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Analysis of the Self-Contained Breathing Apparatus Face Piece For Fire Service Use

Major Qualifying Project Report

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By

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Authorship

The partners involved in this major qualifying project feel as though the project came to completion due to the equal work of both partners. Both partners, Barbara Hall and Ricardo A. Belmontes, worked together to write and edit the project report.

We would like to acknowledge and thank Edmund Walker, Fred LeBlanc, and the other employees of the Massachusetts Firefighting Academy. The major qualifying project group was invited to the Academy to observe recruits during a live training program, to better understand the conditions that firefighters enter. The group was also able to view the self-contained breathing apparatus facepieces that failed during the near miss training incident at the Academy.

We would like to thank our advisor Kathy Notarianni for all of the help that she provided us throughout the duration of the project. Her knowledge and contacts in the industry was extremely useful in the determination of a project that would help the fire service and the fire protection industry.

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Abstract

The objective of this Major Qualifying Project was to determine the thermal limit of a polycarbonate facemask material used by firefighters and compare it to an alternative high temperature resistant material, polyethersulfone. A series of tests were conducted at the product level on polycarbonate and polyethersulfone samples by exposing both materials to a radiant heat source. It was shown that the coatings that were applied onto the materials significantly improved the heat deflection properties. The results of the tests were compiled and presented to the National Fire Protection Association 1981, Standard for Open Circuit Self-Contained Breathing Apparatus for Use in Emergency Services, Technical Committee.

Executive Summary

The personal protective equipment firefighter use consists of turnout pants, ~~a~~ turnout coat, gloves, ~~a~~ hood to protect the ears and neck, boots, helmet, and most importantly ~~a~~ self-contained breathing apparatus. The self-contained breathing apparatus (SCBA) has three main components: breathing air cylinder, regulator hose, and a facepiece. There have been multiple cases of failure of the polycarbonate lens housed in the SCBA facepiece system, which has caused catastrophic failure. Failure of the polycarbonate facepiece has been documented as crazing, bubbling, deformation, and in the most severe cases rupture of the material.

A conference was held in Pittsburgh, Pennsylvania during July of 2010 by the Fire Protection Research Foundation (FPRF) acted as a forum to discuss the failure of the facepiece lenses, with the long term goal of making improvements to prevent further failure. In addition, the conference provided discussion on changes to the NFPA 1981 Standard on Open Circuit Self-Contained Breathing Apparatus for Emergency Services. The individuals attending the conference came from varying backgrounds such as the fire service, industry, and individuals involved with regulation. At the conference there was a request for research to be carried out on alternative materials for use in the SCBA facepiece. The material polyethersulfone was identified by a manufacturer at the conference as a possible alternative.

Tests were carried out in the Fire Laboratory on the Worcester Polytechnic Institute campus. The tests consisted of polycarbonate and polyethersulfone plaques being exposed to a radiant heat flux generated by the cone calorimeter. The radiant heat tests were carried out at the product level to test the thermal capabilities of the two materials. The plaques were made of an uncoated polycarbonate, polycarbonate coated with a Siloxane based UV cured Acrylate, uncoated Polyethersulfone, and Polyethersulfone coated with a Siloxane based thermal cured hard coat. The two coated materials were coated and prepared in accordance with regulations by the plastics manufacturer and were in the format that is used in commercial SCBA facepieces.

The tests were carried out at three different heat flux levels low (10 kW/m^2), medium (15 kW/m^2), and high (20 kW/m^2). The low flux was chosen because it was lower than any of the failures carried out in the National Institute of Standards and Technology (NIST) test that followed the conference. The medium was chosen because it is the radiant flux that is in the suggested changes to NFPA 1981 for the 2013 version. The high flux was chosen because it is the flux chosen by the industry to signify flashover.

The experimental procedure consisted of adjusting the cone calorimeter to 10kW/m^2. This was done by placing a Schimdt-Boelter water cooled heat flux gauge, which has the accuracy of ±1kW/m^2, 1 inch away from the heating coils where the sample would be positioned. Once the heating cell reached the desired heat flux, the shutter was placed in front of the heat source and the polycarbonate plaque was mounted onto the load cell of the cone calorimeter. The shutter was then removed and the plaque was exposed to the heat flux for 5 minutes. The time to failure and temperature of the surface at failure was recorded. The experiment was repeated 3 times for the coated samples and 2 times for the uncoated samples to reduce the error and uncertainty. The process was then carried out for the previously specified medium and high heat flux levels. Note the same experimental procedure was carried out for each of the four materials.

Overall the data presents conservative limits just before thermal degradation of polycarbonate and polyethersulfone for different heat fluxes. It showed that enough exposure to lower heat fluxes could cause thermal degradation. Product level materials testing have demonstrated that the application of coatings make a significant difference, even more so when using polycarbonate. There is a possibility that the polyethersulfone, with the right coatings applied, may be a better match for the requirements that the fire service provides. However, the coating used on the polycarbonate accounted for the lower heat deflection and it was able to perform similar to polyethersulfone and simply replacing the lens material may not be the direct solution for eliminating the weakest link of the SCBA.

Background

Self-Contained Berating Apparatus (SCBA)

SCBA devices are composed of three major components: a high pressure cylinder, a pressure regulator and a face mask that in combination provides firefighters with a remote breathing supply during a fire. These devices are one of the most essential personal protective equipment available to fire fighters. It allows them to enter hazardous environments and perform interior operations that range from search and rescue, ventilation and offensive fire attacks. It protects them from smoke, irritants attacking sensory nerves and hypoxic effects on vital organs. Smoke and irritants can become extremely painful and debilitating leading to problematic rescue operations. An optical density of 0.2/m for irritant smoke can decrease walking speeds from 1.2m/s to 0.3m/s.

Gases like carbon monoxide and hydrogen cyanide are two of the main causes of loss of consciousness and death during a fire and its effects may be accelerated by other gasses like carbon dioxide which increases a person's breathing rate. The SCBA also provides a positive pressure effect which automatically prevents inward leakage by maintaining a higher pressure inside than outside the mask. Furthermore, it offers a layer of thermal protection by utilizing the thermal resistance of the protective materials and make use of the internal airflow which creates a cooling effect.

Figure 1: SCBA

Polycarbonate Facepiece

In the United States lenses in the SCBA facepieces are composed of polycarbonate due to its good overall properties. It has a high impact resistance and can undergo large plastic deformation without cracking, making it very durable. Apart from its good mechanical properties polycarbonate also has good thermal characteristics with a heat deflection temperature of 140 degrees Celsius and a melting temperature of 267 degrees Celsius. Furthermore it has 90% transparency to visible light which makes it excellent for lens applications. On the other hand, polycarbonate has a low scratch resistance but this is easily corrected with an exterior coating, usually of silicon oxide.

Polyethersulfone

Currently in Europe SCBA facepieces are required to use polyethersulfone as the lens material in accordance to EN 136, Standard for Respiratory Protective Devices [11]. It has superior high temperature properties compared to conventional engineering plastics. Polyethersulfone has a heat deflection temperature of 200°C and melting temperature of approximately 350°C, much higher than polycarbonate. However, polyethersulfone has a light transmission of 88% and does not meet the current industry standard, which is one of the major reasons why it is not used in the United States. The standard test is performed by an individual with 20/20 vision, uncorrected or corrected, in each eye. The individual stands 6.1 meters away from a standard vision test chart and attempts to read the chart. The 2% difference does not seem like much however firefighters must be able to see the exit signs and other directional media leading them to safety [10].

Coatings

Coatings are used frequently to provide an enhancement of characteristics to a material. For example polycarbonate is typically coated to provide additional protection against scratches. In most cases coatings are made by depositing a film from a source material onto the material being enhanced, known as the substrate. According to the Handbook of Deposition Technologies for Film and Coatings Science, Technologies, and Applications there are three basic steps in the formation of a deposit.

- Synthesis or creation of the species being deposited.
- Transportation of the film atoms and molecules from the source to the substrate.
- The deposition of the source material onto the substrate and subsequent growth of the film.

There are two broad categories of coatings that are in use; physical vapor deposition (PVD) and chemical vapor deposition (CVD). There are a variety of processes that may be placed in each category but the basics of each are similar to those of the broad category.

When it comes to physical vapor deposition there are three typical ways to create the vapor species that is to be deposited onto the substrate; evaporation, sputtering, and chemical vaporization. When the species is vaporized it is then transported to the location of the substrate. During the transportation process the atoms and molecules may collide if ionized or the transport gas has a high partial pressure. The atoms and molecules in the vapor may also be transported with no collisions and subsequent combinations occurring. The third step in the process, deposition of the film, is usually carried out by nucleation and the growth of the film on the surface of the substrate. During this process ions still in the vapor phase have the ability to barrage the film and bring changes to the microstructure and composition.

Chemical vapor deposition occurs in much the same manner, the difference being the three main segments of the process are carried out by chemical reactions. A chemical reaction is used to vaporize the source material. The solid particulates are then transported by a gas or vapor to the area of the substrate. When the vapor carrying the solid particles is on or in the area nearby the substrate a chemical reaction is triggered to cause the deposit of the solid material onto the surface. In most cases during the chemical vapor deposition the substrate is heated to aid in the chemical reactions and the process being carried out [3].

Failures and Standards

In recent years there have been seven firefighter fatalities as a result of the thermal degradation of SCBA's. The victims were found with their masks damaged but still in place which suggests that there may have been an increase in thermal energy and the firefighters were unable to escape in time [7]. This is one of the setbacks of the personal protective gear, firefighters may be unaware of the extreme dangers they are in because they are unable to get a real sense of the amount of thermal energy present. Firefighter bunker gear is designed to withstand temperatures around 250 degrees Celsius however the closer you are to the ceiling the higher the temperatures are due to hot gases and smoke rising which forms what we call the upper gas layer where temperatures can range from 100-300 degrees Celsius and heat fluxes between 5-12 kW/m^2 at pre flashover [7]. While the thermal environment varies depending on fuel load, ventilation and construction layout Donnelly classified firefighting environments into four classes that can be used to establish performance requirements for protective equipment standards as shown in Figure 2 [4].

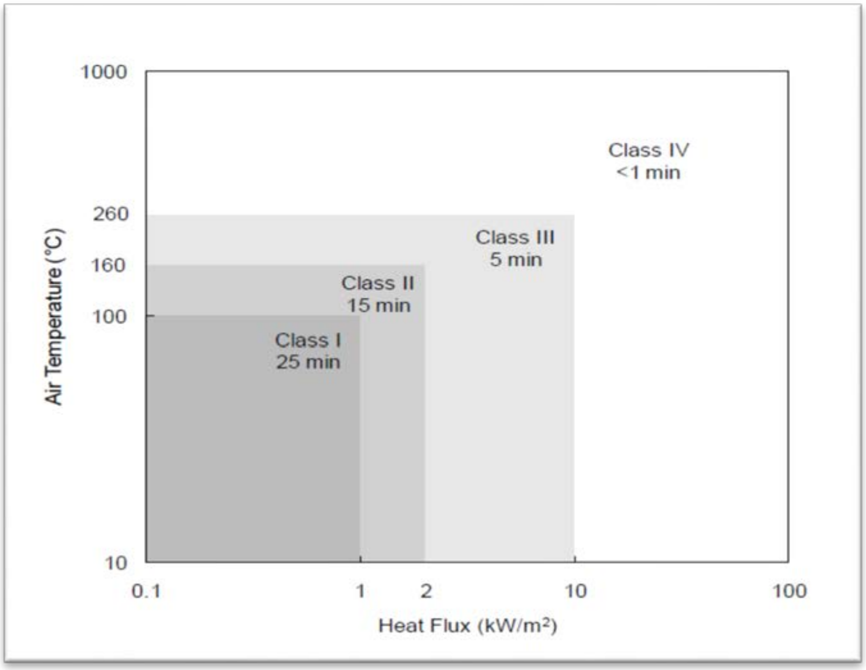


Figure 2: Fire Classifications

The two main standards that exist for the SCBA in America are NFPA 1981, Standard for Self Contained Breathing Apparatus for Emergency Services, and 42 CFR Part 84, Approval of Respiratory Devices. NFPA 1981 is managed by the National Fire Protection Association which specifies the minimum requirements for the design, performance, testing, certification, and replacement of parts and accessories [10]. The National Institute of Occupational Safety and Health (NIOSH) is the authority governing 42 CFR Part 84 for testing and certifying respiratory equipment in the United States. It involves evaluation of device weight, impact resistance, service time, breathing resistance, gas flow, and valve performance.

In the current standard for the testing and certification from NFPA 1981 the SCBA is mounted on a high temperature resistant test headform with a breathing rate of 40 L/min and placed in a convection oven at 95 degrees Celsius for 15 minutes which would be classified as a Class I exposure. The breathing rate is then increased to 105 L/min and not more than 20 seconds later the face piece is exposed to a direct contact flame with temperatures between 815-1150 degrees Celsius for 10 seconds [10]. This section of the test is certainly the most strenuous portion and is classified as a Class IV exposure. Following the direct contact flame test the headform is dropped from a height of 15.2 cm to simulate an impact test [9]. However, even though the test evaluates the SCBA at high temperatures it fails capture conditions in Class II and III which could be a possible reason for lens failure. The NFPA has recognized this shortcoming and has been working on updating NFPA 1981. The 2013 edition of the NPFA 1981 will require the face piece to be placed in a convection oven at 260 degrees Celsius (500 °F) for 5 minutes compared to 95 degrees Celsius for 15 minutes in the previous edition, which will fall under a Class III exposure. NFPA has also included a radiant heat test, something it was also lacking, which will require the SCBA to be exposed to a radiant heat flux of $15 kW/m^2$ for 5 minutes.

NIST Experiment

The National Institute of Standards and Technology (NIST) conducted a live burn experiment that demonstrated a range of realistic thermal exposures which can lead to catastrophic SCBA lens failure [6]. The live burn experiments, which lasted for 5-10 minutes, were conducted in a two story furnished townhouse with ceiling temperatures ranging from 500-750 degrees Celsius using calibrated propane fuel. There were six different experiments conducted and three out of the eight face pieces being tested showed clear signs of thermal degradation with maximum exterior lens temperatures of 300 degrees Celsius.

Figure 3: NIST Experimental Set Up

As seen in Figure 3, the facepiece was mounted onto a polyurethane test headform and secured to an aluminum test stand that was covered with fire fighter protective gear. A Schmidt-Boetler water cooled heat flux gauge protected by ceramic fiber insulation and aluminum foil placed 1 meter above the ground facing the same direction as the face piece was used to record the heat flux during the experiment. In addition, k-type thermocouples were placed in various areas in the room to measure temperature layers all around the face piece and five thermocouples were secured around the face piece to measure air and surface temperatures. For more information on the experimental set up and conditions see [5].

In one of the NIST live burn experiments it was found that radiation may be the primary form of heat transfer leading to the degradation of SCBA lenses. A SCBA facepiece was placed on the porch of the two story building during the live burn experiment where a door separated the facepiece from the fire. The door was opened 300 seconds after and temperatures quickly increased due to the ventilation. The fire proceeded to burn for about 4 additional minutes before it was extinguished by firefighters.

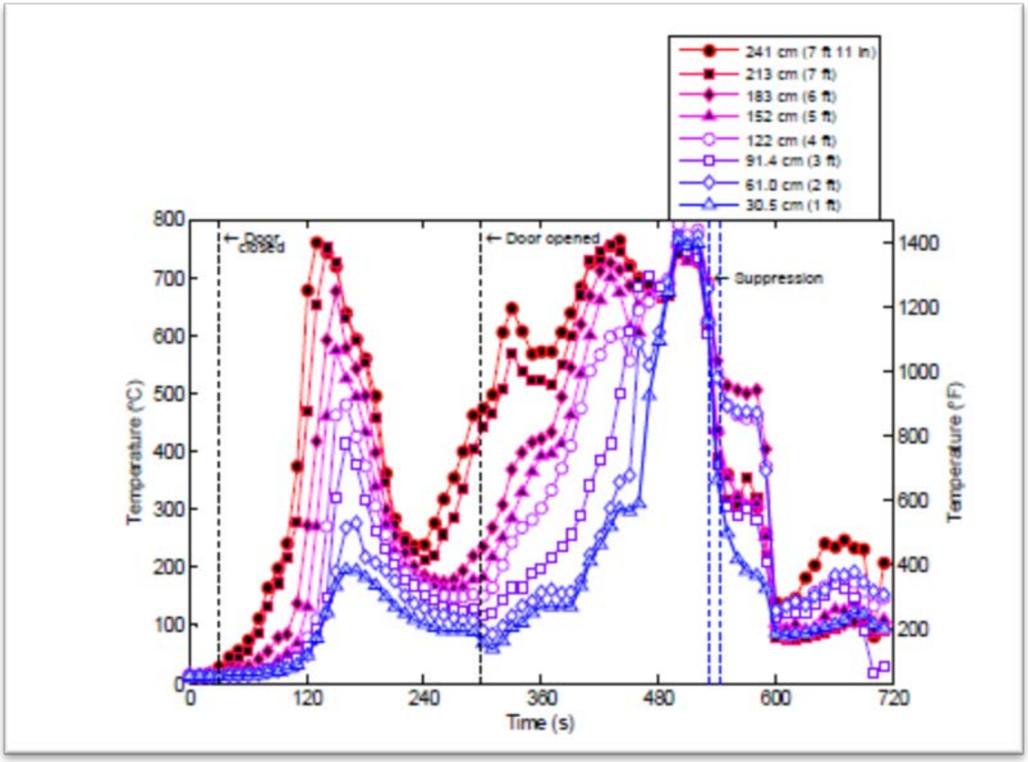


Figure 4: NIST Temperature Profiles

Figure 4 shows the temperature profiles from the experiment. Notice how the fire peaks twice, first when the fire was created and the second time when the door was opened. Note that facepiece was not exposed to any heat until the door was opened. It was found that the outside air temperature was always cooler than the temperature of the surface of the facepiece. This is strong evidence suggesting that radiation was the key form of heat transfer. If convection was the main form of heat transfer the surrounding air would at least be the same temperature as the surface of the facepiece. Furthermore no flames from the door ever came in contact with the facepiece yet the heat flux gauge measured 40kW/m^2 and 50kW/m^2 for about a minute. After the experiment the face piece showed clear signs of failure with extensive bubbling of the polycarbonate lens as seen in Figure 5. Due to the findings of previous studies the major qualifying project will investigate the effect of radiation on polycarbonate and polyethersulfone.

Figure 5: Thermal Degradation

Methodology

The failure criterion for the test was crazing, bubbling or deformation of the plaques. Crazing is the formation of small cracks and fractures, which look like spider web lines, on the surface of the material being tested. The deformation of the plastic was qualified as the loss of the rigid quality of the plaque and any added pliability that was not originally present. Figure 6 demonstrates examples of failures that were originally documented in NIST Technical Note 1724.

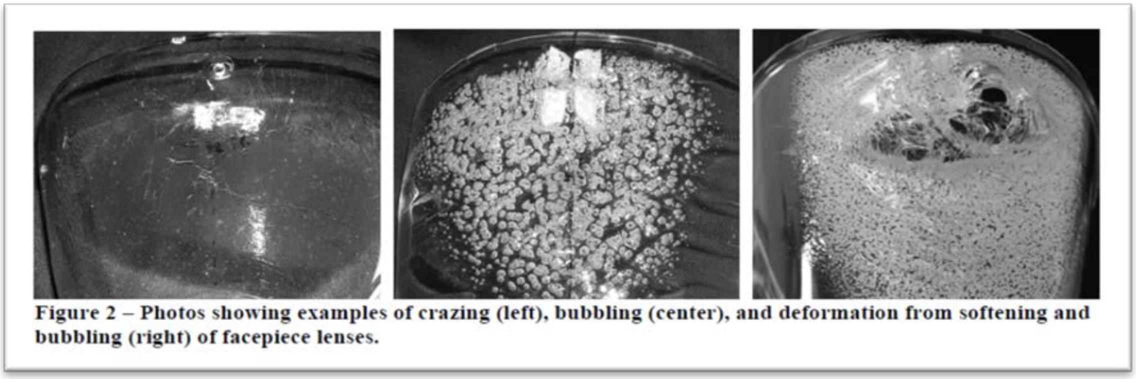


Figure 2 – Photos showing examples of crazing (left), bubbling (center), and deformation from softening and bubbling (right) of facepiece lenses.

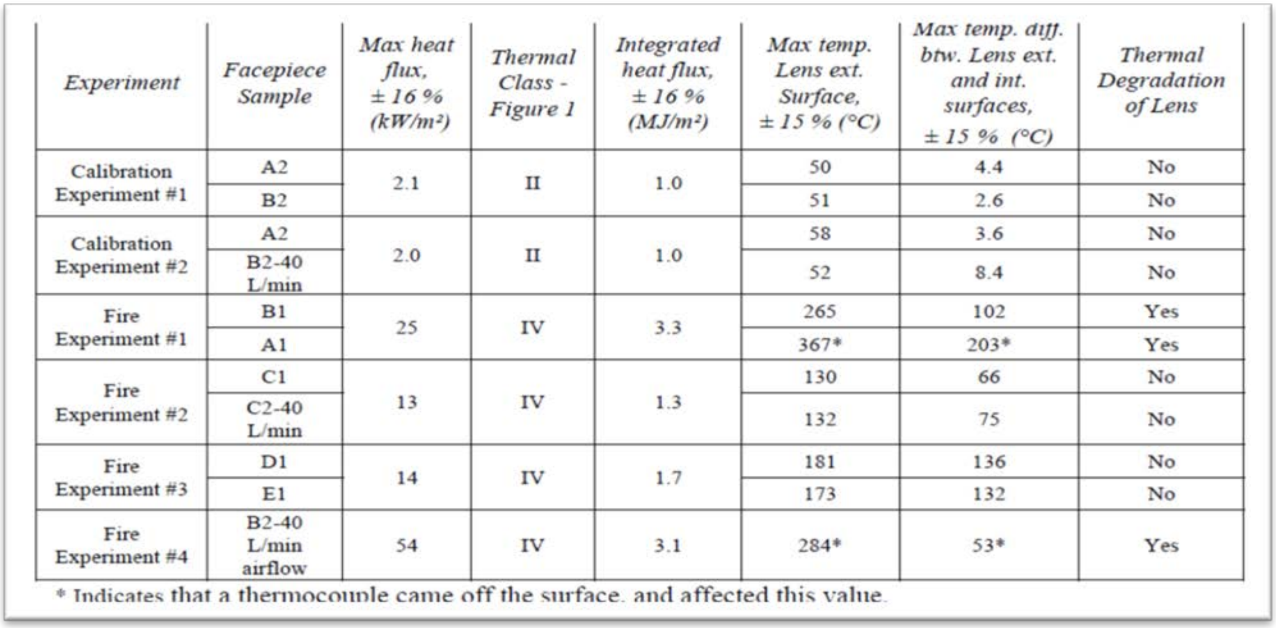
Figure 6: Thermal Degradation

Tests were carried out in the Fire Laboratory on the Worcester Polytechnic Institute campus. The tests consisted of polycarbonate and polyethersulfone plaques being exposed to a radiant heat flux generated by the cone calorimeter [5]. The radiant heat tests were carried out at the product level to test the thermal capabilities of the two materials. There were two variations of each material tested. The plaques were made of an uncoated polycarbonate, polycarbonate coated with a Siloxane based UV cured Acrylate, uncoated Polyethersulfone, and Polyethersulfone coated with a Siloxane based thermal cured hard coat. The two coated materials were coated and prepared in accordance with regulations by the plastics manufacturer and were in the format that is used in commercial SCBA facepieces.

The radiant heat flux test was performed to determine the heat flux levels and temperature limits that the polycarbonate and polyethersulfone materials can endure with and without coatings. The apparatus consisted of a cone calorimeter, a heat flux gauge, k type thermocouples, and a data acquisition system. Two plaques of uncoated polycarbonate with dimensions 4cm x 4cm x 0.2cm were used. Three plaques of coated polycarbonate with dimensions 4cm x 4cm x 0.2cm were used. Two plaques of uncoated polyethersulfone with dimensions 4cm x 4cm x 0.2cm were used. And finally, three plaques of coated polyethersulfone of dimensions 5cm x 3.5cm x 0.2cm that slightly concave down were used (See Appendix A).

Each test specimen was prepared by attaching thermocouples to the center plane surface of the material using aluminum tape (See Appendix A). The thermocouple was shaped and manipulated so that the bead sat in the correct position. This setup procedure was modeled off of the procedure used in the experiments carried out and reported in NIST Technical Note 1724.

The tests were performed at three different heat flux levels. The first level, low, was chosen to be 10kW/m^2 because it was lower than any of the heat fluxes where failure occurred that was reported in NIST Technical Note 1724 (Figure 7). The second level, medium, was chosen to be 15kW/m^2 which is the heat flux that the 2013 edition of NFPA 1981 (7.21) will be using in the Lens Radiant Heat Resistance Performance test. The final level, high, was selected to be 20kW/m^2 which was chosen to be a heat flux that we would expect just prior to and during flashover [7].



Experiment	Facepiece Sample	Max heat flux, ± 16 % (kW/m^2)	Thermal Class - Figure 1	Integrated heat flux, ± 16 % (MJ/m^2)	Max temp. Lens ext. Surface, ± 15 % (°C)	Max temp. diff. btw. Lens ext. and int. surfaces, ± 15 % (°C)	Thermal Degradation of Lens
Calibration Experiment #1	A2	2.1	II	1.0	50	4.4	No
	B2				51	2.6	No
Calibration Experiment #2	A2	2.0	II	1.0	58	3.6	No
	B2-40 L/min				52	8.4	No
Fire Experiment #1	B1	25	IV	3.3	265	102	Yes
	A1				367*	203*	Yes
Fire Experiment #2	C1	13	IV	1.3	130	66	No
	C2-40 L/min				132	75	No
Fire Experiment #3	D1	14	IV	1.7	181	136	No
	E1				173	132	No
Fire Experiment #4	B2-40 L/min airflow	54	IV	3.1	284*	53*	Yes

* Indicates that a thermocouple came off the surface, and affected this value.

Figure 7: NIST Summary

The experimental procedure consisted of adjusting the cone calorimeter to 10kW/m^2. This was done by placing a Schimdt-Boelter water cooled heat flux gauge, which has the accuracy of ±1kW/m^2, 1 inch away from the heating coils where the sample would be positioned. Once the heating cell reached the desired heat flux, the shutter was placed in front of the heat source and the polycarbonate plaque was mounted onto the load cell of the cone calorimeter. The shutter was then removed and the plaque was exposed to the heat flux for 5 minutes. The time to failure and temperature of the surface at failure was recorded. The experiment was repeated 3 times for the coated samples and 2 times for the uncoated samples to reduce the error and uncertainty. The process was then carried out for the previously specified medium and high heat flux levels. Note the same experimental procedure was carried out for each of the four materials.

Results and Discussion

The failure criteria for all the tests were characterized by crazing, bubbling, or melting of the samples. The times at which each sign of failure was observed were recorded. When bubbling occurred in the materials this was considered failure. During the radiant heat flux tests all of the samples failed well before the end of the five minute test period. This was found for each of the three heat flux levels 10 kW/m^2, 15 kW/m^2, and 20 kW/m^2. The samples were kept under the radiant heat source until the end of the five minutes to see if the failure criteria would compound and if a more severe thermal degradation, such as a large hole forming in the material, would occur.

For each test that was carried out the first sign of failure that occurred was crazing on the surface of the sample. Next, usually within approximately 2-5 seconds, small bubbles would start to form in the sample. The bubbles usually began to form in the center of the plaque until eventually it would spread outward. This was attributed to the fact that the heating coil of the cone calorimeter is in a circular shape and the plaque was centered underneath the heating coil.

Bubbling such as in Figures 8 & 9 was considered failure. It should be noted that deformation occurred within 10 seconds of the first sign of bubbles on the samples. Note Figures 8 & 9 illustrates failure at 10kW/m^2. The formation of bubbles on the center of the polyethersulfone is attributed to the slight concave down shape, in addition to the heating coil located above the sample.

Figure 8: Polycarbonate Failure

Figure 9: Polyethersulfone Failure

Observations during Testing

The polycarbonate plaque samples typically stayed a clear color through the duration of the test, for each test that was carried out. Tests were carried out for uncoated and coated polycarbonate at the three heat flux levels previously stated. The bubbles created interference if trying to view something while looking through the plaque after the test was complete, but the object would still be visible and discernible. The surface of the samples did bubble slightly outward but collapsed back to a generally flat form by the end of the five minute test.

When the coated polycarbonate samples were tested it was possible to see the coating separate from the surface of the polycarbonate material and move to the corners of the plaque. During the 20 kW/m^2 test the coating failed even more so because it separated to the corners of the material and then seemed to degrade, becoming a dark brown color. The polycarbonate substrate also failed in each of the tests, depicted by crazing and bubbling of the material. The bubbling in the polycarbonate substrate would begin in the center of the plaque and move out towards the edges, but the material was still clear. This happened in each of the tests that were carried out.

In each level of tests 10 kW/m^2, 15 kW/m^2, and 20 kW/m^2 the polycarbonate plaque started to soften. This could be seen because the plaque, with a surface area slightly larger than that of the holding plate, would curve downward and mold to the face and sides of the holding plate. This happened most in the 15 kW/m^2 and 20 kW/m^2 tests. In the 20 kW/m^2 tests the samples would stick to the glove, of the individual carrying out the test, even five minutes after the test was complete.

When the tests were carried out using the polyethersulfone plaques the observed effects were slightly different. When tested crazing and bubbling did occur, however the bubbling was different in the polyethersulfone than the bubbling that occurred in the polycarbonate material. In the polyethersulfone the bubbling still began in the center and spread outward. During the 10 kW/m^2 tests the bubbling stayed in the center of the plaque; however the bubbling extended to the edges of the plaques for the 15 kW/m^2 and 20 kW/m^2 tests.

The bubbling of the material seemed to happen in layers. The center of the material bubbled and then bubbles formed on top of that layer, and this happened continually until almost all of the plaque, excluding the edges, consisted of bubbled material. The material would also bubble outward and form a mound of sorts in the center of the top face of the plaque. As the test wore on the bubbles would burst, emitting an audible popping sound and new bubbles would appear. Polyethersulfone also becomes a murky yellow-white color when it fails, this was said to be due to the absorption of moisture. After failure occurred it was very difficult to see through the polyethersulfone plaque.

Observations after Testing

The uncoated samples portrayed the expected behaviors that correspond to the material properties of polycarbonate and polyethersulfone. For the low heat flux polycarbonate failed on average of 11°F higher than the polyethersulfone however even though the temperature of failure was lower the average time to failure was 110 seconds greater for the polyethersulfone. For the medium heat flux the polyethersulfone failed on average of 28°F higher than the polycarbonate and the time to failure was greater by 107 seconds. For the high heat flux the temperature of failure for polyethersulfone was greater on average by 51°F and the time to failure on average was greater by 55 seconds. Figure 12 & 13 compares the average temperature and time of failure for uncoated polycarbonate and uncoated polyethersulfone.

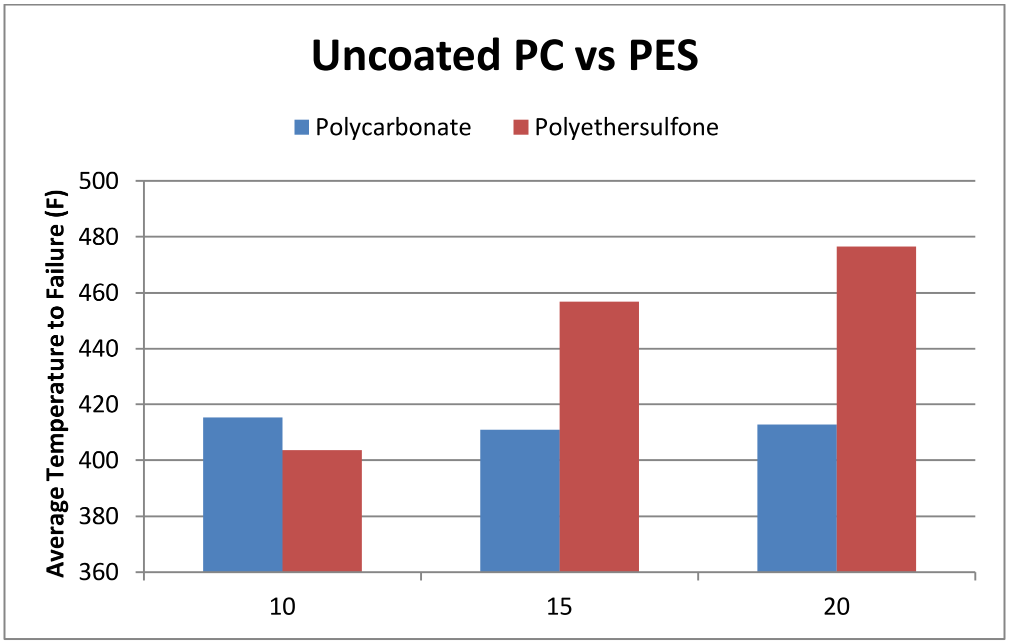


Figure 10: Uncoated PC vs PES

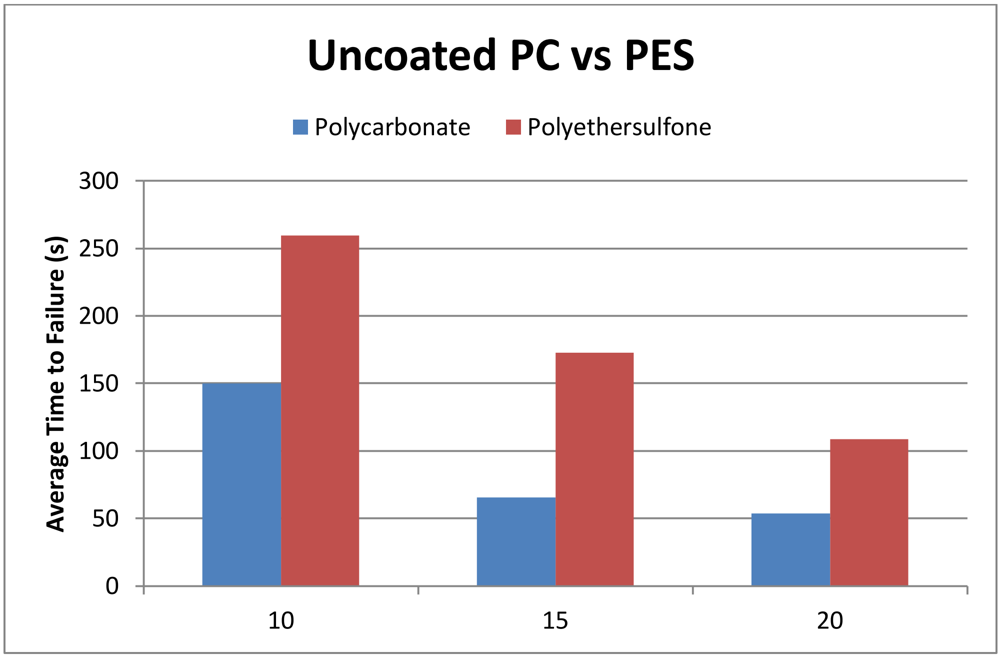


Figure 11: Uncoated PC vs PES

The results suggest that polyethersulfone does indeed possess some superior material properties when compared to polycarbonate but when both materials are coated their intrinsic properties are no longer a measure of how the materials perform when exposed to fire environments. On average the uncoated polyethersulfone fails at a higher time and temperature than the uncoated polycarbonate. The application of coatings to the polycarbonate plaques were able to increase the average failure temperatures by 16°F for low heat flux, 34°F for medium heat flux and 70°F for high heat flux. In comparison the application of coatings for polyethersulfone did not show much change for a low and high heat flux but for the medium heat flux it was able to increase the temperature by 19°F. This suggests that the coatings have more of an impact for the polycarbonate because there is still a limit to the amount of protection which the coatings offer.

The coated samples for polycarbonate and polyethersulfone had the same fundamental behavior when exposed to all the three levels of radiant energy. At a low heat flux the polycarbonate sample failed on average 30°F higher than the polyethersulfone sample. At a medium heat flux the polyethersulfone failed on average 30°F higher than the polycarbonate sample. At a high heat flux both materials failed at approximately the same temperature with the polycarbonate failing at only 3°F higher than the polyethersulfone.

Likewise the times to failure of both materials were similar for the coated samples at all three heat fluxes. The time to failure was higher on average by 11 seconds for the low heat flux. For the medium heat flux the time to failure was higher on average by 4 seconds for polycarbonate. And for the high heat flux the polycarbonate average time to failure was higher by only 1 second. This similarity suggests that the material coatings trump the shortcomings of the material properties of polycarbonate. Failure occurred at approximately the same time and temperature for both materials even though polycarbonate has a lower heat deflection and melting temperature than polyethersulfone.

Therefore at the low heat flux polycarbonate performed better than polyethersulfone. At a medium heat flux polyethersulfone performed better than polycarbonate. And at a high heat flux both materials behaved the same. Figure 10 & 11 compares the average temperature and time of failure for coated polycarbonate and coated polyethersulfone.

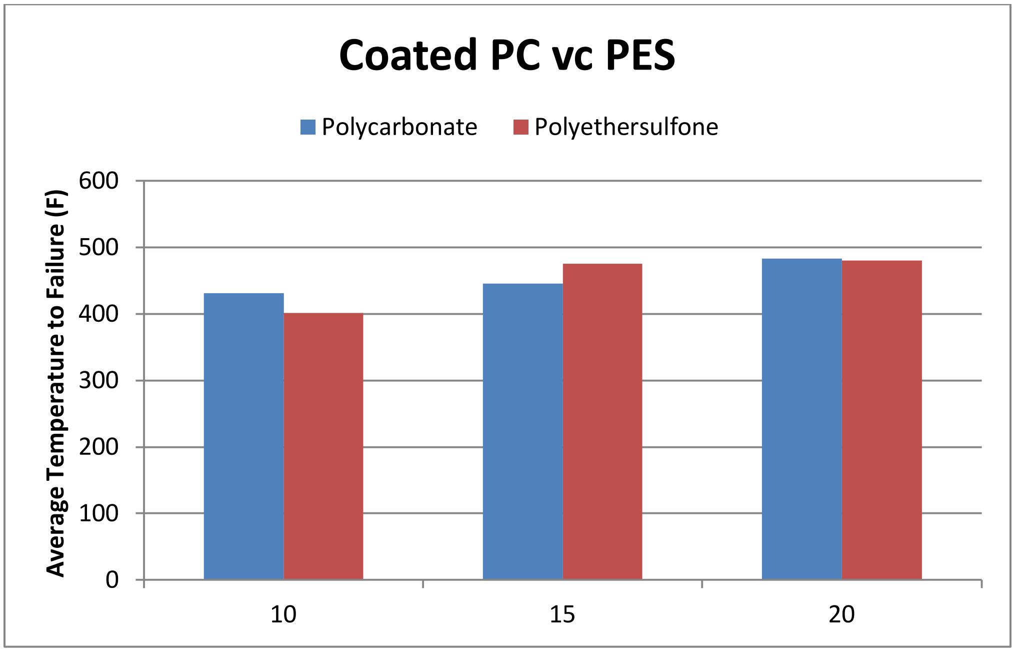


Figure 12: Coated PC vs PES

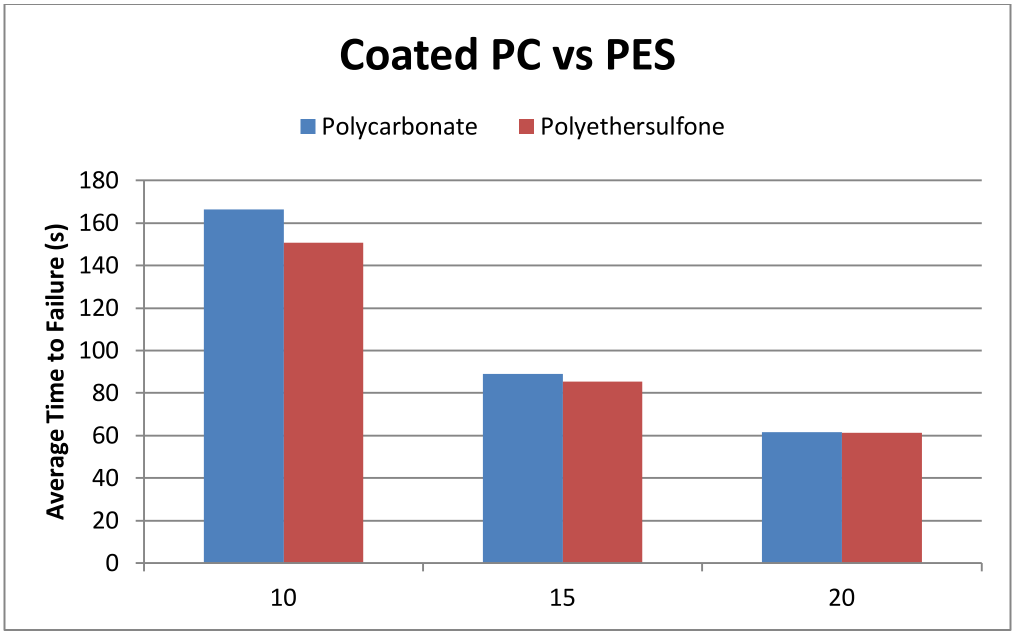


Figure 13: Coated PC vs PES

Summary

Note that (*) indicates where the thermocouple slightly came of the surface of the polycarbonate due to the material melting causing the bead of the thermocouple to slightly rise in an upward direction.

Heat Flux (kW/m^2)	Test	Time Uncoated (s)	Time Coated (s)	Temperature Uncoated (°F)	Temperature Coated (°F)
10	1	150	168	405	432
	2	150	163	403	428
	3	-	168	-	433
15	1	65	93	424	480
	2	66	94	397	493
	3	-	80	-	363*
20	1	55	60	413	513
	2	52	60	412	426*
	3	-	65	-	511

Table 1: Polycarbonate Unoated and Coated

Heat Flux (kW/m^2)	Test	Time Uncoated (s)	Time Coated (s)	Temperature Uncoated (ºF)	Temperature Coated (ºF)
10	1	279	152	405	414
	2	240	154	403	421
	3	-	146	-	369*
15	1	132	84	453	455
	2	126	87	460	473
	3	-	85	-	498
20	1	80	62	473	441
	2	73	60	480	531
	3	-	62	-	469

Table 2: Polyethersulfone Uncated and Coated

Figure 14 shows the relationship between heat flux and temperature for polycarbonate coated. The values where the thermocouple slightly came off were removed and the least square values suggest a good fit and repeatability. The blue line indicates the heat deflection temperature of polycarbonate at 184°F and the red line indicates the melting temperature of 513°F. It was proven that the application of coatings allowed polycarbonate to withstand temperatures over its heat deflection but the coatings failed before the melting temperature and this caused the material to lose all of its integrity.

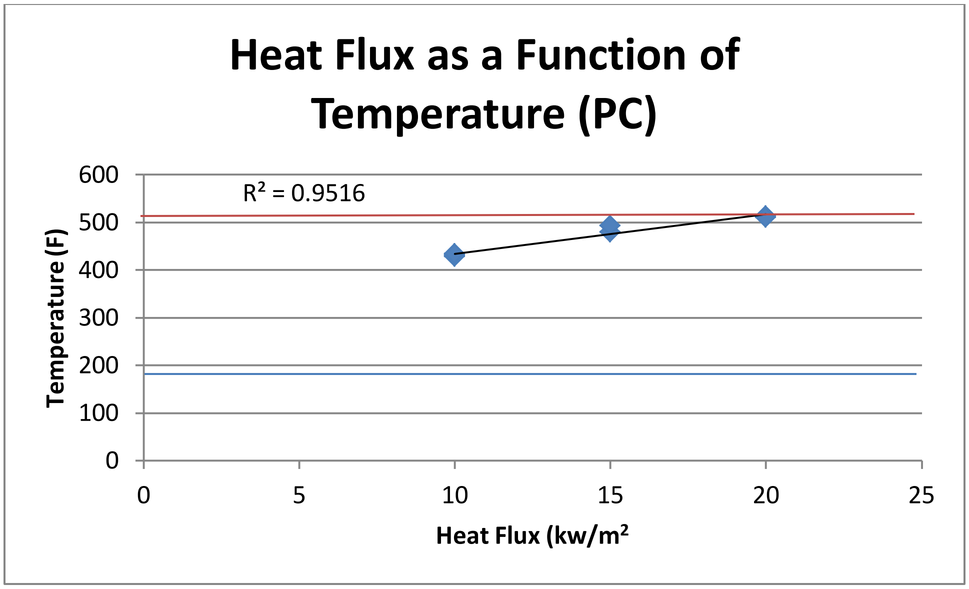


Figure 14: Heat Flux and Temperature

Conclusion

Overall the data presents conservative limits just before thermal degradation of polycarbonate and polyethersulfone for different heat fluxes. In the NIST study they concluded that thermal degradation usually occurred at heat fluxes of 20kW/m^2. Our data confirms this with a time to failure of around 1 minute for both materials when exposed to a high heat flux. However, it also showed that enough exposure to lower heat fluxes could cause thermal degradation. Product level materials testing have demonstrated that the application of coatings make a significant difference, even more so when using polycarbonate. There is a possibility that the polyethersulfone, with the right coatings applied, may be a better match for the requirements that the fire service provides. However, the coating used on the polycarbonate accounted for the lower heat deflection and it was able to perform similar to polyethersulfone and simply replacing the lens material may not be the direct solution for eliminating the weakest link of the SCBA.

Recommendations

We recommend further testing of the two materials, polycarbonate and polyethersulfone. Due to limited time and the availability of testing materials we were unable to carry out a large number of tests. It would be helpful to conduct the same test more than 3 times to receive more data and lower the uncertainty of the results. Further testing would also reinforce the fact that the test may be reproduced.

Further research and development of coatings is also needed to help with the thermal deflection and other qualities of the materials used in SCBA facepiece lenses would be of use to the industry. In other countries metallic coatings, such as gold, are being applied to the lenses to help with this. Finding a coating that would increase the capabilities of the lens and also be cost effective would be of great help to the fire service.

Research and testing focusing on the visual acuity of polycarbonate and polyethersulfone in different situations may also be helpful. One of the main reasons that polyethersulfone is not currently being used in the United States is because it does not pass the visual acuity test due to a slight yellow tint to the material. The visual of the acuity through the materials once the first signs of failure, crazing and bubbling, would be another area to study. This data and information could be a key component to a firefighter reaching safety if he or she notices the beginning of the failure of the lens while in a hazardous environment.

Further testing of the materials at the system level, in the full facepiece assembly, is of great importance. The data found in our tests was at the product level, testing only the material plaques. When the lens is housed in the full facepiece assembly it will be reinforced by the rest of the components which may also absorb heat and delay failure.

Tests should be carried out using a breathing dummy, to provide a positive pressure in the facepiece during testing, and without. The information and data collected can be used to determine whether or not the positive pressure, used by firefighters in a hazardous environment, has a part in the failure or delay of failure of the SCBA facepiece lens.

The National Fire Protection Association currently has a Technical Committee reviewing the NFPA 1981: Standard on Open Circuit Self-Contained Breathing Apparatus for Emergency Services. The Technical Committee is determining whether changes should be made to the testing segment of the standard, and what those changes should be. When the new testing standard is available to researchers SCBA facepieces with lenses of polycarbonate, and also polyethersulfone, should be tested to the new standard to see if the current materials and design will pass.

Appendix A: Set Up and Samples

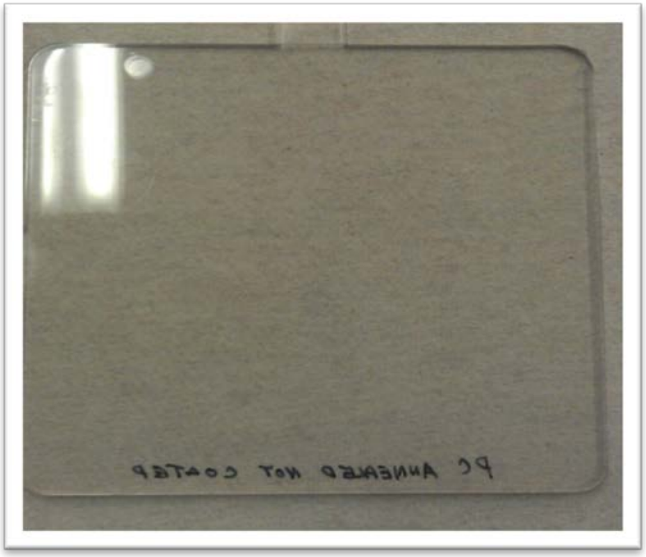


Figure 15: Polycarbonate Plaque

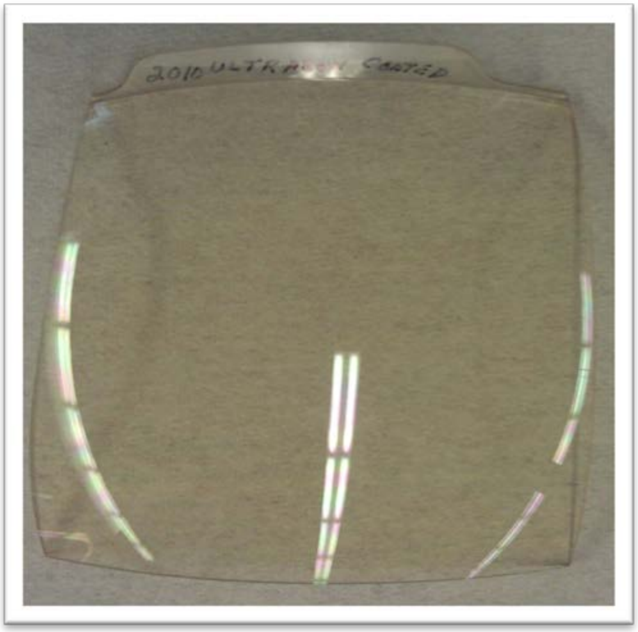


Figure 16: Polyethersulfone Plaque

Figure 17: Thermocouple Attached to Center of Plaque

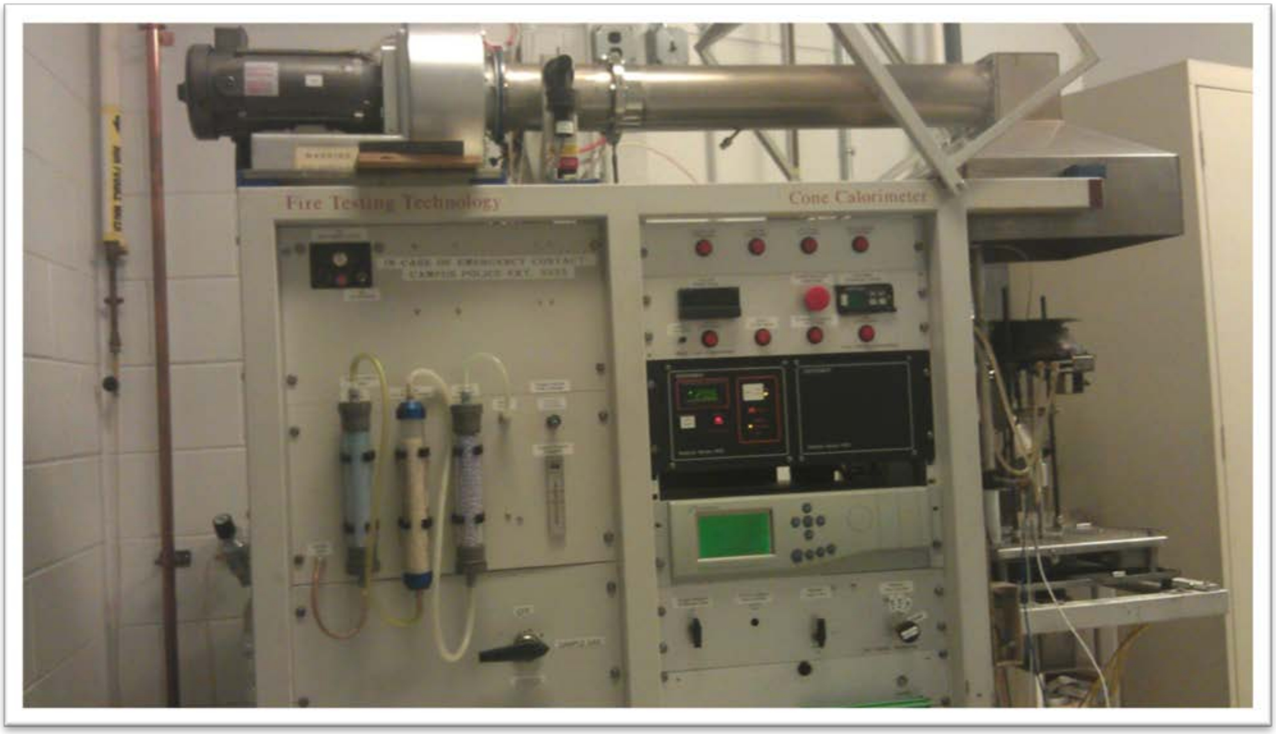


Figure 18: Cone Calorimeter Set Up for Radiation Tests

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