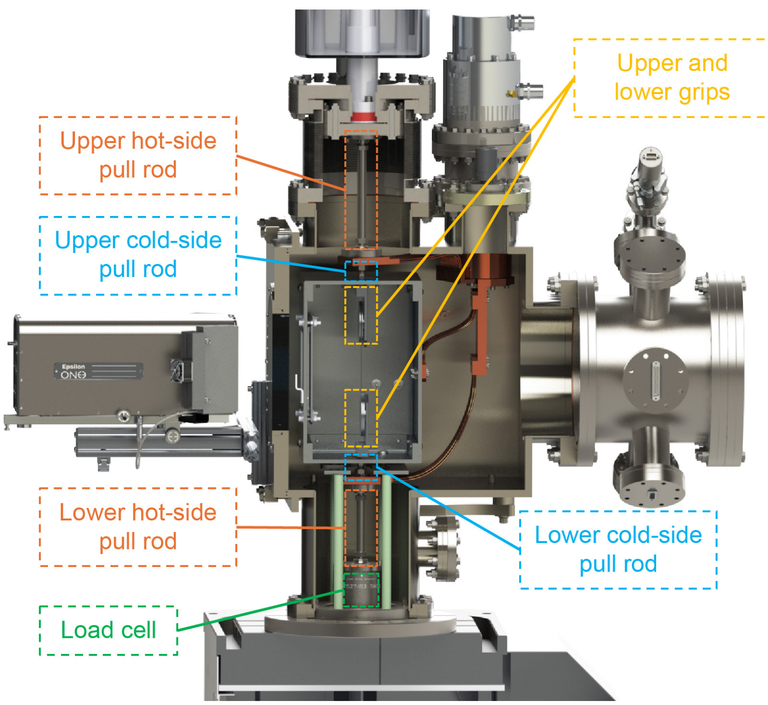

Figure 3. LESTR Unit 01 schematic depicting upper and lower pull rods.

Figure 4. LESTR Unit 01 lower load train and four cold-box support beams.

3.2 Environmental Chambers

The environmental chamber system in LESTR is designed to replicate lunar conditions by combining cryogenic cooling, vacuum isolation, and thermal shielding within a compact architecture. This system enables precise control of temperature and pressure without relying on hazardous or consumable cryogenic fluids, making long-duration, high-cycle fatigue testing practical and cost effective.

To achieve cryogenic test conditions, LESTR employs a commercial off-the-shelf (COTS) closed-cycle cryocooler as the primary refrigeration source. The cryocooler works in combination with flexible copper thermal straps embedded with resistive heaters, enabling active heating and precise temperature control of the mechanical load train and radiation shield across a range of approximately 40 to 125 K while rejecting heat to the cryocooler (refer to Figure 5). The heat lifted to the cold head of the cryocooler is transported to an outboard compressor unit by the expansion of high-pressure helium gas to low pressure. The outboard compressor unit recompresses the helium for reuse and rejects the heat from the process through facility cooling water. The refrigeration system operates as a closed loop, continuously recycling gaseous helium between the remote compressor and the cold head, eliminating the need for additional cryogenic liquids. The system arrives from the factory precharged with the helium needed for operation, and any need for recharge is infrequent.

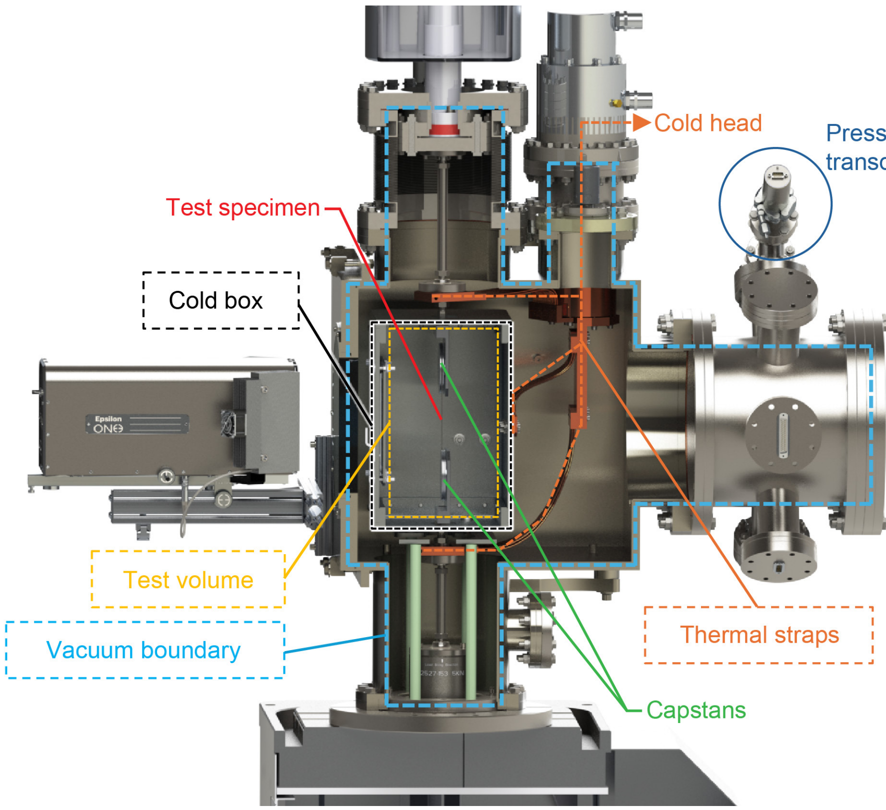

Figure 5. Cross-sectional sideview of LESTR Unit 01 test rig showing vacuum chamber surrounding cold box with thermal straps attached and capstan grips with wire test specimen in place.

3.2.1 Vacuum Chamber

A custom 16- by 16- by 16-in. (4,096-in.^{3}) (67,121-cm^3) vacuum chamber constructed from 304 stainless steel provides a lunar-like high-vacuum environment to meet or exceed the requirement of 10^{-6} torr. (In practice, LESTR Unit 01 has observed vacuum levels $<10^{-7}$ torr, with a recorded instance of 8.8×10^{-9} torr.) This level of vacuum eliminates water vapor, oxygen, and other contaminants that could alter the mechanical performance of the test specimen. The chamber is integrated with the load frame and includes multiple flanges, feedthrough ports, and two access doors: a front door with a transparent window for visual inspection and/or optical measurements and a rear door with a large (13.25-in.-diameter) (33.66-cm-diameter) spool bump-out (Figure 6) for additional access and feedthrough capability[1]. The chamber fits within the working volume of the load frame and surrounds the cold box, which houses the test specimen (Figure 5). The top and bottom of the chamber feature concentrically aligned 10-in. (25-cm) ConFlat® (Agilent Technologies, Inc.) flanges to maintain alignment between the bottom-mounted load cell and the upper crosshead, and other chamber walls provide flanges for electrical and instrumentation feedthroughs. The chamber meets NASA-STD 8719.17 for pressure systems (Ref. 14). A summary of feedthrough ports is provided in Table 8.

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[1]The bump-out was necessary to allow for fitment and installation of the chamber between the beams of the load frame. Early concepts were for ports on the sides of the vacuum chamber; however, these would interfere and prevent installation. LESTR Unit 02 instead extends the chamber forward of the door and relocates these ports back onto the vacuum chamber.

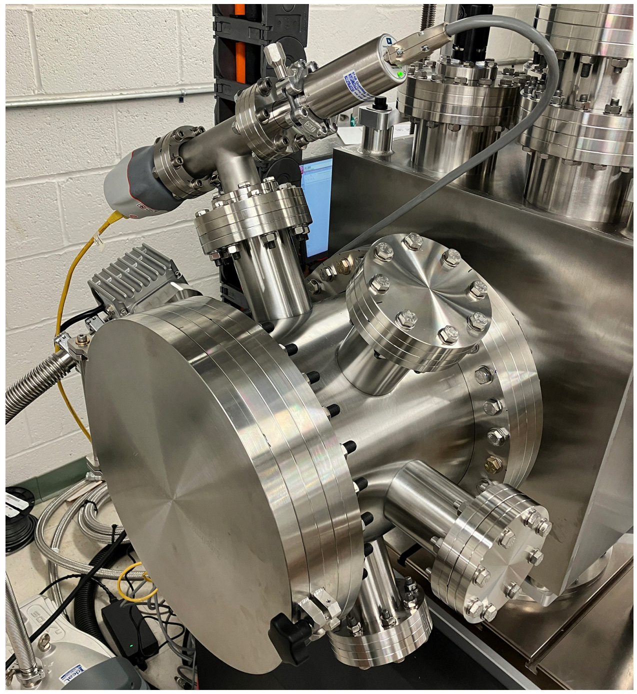

Figure 6. LESTR Unit 01 rear bump-out.

Table 8. Summary of feedthrough ports on LESTR vacuum chamber

Purpose	Position	Flange standard	Quantity
Drivetrain	Top	DN200CF, 10-in. (25-cm) OD	1
Cryocooler	Top	DN125CF, 6.75-in. (17.1-cm) OD	1
Turbomolecular vacuum pump	Bump-out	DN63CF, 4.5-in. (11.4-cm) OD	1
Heater and light-emitting diode (LED) power	Bump-out	DN63CF, 4.5-in. (11.4-cm) OD	1
Temperature (silicon diodes ×10)	Bump-out	DN63CF, 4.5-in. (11.4-cm) OD	1
Temperature (thermocouples ×3)	Bump-out	DN63CF, 4.5-in. (11.4-cm) OD	1
Load cell data port	Load frame rear, lower flange	DN63CF, 4.5-in. (11.4-cm) OD	1
Vacuum pressure sensing	Bump-out	DN63CF, 4.5-in. (11.4-cm) OD	1

Vacuum integrity is maintained by a pumping system consisting of an Edwards nEXT85D turbomolecular pump backed by an Edwards nXDS6i dry scroll pump. The nEXT85D pump provides pumping speeds from 100 to 2,649 ft^3/min (2.83 to 75.01 m^3/min) and uses a duplex design combining turbomolecular blades with a drag mechanism for operation at higher backing pressures (Ref. 15). It includes a vent port for controlled venting and is managed by an integrated motor controller or an Edwards Turbo Instrument Controller (TIC). The nXDS6i scroll pump achieves an ultimate vacuum of 3 torr with a displacement of 4.0 ft^3/min (0.113 m^3/min), using an orbiting scroll mechanism to compress and exhaust gas without oil contamination. Vacuum levels are monitored by a wide-range gauge and transducer, which controls the hand-off of primary pumping from the roughing pump to the turbomolecular pump. The turbomolecular pump brings the pressure from the roughed 3 torr down to roughly 10^{-5} to 10^{-6} torr.

3.2.2 Cold Box and Cryocooler

Inside the vacuum chamber, the cold box serves as a thermal shield and houses the sample grips and test specimen. It can achieve temperatures as low as 30 K at the grips and 33 K at the test specimen and includes a transparent window for optical measurement. The front panel is completely removable for fixture installation and maintenance. In the case of LESTR Unit 01, the grips are typically wire grips, though different grips, such as capstans and wedge grips, have been utilized.

Four Garolite G-10 support struts extend from the cold box base to the adapter plate where the load cell mounts, providing structural stability to the lower load train (Figure 4 and Figure 7). The cold box bounds the test space, which has a total internal volume of 7.5 by 9.5 by 11.5 in. (819.4 in^3) (19.1 by 24.1 by 29.2 cm (13,427.6 cm^3)) (Figure 8). The cold-box volume is heavily driven by cooling capacity (greater capacity supports larger volume) and the “daylight opening” (the volume between the two pillars and the crosshead/floor of the load frame).

The cryocooler consists of a Sumitomo® (Sumitomo Electric Industries, Ltd.) CH-110LT cold head, a single-stage cryogenic refrigerator operating on the Gifford-McMahon cycle, and a Sumitomo® F-70L Freedom® Series helium compressor (Refs. 16 and 17). This compressor delivers high-pressure, oil-free helium gas to the cold head, enabling continuous removal and stable temperatures down to 40 K. It is liquid cooled using facility chilled water and operates without consumable cryogens, making it ideal for extended-duration testing.

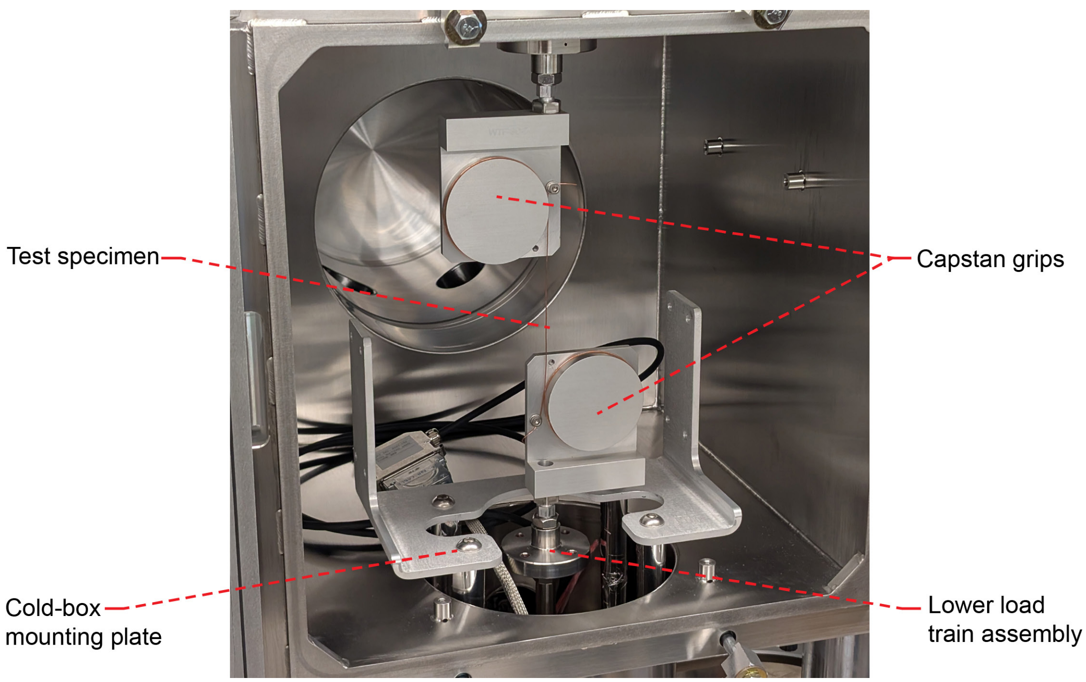

Figure 7. Interior of vacuum chamber with lower load train assembly installed.

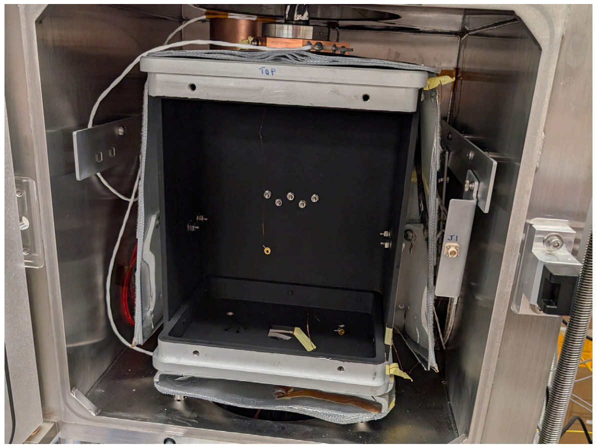

Figure 8. LESTR Unit 01 cold box.

3.2.3 Thermal Conductors

Flexible copper thermal straps provide a heat transfer pathway from the test section to the cryocooler, with a design target of ≥1 W/m·K thermal conductance (Figure 5). Embedded resistive heaters allow active temperature control. These straps connect the cryocooler to the mechanical loading system and the thermal shield, which is constructed from multilayer insulation (MLI) to minimize heat infiltration and prevent excessive thermal gradients (<5 K) across the test specimen (Figure 5). One strap connects the hot-side and cold-side vacuum rods in the upper pull-rod assembly, using titanium for moderate thermal isolation and aluminum for efficient heat removal. A similar configuration is used for the lower pull-rod assembly, and a third strap links the cold head to the cold-box shroud.

3.3 Gripping and Alignment Mechanisms

The gripping mechanisms are located within the sample space, which is enclosed by the cold box and bounded by the vacuum chamber (Figure 5). This configuration ensures that the test specimen remains isolated in a controlled thermal and pressure environment while heat is efficiently removed through the cooling system and rejected to the external compressor system.

3.3.1 Capstans and Wire Grips

Custom capstan grips, fabricated by Wyoming Test Fixtures, Inc., were designed to secure wires without inducing stress concentrations. Each grip measures 4.2 in. tall by 3.5 in. wide by 0.75 in. thick (10.7 by 8.9 by 1.91 cm) and incorporates a 3.0-in. (7.6-cm) diameter capstan. The grips are machined from 6061-T6 aluminum for strength and thermal compatibility. During initial system checkouts, maintaining alignment and installing wire specimens proved challenging due to limited space inside the cold box. To address this, a custom alignment fixture was fabricated to hold the capstans in a precise configuration outside of the test space, providing additional clearance for specimen installation. A custom tensioning tool, adapted from a socket wrench and drive, was developed to wrap and tension the wire around the capstans. To prevent wire slippage during installation and testing, a metal plate slightly larger than the capstan was added to each grip face.

For low-cycle fatigue testing, another set of custom bolt-on grips was procured from Wyoming Test Fixtures. These grips were specifically designed to clamp fine wires securely without inducing stress concentrations. Each grip measures 2.5 in. tall by 2.9 in. wide by 1.6 in. thick (6.4 by 7.4 by 4.1 cm) and features a 1.5- by 1.5-in. (3.8- by 3.8-cm) gripping area. The grips are constructed from 316 stainless steel and incorporate a tungsten carbide-coated gripping surface with 60-grit roughness to ensure reliable specimen retention under cyclic loading.

3.3.2 Four-Point Bend Fixture

For flexural testing, the four-point bend fixture consists of two actuator pins mounted to the upper cold-side pull rod and two supporting pins attached to the lower cold-side pull rod. The actuator pins apply force to the specimen between the support pins toward the stationary base, creating a uniform bending moment across the gauge section. The fixture is designed for a maximum load of 40 lbf (178 N) and conforms to the requirements of ASTM D-6272, with reasonable adaptations for cryogenic operation. It is rated for up to 100,000 cycles at 1 Hz, ensuring durability for extended fatigue testing.

3.4 Instrumentation, Data, and Control

LESTR's instrumentation and control architecture provides closed-loop load, displacement, strain, temperature, and vacuum monitoring during both tensile and four-point bend tests (Figure 9). Machine control is handled by an Instron® 8800MT digital controller, which delivers synchronous data acquisition and loop closure rates up to 10 kHz, up to 24-bit data resolution, adaptive proportional-integral-derivative (PID) control, transducer auto-identification, and safety interlocks (e.g., Specimen Protect and actuator lockout when a waveform is running) (Ref. 18). These features enable accurate control for quasistatic and high-cycle fatigue regimes and reduce configuration errors and setup time.

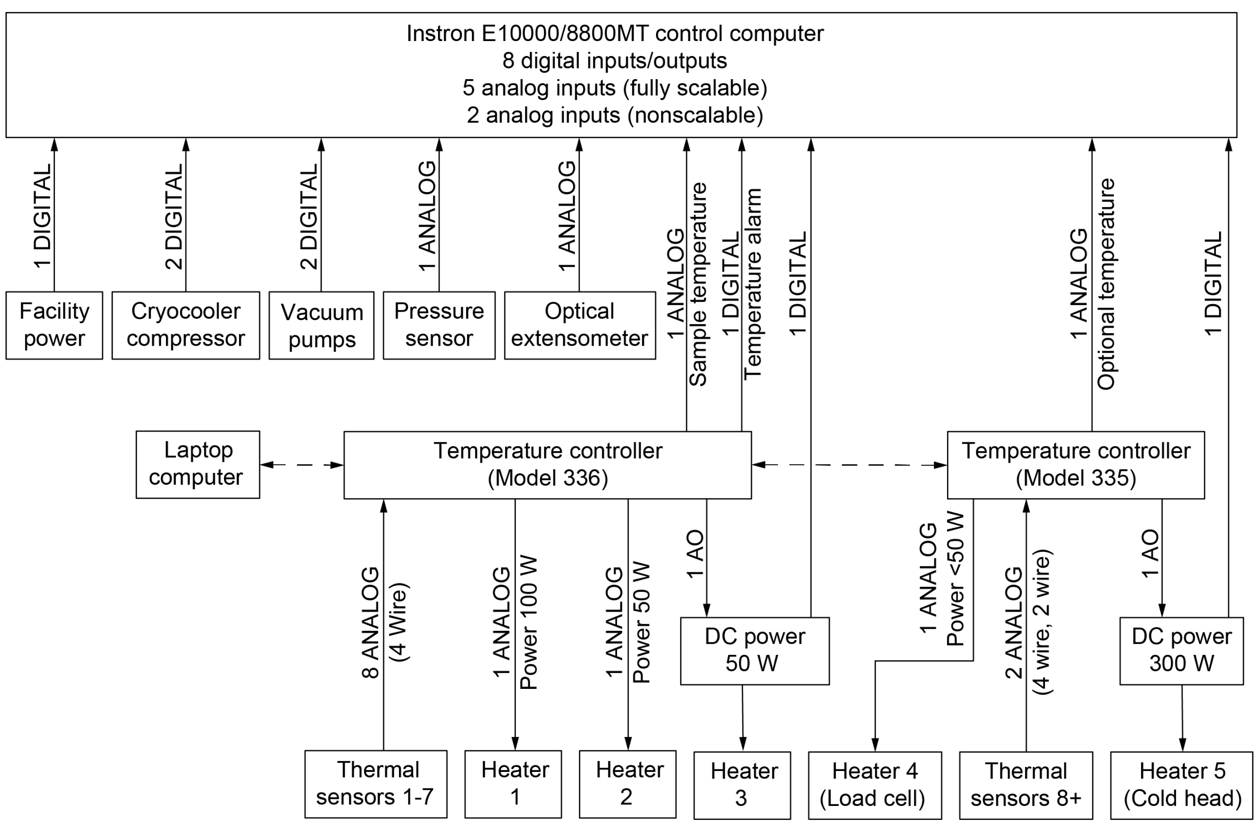

Figure 9. Instrumentation and thermal control wiring diagram.

Position and extension are measured using the ElectroPuls™ E10000 system's optical encoder channel coupled to oil-free linear motor acquisition, which provides high dynamic performance (>100 Hz), ±2,250-lbf (10,009-N) dynamic and ±1,570-lbf (6,984-N) static linear capacities, and a 2.36-in. (5.99-cm) stroke within its compact twin-column frame (see Section 3.1.1).

Strain is measured using a noncontact optical video extensometer mounted at the vacuum chamber window. Temperature is controlled via closed-cycle cryocooling with embedded heaters and is monitored by cryogenic diode. Vacuum level is traced using wide-range combination gauges to ensure the chamber reaches and maintains high vacuum prior to cryocooler operation.

3.4.1 Position Control

Displacement control is provided by Instron's oil-free linear motor technology with precise digital extension feedback from an optical encoder and a dedicated position channel. This arrangement supports both static and cyclic control modes and simplifies setup and end-of-test positioning. The ElectroPuls™ E10000 platform is expressly designed for dynamic and static testing, with stiffness-based tuning to maintain loop stability across specimen stiffness change.

3.4.2 Optical Extensometer

LESTR makes use of an Epsilon ONE® (Epsilon Technology Corp.) optical, noncontact extensometer (130PT, telecentric optics) for high-accuracy axial strain measurement through the vacuum and cold chamber windows (Ref. 19). The system provides real-time data rates of >300 Hz; meets ISO 9513 Class 0.5 and ASTM E83 Class B-1 accuracy ratings for gauge lengths of ≥10 mm; and uses telecentric lenses that minimize out-of-plane error, which is a common source of bias in video extensometry. The system uses laser-assisted alignment to project prealigned laser lines onto the specimen, enabling rapid alignment checks before testing. These capabilities make the system suitable for measuring small strains (modulus) to large elongations while maintaining noncontact operation compatible with cryogenic environments.

3.4.3 Temperature Sensors

Cryogenic temperatures in the cold box and drivetrain are monitored using Lake Shore Cryotronics® (Lake Shore Cryotronics, Inc.) DT-670 silicon diode sensors, widely used from 1.4 to 500 K and available with calibration for improved accuracy across cryogenic ranges (Ref. 20). DT-670 sensors conform to a standard voltage-versus-temperature curve (Curve DT-670), reducing the need for individual calibration in many applications, and are offered in packages compatible with ultrahigh vacuum and repeated thermal cycling.

Lead wiring to sensors is routed using phosphor-bronze cryogenic wire (typically 32 or 36 AWG, polyimide or Formvar insulation) to minimize thermal conduction into the cold box while maintaining robust electrical performance. Configurations such as Duo-Twist™ and Quad-Lead™ (Lake Shore Cryotronics, Inc.) are used to reduce pickup noise and simplify heatsinking and dressing inside the chamber.

3.4.4 Temperature Controller

Temperature control is implemented with Lake Shore Cryotronics® Model 336 and Model 335 cryogenic controllers (Refs. 21 to 22). Model 336 provides four sensor inputs and four independent control outputs; two PID loops (100 W and 50 W); autotuning; zone-based sensor switching; alarms; and analog outputs that support diodes, resistance temperature detectors, and thermocouples from 300 mK to >1,500 K. These features enable multipoint control (e.g., top and bottom capstan setpoints) and automated safety interlocks that disable heater power on sensor error.

Model 335 offers two sensor inputs and two PID-controlled outputs with total heater power up to 75 W as well as zone tuning, alarms, relays, and ±10V analog outputs. This controller is well-suited for cold-head and auxiliary component temperature regulations (e.g., load cell thermal management within its rated operating range).

3.4.5 Pressure Sensors

Vacuum pressure is monitored from atmosphere to high vacuum using combination gauges and wide-range modules:

- The Edwards WRG-S (DN40CF) Active Wide Range Gauge provides single-port measurement from atmosphere to 10^{-9} mbar, with a microprocessor-processes linear output, programmable setpoints, and typical accuracy of ±15% (<100 mbar) (Ref. 23). It automatically transitions between a Pirani gauge and an inverted magnetron sensor to cover full range.
- The Granville-Phillips® 390 Micro-Ion® ATM module from MKS® (MKS Inc.) uses Micro-Ion® ionization, a Conductron® heat-loss sensor, and dual piezoresistive sensors to deliver continuous measurement from 10^{-9} torr to atmosphere, with RS-485 or analog outputs, optional setpoint relays, and a compact form factor suitable for chamber ports and load locks (Ref. 24).
- For load-lock and broad-range monitoring, the MKS® 974B QuadMag™ transducer integrates cold cathode, MicroPirani™, and piezo sensors for a range of 10^{-8} to 1500 torr, offered with Recommended Standard (RS) 232 and RS485 communications, optional local display, and user-serviceable cathode and modules to minimize downtime (Ref. 25).

These instruments provide redundant, cross-validated pressure readouts across the full pump-down and test spectrum, ensuring the chamber reaches setpoint vacuum before cryogenic operation.

3.5 Data Acquisition and Software

Machine control and data acquisition are performed by the Instron® 8800MT controller and integrated Console software interface, which serve as the hardware and firmware foundation for load, position, strain, and auxiliary channels. High-rate acquisition (up to 10 kHz) and up to 24-bit resolution across the span of each transducer support accurate fatigue and static testing, and adaptive control dynamically updates PID terms as specimen stiffness evolves.

Test method creation and execution leverage two Instron® software applications: Bluehill® Universal for static/quasistatic workflows and WaveMatrix™3 for dynamic/fatigue sequences (Illinois Tool Works Inc.) (Refs. 26 and 27). Bluehill® Universal provides templated standards, QuickTest setup, guided workflows, live displays/graphs, and audit trails to streamline operator training and reduce errors.

WaveMatrix™3 adds a visual sequence builder for ramps and cyclic waveforms, stiffness-based tuning, retrospective test review, and Microsoft® Windows 11® (Microsoft Corp.) compatibility, which accelerates setup for complex multistep and multiaxial tests on the ElectroPuls™ platform.

Together, these tools support LESTR’s requirements of precise load/position control, noncontact strain via optical extensometry, temperature regulation via Lake Shore Cryotronics® controllers, and vacuum assurance via wide-range gauges, all with integrated safety annunciation and logging for out-of-range or off-nominal conditions throughout long-duration tests.

4.0 Operating Procedures

LESTR tests are conducted under vacuum and cryogenic conditions using displacement control and noncontact strain measurement. Each test follows the same high-level sequence:

1. Specimen installation and alignment: Install the wire specimen in the capstan or wire grips using the alignment fixture and custom tensioner. Apply a small preload (typically 2 to 5 lbf) (9 to 22 N) to remove slack and confirm straight, centered alignment with the optical field of view.
2. Chamber seal, pump-down, and leak check: Close and latch the vacuum chamber doors and verify all ConFlat® flanges and feedthroughs are sealed. Pump down using the scroll pump; when the threshold pressure is reached, the turbomolecular pump engages automatically. Confirm vacuum stability using the wide-range gauges before proceeding to cooldown.
3. Cooldown and temperature stabilization: Activate the closed-cycle cryocooler and control the cold-box and drivetrain setpoints with the Lake Shore Cryotronics® 336 and 335 controllers. Stabilize the specimen at the required test temperature (e.g., 40 K) with wire temperature uniformity <5 K across the gauge length.
4. Test execution: Run tests under displacement control at nominal strain rates between 10^{-4} and 10^{-2} s^{-1}, or under cyclic control (e.g., ≤1 Hz) for fatigue and four-point bend durability. Force and displacement are synchronized with optical strain from the extensometer. Safety interlocks constrain maximum force and travel to protect the specimen, rig, and sensors.
5. Warm-up and vent: After testing, warm the chamber (e.g., by controlled heater power), turn off the cryocooler, vent to atmosphere, and remove the specimen and fixtures. Document results and photograph the specimen and grips as needed.

Notes on safety and data integrity:

- Use controller interlocks and limits appropriate to the installed load cell capacity.
- Handle silicon diode sensors and cryogenic leads with care; avoid pinching, bending, or contact damage.
- Confirm optics window is dry and clear for optical extensometry in cryogenic tests.

4.1 Thermal Cyclic Tests

Thermal cycling evaluates property changes and stability across a mission-relevant temperature envelope. The specimen temperature is cycled between discrete setpoints; at each setpoint, measurements (e.g., modulus, recoverable strain for SMAs, and deformation behavior) are recorded.

- Thermal range: 40 to 125 K for lunar-relevant tests.
- Cycle frequency: Variable. Selected to ensure thermal equilibrium at the specimen, and therefore dependent on the time required to reach the target temperature.
- Fixture/instrumentation: Capstan or wire grips. Temperature is controlled via closed-loop PID; wire temperature dispersion ≤5 K is maintained. Optical strain is measured noncontact to avoid thermal loading artifacts.
- Measured quantities: Establish temperature-dependent stiffness, strength, and transformation behavior (for SMAs) and identify temperature-induced degradation.
- Use cases: Assess stability and identify degradation under mission-relevant thermal conditions.

4.2 Four-Point Bend Tests

The four-point bending provides flexural properties with a constant bending moment over the gauge section.

- Thermal range: 40 to 125 K for lunar-relevant tests.
- Cycle frequency: Up to 1 Hz for cyclic bending.
- Fixture/instrumentation: Two actuator pins (upper cold-side pull rod) and two support pins (lower cold-side pull rod) aligned within the cold box.
- Load and rate: Designed for ≤40 lbf (178 N) and up to 100,000 cycles at 1 Hz.
- Measured quantities: Flexural strength, flexural stress, and flexural modulus derived from load displacement and optical strain data.
- Use cases: Durability screening and comparison of processing routes under cyclic bending at cryogenic temperature.

4.3 Tensile, Fatigue, and Durability Tests

Tensile characterization establishes stress-strain behavior, yield strength, ultimate strength, ductility, and modulus using quasistatic displacement control and optical strain measurement. Fatigue durability evaluates cyclic performance at fixed temperature (e.g., 40 to 125 K). Cyclic tension or bending is applied at ≤1 Hz, typically continuing to $\geq 10^6$ cycles for lifetime estimation of SMA wires intended for rover tires and mobility systems. LESTR's closed-cycle refrigeration and high-vacuum environment avoid consumable cryogens, enabling long-duration tests with steady conditions.

Results from tensile and cyclic tests iteratively feed back to the alloy wire processing routes. The combined tension and bending datasets guide optimization of alloy composition, heat treatment, diameter tolerance, surface finish, and draw schedules for lunar and Mars wheel and tire technologies.

5.0 Calibration and Performance Evaluation

Calibration and performance verification are essential to ensure that LESTR delivers accurate and repeatable results under cryogenic and vacuum conditions. These activities validate the correlation between environmental setpoints and specimen conditions, confirm sensor accuracy, and benchmark mechanical and thermal performance against design requirements. Accurate and repeatable testing requires all hardware to be in good working order and all instrumentation to be maintained within its required calibration period.

5.1 Thermal Testing and Calibration

Taking direct temperature measurement on fine wire specimens during operational tests is impractical due to space constraints and the risk of altering thermal behavior. Therefore, indirect calibration must be performed during system checkout using instrumented wire samples. This process establishes a correlation between tooling temperature, cold-box environment, and wire temperature.

Thermal calibration involves several key steps:

- Instrumented wire setup: Install sample wires with miniature cryogenic sensors (e.g., Lake Shore Cryotronics® DT-670 diodes) at multiple points along the gauge length.

- Cooldown characterization: Record the cryocooler cold-head temperature, tooling temperature, and wire temperature during cooldown to evaluate thermal load and heat transfer efficiency.
- Equipment mapping: At discrete setpoints (e.g., 40, 60, 100, and 125 K), compare wire and tooling temperature to derive a soft calibration curve for operational tests.
- Gradient assessment: Verify that wire temperature dispersion remains within ±5 K, as required for uniform strain measurement.
- Cooldown rate analysis: Document the time required to reach thermal equilibrium at each setpoint to optimize test scheduling.

This calibration ensures that during actual tests, wire temperature can be inferred from tooling and environmental readings with high confidence, enabling accurate material property evaluation without intrusive sensors.

6.0 Representative Results

Initial validation tests demonstrated LESTR's capability to deliver high-fidelity mechanical data under cryogenic conditions. Tensile tests on Inconel® 718 wire at room temperature (0.0201-in. (0.0511-cm) diameter, 3.5-in. (8.9-cm) gauge length) showed that ultimate strength values and post-yield behavior were consistent with published literature (Figure 10). In addition, preliminary thermal cycling between 40 and 125 K showed stable temperature control and minimal thermal drift, validating the cryocooler and heater integration. Further testing is required, but these results suggest that LESTR is operating in alignment with its intended design objectives for accuracy, repeatability, and environmental fidelity.

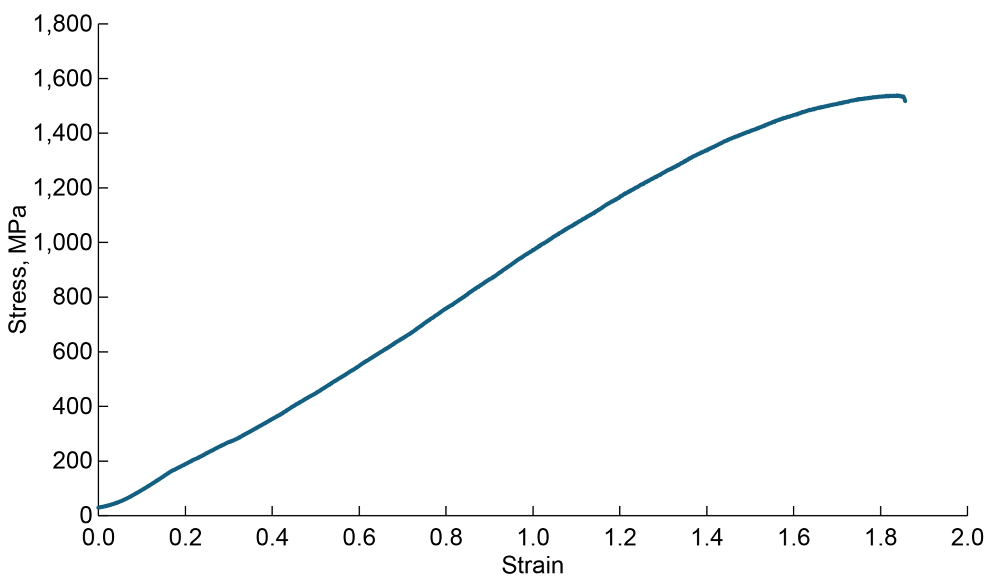

Figure 10. Stress versus strain for tensile testing of Inconel® 718 wire.

7.0 Discussion

The LESTR test rig successfully addresses three long-standing challenges in fine wire testing under extreme conditions:

1. Alignment sensitivity: LESTR's custom alignment fixture and precision load train minimize bending and misalignment errors.
2. Grip-induced artifacts: The test rig's capstan and bolt-on grips have been optimized to prevent stress concentrations and slippage, ensuring uniform load transfer.
3. Environmental control: Closed-cycle cryocooling eliminates reliance on hazardous cryogens, enabling long-duration testing without consumable replenishment.

Further, whereas the current configuration of LESTR supports single-sample testing, the modular architecture enables future upgrades for multiple-sample throughput, automated thermal cycling, and extended fatigue protocols. These enhancements will accelerate material screening for lunar and Martian mobility systems.

More important is the capability that LESTR offers to inform and expand current materials databases. Conventional materials databases, such as those underpinning finite-element analysis tools, the NIST Index of Material Properties (Ref. 6), and the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) Cryogenic and Low Temperature Database (Ref. 28), typically cover a wide temperature range from room temperature down to 4 K. For example, NIST's curated data for thermal conductivity, specific heat, elastic modulus, and thermal expansion extend from 4 to 300 K for common metals such as stainless steels, aluminum alloys, copper, and nickel-based superalloys (Ref. 6). However, these databases focus on quasistatic, bulk thermophysical properties rather than mechanical behavior under load, and they generally lack validated mechanical property data below 77 K for fine-diameter wires or fatigue conditions.

SMA and other aerospace-focused material property databases, such as NASA's MAPTIS (Ref. 3), predominantly provide data relevant to temperatures down to 77 K, with very few entries for material behavior below liquid-nitrogen temperatures. These datasets generally focus on structural metals in bulk form and do not include mechanical performance under load for fine wires, nor do they cover cyclic fatigue behavior at ultralow temperatures. Most mechanical property data for aerospace alloys are concentrated in the ambient-to-200-K range, leaving a significant gap below 77 K.

This lack of mechanical performance data becomes critical for space applications, such as lunar south pole exploration, where temperatures regularly drop below 40 K. NASA's SMA rover tires and other components will be exposed to a wide range of temperatures between 40 and 400 K. Existing databases cannot fully support design validation for these conditions.

LESTR fills this gap by enabling the direct measurement of mechanical properties of fine wires at temperatures between 40 and 125 K under high-vacuum conditions, with capabilities for tensile, fatigue, and four-point bend testing. Unlike existing material repositories, LESTR provides strain-controlled mechanical data at sub-77-K temperatures; dynamic and cyclic testing under controlled strain rates and cyclic frequencies ≤1 Hz; thermal and pressure precision with wire temperature uniformity within ±5 K and vacuum down to 10^{-7} torr; noninvasive, optical strain measurement of fine-diameter wires under cryogenic stress; and long-duration testing without consumable cryogens, ensuring stable conditions for millions of cycles.

By generating this unique dataset, LESTR substantially enhances the available mechanical property information for wire-form SMAs and metals in the 40- to 125-K regime, which is critically underrepresented yet essential for Artemis mission hardware qualification and future planetary mobility systems where ultralow temperature performance is mission critical.

8.0 Conclusions

The Lunar Environment Structural Test Rig (LESTR) represents a significant advancement in the capability to characterize fine wire material under lunar-relevant conditions. Conventional aerospace material databases, such as NASA's Materials and Processes Technical Information System (MAPTIS) and National Institute of Standards and Technology (NIST) cryogenic property repositories, provide extensive thermophysical data for bulk metals down to ~4 K. However, these resources largely omit mechanical performance data for fine wires, particularly under load, in vacuum, and at temperatures below 77 K. This gap is critical for space applications, where hardware such as shape memory alloy (SMA) actuators and rover tires must operate reliably in environments as cold as 40 K or lower. Without validated mechanical property data in this regime, design margins remain uncertain, and mission risk increases.

LESTR directly addresses this challenge by enabling precise mechanical testing of fine wires at temperatures between 40 and 125 K in a high-vacuum environment. The system combines a high-stiffness electrodynamic load frame with closed-cycle cryogenic cooling, optical strain measurement, and integrated thermal and vacuum control. This architecture eliminates reliance on consumable cryogens, allowing long-duration tests that capture fatigue and durability behavior over millions of cycles. By correlating tooling and specimen temperatures through calibration, LESTR ensures accurate thermal control without intrusive sensors on delicate wires. The rig's ability to perform tensile, four-point bend, and cyclic fatigue tests under displacement control provides a comprehensive dataset for material models and finite-element simulations.

Initial validation tests confirm that LESTR Unit 01 delivers high-fidelity mechanical data, resolving elastic modulus, yield strength, and post-yield behavior for fine wires without grip-induced artifacts. Thermal cycling experiments demonstrate stable temperature control and minimal gradients, validating the cryocooler and heater integration. These results establish LESTR as a robust platform for iterative material development, enabling optimization of SMA processing routes for Artemis mission hardware and future planetary mobility systems.

Beyond its immediate application to SMA wire characterization, LESTR fills a critical gap in the global materials data infrastructure by generating mechanical property data at ultralow temperature, data that are virtually absent from existing databases. This capability not only supports NASA's long-term objectives for lunar and Martian exploration, where extreme thermal environments demand material science for space applications, but also sets a new benchmark for precision testing under combined cryogenic and vacuum conditions.

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