



Title	Effect of reduced ambient pressures and opposed airflows on the flame spread and dripping of LDPE insulated copper wires
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1 **Effect of Reduced Ambient Pressures and Opposed Airflows on the Flame Spread and**
2 **Dripping of LDPE Insulated Copper Wires**

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11 **Highlights:**

- 12 • Effect of pressure and opposed flows on flame spread across copper wire was studied.
13 • Pressures ranged from 40 to 100 kPa and opposed flows were 10 or 20 cm/s.
14 • Flame spread was found to increase with pressure and decrease with faster flows.
15 • Dripping of LDPE insulation from wire was also studied under described conditions.
16 • Mass dripped was found to decrease with pressure and increase with faster flows.

17

18 **Abstract:**

19 The effect of ambient pressure on flame spread and insulation dripping of copper-cored,
20 LDPE-insulated wires exposed to opposed airflows was investigated to increase understanding of
21 electrical wire fire hazards in spacecraft environments. Utilized wire samples consisted of
22 0.64mm-diameter copper cores surrounded by 4mm-outer diameter LDPE insulation sheaths.
23 The wire characteristics were selected for comparison with future experiments planned in the
24 International Space Station (ISS) with similar wires. Environmental pressure was varied from
25 sub-atmospheric (40 kPa) to atmospheric (100 kPa). Wires oriented horizontally were exposed
26 to opposed airflows with speeds of 10 or 20 cm/s. Results showed that flame spread rates
27 increase with pressure and decrease with increasing opposed flow speeds. Melted and burning
28 insulation left behind by flame spread dripped with a frequency that increased with pressure; the
29 total mass dripped decreased with pressure. It was also found that lower flows produced more
30 frequent dripping with less total mass dripped, and higher flows produced the opposite.
31 Coincidentally, as the mass of dripped insulation increased, the flame spread rate decreased.
32 Comparison of present results with those from studies with different wire samples show that the
33 effect of environmental parameters on flame spread and insulation dripping depends strongly on
34 core conductivity and core/insulation diameters. Consequently, care should be taken in
35 extending results obtained from specific wire tests to other wires without justification.

36

37 **Keywords:** electrical wires, reduced and atmospheric pressures, opposed flow, flame spread
38 rate, insulation dripping

39 1. Introduction

40 Electrical wires are potential sources of fire ignition and spread in spacecrafts, aircrafts, vehicles,
41 and structures [1]–[4]. Therefore, it is important to understand the burning behavior of electrical
42 wires in their operating environments. Of interest here is the potential for fires in spacecrafts,
43 which can be originated by electrical wires and have disastrous consequences. Furthermore,
44 cabin environments for NASA’s next generation of spacecrafts are planned to operate under
45 reduced pressure and increased oxygen concentration conditions [5], and further study on the
46 effect of such environments on wire flammability is desired.

47 Flame spread is one of the burning mechanisms used to assess the flammability of materials
48 because after a material is ignited, the rate of heat released by the fire is dependent on its rate of
49 spread. In addition, dripping of molten burning materials, although not normally considered as a
50 material flammability parameter, is important in the propagation of a fire because the dripping
51 material can ignite materials underneath or create pool fires. Furthermore, since dripping is
52 caused by gravity there is a fundamental difference in the propensity for a molten burning
53 material to spread a fire in normal gravity, in the absence of gravity, or in reduced gravity, as in a
54 spacecraft or space habitat. Thus, it is relevant in the study of wire flammability and dripping to
55 assess their fire hazard in spacecraft environments.

56 In wire combustion, the relevant parameters can be loosely grouped into three categories: the
57 characteristics of the wire (the dimensions and makeup of the core and insulation),
58 environmental conditions (airflow speed, ambient pressure, oxygen concentration, external
59 radiant heating, strength of gravity, and even electro-magnetic fields), and geometric parameters
60 (direction and inclination of flame spread relative to flow speed and gravity). These variables,
61 together with the fact that different insulations have different combustion characteristics and that
62 the interaction of the conductive core and insulation affects the burning of the wire, make the
63 study of wire flammability very complicated. For this reason, wire flammability studies often
64 use “laboratory” wires which are assembled from a metal rod for the core and plastic tubes for
65 the insulation, which is the case in this study.

66 Several previous studies have investigated the effect of these parameters on wire burning,
67 including various wire characteristics [6]–[9], environmental conditions [6], [10]–[17], and
68 geometries [8], [18], [19]; however, there are only a limited number of studies examining the
69 effect of ambient pressure, specifically sub-atmospheric, on flame spread [15], [19]–[22]. This
70 research is important because it has previously been found that low pressure environments can
71 approximately mimic results found in micro-gravity environments [16], [17], [21]. Among the
72 studies that have examined the effect of pressure on wire flammability, Nakamura *et al.* [19]
73 found flame spread rate to increase with decreasing pressure for wires with nichrome cores.
74 However, in the same study, iron wires were also examined, and it was found that the spread rate
75 along these wires remained constant with varying pressure, showing that flame spread behavior
76 at different pressures can vary for different core materials. Zhao *et al.* [20] performed
77 experiments with wires containing copper cores, and found that the flame spread rate decreased
78 with decreasing pressure. Hu *et al.* [22] studied the flame spread of both copper and nichrome
79 wires, and it was again confirmed that flame spread over nichrome wires increases with
80 decreasing pressure. The results for flame spread over the copper wires were more interesting,
81 however, as it was found that there was an initial decrease in flame spread rate with pressure, and
82 further decreasing the pressure resulted in an increase in flame spread rate. Additionally, the

83 effect was found to be less prominent as the core diameter increased, with a solely decreasing
84 flame spread rate as pressure decreased being observed for a copper core with a diameter of
85 0.80 mm, as opposed to wire diameters of 0.30 or 0.50 mm in the same study [22]. Considering
86 the results of these previous studies, particularly those providing results for copper-cored wires,
87 it is thought that additional research concerning the described variables will bring more clarity to
88 the available findings.

89 Additionally, it is important to look at the combined effect of low-velocity opposed airflow and
90 ambient pressure on flame spread because space crafts designed for human crews typically have
91 low flows of 6 – 20 cm/s generated by their HVAC systems [23]. At the present, only one study
92 has examined such a combined effect [19], where it was found that, for nichrome wires, flame
93 spread rate decreased at higher opposed flows and increased with decreasing pressure, and for
94 iron wires, the flame spread at first decreased but then remained constant for increased opposed
95 flows and also increased with decreasing pressure. However, the work in this study [19] did not
96 include any analysis of wires with high-conductivity cores; therefore, one of the goals of the
97 present study was to examine the combined effect of sub-atmospheric, ambient pressure and
98 opposed airflows on flame spread over wires with a high conductivity core, such as copper. The
99 insulation dripping off these wires was also analyzed under these conditions, since it has been
100 shown that it affects the rate of flame spread and burning of insulated wires. The results of the
101 present work are also relevant for comparison with future experiments planned in the
102 International Space Station (ISS) with similar wires [24], which is the primary objective of this
103 work.

104

105 **2. Material and Methods**

106 **2.1 Experimental Apparatus**

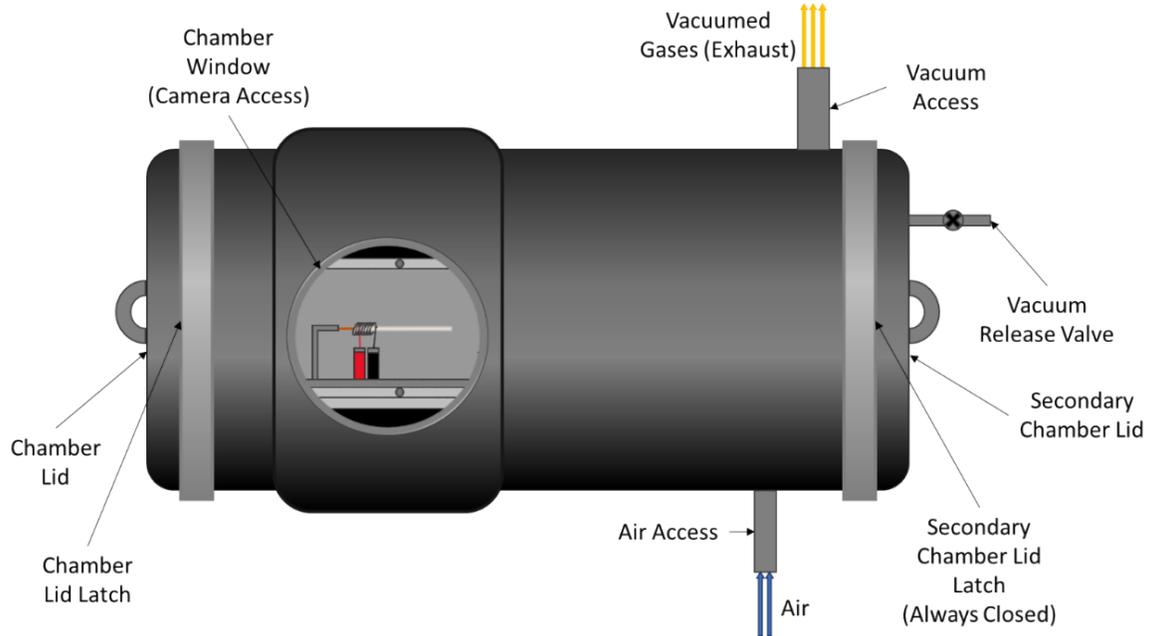
107 The experimental apparatus used in this study is shown in Fig. 1 and Fig. 2. The setup was used
108 to facilitate flame spread tests of Low-Density Polyethylene (LDPE)-insulated, copper-cored
109 wire samples under various environmental conditions, including ambient pressure and opposed
110 flows. For this study, the wire samples were suspended horizontally in the middle of a flow duct
111 with a cross section of 128x128 mm² and a total length of 255 mm, all contained within an air-
112 tight pressure vessel with access to fresh air and the ability to remove exhaust to keep the
113 experimental environment consistent throughout the length of each test. Within the duct, the
114 sample tip was located approximately 95 mm from the upwind end of the flow duct where
115 uniform air entered the duct from a flow laminarizing and straightening section. Air was used as
116 an oxidizer, and the pressure was varied from 40 to 100 kPa, with an average standard deviation
117 of 0.2 kPa, in intervals of 20 kPa. The pressure range was selected due to design and equipment
118 constraints. The opposed flows were set to speeds of either 10 or 20 ± 0.5 cm/s parallel to the
119 wire. The flow speeds were selected because they are similar to those generated by the HVAC
120 system in a manned aircraft.

121 For the described experimental setup, the air was provided from a tank of pressurized air, fed by
122 a compressor. The mass of insulation material dripped was determined by collecting the drips in
123 a pan placed underneath the sample and weighing the mass after the test was completed.

124 Windows on the sides of the flow duct and chamber provided optical access, which allowed for
125 video recording using a Nikon D3200 camera with a DX AF-S NIKKOR 18 55 mm 1:3.5-5.6G

126 lens. The recordings were taken at 30 fps with an incandescent white balance, ISO of 200,
127 exposure time of 1/60, and aperture setting of F6.3. Subsequent video analysis allowed for
128 measurement of the flame spread rate across each sample as well as the drip frequency.

129

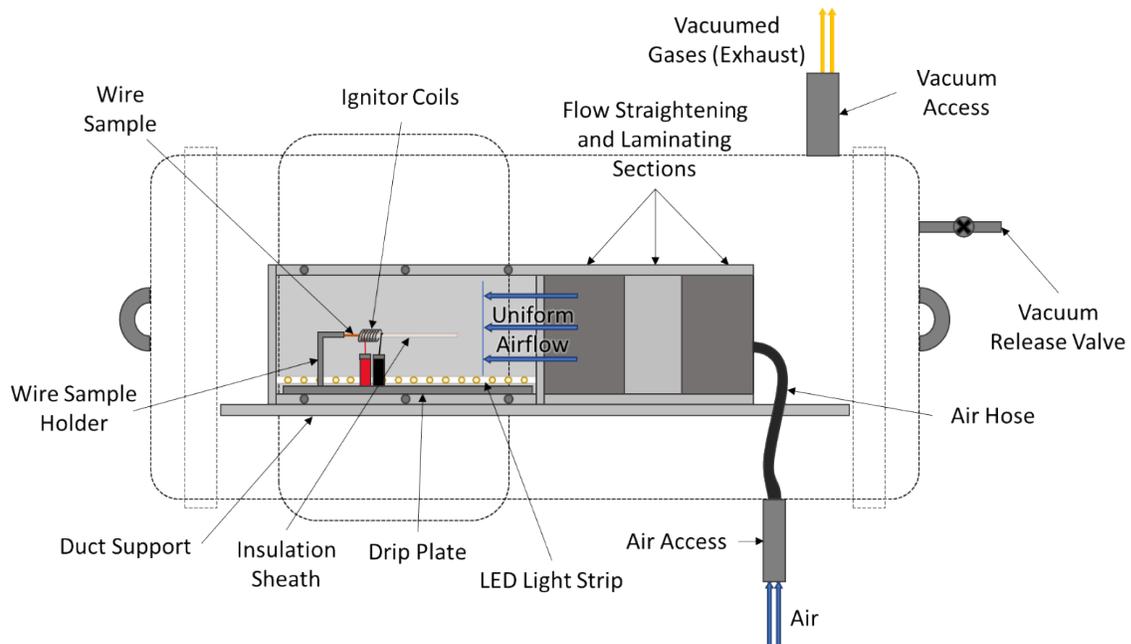


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Fig. 1. External view of pressure chamber experimental setup.

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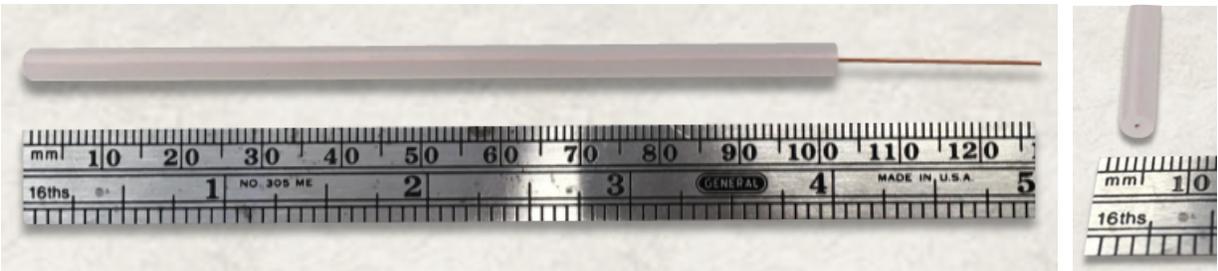
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Fig. 2. Internal view of pressure chamber experimental setup.

135 **2.2. Sample Description**

136 All the tests were conducted with “laboratory” wires consisting of 125mm-long copper cores and
137 100mm-long LDPE insulation sheaths. The copper cores had diameters of 0.64 mm, and the
138 insulation sheaths had inner diameters of 0.7 mm and outer diameters of 4 mm, as shown in
139 Fig. 3. Relevant material properties of copper include its density of 8,880 kg/m², thermal
140 conductivity of 398 W/m·K, and specific heat of 390 J/kg·K. The relatively large size of the
141 “laboratory” wires and the insulation material, while not intended to necessarily reproduce actual
142 electrical wires, were selected to facilitate the interpretation of the experimental results and to
143 compare the results with future experiments to be conducted on the ISS with the same type of
144 wires. Unfortunately, the wire characteristics do not allow for the direct comparison of the
145 present results with wires of previous experiments, such as those of ref. [19], but the primary
146 objective of the work is to provide normal gravity data for comparison with future microgravity
147 experiments [24]. Also shown in Fig. 3 is that the arrangement of the insulation along the metal
148 core for the experiments was such that their tips were aligned at one end and bare metal core was
149 exposed on the other, allowing the bare end to be secured by the sample holder.

150



151

152 Fig. 3. Wire sample with (left) core length of 125 mm and LDPE insulation length of 100 mm
153 and (right) 0.64mm-diameter copper core and LDPE insulation with 4 mm outer diameter.

154

155 **2.3 Experimental Procedure**

156 In all tests, the samples were ignited by a 0.64mm-diameter nichrome wire that was coiled into a
157 diameter of about 8 mm with 6 loops and powered with a Variac power source, which was set to
158 provide an RMS voltage of approximately 15 V, resulting in a power output of approximately
159 155 W. Due to the thickness of insulation on the sample, an ignition time of 35 s was used.

160 During each experiment, once the sample was in place, the camera was started to record real-
161 time video. An LED light strip was used to illuminate the wire sample for approximately 3 s at
162 the start of the experiment, so the insulation on the sample, which provided a length scale, could
163 be more easily measured during post image-processing of the videos. Then, the Variac power
164 source was turned on for the desired amount of time. Once the power source had been switched
165 off, the test was allowed to continue until the flame propagated along the whole length of the
166 wire or the burning along the wire naturally extinguished. During the tests, melting and dripping
167 of the LDPE insulation occurred, and a drip plate was placed beneath the length of the wire

168 sample to collect the fallen material which was weighed after the test. Six tests were conducted
169 for each test condition.

170 **2.4 Post Processing and Video Analysis**

171 After the experiments were conducted, the videos were analyzed using an interactive image
172 processing script, which had been developed previously [16], [17], to extract geometric
173 information about the flame at regular intervals during its spread. The intervals were selected
174 such that 50 to 80 of the recorded frames of steady flame spread were examined; edge effects
175 were not considered. In each of the analyzed frames, the position of the leading edge of the
176 flame was recorded. With further analysis, these locations of the leading edges were fit with a
177 linear regression, and the flame spread rate was calculated by the slope of the regression, which
178 was found to be linear in all cases. Using the length of the insulation sheath on the sample as a
179 length scale, a conversion from pixel coordinates to lab scale (mm) was made. Subsequent
180 analysis of the videos was used to determine the frequency of insulation dripping by counting the
181 number of drips that occurred during steady spread and noting the corresponding time frame.

182

183 **3. Results and Discussion**

184 **3.1 Effect of Reduced Ambient Pressure and Opposed Flow Speed on Flame Spread**

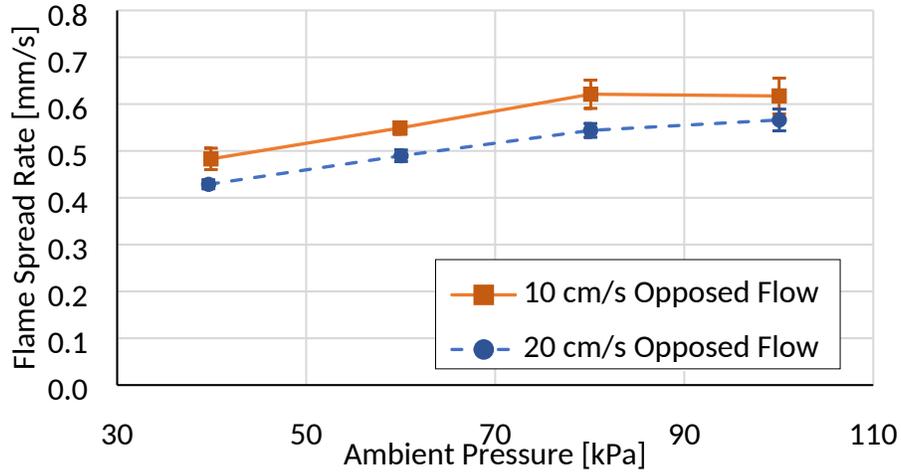
185 Fig. 4 shows the combined effect of reduced ambient pressure and various opposed flow rates on
186 the flame spread rate along the wire samples. In this figure, the averages of the measured data
187 points are presented, and the included error bars represent a 95% confidence interval. This data
188 shows a decrease in flame spread rate as the speed of the opposed flow was increased, agreeing
189 with ref. [19], which found flame spread rate to either decrease or remain constant (depending on
190 wire core material) as the opposed flow speed was increased. However, regarding potential error
191 in this study, it should be noted that the average uncertainty in the flame spread rate data was
192 calculated to be 0.06 mm/s (assuming an accuracy within 5 mm when tracking the positions of
193 the flame front), which is comparable to the average 0.06 mm/s difference in the flame spread
194 rate observed between the two tested flow speeds, so more testing may be need to confirm this
195 effect.

196 Looking at the effect of pressure in Fig. 4, the flame spread rate along the wire insulation was
197 found to decrease as the pressure decreased, which is consistent with some previous
198 findings [20]. As well, the aforementioned calculated uncertainty of 0.06 mm/s in the flame
199 spread rate is significantly less than the total variation of 0.2 mm/s in the flame spread rate across
200 the range of tested ambient pressures. Interestingly, however, this trend showing that reducing
201 ambient pressure resulted in slower flame spread is in opposition to the trend observed in
202 ref. [19]. Additionally, there is only partial agreement with the results of Hu *et al.* [22], which
203 showed that the flame spread rate along thin LDPE-insulated copper wires (0.30 or 0.50 mm
204 diameter cores) first decreased then increased with decreasing pressure. The difference in the
205 results may be due to the different copper core diameters used in the studies or because they
206 were performed in the absence of a forced flow.

207 While the exact effects of both the pressure and flow speed on the flame spread behavior, most
208 likely due to a combination of their effect on the rate of heat release by the flame and the thermal
209 contact with the wire core, remain slightly ambiguous, Fig. 5 makes it clear that there is, indeed,

210 an effect taking place. Here, it can be seen that there is a change in the flame shape and
211 appearance for reduced ambient pressures and increasing opposed flow speeds. It is also
212 observed from Fig. 5 that the flame became less luminous and weaker at lower pressures, which
213 agrees with previous studies [15], [21]. Because the heat release rate decreases for weaker
214 flames, the heat that is transferred from the flame into the wire insulation and core also
215 decreases, thus providing an explanation for a reduced flame spread rate [22].

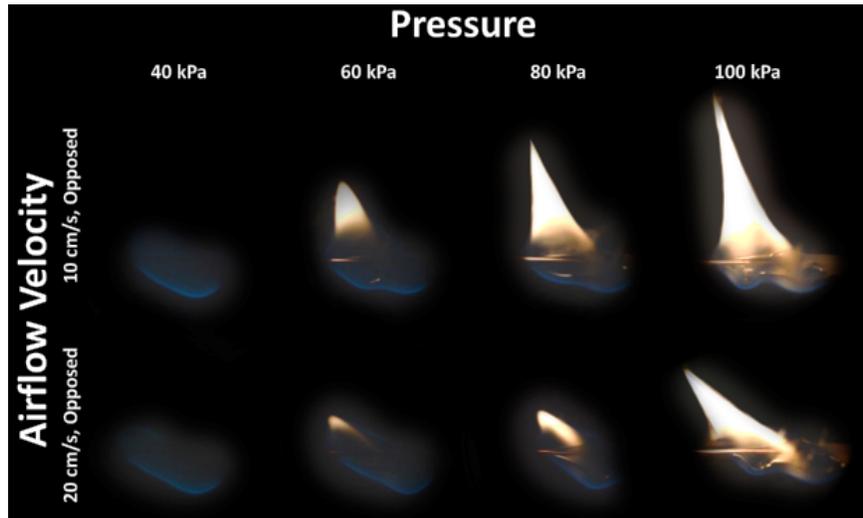
216



217

218 Fig. 4. Effect of reduced ambient pressure and opposed flow speed on flame spread rate over
219 LDPE-insulated copper wire.

220



221

222 Fig. 5. Effect of reduced ambient pressure and opposed flow speed on flame appearance during
223 flame spread along LDPE-insulated copper wire.

224

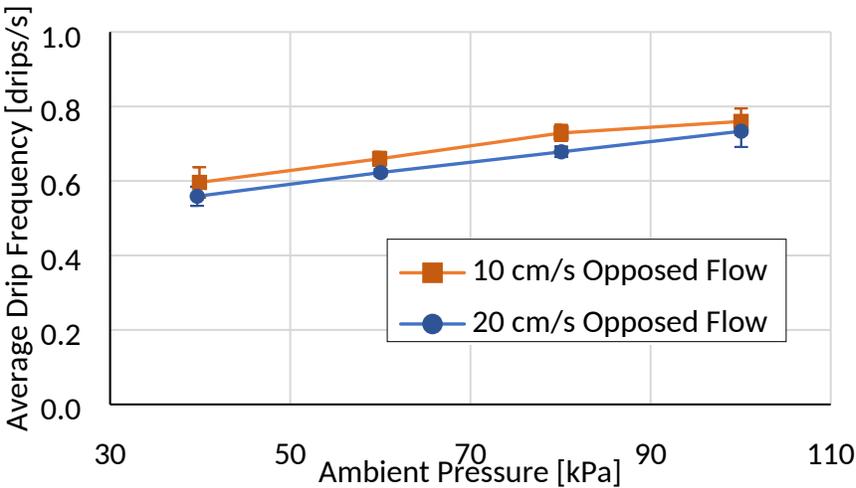
225 Also shown in Fig. 5 is that as the opposed flow speed increased, the flame leaned toward the
 226 wire in the direction of flow, as seen previously in tests with opposed flows [19]. The reduction
 227 of the opposed flow flame spread with the flow speed has been observed in previous studies with
 228 flat surfaces and was attributed to chemical kinetic effects on the flame [25]. However, as
 229 discussed in prior studies [19], the presence of the conducting core also plays a role in the heat
 230 transfer from the flame to the unburnt insulation ahead of the flame front. It is thought that the
 231 flame leaning observed when the flame is subject to opposed flows increases the heat transfer
 232 from the flame to the wire, due to their increased proximity. This increase in heat transfer from
 233 the flame, and subsequently along the core, again reduces the amount of heat transfer from the
 234 flame to the pre-heat zone ahead of the flame. The mechanisms controlling the effect of the flow
 235 velocity on the flame spread are similar to those discussed in ref. [19], thus their discussion is not
 236 repeated here; the reader is referred to the work of ref. [19] for a detailed description of these
 237 mechanisms.

238

239 **3.2 Effect of Reduced Ambient Pressure and Opposed Flow Speed on Insulation Dripping**

240 Fig. 6 and Fig. 7 show the effects of reduced ambient pressure and opposed flows on the
 241 dripping frequency and the total mass dripped of the LDPE insulation from the wire sample
 242 during flame spread, respectively. Just as in Fig. 4, in these figures, the averages of the
 243 measured data points are presented, and the included error bars represent a 95% confidence
 244 interval.

245



246

247 Fig. 6. Effect of reduced ambient pressure and opposed flow speed on drip frequency during
 248 flame spread along LDPE-insulated copper wire.

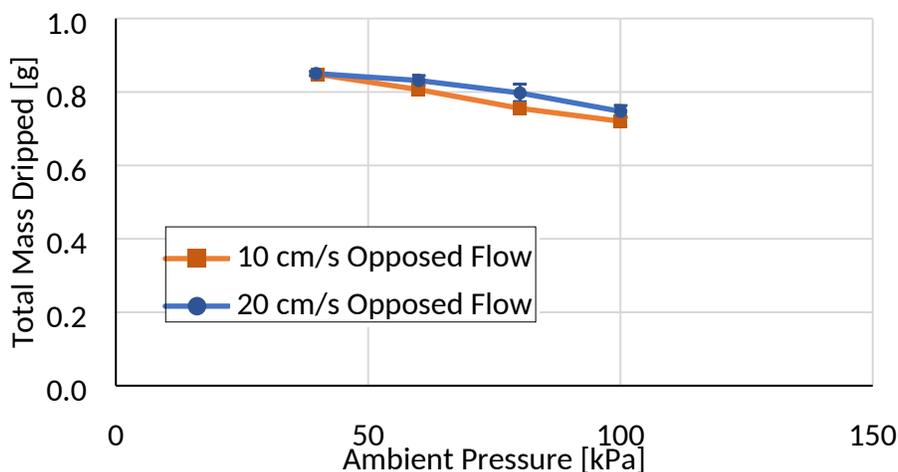
249

250 The trend in Fig. 6 shows that the frequency of insulation dripping decreased as pressure
 251 decreased. The average uncertainty for each test condition, assuming a discrepancy of 2 drips
 252 either above or below the actual counted value, was calculated to be 0.03 drips/s, which is
 253 considerably smaller than the total variation of 0.2 drips/s observed across the range of ambient

254 pressures tested, but comparable to the 0.04 drips/s variation between the two flow speeds tested.
255 Previous studies with thin wire insulation found that the insulation drip frequency increased with
256 decreasing pressure [20], [21]. In these prior studies, thinner wires were used with core
257 diameters of 0.50 mm, versus 0.64 mm in the current study, with thin insulation thicknesses of
258 0.5 mm [20] and 0.15 mm [21], versus 0.9 mm thickness in the current study. This geometry
259 difference corresponds to substantially more insulation mass per unit length of the wires in the
260 current study. Furthermore, some experiments were only performed on nichrome wires [20],
261 which have a lower thermal conductivity than copper. Thus, it is not possible to directly
262 compare the different results, and more research is needed to determine how the wire core
263 properties, both material and diameter, as well as the amount of insulation impact the dripping
264 behavior.

265 The results in Fig. 7 show that the total mass of insulation that dripped per flame spread test
266 increased as the pressure decreased and slightly increased as the opposed flow speed increased.
267 Here, the averages of the measured data points are presented, and the included error bars
268 represent a 95% confidence interval. The uncertainty of this data is quite low at only 0.001 g due
269 to the precision of the utilized mass balance. Therefore, because the difference in total mass
270 dripped across the range of pressures is on average 0.1 g, and the average change in total mass
271 dripped between the two tested airflows is 0.02 grams, it is observed that both pressure and flow
272 speed have a notable effect on the mass of molten insulation dripping from the wire during flame
273 spread.

274



275

276 Fig. 7. Effect of reduced ambient pressure and opposed flow speed on total mass dripped during
277 flame spread along LDPE-insulated copper wire.

278

279 Comparing the total mass of insulation dripped results with the frequency of insulation dripping
280 from Fig. 6 in environments that were subject to different opposed airflows, it was found that
281 slower flow speeds produced more frequent dripping with less total mass dripped. Since the
282 flame spread rate decreased as the flow velocity increased, this result is like what was observed
283 as the pressure was reduced. In other words, just as larger drops were observed at lower

284 pressures, they were also observed at faster opposed flow speeds, and both conditions resulted in
285 a substantially reduced flame spread rate.

286 As noted in prior studies [21], LDPE insulation is burnt less in low-pressure environments. It is
287 thought that this effect can be attributed to the wire core acting as a significant heat sink to an
288 already weakened flame. Regarding the core heat sink effect thought to occur at faster flow
289 speeds, as discussed in previous studies [19], when heat is transferred to the core from the flame,
290 a fraction is conducted ahead of the flame into the pre-heat zone helping flame spread, while a
291 fraction, which is larger for opposed flows, is also conducted away along the bare end of the wire
292 and subsequently lost to the ambient surroundings, which hinders flame spread. If it is assumed
293 that the relative fraction of each is constant across these test conditions, increased heat transfer
294 from the flame to the wire would mean more heat losses to the environment, but also a larger
295 molten section of the preheat zone, as shown in Fig. 5. A larger molten section of the preheat
296 zone would provide more conductive conditions for dripping, explaining the increase in total
297 mass dripped. Thus, the phenomena of decreased flame spread rate and increased total mass
298 dripped with increased opposed flow velocity are linked because they are both caused by an
299 increase in flame to metal core heat transfer.

300

301 **4. Conclusions**

302 The combined effect of reducing the ambient pressure and increasing the opposed flow speed on
303 horizontal flame spread and dripping of copper-cored, LDPE-insulated wires was examined
304 through experiments to increase understanding of the fire hazard electrical wires pose in
305 spacecraft environments, and to provide data for comparison with future microgravity
306 experiments. Results showed that the flame spread rate as well as the molten, burning insulation
307 drip frequency decrease both with decreasing pressure as well as increasing opposed flow
308 speeds. Contrarily, it was found that the total mass dripped increased both with decreasing
309 pressure and increasing opposed flow speeds. It is thought that these results are due to the wire
310 core acting as a heat sink and drawing a significant amount of heat out of the flame, which
311 affects both the rate of flame spread and the rate of insulation burning. Comparison with results
312 from other studies with wires of different core material or dimensions show that the effect of the
313 environmental parameters on the flame spread and mass burning of insulated wires depends
314 strongly on the core conductivity as well as core and insulation diameters. Consequently, data
315 obtained from specific wire tests should not be extended to other wires without justification.

316

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323

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386

387 **Figure captions**

388 Fig. 1. External view of pressure chamber experimental setup.

389 Fig. 2. Internal view of pressure chamber experimental setup.

390 Fig. 3. Wire sample with (left) core length of 125 mm and LDPE insulation length of 100 mm
391 and (right) 0.64mm-diameter copper core and LDPE insulation with 4 mm outer diameter.

392 Fig. 4. Effect of reduced ambient pressure and opposed flow speed on flame spread rate over
393 LDPE insulated copper wire.

394 Fig. 5. Effect of reduced ambient pressure and opposed flow speed on flame appearance of
395 LDPE insulated copper wire.

396 Fig. 6. Effect of reduced ambient pressure and opposed flow speed on drip frequency of LDPE
397 insulated copper wire.

398 Fig. 7. Effect of reduced ambient pressure and opposed flow speed on total mass dripped of
399 LDPE insulated copper wire.