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Wire-break Ignition Testing of Materials for Spacesuit Fire Hazard Control

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The input design constraints applied to the extravehicular activity (EVA) spacesuit pose a significant challenge for mitigation of fire hazards. To minimize fatigue and increase comfort of the crewmember operating the suit, the suit pressure is lowered below sea level conditions with typical EVA suit designs operating with 4.3 psia (29.7 kPa). With the lowered operating pressures and the use of closed-loop life support, the suit requires elevated concentrations of oxygen, typically >95%. At these oxygen concentrations, nearly the entirety of the suit internal materials are flammable. This leaves one remaining possible control leg of the fire triangle: ignition sources. Since the Gemini and Apollo programs, this has been a risk that has undergone constant reassessment, with a focus on improved mitigation. After the Apollo I fire, an arc ignition method was developed and used to quantify ignition thresholds for in-suit materials resulting in a current limit for powered in-suit devices applied to all subsequent suit designs. After the discovery of a frayed spacesuit biomed cable on STS-113 during the Shuttle Program, the previous arcing method was repeated with additional methods developed to extend the testing further. One of those methods was wire-break ignition testing, in which the current in a single strand of wire was progressively increased, preheating the material in proximity with a resultant break and the application of a reasonably repeatable arc to ignite the material, all while exposed in the selected environment. This method was used to test a suite of spacesuit materials providing relative performance with respect to ignition with this configuration for application of energy. This paper discusses extension of the current data set to address recent material additions, lowering of energy test levels for quantification of materials too low to measure in previous testing, as well as future plans to improve this method.

Nomenclature

ASTM	=	American Society for Testing Materials
AWG	=	American Wire Gauge
CCA	=	communications carrier assembly
CHX	=	condensing heat exchanger

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CO_2	=	carbon dioxide
DC	=	direct current
DCS	=	decompression sickness
DIDB	=	disposable in-suit drink bag
E	=	energy
EMU	=	extravehicular mobility unit
ESD	=	electrostatic discharge
ESPL	=	Electrostatics and Surface Physics Laboratory
EVA	=	extravehicular activity
HAB	=	helmet absorption band
HAP	=	helmet absorption pad
HAP-E	=	helmet absorption pad extender
ISS	=	International Space Station
IVA	=	intravehicular activity
JCI	=	John Chubb Instrumentation
JSC	=	Johnson Space Center
KSC	=	Kennedy Space Center
LCVG	=	liquid cooling and ventilation garment
NASA	=	National Aeronautics and Space Administration
O_2	=	oxygen
OCA	=	Oxygen Compatibility Assessment
PLSS	=	portable or primary life support system
PVC	=	polyvinyl chloride
SRP	=	Safety Review Panel
STS	=	Space Transportation System
t	=	time
TCHDE	=	2-4-4'-trichloro-2'-hydroxydiphenyl ether
TCU	=	thermal comfort undergarment
V	=	voltage
WSTF	=	White Sands Test Facility

I. Introduction

For extravehicular activity (EVA) spacesuit applications, the use of 100% oxygen is required to enable operation of the total suit pressure at levels down to 3.1 psia [21.4 kPa] with nominal operation for suits such as the Space Shuttle and International Space Station (ISS) extravehicular mobility unit (EMU) at 4.3 psia [29.6 kPa]. As the EMU and all other flown or active suit designs use an anthropomorphic pressure vessel approach, the suit is pressurized, the crew operates within the shaped pressure vessel, and must work against it to perform tasks. Despite the great care and extensive design work implemented in these suit designs, the fact remains that as the suit operating pressure increases, so does the effort the crew must exert increasing fatigue of the crew over the course of an EVA or spacewalk. As a result, the suit operating pressure is lowered as far as possible, with the low end based on hypoxia limitations of human physiology. Use of 100% oxygen is required to achieve this lowest possible absolute pressure. Considering that materials within the spacesuit are flammable in 100% oxygen and that 100% oxygen is required for the functional performance of the spacesuit, the suit application already includes two of the three legs of the fire triangle: fuel and oxygen (Figure 1). Consequently, the control of ignition sources in the suit volume is the only remaining option for mitigation of the fire hazard in a spacesuit.

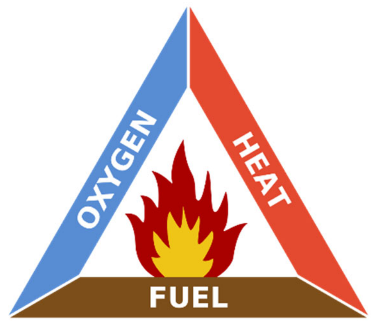

Figure 1. Fire triangle.[1]

A detailed and extensive investigation (21 parallel working panels) took place in the wake of the Apollo I (Saturn I Vehicle 204) incident in January 1967. A vehicle wire chafing issue was ultimately identified as a likely proximate cause for the fire. One of the findings in the Apollo 204 Accident Report[2]was that inadequate data, understanding, and control of materials in the spacecraft were contributors to the accident. A Discovery Channel documentary provides a reasonable summary of this event[3]. The Gemini spacesuit that preceded the Apollo suit had a verified catastrophic fire hazard regarding the ignition of the cotton constant-wear garment from arc ignition via an intermittent short[4]. Testing of the 20V biomedical supply was performed at the time using 258 and 720 mmHg total pressure in 100% oxygen, with values of 4.0A and 1.5A determined as the minimum short circuit current required for ignition, respectively. A subsequent test simulated the short circuit with current limiting at pressures of 650 and 760 mmHg in 100% oxygen without ignition in 200 tests. This test data was used to establish the 0.5A current limit for suit internal volume (often referred to as the pressure garment volume or ventilation loop) input power from that point forward. Analysis of the Apollo suit biomedical and communications power determined that the maximum short circuit currents were 0.18A and 0.065A, respectively. Both were well below the 0.5A established current limit.

After the Apollo I incident, the current limiting implementation of the suit electronics was reassessed, and more extensive testing of materials used in the suit volume was performed. In this test, which will be referred to as the "scratch and poke" test, a flat electrode plate including the material sample was placed in a chamber that was evacuated and then refilled with 100% oxygen to achieve the selected test pressure. A needle electrode was then used to scratch and poke the material creating shorts to the flat plate through the material in an attempt to create an ignition (Figure 2). Samples were intentionally frayed to represent potential abrasion of the material from relative motion within the suit volume.

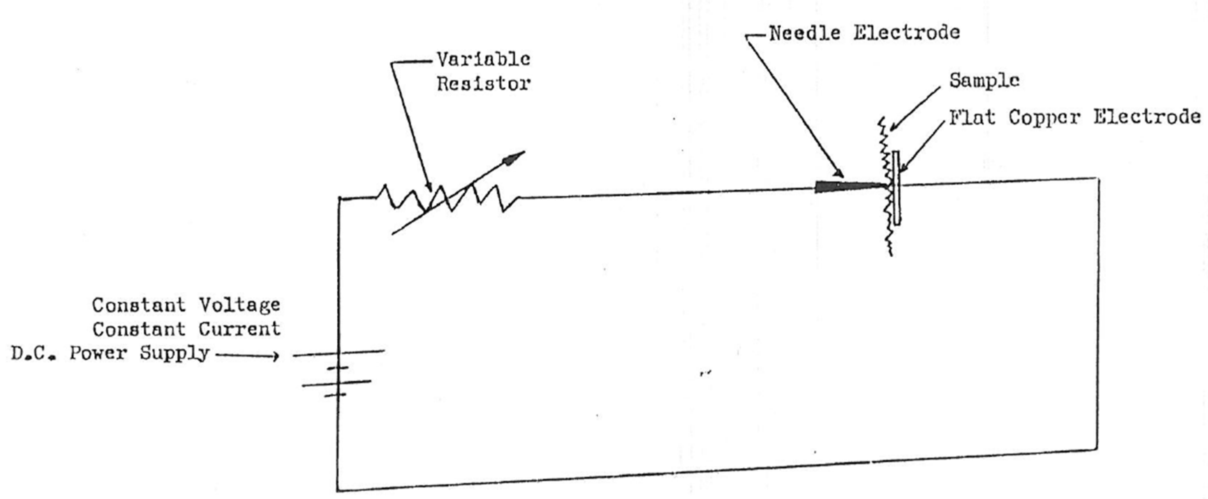

Figure 2 - Scratch and Poke Test Diagram [4]

A material was determined to be "safe" if no ignition occurred during 15 minutes of arcing across the frayed sample[4]. For the 19 psia, >95% oxygen case, clean cotton underwear was determined to be the limiting material igniting with a current of 1.1A during the testing. Using clean cotton underwear as the limiting material, a subsequent test was performed to evaluate the suit current limiting of the biomedical system and determine the additional output lead resistance necessary to mitigate the ignition hazard from the transient shorting failure mode. The steady-state current limit was 50mA, with an additional transient current from the pulse discharge of two 60uF capacitors in the event of a transient short circuit. The test setup was similar to that from Figure 2 but with the addition of the transient pulse discharging capacitors as part of the DC/DC converter (Figure 3); an oscilloscope was set up to measure the transient current spikes associated with the shorts. With the lead resistance "R" at "0 Ohm," ignition was achieved. As the lead resistance was increased to 5 Ohm, the ignition was not achieved in 1.5 hours of testing.

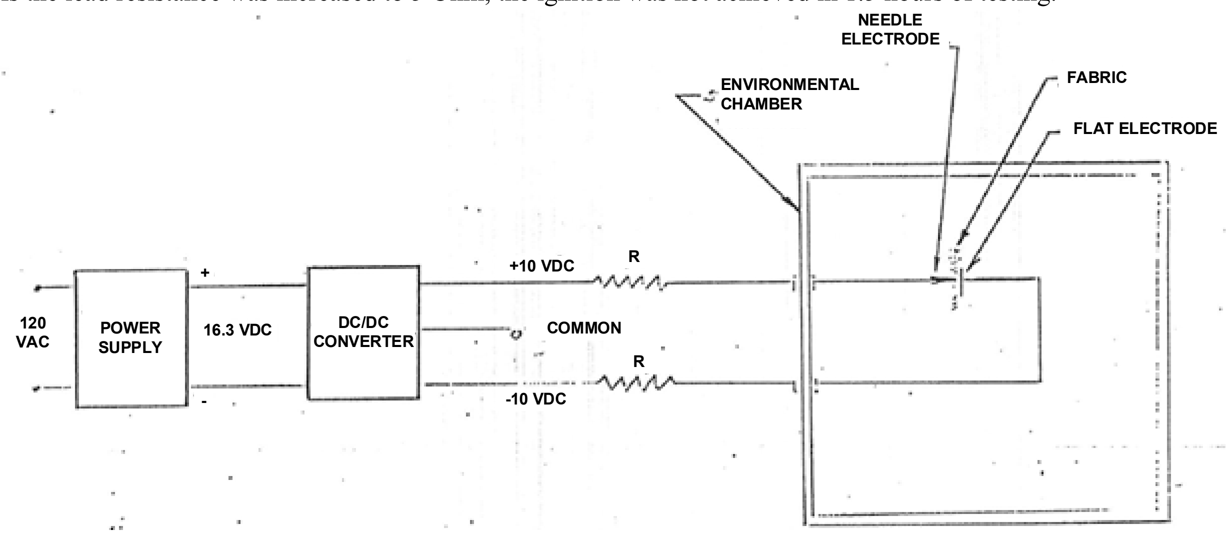

Figure 3 - Biomedical Transient Short Test Setup[4] with clarified annotations

The established steady-state current limit of 0.5A or 500mA was then used broadly across the suit programs such as Shuttle and ISS EMU, including ground testing through and up to the early 2000's.

During Shuttle Mission STS-113, after completion of EVA 2, Crewmember EV1 reported that the biomedical cable in his ISS EMU that had been used for EVAs 1 and 2 had broken wire insulation with some wires protruding through the insulation[5]. A team was assembled, taking many parallel paths to work the problem. One of the immediate considerations was the quantification of risk for not only the biomedical cable but also for the communications cable used in the same environment and carrying higher voltage and current conductors. As a result, arc energy assessments were made considering the biomedical and communication system designs. A test effort was initiated with the White Sands Test Facility (WSTF), as the current EMU materials were not fully covered in the Apollo era testing, the electrical system design for the Shuttle EMU was different, and some information from the Apollo era testing was lost. The team developed three different methods to evaluate materials for flammability in this application: "scratch test," "poke test," and "wire-break test." Data was collected with each of these methods and variants of them for relative comparison. The scratch testing dragged a stylus across the material while arcing through the material. The poke test was similar to the Apollo era testing performed that poked a small stylus into the material, arcing through the material (Figure 4).

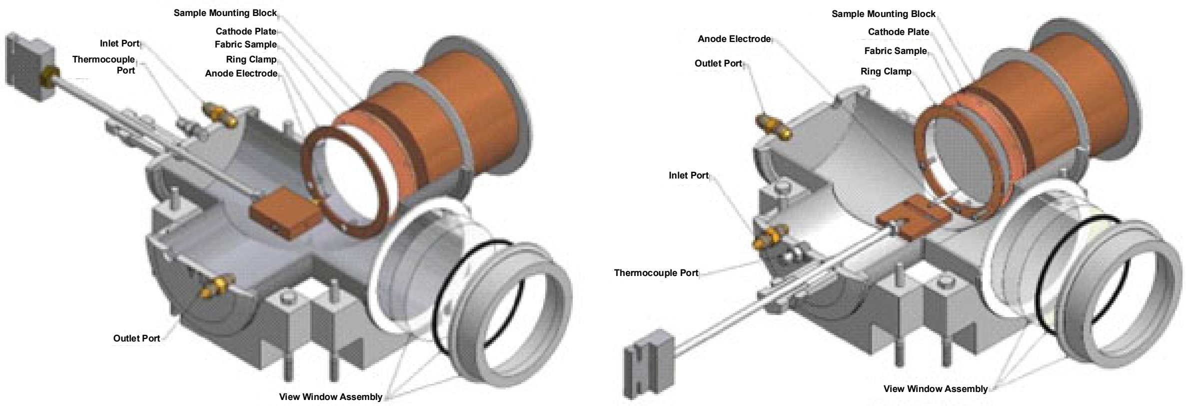

Figure 4 - Scratch Test (left) and Poke Test (right)[6]

Upon evaluation of both of tests, the team found that in both the scratch and poke tests, an arc occurred at one location perhaps multiple times sequentially. With subsequent evaluation of frayed wire with arcs in multiple locations a lower ignition current was measured indicating that it is more severe to arc in multiple locations. With the arc-to-arc, test-to-test variation of these two methods, the team focused on a more repeatable method that became the wire-break method (Figure 5). In this method, a single "U"-shaped wire was placed in contact with the test material while the current was slowly ramped to the melting point of the wire, where it broke and arced. The material was preheated to 95° +/- 5°F. The ramp to the breaking current of the wire preheated the test material which thermally decomposed the test material and generated a combustible vapor which was trapped in proximity by the slide glass while still mixing with the oxygen in the chamber. Upon wire breakage an arc was created which was then able to ignite the vapor and kindle to the material.

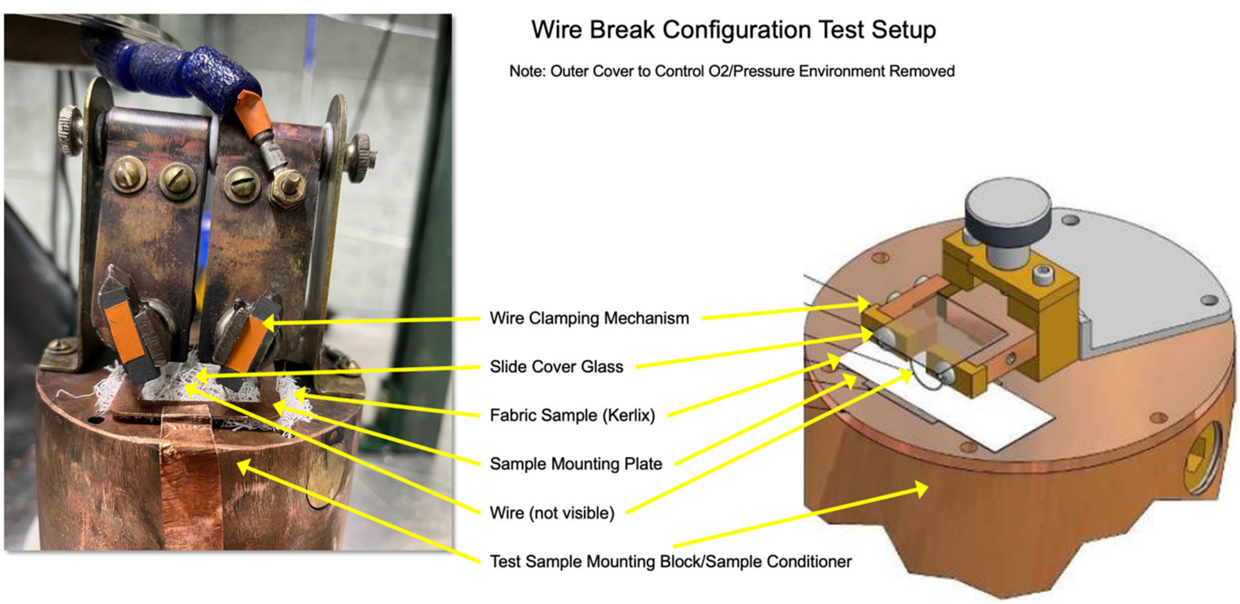

Figure 5 - Wire Break Test[6]

As wire-break test definition was a materials-focused ignition test tailored to the EMU application, the wire gauge range tested focused on wire sizes (Table 1) bracketing the flight design at 46 AWG (34 to 54 AWG). The wire gauge range spanned to the smallest available wire gauge at the time attempting to account for the status of a damaged or abraded cable. As this was something that could not be known, the test was essentially determining the material limit with this particular mechanism type as implemented by this test setup.

A range of current EMU materials was tested, ranging from wire jacketing to generic cotton to Moleskin, is thoroughly documented in the summary report[6] and Table 3-17 of ASTM Manual 36[7] with the relevant information provided in Table 2.

Table 1 - Wire Sizes Used in Wire Break Test[6]

AWG	Supplier	Diameter (in.)	Percent of Flight Wire[a] Cross Sectional Area	Approximate Current Required to Break Wire (A)
34	Phelps Dodge	0.0063	1550	9.00
38	Phelps Dodge	0.004	625	5.00
39	Phelps Dodge	0.0035	479	3.80
40	Phelps Dodge	0.0031	375	3.00
41	Phelps Dodge	0.0028	306	2.60
42	Phelps Dodge	0.0025	244	2.30
43	Phelps Dodge	0.0022	189	1.80
44	Phelps Dodge	0.002	156	1.50
45	Phelps Dodge	0.0018	127	1.30
46[a]	Phelps Dodge	0.0016	100	1.10
47	Phelps Dodge	0.0014	77	0.90
48	Phelps Dodge	0.0012	56	0.83
49	Phelps Dodge	0.0011	47	0.70
50	Phelps Dodge	0.001	39	0.63
51	Phelps Dodge	0.00088	30	0.50
52	Phelps Dodge	0.00078	24	0.45
54	Rea Wire	0.00062	15	0.35

[a] The flight wire is 46 AWG.

Table 2 – Wire-Break Ignition Testing DCS Test Results (23.5 ± 1 psia, >99 percent oxygen)[6]

Material	Wire Gauge (AWG)	Voltage (V)[4]	Current at Ignition (A)	Wattage at Ignition[4] (W)
Generic cotton[2]	54	22.5	0.36	8.1
Moleskin[2]	54	22.5	0.3	6.8
Kerlix dressing[2]	54	22.5	0.3	6.8
TCU assembly (Capilene – hollow fiber polyester treated with 3% TCHDE solution) (gray) [2]	54	22.5	0.33	7.4
Urethane-coated nylon suit bladder (shiny side)	52	22.5	0.7	15.8
Urethane-coated nylon suit bladder (fabric side)	47	22.5	0.97	21.8
Interface cable Gore-Tex sleeve[3]	34	22.5	9.23	N/A
Interface cable polyurethane jacket	48	22.5	0.78	17.6
CCA cap spandex (nylon & Lycra knit fabric)	50	22.5	0.59	13.3
Estane polyurethane[5]	48	22.5	0.92	20.7
Astronaut longhandle undergarment	50	22.5	0.64	14.4
Cotton flocked Rucothane glove bladder (flocked side)	52	22.5	0.45	10.1
LCVG garment inner liner (nylon tricot treated with 3% TCHDE solution)	52	22.5	0.49	11.0
LCVG garment inner liner (nylon tricot untreated)	50	22.5	0.61	13.7
LCVG garment (multifilament nylon / spandex knit 1106 treated with 3% TCHDE solution)	52	22.5	0.53	11.9
PVC wire jacket	47	22.5	0.92	20.7

NOTE:

(1) Tests were performed with a single strand of silver-coated copper wire in contact with test material. Current was increased until wire failed, producing an electrical arc.

(2) This material ignited at the lowest possible current; therefore, no threshold for ignition was determined.

(3) This material was never ignited in the test conditions; however, it could be ignited in higher-pressure oxygen.

(4) *Wattage at ignition using P = I*V is not accurate with respect to the power actually provided. Supply was operated in constant current mode, with voltage varied to hold the current through the test wire constant by varying the supply voltage accounting for changes in resistance of the wire as the temperature increases.*
(5) *This material was mistakenly sent to WSTF as an arc-ignition test material. Apparently it is not in the EMU. However, some tests were performed before this was discovered. A threshold for ignition was not determined.*

As a corrective action for the "water in the helmet" investigation for US EVA 80 on ISS[8], additional materials were added to the helmet area in contact with the communications harness such as viscose (rayon) chamois material. The chamois absorbs and sequesters sublimator condensate carryover from the ISS EMU that migrates into the helmet under certain failure and usage conditions. This material had not been tested using the wire-break test method but was deemed safe to use via the ISS Safety Review Panel (SRP) process based on the multi-layer harness layup with additional inspections of that harness as part of preparation for each EVA on ISS. During the initial design and development of this testing approach[6], it was noted that 46 AWG was the EMU flight individual wire strand size but that testing was to be performed down to 54 AWG wire given that, due to damage, it is impossible to state the ampacity of a damaged single 46 AWG wire. Additionally, an intact 46 AWG wire would not break until current exceeded ~1.1A, necessitating the use of smaller wire gauges to aid in application of the lower energy levels. Hence, while this test had been originally conceived as a bounding case on a credible ignition method within the Shuttle/ISS EMU, the test had already transitioned to a materials-centric test method representing a worst-case suit application less engineering controls not unlike other tests represented in ASTM Manual 36[7]. Examples of similar materials-centric test methods include: mechanical impact, particle impact, and upward flame propagation of an 1/8-inch diameter rod. For each of these, the system designer/assessor must review the standardized test data for applicability to a specific implementation; this is routinely performed as part of the oxygen compatibility assessment (OCA) process for an oxygen system. At the time of completion of the initial wire-break testing[6], four materials — cotton, thermal comfort undergarment (TCU) polyester, moleskin, and Kerlix dressing — could not be tested to a low enough energy level using the smallest available 54 AWG wire. Hence, to quantify the performance of the new materials added post-EVA 80 as well as other materials added to the suit volume since the time of the initial wire-break testing, another wire-break test effort was initiated. A custom wire vendor was identified for wire gauges of 56 AWG and 58 AWG copper and sourced to attempt to further lower the applied energy at the test conditions.

Herein, the extended wire-break ignition test data for the materials will be discussed considering the instantaneous voltage/current at time of ignition. To make this data more usable to system designers and those assessing the systems, an additional discussion and data reduction will be performed to convey that same data but in a more accurate manner with respect to the energy input into the sample through the test. Lastly, the plan for an updated test method derivative of the wire-break method will be examined to improve repeatability and usability of the data going forward.

II. Summary of Extended Wire-break Testing

The standard method defined in document reference[6] and is also called as an optional materials test in NASA-STD-6001[9], Appendix A.2.11 was originally developed in 2003-2005 and used to generate data summarized in Table 3. The basic procedure and test setup were discussed above.

Table 3 – Total Set of EVA DCS Condition Wire-break Ignition Testing Data
The added data from 2023/2024 is highlighted in orange.

Material[(7)]	Wire Gauge (AWG)	Voltage (V)[(4)]	Current at Ignition (A)	Wattage at Ignition[(4)] (W)
HAB/HAP-E (Viscose) Rayon Chamois	56	22.5	0.049	1.09
HAP Outliner - Tranquility	56	22.5	0.200	4.49
Moleskin	58	22.5	0.078	1.76
Cotton (t-shirt)	51	22.5	0.490	11.03
Pyropel[(8)]	52	22.5	<0.493*	11.10
Kerlix dressing[(6)]	52	22.5	TBD	TBD
Kerlix dressing[(2)]	54	22.5	0.3	6.8
Generic cotton[(2)]	54	22.5	0.36	8.1
TCU assembly (Capilene – hollow fiber polyester treated with 3% TCHDE solution) (gray) [(2)]	54	22.5	0.33	7.4
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NOTE:

(1) *Tests were performed with a single strand of silver-coated copper wire in contact with test material. Current was increased until wire failed, producing an electrical arc.*
(2) *This material ignited at the lowest possible current; therefore, no threshold for ignition was determined.*
(3) *This material was never ignited in the test conditions; however, it could be ignited in higher-pressure oxygen.*
(4) *Wattage at ignition using P = I*V is not accurate with respect to the power actually provided. Supply was operated in constant current mode with voltage varied to hold the current constant through the test wire by varying the supply voltage, accounting for changes in resistance of the wire as the temperature increases.*
(5) *This material was mistakenly sent to WSTF as an arc-ignition test material. Apparently, it is not in the EMU. However, some tests were performed before this was discovered. A threshold for ignition was not determined.*
(6) *Data reduction in-process to provide value given considerable scatter in observed test results. Testing was ceased on this sample as the gauze filament spacing added a significant amount of variability in the results for combustible vapor generation and ignition.*
(7) *The EMU thermal comfort undergarment (TCU) Capilene - hollow fiber polyester, with and without 3% TCHDE, pristine or frayed was not retested in 2023/2024 given its lack of proximity to the current source and similar performance to moleskin and cotton.*
(8) *Pyropel was initially tested but was dropped mid-test without completion to lower limit determination due to demanifesting of the solution involving this material as the post-EVA 80 corrective action. Hence, a no burn limit was not achieved.*

Allowing for changes noted in Figure 5, the test setup was reconstructed to the state used in previous testing performed in 2005. In particular, the clamping mechanism to retain the ends of the wire was changed from screw-down terminals to magnetic clamps, which resulted in greater contact resistance at the joint. This is not an issue when controlling the current through the wire with local voltage drop measurement across the wire but does pose a variable offset for a method using constant voltage potential across the setup. As noted in Table 3, the voltage reported in the table is not relevant as it is the power supply voltage not considering the constant current mode and the actual voltage drop across the test wire. Also note that the power shown in the right-hand column is erroneous or not relevant as it basically multiplies the power supply voltage by the current using Ohm's Law (P = I*V), where P = power in watts, I = current in amperes, and V = voltage or potential in volts of direct current (VDC). Figure 6 provides a simple electrical diagram of the setup. Heat is generated and voltage is dropped a significant amount in three locations. R1 and R3 each vary with holder design and test to test, with greater contact resistance for the magnetic clamp holders versus screw-down terminal holders. If the voltage noted in Table 3, column 3 is recorded for the total voltage that floats to allow the constant current and varied path resistance, then large errors are introduced into the power computation.

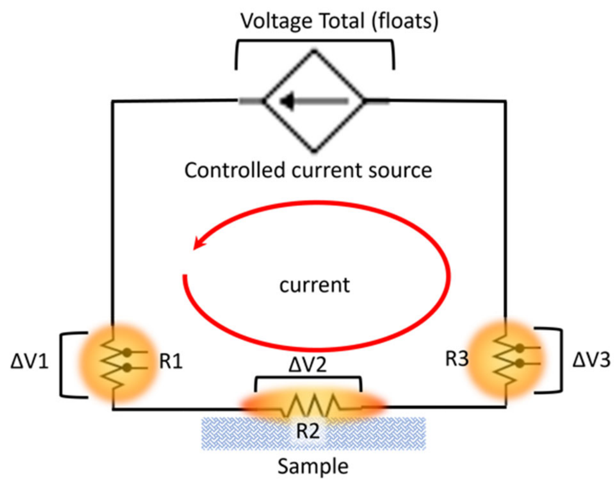

Figure 6 - Electrical Diagram for Wire Break Test Setup

The data in Table 3 is still relevant but the interpretation provided is not useful for driving system design and allowing assessment of the ignition hazard. An alternate approach is needed when applying this data.

III. Discussion of Summary Energy Input

As discussed above, the test method described in this paper was originally developed as a materials-centric configuration specific ignition test. However, the approach and application of data derived from it, has been evolving into a material characterization test to determine a minimum threshold of energy necessary for ignition given an electrical circuit failure where heat energy can be put into the material at a rate sufficient to ignite and propagate to bulk burning. To do so, the current through the wire and the voltage across the wire just before the moment the wire is fused open can be taken to derive an instantaneous power level. This value could then be used as a power threshold or a go/no-go where the material that has been characterized could or could not be used. This approach should be considered carefully. Closer examination shows this approach is inadequate. To illustrate this, consider Figure 7. During the test, the power (voltage and current) rises above the power level at the time of break several times before the wire ultimately fuses open, ignites, and burns the material.

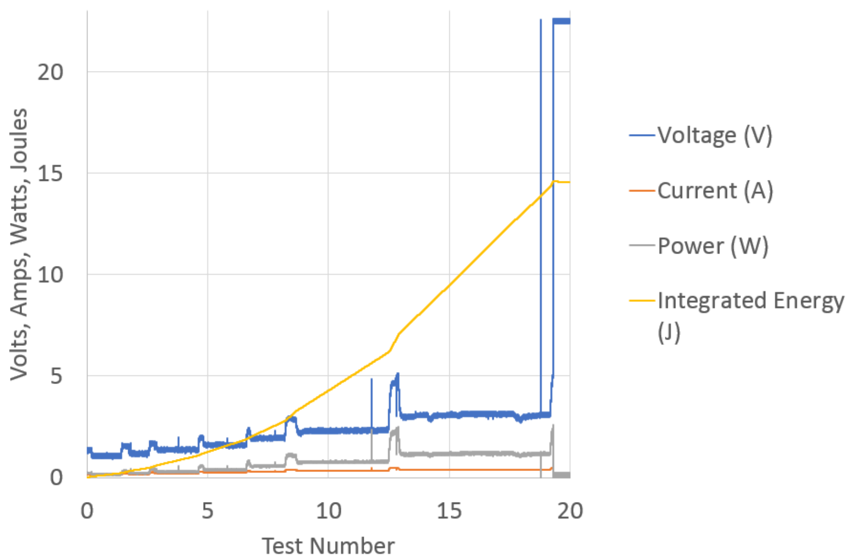

Figure 7 - KER 54-1 Wire-Break Test

Logically, it stands to reason that the ignition and burning of the material should be observed at these higher power levels rather than at the final lower power where the wire did fuse open. Conversely, it could also be shown that the material can also be ignited at a lower power level lower than observed in the test. Therefore, using power exclusively to describe performance of the material is insufficient and suggests that more information is needed for a fair and honest application of the data to occur. Consider Figure 8 in which the plot on the left provides the current at break on the Y-axis and the test number on the X-axis; the plot on the right provides the power at break on the Y-axis and the test number on the X-axis. The orange series is the 2024 magnetic clamp approach while the gray series is the screw-terminal contacts from 2004-2005. The blue series is moleskin, which was placed for reference. Note that the reported power is skewed by the contact resistance difference between the two variations of the setup.

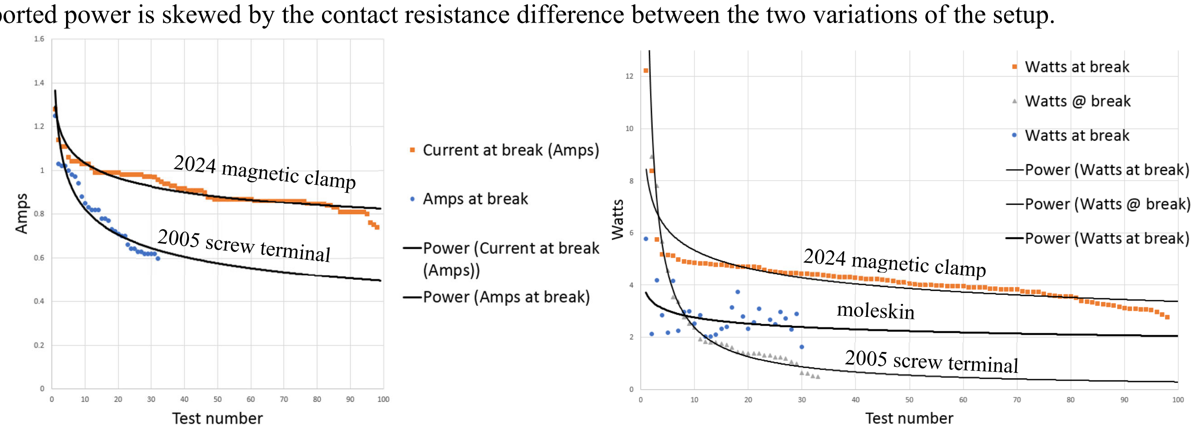

Figure 8 - Current vs Test Number (Left)/Power vs Test Number (Right)

Looking at the process of ignition and burning more closely, the material needs to be thermally decomposed (pyrolyzed) for it to be in a state in which it can readily burn. This process takes time and exclusively using a power derived from voltage and current overlooks that critical part of the process. If time is taken into account, then what is really being described and observed is the energy or work that it takes to get the material to become pyrolyzed to the point that it can be ignited and burned. More specifically, total energy is the focus. This total energy is what describes the cumulative work done by the flowing current in the wire that is in intimate contact with the material, heating and pyrolyzing it. However, heating the material is also a balance of getting enough material to thermally decompose yet not having too much time and getting too much pyrolyzed material. In other words, for the material to burn, it needs to be above the lower flammability limit and below the upper flammability limit. Time is required, but not too much.

Once enough material is pyrolyzed (thermally decomposed) and in the flammability zone, the amount of energy needed to ignite the evolved material is extremely low (on the order of millijoules) and the probability for ignition is at its greatest.

If energy or total energy is a more appropriate way to handle to the application of data generated from this test method, then a term that would describe it is desirable. Such a term exists and can be borrowed from the electrical engineering field where such a term is employed. The term is I^2t, where I is the current squared multiplied with time, t. It is commonly used, particularly in the context of protection devices such as fuses and circuit breakers. It represents the thermal energy or "let-through energy" that flows through a device due to a short-circuit or overload condition, a condition or scenario that is of interest in this context.

As a possible defense for using this approach, consider the derivation of the term. The term is derived from the equation for the energy dissipated as heat in a conductor due to the electrical current flowing through it. According to Joule's law, the heat generated in a conductor is proportional to the square of the current flowing through it and the time duration for which the current flows. Mathematically, this relationship can be expressed as:

$$Q = I^2Rt \tag{1}$$

Where Q is the heat energy dissipated in Joules, I is the current flowing through the conductor in amperes, R is the resistance of the conductor in ohms, and t is the time duration for which the current flows in seconds.

In protective devices, the time taken for the device to react and interrupt the current flow is very short (typically in milliseconds). Therefore, for protective devices like fuses and circuit breakers, the energy let-through or "let-through energy" is more relevant than the total heat dissipated. This is often represented by the integral of the square of the current over time, hence the term I^2t.

The I^2t rating of a protective device is a measure of its ability to withstand and safely interrupt short-circuit currents without sustaining damage or causing downstream equipment damage. It helps in selecting the appropriate protective device for specific applications based on the expected magnitude and duration of fault currents. Likewise, a similar approach may be used in adopting the I^2t term and applying it to a material and thinking of the material in much the same manner as a fuse or breaker, where the interest is in protecting the material from a total energy input that would lead it to become ignited.

To illustrate this approach, consider Figure 9, which reflects the power (W) during the test showing the energy input into the wire and sample building up to the wire break where the actual power during the ignition of the resulting combustible vapor is much lower than that required to heat it initially. Now consider Figure 10. For the leftmost plot, the energy input is integrated and plotted and on the rightmost plot, the I^2t is plotted. For the orange series and gray series, they are the same material but the orange represents the 2024 magnetic clamping fixture and the gray represents the 2004-2005 screw-terminal fixture. The blue series is moleskin, which was plotted for reference. With the energy input integrated alone, the contact resistance is still driving an erroneous result, showing the material with much lower ignition energy than actual due to the losses across the higher contact resistances of the magnetic clamps. For the I^2t approach, the contact resistances for the screw-terminal vs magnetic clamps are tared out of the data as the power supply corrects the actual supply voltage to maintain a constant current. Hence, on the rightmost plot, the orange series with the magnetic clamping fixture is in line with the gray screw-terminal clamping fixture and a clearer picture of the actual material performance is observed.

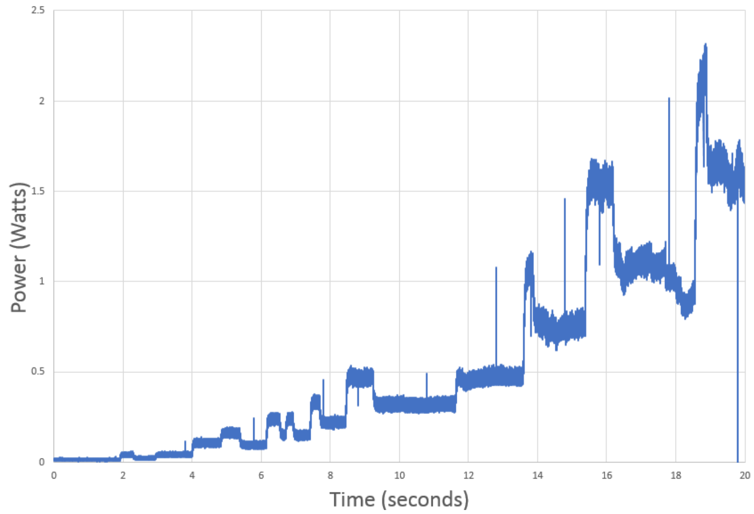

Figure 9 - Power at Wire Break (W) Example

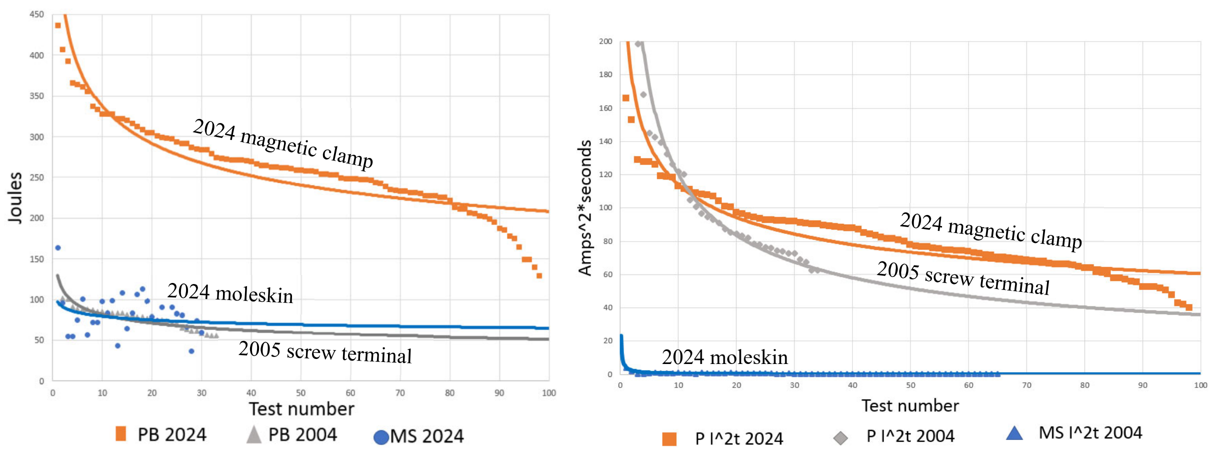

Figure 10 – Integrated Energy Input (J) (Left)/ I^2t Example with Polyurethane (Right)

This approach is novel, and there are still many aspects of the approach that require further consideration, including understanding the limits of the application's extrapolation, which is beyond the scope of this paper. Further work is being done to understand the limits and modifications to the test method.

IV. Method Updates

As expressed in reference document[6] several test setup parameters were found to alter the wire-break ignition test results. Some of these factors included:

- Wire placement
  - The wire must be in direct contact with the sample to obtain ignition.
  - Occasionally, the wire would lift off of the surface of the material when heated.
  - High-speed video has to be reviewed from each run to ensure that the wire remained in contact with the sample.
- Wire length
  - An increase in the wire length lowered the ignition energy, as this resulted in transmission energy loss with less delivered to the sample as measured at the contacts.
- Wire gauge/handling to avoid breakage
  - As the wire gauge increases and the resulting cross-section decreases, it becomes much more difficult to handle and secure the wire without damage.
- Ability to control wire-breakage location in small-gauge wires

- With the heat sinking at the terminals, the wire has peak heating at the center of the U-loop. However, peak heating can occur elsewhere if the wire is damaged or altered.
- Heat flux/thermal conductivity of the materials under test
  - If the material sample is highly conductive, it can dissipate heat away from the localized heating zone, with the wire sinking it to the copper baseplate. This produces a higher apparent ignition energy, skewing the results.
- Combustible vapors
  - The combustible vapors must be accumulated above the lower flammability limit and below the upper flammability limit. This time component of the test forces iteration to find the optimal ignition point.
  - The material density in proximity to the wire also contributes to how much of the heat-affected zone will experience thermal decomposition and potentially source combustible vapors. Figure 11 shows the rather small size of the heat-affected zone along with the open fiber density of the Pyropel leading to less direct contact with the given material.

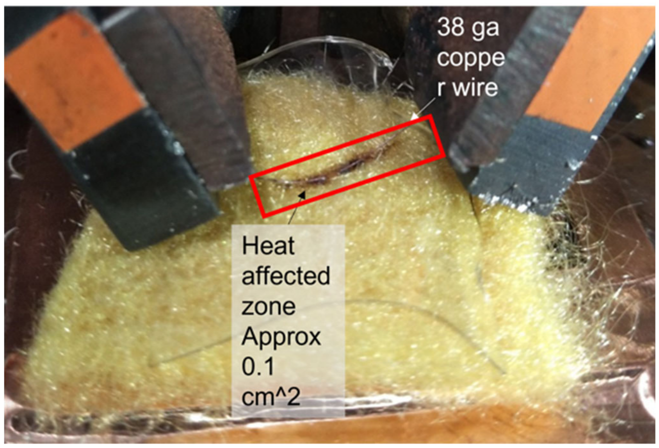

Figure 11 - Photo of Pyropel with 38 AWG Wire

Potential improvements under active investigation include refining or evolving the existing wire-break method with changes such as:
- Programmed current (A) ramp rate
- Re-test sweet spot (seconds) to maximum ignition frequency
- Add spark plug for more repeatable arc ignition
- Instant calculation of integrated I^2t, current at break, voltage at break, power at break, and integrated energy (Joules) so operator knows step-down accomplished
- Measure heat flux of ignited smoke

Additional considerations include the splitting of the different functions performed by the current wire-break setup:
1. Perform a materials characterization prior to the test using thermos gravimetric analysis (TGA), differential scanning calorimetry (DSC), and gas chromatograph/mass spectrometer (GC/MS) to determine when thermal decomposition occurs for the given material and what combustible vapor is produced.
2. Use the setup-controlled preheat to generate the combustible vapor via thermal decomposition across a larger area of the sample, addressing the small heat-affected zone issue.
3. Use a controlled igniter similar to a spark plug to generate a repeatable and controlled spark with variable energy for the selected test condition.

V. Conclusion

The wire-break ignition test was developed after re-creation and review of the Apollo era tests that employed scratch and poke electrode techniques to devise a more repeatable and conservative test that still represents a system failure mode. A body of data was generated for materials characterization considering thermal decomposition into a combustible vapor with subsequent ignition from an arc discharge. The interpretation of that data is being evolved to improve its usability for design and assessment of oxygen systems. Work is ongoing to further evolve and improve the repeatability of the test method and data produced.

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