# Development and Validation of a Novel Instrumented Thermal Hand Manikin for the Evaluation of Lunar Gloves.

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**Abstract: Under this project, a novel thermal hand manikin was developed and validated to overcome limitations of existing instruments and provide a repeatable tool for ongoing extravehicular activity (EVA) glove evaluation. Initial development included creating computer aided design (CAD) and physical models of hand forms that met characteristic dimensions and could be fitted into a glove. Subsequent development focused on the manikin thermoregulation system, sensors, and data acquisition. The final design consisted of a four-piece hand manikin with fluid-regulated nylon shell, and 15 miniature surface-mounted temperature/heat flux sensors. The instrument was constructed and validated for thermal stability, accuracy, and correlation with an existing thermal hand instrument. The final system integrates directly with the Jet Propulsion Laboratory Cryogenic Ice Testing, Acquisition Development, and Excavation Laboratory (CITADEL) test chamber for ambient exposure and cold surface contact testing.**

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## Acronyms and Nomenclature

CAD = Computer Aided Design
CITADEL= Cryogenic Ice Testing, Acquisition Development, and Excavation Laboratory
COTS = Commercial Off The Shelf
CSV = Comma Separated Values
EVA = Extravehicular Activity
HITL = Human In The loop
$I^2C$ = Inter-Integrated Circuit
JPL = Jet Propulsion Laboratory
NCSU = North Carolina State University
PID = Proportional, Integral, Derivative (control model)
Rcl = Intrinsic thermal resistance (insulation) of clothing
TPACC = Textile Protection and Comfort Center (at NCSU)
USB = Universal Serial Bus

## I. Introduction

RIGOROUS thermal testing of lunar and extravehicular activity (EVA) gloves is critical to establish safe usage parameters and reduce cold injury risk to astronauts. The use of an instrumented thermal manikin in combination with simulation and human-in-the-loop (HITL) testing can help optimize handwear performance and shorten design cycles. Existing thermal hand manikins are widely used to characterize cold weather and protective work gloves[1,2,3], but difficult to apply for EVA handwear testing due to highly constrained geometry during don/doff, wide range of exposure environments, and physical integration requirements of the test fixture. The motivation for this project and the companion effort to standardize a test and data analysis protocol[4] is that HITL testing is extremely expensive, so thermal manikin use allows more rapid iterations of gloves designs earlier in the design process.

Historical evaluation of EVA handwear has been conducted by instrumented human subjects in controlled environments. The natural advantage of this approach is the high degree of human sensory realism. Measurements of skin and glove inter-layer temperatures can be directly related to subject thermal sensation and discomfort surveys[6]. The challenges of using human testing for product development and end-use garment validation are three-fold. Potential failure of test specimens can put the test subject at risk of injury. Human subjects are inherently variable due to thermo-physiology and acclimatization history. Lastly, accurately quantifying the true energy exchange between skin and environment using a human subject as a heat source is extremely difficult, especially for extremities where full-body calorimetry methods[5] cannot be used.

In prior research with Phase VI EVA Gloves[6], a human subject was instrumented at 13 locations (Figure 1) with 13 thermocouples to measure skin surface temperature at critical contact points during a cold object grasp exercise. This work formed the basis for environment and contact temperature and duration limits for actual EVA uses. The cost and risk associated with applying this methodology to future handwear development motivated the development of a hand thermal manikin that could replicate this historical methodology while providing more precise and repeatable measurement data.

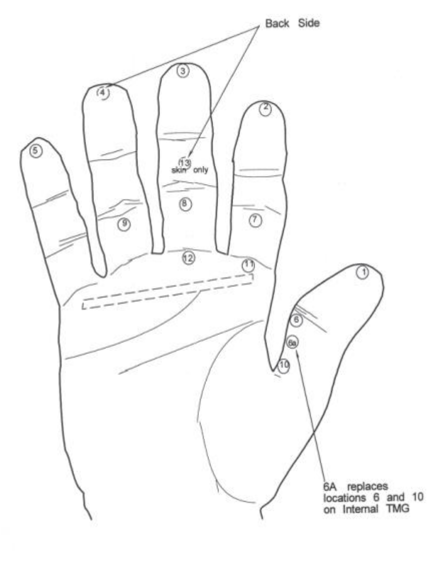

**Figure 1. Sensor locations 1-13 from prior Phase VI EVA Glove HITL test protocol**

Typical thermal manikins are anatomically shaped full or partial body instruments designed to simulate heat exchange between the human body and its surrounding environment. They are subdivided into individual measuring segments, each equipped with heating elements and surface temperature sensors to replicate metabolic heat production and measure heat transfer between skin, clothing, and environment[2,9]. Used in fields such as textile research, building climate assessment, and human thermal comfort studies, thermal manikins provide controlled, repeatable conditions for evaluating insulation properties, heat dissipation, and physiological responses to environmental stimuli[7]. Advanced instruments may include sweating capabilities, application-specific functions such as breathing or environment sensors, or tailored design for exposure in extreme environments.

The rigid design limitations of commercially available thermal hand manikins make them largely unsuitable for EVA handwear. The primary issue is fitment of the glove onto the instrumented hand form without requiring modifications to the glove. Rigid structures that are integrated into the glove design such as wrist gimbal rings and palm bars found in the Phase VI glove demand a lot of hand flexibility during don and doff which cannot be achieved with hard-shell manikin forms. Manikin designs with a flexible or inflatable substrate have been used for some applications[8] but are challenging to apply for EVA in-situ testing due to the need to apply external surface contact forces and glove test protocol that requires pressurization or vacuum. Another issue driving the use of a manikin is that HITL testing is extremely expensive, therefore, this approach allows more rapid iterations of glove designs earlier in the design process.

The measurement capability of thermal manikins relies on a segmented design, where each segment functions as an independent measuring unit for thermal regulation and measurement. While this capability to report spatial average results is well-suited for garment or environment testing, it can mask potential point locations where peak thermal transfer is occurring and does not align well with the prior high-resolution local temperature human tests of EVA gloves.

## II. Methods

Developing a novel hand thermal manikin capable of in-situ measurements and correlation to existing human subject data required concurrent development efforts in multiple areas. Hand morphology and articulation design was a gating design constraint. If the hand could not fit into the unmodified glove, the entire effort would be futile. The thermal regulation method had to be compatible with the physical hand form and provide skin temperature control over a wide range of exposure conditions. Localized sensors were needed to quantify heat transfer at critical contact locations, and a suitable data acquisition design was required to integrate all the hand functions and data collection and provide an operator interface. The resulting instrument was calibrated and validated through a series of tailored experiments, prior to delivery and installation at NASA's JPL Cryogenic, Ice Testing, Acquisition Development, and Excavation Laboratory (CITADEL).

### A. Morphology and Articulation

Hand form development included a combination of CAD modelling and iteration through test-fitting 3D printed sintered nylon prototype forms into actual glove test specimens. Following the decision to build the instrument as a right-hand model, data was compiled on existing astronaut glove sizes and hand dimensions targeting a larger glove size that was readily available to borrow from existing inventory. A CAD surface model was created in SolidWorks using a commercially available 3D scanned mesh of a human hand, which was modified to align with key dimensions including hand length, hand circumference, and finger length (Figure 2).

The EVA glove test specimen is a three-layer design consisting of an inner bladder, a thermal/structural layer, and an outer shell. (Figure 3) The thermal hand manikin would need to install in this glove system in a comparable manner to the human hand. Additional considerations applied to the CAD hand form were at-rest hand posture and hand geometry to contact a designated grasp object defined in the test protocol. A CAD model of a pressurized bladder was used as an initial shape target for the at-rest posture. A 3D printed nylon prototype of the resulting hand form was compared against an assembled glove system (Figure 4) demonstrating the alignment of the at-rest hand form with the undeformed glove shape.

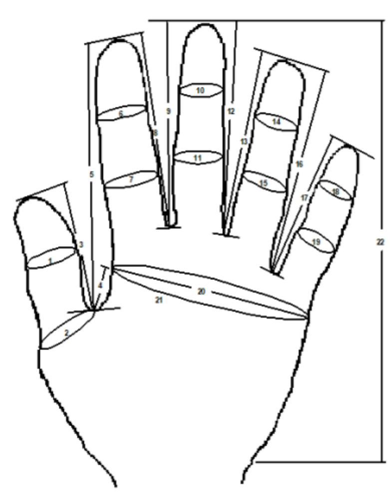

**Figure 2. Reference Hand form landmark dimensions.**

**Figure 3. 3-Layer EVA glove assembly comprising the pressure bladder, thermal restraint layer and outer shell.**

**Figure 4. Hand form prototype overlay with EVA glove.**

Articulation or physical segmentation of the hand manikin was necessary to don/doff the glove system. Multiple degrees of articulation in the design were discussed to mimic the range of human mobility, but most were ruled out due to design complexity and the requirement to make solid and repeatable contact with the grasp object. Design options were identified and refined in the CAD environment, but the complexity of the 3-dimensional fit up and flexible glove system made reliable fit assessment in CAD impractical. Four physical models were produced via 3D printing to assess variations of thumb articulation combined with either a folding or multi-part hand form. (Figure 5)

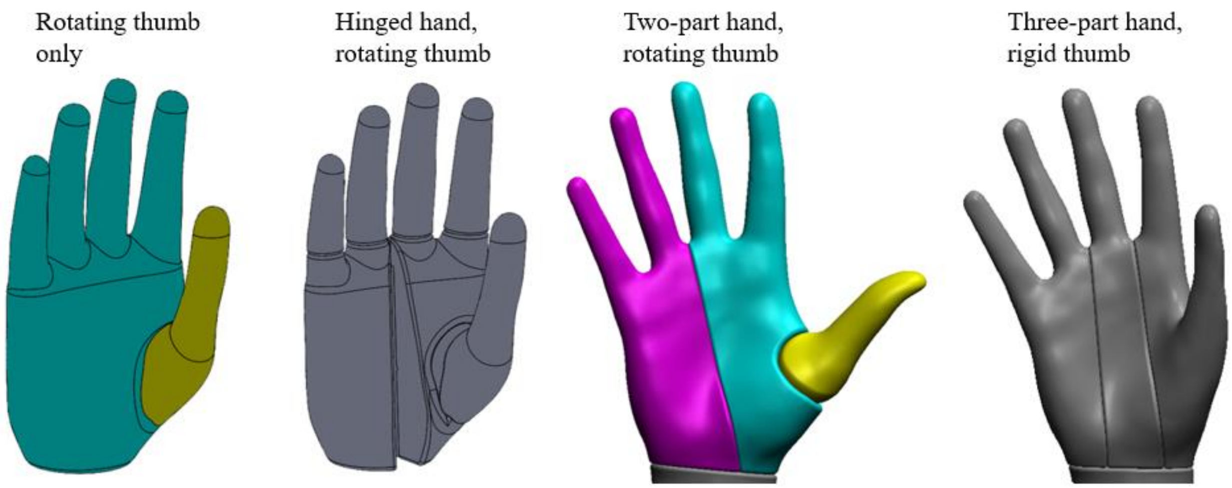


**Figure 5. Hand articulation options considered.**

The best combination of don/doff feasibility, active measuring surface area, and mechanical positioning repeatability was a three-part hand form. With this design, the thumb and index finger were a single rigid unit which was inserted into the glove specimen first, followed by the ring and pinky finger assembly, and lastly the center of the hand and middle finger assembly were installed in the gap remaining. Alignment pins mounted on the mating parts provided positive alignment once assembled. With the complex geometry of the hand fully defined, the forearm region was designed to interface with the hand at the wrist and connect to the test apparatus.

### B. Interface Sensor Development

The project specification included surface-mounted temperature sensors at locations similar to prior human subject studies and defined by the NASA team, with a stretch goal of also measuring heat flux at each sensor location. "Soft skin" construction to mimic skin and fat layers at the sensor locations were discussed in the design phase but ultimately deemed too complex and potentially challenging for touch test repeatability.

Fifteen surface sensor locations were selected from the candidate measuring sites, based on importance of measurement and available physical space in the hand form (Figure 6). This included 9 sensors on the fingers, and 5 sensors on the palm, being the areas of most interest identified for touch tests. The wrist included a single surface sensor, considered primarily a guard region to protect the glove from cold temperatures and to prevent lateral heat loss from the zones of most interest.


**Figure 6. Surface sensor locations on hand form.**

Commercially available sensors, including thermistors, thermocouples, and thin film temperature/heat flux sensors were considered. A prototype sensor was built by modifying a commercial off-the-shelf COTS thin film heat flux sensor to reduce physical size and allow mounting on the small finger and hand contact surfaces. (Figure 7). Lead wires were routed from the base of the sensor into the hand cavity for termination to data acquisition modules. The sensor was also fitted with a copper foil contact face to create a uniform sensing area and coated with a thin protective acrylic sealant (Figure 8).

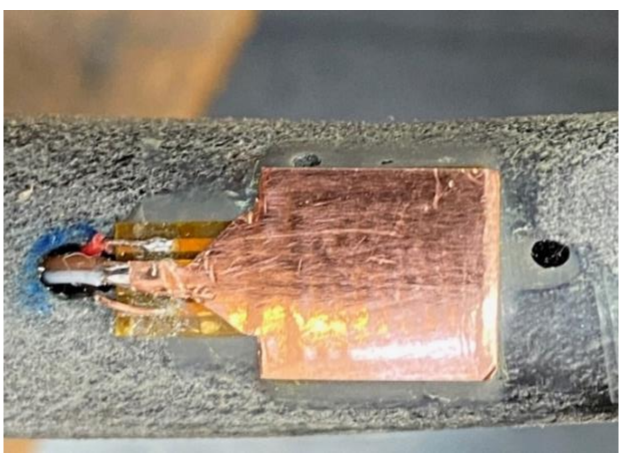

**Figure 7. Surface heat flux and temperature sensor bonded to hand surface.**

**Figure 8. Surface sensors installed with protective layer.**

## C. Thermal Regulation Development

Preliminary system design considered installing resistive heaters on the manikin shells with surface temperature sensors as feedback. A closed loop proportional-integral-derivative (PID) algorithm would regulate the heater power to achieve the desired skin setpoint temperature. Resistance heaters are predictable to control and can be applied to the inside of the hand shells to provide uniform heat generation over the surface. However, if the test chamber conditions include solar loading where heat added to the hand form is greater than that heat lost to the environment, the skin temperature will exceed setpoint and the heaters will shut off. Additionally, the use-case of this instrument inherently results in non-uniform heat loss, especially at the contact interface points. Uniform heat generation and non-uniform heat loss would create temperature non-uniformities that would be difficult to quantify and could confound the results.

A fluid regulated design was identified to be more versatile, capable of regulating the manikin temperature in both heat loss and heat gain environment conditions. By using a temperature regulated recirculating fluid, the hand skin temperature could be more spatially uniform under non-uniform heat loss conditions. Water was selected as the recirculating fluid, with the option of adding a fraction of propylene glycol if freezing risk was identified during initial system testing. The fluid flowrate to each manikin zone was optimized to transfer the theoretical maximum amount of heat to the hand surface and maintain a 1.0 °C maximum temperature difference between inlet and outlet. With these conditions, the skin temperature could be regulated within +/- 1.0 C of desired setpoint, and the resulting fluid dT and mass flow rate used to calculate the energy transfer for each hand region.

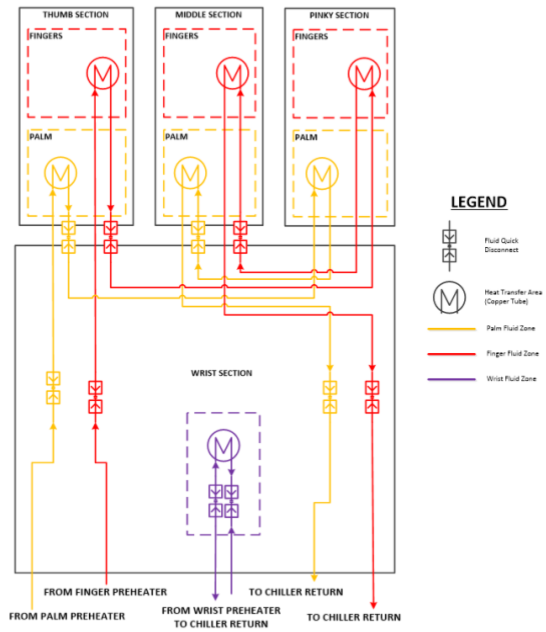


**Figure 9. Hand fluid routing schematic**

The human hand can have a highly variable spatial temperature distribution. Replicating that was not technically viable for this project, but operating the digits at a different temperature from the hand and wrist was identified as a key requirement early in the project. To reconcile this technical requirement with instrument complexity, the hand was subdivided into three independent thermal regions for regulation: fingers, hand, and wrist. (Figure 9)

Each region was fitted with serpentine copper tube paths on the inside surface, lined with high conductivity copper sheet to improve lateral heat transfer, and encapsulated with a thin layer of urethane potting compound. The wrist region was the only one of the three containing a contiguous length of copper tube. Both the fingers and the hand thermal regions were physically split because of the three-part hand form design. For these split thermal zones, the fluid lines connected in series by miniature quick disconnect fittings to be mated during hand assembly into the test glove. The resulting device had four tube pairs for supply and return flow exiting from the hand at the base of the wrist. (Figure 10)

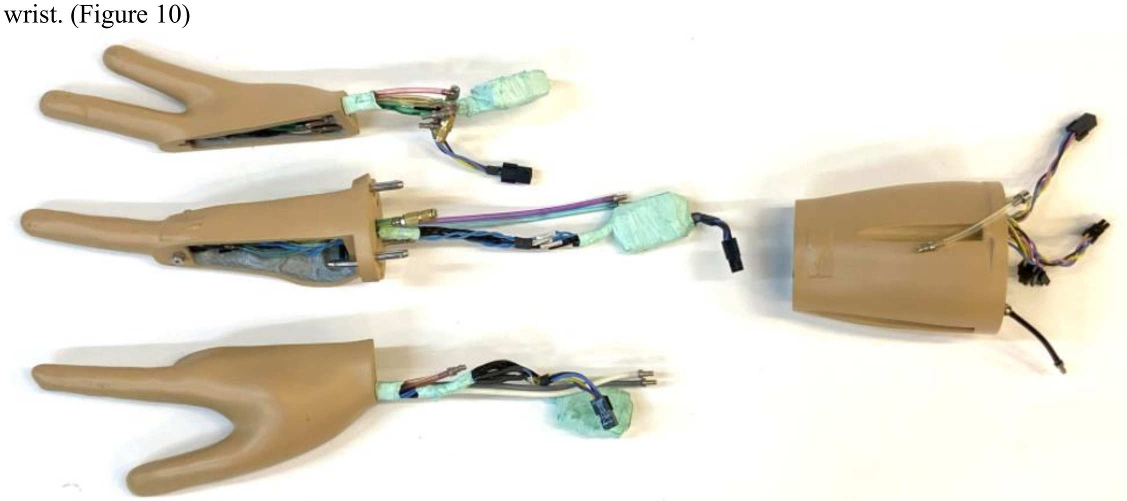

**Figure 10. Four-section hand with integrated digitizing modules, electrical harness, and fluid lines**

The three hand thermal regions were independently regulated by a multi-stage fluid control system external to the hand form. A COTS thermoelectric chiller was selected to control the fluid to a common minimum baseline temperature and provide an integrated fluid reservoir. Three inline fluid heaters were designed to add additional heat to each of the fluid circuits. Pressure sensors for each circuit measured the differential pressure between supply and return. Manually adjustable needle valve restrictions were fitted to the fluid heaters to allow tuning of the maximum fluid flowrate for each of the three circuits.

### D. Data Acquisition and UI Development

The output signals from each of the fifteen surface sensors were a T-type thermocouple and a bipolar microvolt signal linearly proportional to sensor heat flux. Additional temperature sensors were installed within the hand to measure the inlet and outlet fluid temperature during operation. To minimize external cabling and reduce the likelihood of electrical interference on the low-level signals, digitizing modules were located within the hand form. Sensor leads were direct-soldered to the digitizing modules, and the modules connected to a multidrop $I^2C$ network.

The electrical wires and three fluid circuit tube pairs were routed from the base of the hand, through an extension harness built into the CITADEL chamber feed-thru and terminated to a portable control enclosure. This enclosure contained three fluid preheaters, pressure sensors, preheater controllers, power conditioning, and network converters to translate the $I^2C$ communications to USB.

A custom user interface was developed for ThermDAC manikin control software (Figure 11) to display hand measurements in tabular and graphical form, to control the chiller setpoint temperature and regulate the individual fluid preheaters, and to log all system data to comma separated variable (CSV) data files. To provide maximum flexibility during testing, the fluid preheaters could be controlled using temperature feedback from a local sensor on the preheater, or using either a single sensor or group of surface sensors on the hand.

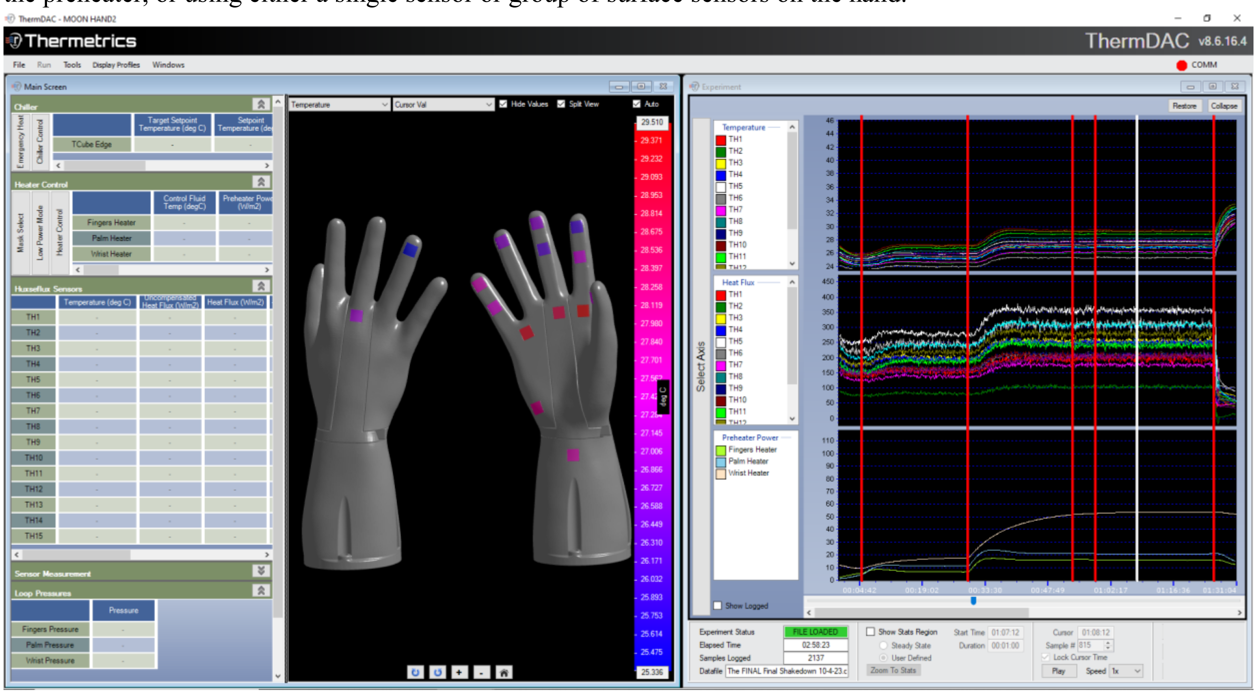


**Figure 11. ThermDAC user interface software configured for thermal hand system.**

### E. Calibration and Validation

Following assembly and system power-up testing, the hand system was calibrated, and a series of validation experiments were performed. The calibration process consisted of component-level measurements of data acquisition module measurement accuracy, single point temperature calibration of the completed hand unit to adjust for temperature offsets, and calibration of heater power for the three fluid preheaters.

#### *1. Validation of thermal regulation*

Base functionality of the thermal regulation system was confirmed by operating the system with only the external chiller regulating to a set temperature of 35°C and the hand in a cool, uniform environment. With the fluid preheaters off, the three parallel fluid circuits in the hand are all subjected to the same supply pressure and chiller fluid temperature. In this condition, the flow control metering valves were adjusted to deliver near-uniform heating on the hand. Regions with warmer temperatures than the average would be further restricted to limit the flow, and cooler hand regions would be adjusted for increased flow and more heating.

The preheater control response was subsequently tuned for optimal regulation using feedback sensors on the hand surface. The response time of this control system was affected by the tube length and fluid flow rate, as the preheaters were located in the portable control enclosure external to the hand. The time lag between heater power adjustments and corresponding sensor response necessitated detuned PID gains to avoid instability.

Once tuned, the thermal control by region was tested by operating the regions at different setpoint temperatures and confirming the surface temperature responds accordingly based on infrared imaging (Figure 12) and the reported surface sensor temperatures.

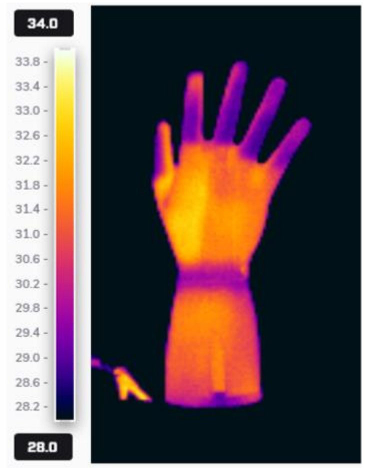


**Figure 12. Infrared image of thermal hand regulating to 30 °C on fingers and 32 °C on hand and wrist.**

*2. Sensor response*

The heat flux sensors were pre-calibrated by the manufacturer, but a validation test was deemed necessary to confirm the sensor response to external cold surfaces, and that the mounting or encapsulation did not adversely compromise the transient behavior of the sensors. A water-cooled aluminum block was fitted with a 3.0 mm silicone pad, and each sensor was manually pressed against the silicone surface to provide a repeatable transient contact event. (Figure 13) The characteristic response curve for temperature and heat flux was recorded for each sensor.

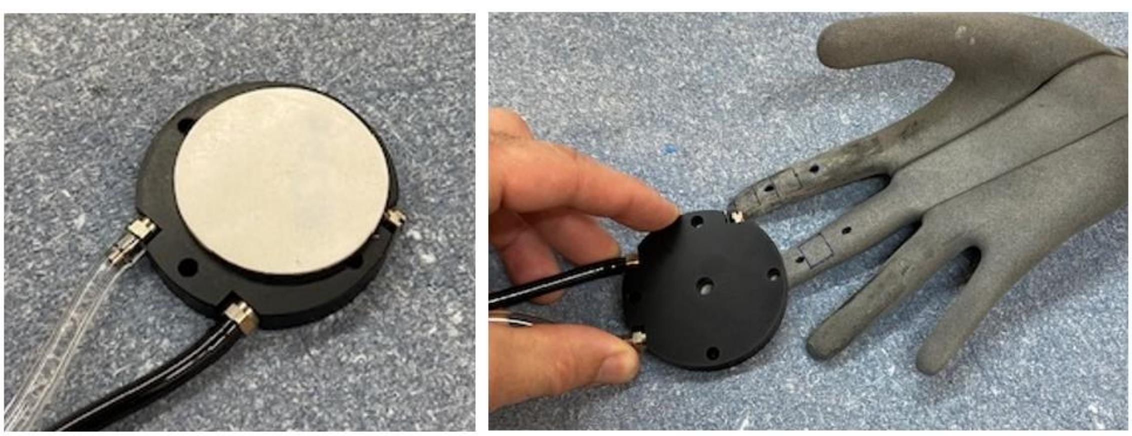

**Figure 13. Cold sink contact testing apparatus for transient sensor response validation.**

*3. Emergency heating function*

To protect the glove specimen and the thermal hand system, an emergency heating function was built into the control system. In the event of glove damage or dangerously low temperature measurements, the software could initiate a safeguard function to immediately increase the heating of the fluid loops to add more heat to the hand and reduce the potential for cold damage.

*4. Glove testing*

As a full system validation test, the newly developed thermal hand instrument was used to measure a commercial cold weather glove, which had previously been tested at North Carolina State University Textile Protection and Comfort Center (NCSU-TPACC) using their thermal hand manikin[3] compliant with ASTM F3426[2]. Both systems were used to measure the thermal resistance (Rcl) of the glove for comparative results.

*5. Cold exposure and contact testing*

System validation testing was performed at Thermetrics where the instrument was built. Available climate chambers at this location could not achieve the range of environmental temperatures possible in the CITADEL chamber. To more closely replicate the heat loss conditions in actual use, the environment temperature was adjusted based on the sample thermal resistance to deliver nominally 10 Watts of heating to the hand and fingers. The cold exposure and contact validation tests were all performed at -15°C.

## III. Results

### A. Thermal Hand Manikin System

This program development and prototyping resulted in a complete thermal hand instrument (Figure 14) for testing EVA gloves.

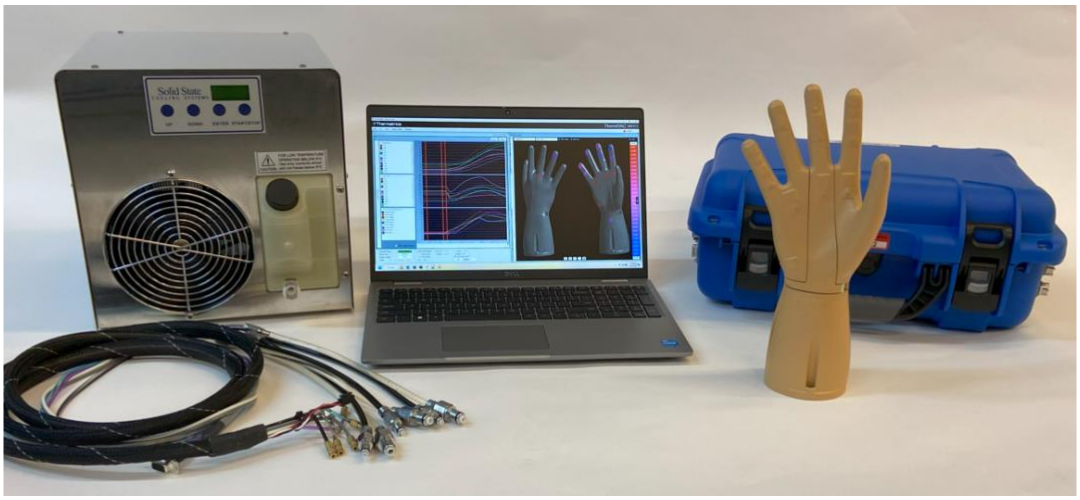

**Figure 14. Completed hand manikin system, from left to right: Fluid + electrical harness, thermoelectric chiller, laptop with data acquisition software, thermal manikin device, portable control enclosure.**

The major subcomponents include:

- The hand model with integrated fluid heating and 15 surface temperature/heat flux sensors, internal signal conditioning and digitizing modules
- Portable control enclosure with three internal fluid heaters, flow control valves with differential pressure sensors, electrical power supply, and communication adapter.
- External solid-state chiller/reservoir
- Laptop computer with ThermDAC graphical user interface
- Interconnect electrical and fluid harness

### B. Validation Results

*1. Thermal regulation*

Surface temperature uniformity of each hand region was evaluated in three conditions: nude in 20 °C environment (NUDE), gloved in 20 °C environment (AMBGLOVE), and gloved in -15°C environment (COLDGLOVE). Uniformity was assessed based on the standard deviation of all sensors using a 33 C water temperature setpoint. Results are listed in (Table 1)

**Table 1. Thermal uniformity (average heat flux and standard deviation of temperature) at 3 heating levels**

| | Fingers | | Hand | | Wrist |
|---|---|---|---|---|---|
| | Avg Heat Flux (W/m$^2$) | Sensor T S.D. °C | Avg Heat Flux (W/m$^2$) | Sensor T S.D. °C | Avg Heat Flux (W/m$^2$) |
| NUDE | 229.7 | 0.80 | 255.8 | 1.03 | 310.1 |
| AMBGLOVE | 66.7 | 0.44 | 46.3 | 0.23 | 92.4 |
| COLDGLOVE | 212.9 | 1.29 | 140.5 | 0.67 | 282.4 |

*2. Sensor Response*

Verification of transient thermal response (Figure 15) was evaluated by pressing a water-cooled block with silicone skin layer against each surface sensor on the hand. The water-cooled block was supplied with 15 °C fluid which regulated the hand to a 35 °C fluid setpoint.

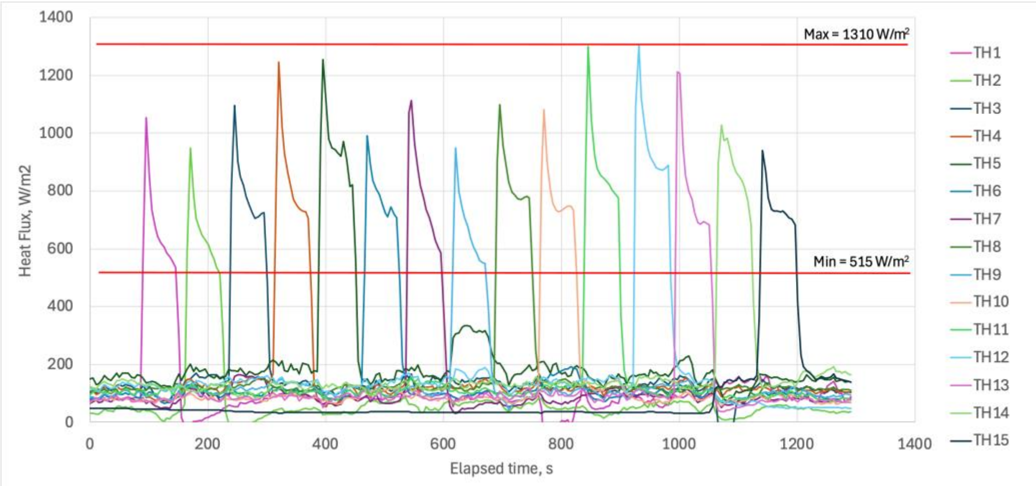


**Figure 15. Transient heat flux response from 60 second contact with cooled surface**

*3. Glove Testing*

Measurement of thermal resistance in Rcl (°C·m²/W) was compared between the existing thermal hand system at NCSU-TPACC and the newly developed EVA glove test apparatus for an identical glove specimen (Figure 16). Rcl is a common unit used in thermal manikin testing to describe the intrinsic thermal resistance of clothing, where a higher Rcl value corresponds to a higher thermal resistance. The 8 zones of the TPACC hand (TPACC Rcl) were compared with against the closest located surface sensors on the new hand (Sensor Rcl), and also a computed Rcl using the estimated hand fluid energy change derived from the measured hand inlet/outlet water temperatures and a mass flow rate calculated from measured pressure and a calibrated flow conductance value (Water Rcl).


| TPACC Rcl | Region | Water Rcl | Sensor Rcl |
|---|---|---|---|
| 0.186 | Thumb | | 0.176 |
| 0.147 | Index Finger | | 0.240 |
| 0.213 | Middle Finger | 0.218 | 0.166 |
| 0.206 | Ring Finger | | 0.132 |
| 0.146 | Pinky | | 0.158 |
| 0.198 | Palm | 0.399 | 0.269 |
| 0.243 | Hand Dorsal | | 0.293 |
| 0.199 | Wrist | 0.248 | 0.625 |
| 0.192 | Total Avg | 0.288 | 0.257 |


**Figure 16. Comparative results of thermal resistance (Rcl) of same specimen measured by NCSU-TPACC thermal manikin (left) and EVA glove test apparatus (right).**

## IV. Discussion

The completed hand system demonstrated reliable operation over the design heat loss range, and ability to control skin temperature with internal fluid circuits. The development and validation process identified several areas for potential improvement and future research.

The hand manikin included the capability to measure local surface temperature and heat flux, and the ability to compute energy transfer and resulting average heat flux based on water temperature difference and mass flow rate. At the time of design, it was unclear which of the two methods would be more effective for the application, and how well they would correlate. The results from this work show the two methods to be within a similar variation in comparison with the reference glove except for the wrist surface sensor. The wrist sensor was identified as an outlier due to the large deviation compared to the computed water Rcl for the wrist, the measured Rcl of the nearby surface sensors.

This outlier was assumed to be either due to bunching of the insulation of the test glove from modifications made to the glove used for comparative testing to facilitate frequent donning and doffing during system testing without disassembly of the manikin hand, or due to heat leakage from adjacent zones. Only one sensor was allocated to the wrist as it was not a region of design importance for this program, further reducing fidelity in this region. For future data reliability, adding one or two additional surface sensors to the wrist section would provide more representative measurements.

Comparison of the performance of the EVA glove test apparatus with an existing hand instrument at NCSU-TPACC on an identical test article showed fair overall agreement, with high variation by hand segment and sensor location. Excluding the surface sensor on the wrist as an outlier, the total garment Rcl measured by the surface sensors was 6.8% higher compared to the NCSU-TPACC thermal hand and 33.3% higher when measured by water Rcl.

ASTM F1291 Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin[9] cites 95% repeatability limit of 0.024 $m^2$°C/W based on a study using a full body reference garment with Rcl of 0.122 $m^2$°C/W. This represents 19.7% measurement variation across laboratories and instruments as an acceptable industry standard. This demonstrates the EVA glove test apparatus to be within an acceptable level of variation using surface sensor measurement, with a larger than expected variation exhibited for water Rcl measurement.

For this glove comparison, multiple factors are presumed to influence the variation. The TPACC manikin computes average thermal insulation distributed over full segment surface areas. The EVA glove test hand computes this as an average of discrete point sensor locations, or as in the wrist, a single sensor. The two hand forms also have significantly different morphology, especially in the thumb area, which will influence glove fit and resulting thermal insulation. Additionally, the glove specimen was modified at the cuff to facilitate frequent donning and doffing on the assembled hand during the validation phase which could have influenced the measurements at the hand and wrist area.

The larger variation observed in computed water Rcl may be explained by heat leakage within the internal air volume of the device, lateral conductive heat loss through the mounting fixture and potential inaccuracies in the estimation of mass flow rate based on measured flow conductance. Future comparative testing in this area may benefit from adding temporary discrete sensors to the reference manikin to provide a better aligned comparison and the addition of a mass flow sensor for a more accurate computed water Rcl.

The primary purpose of the design approach of this manikin system was to provide a repeatable means to evaluate the comparative thermal properties of glove ensembles and to characterize transient environmental events, rather than to be considered a perfect thermo-physiological model of the human hand. The latter would require a significantly higher level of complexity both in design and application than the scope of this project would allow. For example, the human hand allows a wide range of joint mobility, variation in compliance and conductivity due to the distribution of tissue layers and exhibits complex vasomotor responses which alter spatial and temporal temperature distribution significantly. In contrast, the manikin device provides a fixed form and a controlled, known power input and thermal distribution to allow reliable and repeatable testing to validate the relative impact of design changes in glove ensemble that can be difficult to characterize via human subject testing. This data was correlated to human subject testing to evaluate human factor performance metrics such as safe exposure limits as part of the glove design process. That work is detailed in ICES-2025-64[4].

## V. Conclusions

The development and production effort under this project successfully delivered a novel thermal hand manikin meeting the established design requirements to allow for further development of a test protocol suitable for evaluating EVA handwear in extreme environment conditions. The resulting instrument was delivered to JPL in October of 2023 for subsequent testing of handwear to support the Artemis mission.

This project highlighted the importance of body form, garment fit, and don/doff considerations when applying thermal manikin instruments for restrictive EVA garments and components, and that instruments may need to be adapted in the future for these applications. By integrating additive manufacturing with existing technology elements of thermal manikin instruments, new thermal manikin instruments can be produced to meet specific testing needs.

## Acknowledgments

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