NASA/TM—2019-220063

Rehydration Data for the Materials International Space Station Experiment (MISSE) Polymer Films

Kim K. de Groh
Glenn Research Center, Cleveland, Ohio

Catherine E. McCarthy and Kshama M. Girish
Hathaway Brown School, Shaker Heights, Ohio

Bruce A. Banks
Science Applications International Corporation, Cleveland, Ohio

Carolyn Kaminski, Erica E. Youngstrom, Maura Lillis, Christiane A. Youngstrom,
Anne M. Hammerstrom, Stephanie Hope, and Laura M. Marx
Hathaway Brown School, Shaker Heights, Ohio

February 2019

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM—2019-220063

Rehydration Data for the Materials International Space Station Experiment (MISSE) Polymer Films

Kim K. de Groh
Glenn Research Center, Cleveland, Ohio

Catherine E. McCarthy and Kshama M. Girish
Hathaway Brown School, Shaker Heights, Ohio

Bruce A. Banks
Science Applications International Corporation, Cleveland, Ohio

Carolyn Kaminski, Erica E. Youngstrom, Maura Lillis, Christiane A. Youngstrom,
Anne M. Hammerstrom, Stephanie Hope, and Laura M. Marx
Hathaway Brown School, Shaker Heights, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

February 2019

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

Rehydration Data for the Materials International Space Station Experiment (MISSE) Polymer Films

Kim K. de Groh
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Catherine E. McCarthy and Kshama M. Girish
Hathaway Brown School
Shaker Heights, Ohio 44122

Bruce A. Banks
Science Applications International Corporation
Cleveland, Ohio 44135

Carolyn Kaminski, Erica E. Youngstrom, Maura Lillis, Christiane A. Youngstrom,
Anne M. Hammerstrom, Stephanie Hope, and Laura M. Marx
Hathaway Brown School
Shaker Heights, Ohio 44122

Abstract

Atomic oxygen erosion of polymers in low Earth orbit (LEO) poses a serious threat to spacecraft performance and durability. Forty thin film polymer and pyrolytic graphite samples, collectively called the PEACE (Polymer Erosion and Contamination Experiment) Polymers, were exposed to the LEO space environment on the exterior of the ISS for nearly four years as part of the Materials International Space Station Experiment 1 & 2 (MISSE 1 & 2) mission. The purpose of the MISSE 2 PEACE Polymers experiment was to determine the atomic oxygen (AO) erosion yield (E_y, volume loss per incident oxygen atom) of a wide variety of polymers exposed to the LEO space environment. The E_y values were determined based on mass loss measurements. Because many polymeric materials are hygroscopic, the pre-flight and post-flight mass measurements were obtained using dehydrated samples. To maximize the accuracy of the mass measurements, obtaining dehydration data for each of the polymers was desired to ensure that the samples were fully dehydrated before weighing. A comparison of dehydration and rehydration data showed that rehydration data mirrors dehydration data, and is easier and more reliable to obtain. Tests were also conducted to see if multiple samples could be dehydrated and weighed sequentially. Rehydration curves of 43 polymers and pyrolytic graphite were obtained. This information was used to determine the best pre-flight, and post-flight, mass measurement procedures for the MISSE 2 PEACE Polymers experiment, and for subsequent NASA Glenn Research Center MISSE polymer flight experiments.

Introduction

Spacecraft orbiting the Earth in the low Earth orbit (LEO) environment (between about 180 and 650 km) endure harsh environmental exposure conditions, including ultraviolet, x-ray and charged particle radiation, micrometeoroids and orbital debris and exposure to atomic oxygen (AO). Atomic oxygen erosion of polymers in LEO poses a serious threat to spacecraft performance and durability. Therefore in order to design high-performance durable spacecraft systems, it is essential to understand the AO erosion yield (E_y, the volume loss per incident oxygen atom, in cm^3/atom) of polymers being considered for spacecraft applications.

Forty-one different thin film polymer samples, collectively called the PEACE (Polymer Erosion and Contamination Experiment) Polymers, were exposed to the LEO space environment on the exterior of the International Space Station (ISS) for four years as part of the Materials International Space Station Experiment 1 & 2 (MISSE 1 & 2) mission (Refs. 1 and 2). The MISSE 2 PEACE Polymers experiment was flown in sample tray E5 on the Passive Experiment Carrier 2 (PEC 2) Tray 1, which was flown in a ram facing flight orientation. Figure 1 is a photograph of MISSE PEC 2 being attached to the ISS Quest Airlock during an extravehicular activity (EVA). The MISSE 2 PEACE Polymers tray is visible in this photograph. Figure 2 is a photograph of the Quest Airlock showing the location of MISSE PEC 2. The purpose of the experiment was to determine the AO E_y of a wide variety of polymers exposed to the LEO space environment (Refs. 1 and 2). Figure 3 provides pre-flight and post-flight photos of the PEACE Polymers experiment in the E5 flight tray. Extensive AO erosion and color changes can be seen in the majority of polymers after four years of space exposure.

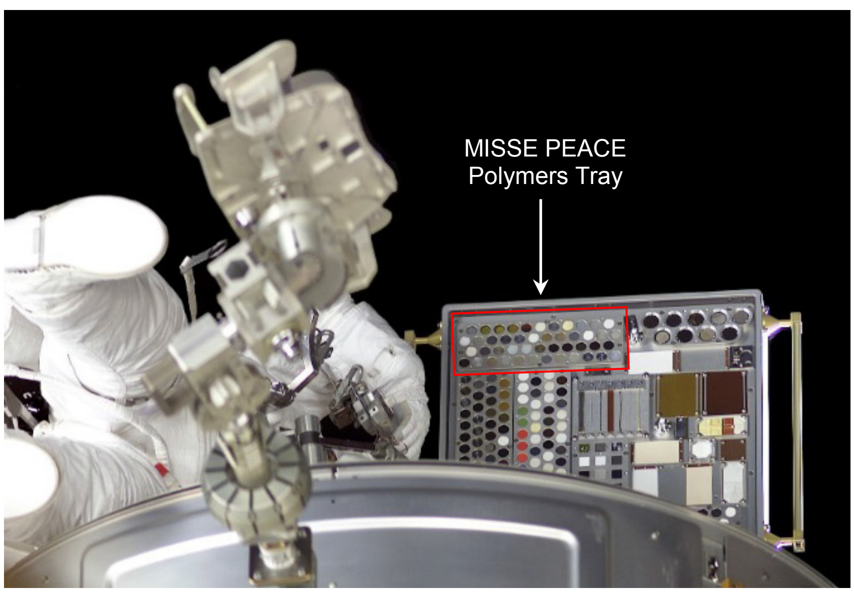


Figure 1. During a spacewalk on August 16, 2001, astronaut Patrick Forrester installs MISSE PEC 2 on the ISS Quest Airlock.

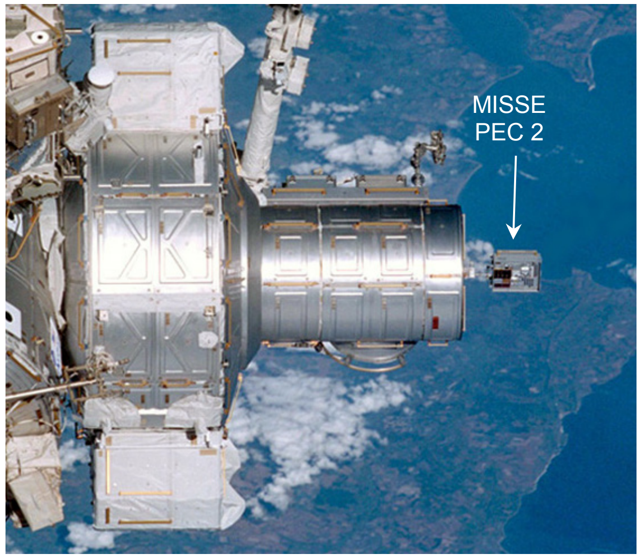
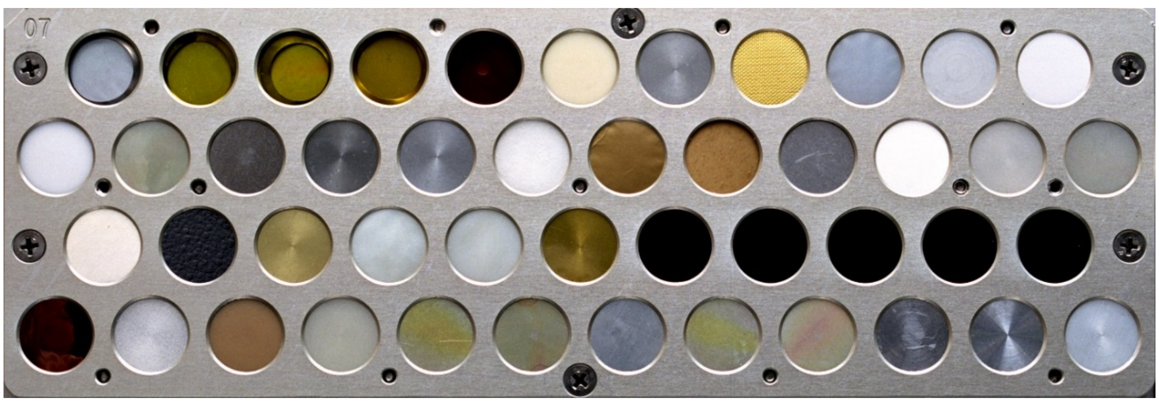
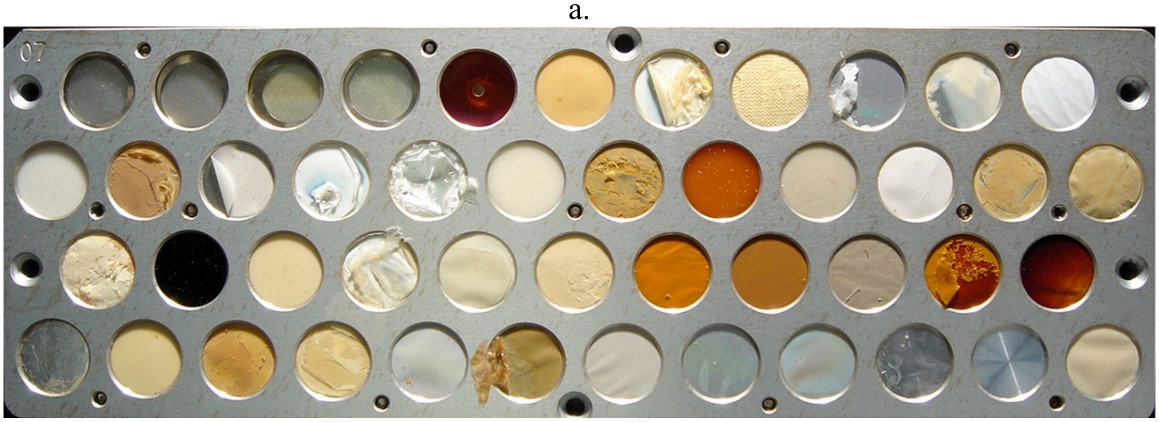


Figure 2. Photograph of the Quest Airlock and MISSE PEC 2 taken during the STS-105.



a.



b.

Figure 3. MISSE 2 PEACE Polymers experiment tray: a). Pre-flight, and b). Post-flight.

The MISSE 2 PEACE Polymers experiment E_y values were determined based on mass loss measurements. Because many polymeric materials are hygroscopic and can undergo dramatic increase in mass with moisture (depending on thickness, temperature and humidity), the pre-flight and post-flight mass measurements were obtained using dehydrated samples. To ensure the polymers were in a fully dehydrated state before weighing, studies were conducted to characterize the hygroscopic nature of each polymer.

Ideally, it was believed that dehydration curves would be best to obtain because the goal was to verify samples were fully dehydrated prior to obtaining their mass. But, to obtain a dehydration curve a sample needs to be moved in and out of the vacuum chamber for each time-based mass data point. This makes it difficult, and time consuming, to accurately measure the time needed to fully dehydrate a polymer. Because rehydration should approximately mirror the dehydration process, a dehydration versus rehydration test was conducted. Based on results of the dehydration vs. rehydration test, rehydration curves were obtained for each of the PEACE polymers. The purpose of the rehydration curves was to characterize the hygroscopic nature of each polymer – specifically, to determine the amount of moisture each of the samples would take on, and how quickly. This information was used to determine the best pre-flight and post-flight mass procedures for the MISSE 2 PEACE Polymers experiment and following MISSE flight experiments.

Material and Procedures

PEACE Polymers

The polymers characterized for rehydration included 41 polymers flown in the MISSE 2 PEACE Polymers experiment (Refs. 1 and 2), along with three additional polymers (cellulose nitrate (CN), polyvinylidene chloride (PVDC) and ultra-high molecular weight polyethylene (UHMWPE)). The MISSE flight ID, polymer material, trade name, abbreviation and film thickness for the polymers are provided in Table 1. The samples, for both the hydration tests and the flight samples, were cut into 1-inch circles from sheets of film using a double bow punch cutter and an Arbor press.

Sample Dehydration and Mass

Samples were dehydrated in a vacuum desiccator at room temperature and maintained at a pressure of 8.0 - 13.3 Pa (60-100 mTorr) with a mechanical roughing pump. Because the actual minimum time needed for dehydration of each polymer was unknown, samples were placed in the vacuum desiccators for a minimum of four days (96 hours), which was believed to be sufficient to allow complete dehydration of the samples. All testing was conducted at room temperature. Mass measurements for the majority of samples were taken using a Mettler M3 balance (± 10 μg). For the heavier samples, such as pyrolytic graphite, a Sartorius balance (± 50 μg) was used.

Table 1. Materials Characterized for Rehydration Mass.

MISSE 2 Serial #	Material	Abbreviation	Trade Name(s)	Thickness (mils)
2-E5-6	Acrylonitrile butadiene styrene	ABS	Cycolac, Absylux	5
2-E5-7	Cellulose acetate	CA	Clarifoil, Tenite Acetate, Dexel	2
2-E5-8	Poly-(p-phenylene terephthalamide)	PPDT	Kevlar 29 fabric	2.2
2-E5-9	Polyethylene	PE	Polyethylene	2
2-E5-10	Polyvinyl fluoride	PVF	Tedlar TTR10SG3 (clear)	1
2-E5-11	Crystalline polyvinylfluoride w/white pigment	PVF-W	White Tedlar TWH10BS3	1
2-E5-12	Polyoxymethylene; acetal; polyformaldehyde	POM	Delrin, Acetal (natural)	10
2-E5-13	Polyacrylonitrile	PAN	Barex 210	2
2-E5-14	Allyl diglycol carbonate	ADC	CR-39, Homalite H-911	31
2-E5-15	Polystyrene	PS	Trycite 1000	2
2-E5-16	Polymethyl methacrylate	PMMA	Plexiglas, Acrylite (Impact Mod.)	2
2-E5-17	Polyethylene oxide	PEO	Alkox E-30 (powder)	29
2-E5-18	Poly(p-phenylene-2 6-benzo-bisoxazole), Balanced biaxial film	PBO	Zylon	1
2-E5-19	Epoxide or epoxy	EP	Hysol EA 956	88-92
2-E5-20	Polypropylene	PP	Contour 28	20
2-E5-21	Polybutylene terephthalate	PBT	Valox 357	3
2-E5-22	Polysulfone	PSU	Thermalux P1700, Udel P-1700	2
2-E5-23	Polyurethane	PU, PUR	Dureflex PS8010	2
2-E5-24	Polyphenylene isophthalate	PPPA	Nomex Crepe Paper T-410	2
2-E5-25	Pyrolytic graphite	PG	Pyrolytic Graphite	80
2-E5-26	Polyetherimide	PEI	Ultem 1000	10
2-E5-27	Polyamide 6	PA 6	Nylon 6	2
2-E5-28	Polyamide 66	PA 66	Nylon 66	2
2-E5-29	Polyimide (Clear)	PI	CP1	3
2-E5-30 & 2-E5-33	Polyimide (PMDA)	PI	Kapton H	5
2-E5-31	Polyimide (PMDA)	PI	Kapton HN	5
2-E5-32	Polyimide (BPDA)	PI	Upilex-S	1
2-E5-34	High temperature polyimide resin	PMR-15	PMR-15	12-14
2-E5-35	Polybenzimidazole	PBI	Celazole	2
2-E5-36	Polycarbonate	PC	PEEREX 61	10
2-E5-37	Polyetheretherketone	PEEK	Victrex PEEK 450	3
2-E5-38	Polyethylene terephthalate	PET	Mylar A-200	2
2-E5-39	Chlorotrifluoroethylene	CTFE	Kel-f, Neoflon M-300	5
2-E5-40	Ethylene-chlorotrifluoroethylene	ECTFE	Halar 300	3
2-E5-41	Tetrafluorethylene-ethylene copolymer	ETFE	Tefzel ZM	3
2-E5-42	Fluorinated ethylene propylene	FEP	Teflon FEP 200A	2
2-E5-43	Polytetrafluoroethylene	PTFE	Chemfilm DF 100	2
2-E5-44	Perfluoroalkoxy	PFA	Teflon PFA 200 CLP	2
2-E5-45	Amorphous fluoropolymer	AF	Teflon AF 1601	2
2-E5-46	Polyvinylidene fluoride	PVDF	Kynar 740	3
N/A	Cellulose nitrate	CN	Cellulose Nitrate	5
N/A	Polyvinylidene chloride	PVDC	Saran	2
N/A	Ultra-high molecular weight polyethylene	UHMWPE	Polyethylene	10

Open-Close Trials

Because of time constraints, it was not practical to dehydrate one sample in the desiccator for four days prior to weighing (to generate a rehydration curve), and then wait an additional four days before dehydrating and weighing the next sample. Therefore, it was desired to know if several samples could be placed in the desiccator and weighed sequentially (i.e., without waiting four days before weighing the next sample), assuming the desiccator was immediately put back under vacuum once one sample was removed. In theory, opening and closing the desiccator several times could cause the polymers in the desiccator to absorb some moisture and not be fully dehydrated when they were weighed for generation of rehydration curves. Therefore, a separate experiment was conducted to determine if opening and closing the desiccator affected the state of rehydration of the polymers. These tests were called the "Open-Close Trials" and they were conducted using a single 2 mil thick (50.8 μm) Kapton HN sample. Kapton HN was chosen for the Open-Close Trials because Kapton can gain up to 4% of its mass with moisture (Ref. 3).

The Open-Close Trials were conducted in five separate tests (trials). In the first trial, the Kapton HN sample was placed in the desiccator and allowed to dehydrate for four days. The desiccator was opened and the sample was removed and a rehydration curve was obtained with mass measurements taken after approximately 2, 3, 5, 10, 20, 30 and 60 minutes of air exposure. This is the ideal rehydration procedure. The sample was then returned to the desiccator and dehydrated for four days. For Trial 2, the desiccator was opened and closed five times, at approximately 11 minute intervals, to simulate removal of five samples. The 11 minute intervals allowed the desiccator to pump down to 20 Pa (150 mTorr) or less. Then the desiccator was opened again (for the 6^{th} time), the sample removed, and the sample was periodically weighed to generate a rehydration curve. The process of obtaining rehydration curves after opening and closing the desiccator six times was repeated 3 additional times (Trials 3, 4 and 5) and the data was graphed for each trial. These curves were then compared to the curve of the sample when it was removed immediately (Trial 1).

Rehydration Data

The samples were placed in a vacuum desiccator maintained at a pressure of 60-100 mTorr with a mechanical roughing pump, and dehydrated for a minimum of four days. Once a sample was ready to be weighed, it was removed from the desiccator and the desiccator was immediately put back under vacuum to ensure that remaining samples returned to a fully-dehydrated state. The exact times that the desiccator was opened and closed were recorded.

Mass measurements were taken of each polymer sample eight times (or more if needed) after increasingly long time intervals, for example after 1, 2, 3, 8, 18, 38, 68 and 128 minutes. The time was measured from the time air was initially allowed to flow into the desiccator (it took about 50 seconds for the desiccator to get to atmospheric pressure). Each data point on the curve represents the average of three measurements taken starting at the time recorded. The balance was re-zeroed between each measurement to ensure accuracy for every set of measurements. The temperature and humidity in the laboratory were noted for each hydration data set.

Data that was documented included the time it took to get to a fully hydrated mass, the total mass gain (in mg) and the percent of mass increase for each polymer. The highest point on the rehydration curve was used as the final mass, and the initial mass was determined by back-extrapolating the first three mass readings to time zero to get a theoretical fully-dehydrated mass. An example of a linear back extrapolation is provided in Figure 4. The percent mass increase was calculated from the initial (back-extrapolated) and final mass values.

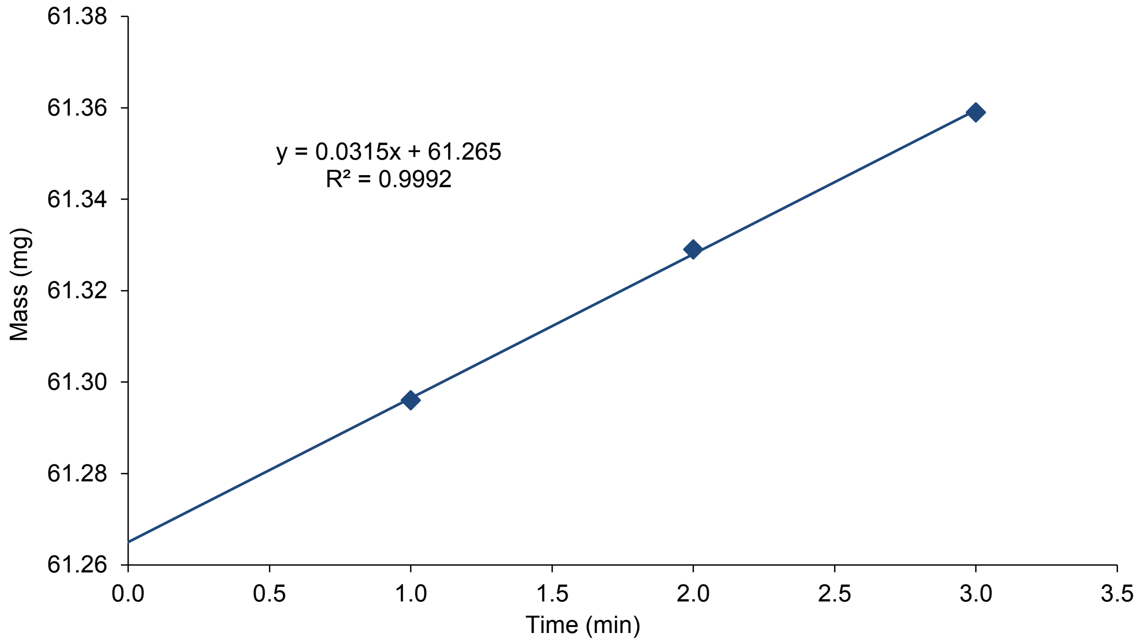


Figure 4. Kapton H (2-E5-30) linear back extrapolation.

Dehydration Data

To verify that a rehydration curve approximates a dehydration curve, 2 mil thick Kapton HN was used for a dehydration-rehydration comparison. To obtain a dehydration curve, eight one-inch diameter samples of Kapton HN were cut from a sheet of film using a bow-punch and an arbor press. The mass for each sample was obtained by taking three mass measurements and averaging the data. This was the mass value for the sample with zero time in the desiccator (Sample 1). Then Sample 2 was placed into the desiccator and left under vacuum for 1 minute. It was then removed and weighed (an average of 3 readings) to obtain a 1 minute dehydration mass. Additional samples were placed in the desiccator and then removed and weighed after 2, 7, 17, 37, 67, and 127 minutes. The change in mass from the original, non-dehydrated mass, was determined and the data was graphed versus time in the desiccator and compared with a rehydration curve of 2 mil Kapton HN.

Results and Discussion

Dehydration vs. Rehydration Data

Dehydration and rehydration curves for 2 mil thick Kapton HN are provided in Figure 5. These curves are plotted as change in mass versus time, because different samples were used and the starting mass varied. As can be seen, the curves are on the same order of magnitude, and approximate each other. But, there is more uncertainty, or error, in the dehydration data for the short dehydration times (1 - 3 minutes). Whereas the rehydration data, which is easier and quicker to obtain, provides a smoother, more reliable curve for short times. This data shows that that rehydration curves are better indicators of the duration necessary for dehydration.

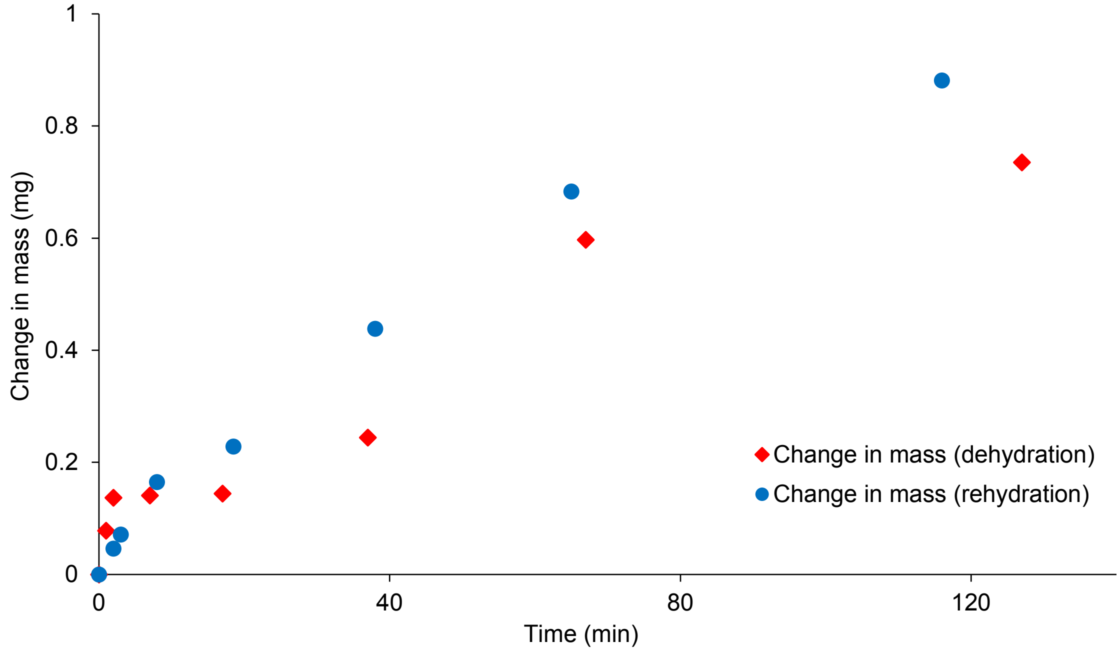


Figure 5. Dehydration and rehydration mass change curves for 2 mil Kapton HN.

Open-Close Trials

Figure 6 provides the rehydration curves for the Open-Close Trial tests of Kapton HN. The Trial 1 curve (red) is for the ideal procedure, where the sample's rehydration curve was obtained directly after four days of dehydration. The data obtained from the samples that were removed after five simulated sample removals from the desiccator, are listed as Trials 2-5, and are plotted with the Trial 1 curve. There is some variability in initial mass, but, the similarity of the shape of the five curves shows that previous opening and closing of the desiccator, does not significantly affect the rehydration data. Therefore, it was concluded that numerous samples could be put into a desiccator and tested for rehydration as long the desiccator is immediately put back under vacuum once a sample is removed.

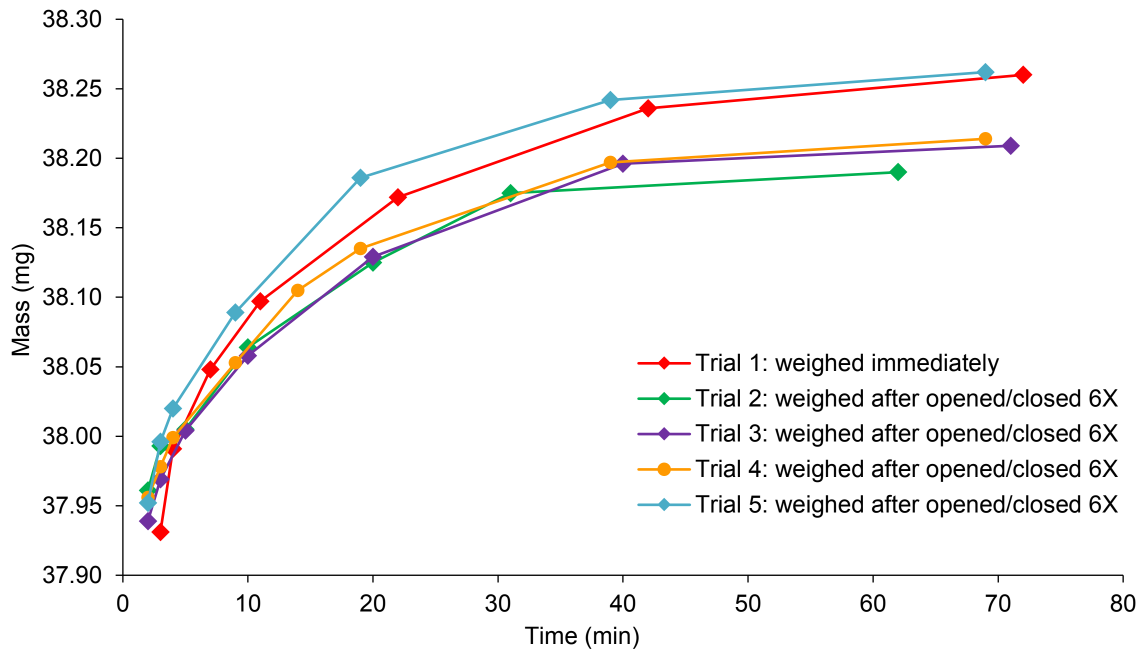


Figure 6. "Open-Close Trials" series of rehydration curves using one Kapton HN sample.

Rehydration Data

The rehydration data for the PEACE polymers are provided in Table 2. The table includes the MISSE serial number, the material and material abbreviation, the sample thickness, the duration over which the rehydration data was collected, the total mass gain (in mg) and the percent mass increase for the duration the data was collected. The rehydration curves are provided in Figures 7 through Figure 50.

As can be seen in Table 2, the polymers displayed a very wide range of moisture absorption, hence the hygroscopic nature of the polymers varied greatly. Some of the polymers, such as PP, PVDC and UHMWPE had very little moisture absorption. The percent mass increase was ≤ 0.032% for these polymers. This was also true for the only non-polymer, pyrolytic graphite, which had a negligible moisture absorption (0.001% mass increase). Fourteen samples had an increase in mass of greater than 1%. And, numerous samples had large moisture absorption including PE, PMMA, PPPA, PA 6, PA 66, Upilex-S, PMR-15 and PTFE. These samples had ≥ 2% increase in mass. The polymer with the greatest mass increase was PBI with a total mass increase of 7.14%. As can be seen in the rehydration curves, the samples absorbed moisture and gained most of their mass within approximately 1 hour, or 60 minutes. It should also be pointed out that not all polymers were fully rehydrated in the time period that data was collected. This particularly noticeable in the graphs of polyamide 6 (PA 6, Figure 28) and polyamide 66 (PA 66, Figure 29).

Table 2. Rehydration Data for the PEACE Polymers.

MISSE 2 Serial #	Material	Abbrev.	Thickness (mils)	Time Interval (min)	Mass Gain (mg)	% Mass Increase
2-E5-6	Acrylonitrile butadiene styrene	ABS	5	72.0	0.215	0.314
2-E5-7	Cellulose acetate	CA	2	133.0	0.076	0.246
2-E5-8	Poly-(p-phenylene terephthalamide)	PPDT	2.2	128.0	0.131	0.749
2-E5-9	Polyethylene	PE	2	128.0	1.212	4.736
2-E5-10	Polyvinyl fluoride	PVF	1	128.0	0.009	0.087
2-E5-11	Crystalline polyvinylfluoride w/white pigment	PVF	1	127.2	0.270	0.990
2-E5-12	Polyoxymethylene; acetal; polyformaldehyde	POM	10	193.0	0.311	0.147
2-E5-13	Polyacrylonitrile	PAN	2	72.0	0.173	0.663
2-E5-14	Allyl diglycol carbonate	ADC	31	238.0	0.351	0.103
2-E5-15	Polystyrene	PS	2	69.0	0.020	0.108
2-E5-16	Polymethyl methacrylate	PMMA	2	128.0	0.454	2.591
2-E5-17	Polyethylene oxide	PEO	29	1200.0	1.965	0.690
2-E5-18	Poly(p-phenylene-2 6-benzobisoxazole)	PBO	1	128.0	0.141	1.281
2-E5-19	Epoxide or epoxy	EP	88-92	4230.0	4.040	0.306
2-E5-20	Polypropylene	PP	20	128.0	0.050	0.032
2-E5-21	Polybutylene terephthalate	PBT	3	128.0	0.097	0.188
2-E5-22	Polysulfone	PSU	2	128.0	0.062	0.196
2-E5-23	Polyurethane	PU	2	128.0	0.239	0.689
2-E5-24	Polyphenylene isophthalate	PPPA	2	128.0	0.633	3.396
2-E5-25	Pyrolytic graphite	PG	80	128.0	0.011	0.001
2-E5-26	Polyetherimide	PEI	10	2852.0	0.876	0.695
2-E5-27	Polyamide 6	PA 6	2	126.6	0.863	3.040
2-E5-28	Polyamide 66	PA 66	2	127.8	0.503	1.956
2-E5-29	Polyimide (Clear), CP1	PI	3	128.0	0.262	0.443
2-E5-30 2-E5-33	Polyimide (PMDA), Kapton H	PI	5	128.0	0.445	0.726
N/A	Polyimide (PMDA), Kapton H	PI	2	147.0	0.149	0.860
2-E5-31	Polyimide (PMDA), Kapton HN	PI	5	72.0	0.391	1.033
2-E5-32	Polyimide (BPDA), Upilex-S	PI	1	128.0	0.424	2.960
2-E5-34	High temperature polyimide resin	PI	12-14	2862.0	3.833	2.084
2-E5-35	Polybenzimidazole	PBI	2	129.8	2.031	7.141
2-E5-36	Polycarbonate	PC	10	69.0	0.226	0.153
2-E5-37	Polyetheretherketone	PEEK	3	70.0	0.123	0.259
2-E5-38	Polyethylene terephthalate	PET	2	133.7	0.077	0.206
2-E5-39	Chlorotrifluoroethylene	CTFE	5	128.0	0.526	0.558
2-E5-40	Ethylene-chlorotrifluoroethylene	ECTFE	3	128.0	0.201	0.525
2-E5-41	Tetrafluorethylene-ethylene copolymer	ETFE	3	129.0	0.095	0.180
2-E5-42	Fluorinated ethylene propylene	FEP	2	128.0	0.493	1.013
2-E5-43	Polytetrafluoroethylene	PTFE	2	129.0	1.698	2.802
2-E5-44	Perfluoroalkoxy	PFA	2	128.0	0.449	0.819
2-E5-45	Amorphous fluoropolymer	AF	2	128.1	0.371	0.223
2-E5-46	Polyvinylidene fluoride	PVDF	3	128.0	0.110	0.163
N/A	Cellulose nitrate	CN	5	128.000	0.278	1.021
N/A	Polyvinylidene chloride	PVDC	2	129.120	0.010	0.020
N/A	Ultra-high molecular weight polyethylene	UHMWPE	10	129.000	0.027	0.024

Note: Not all polymers were fully rehydrated in the time period the data was collected.

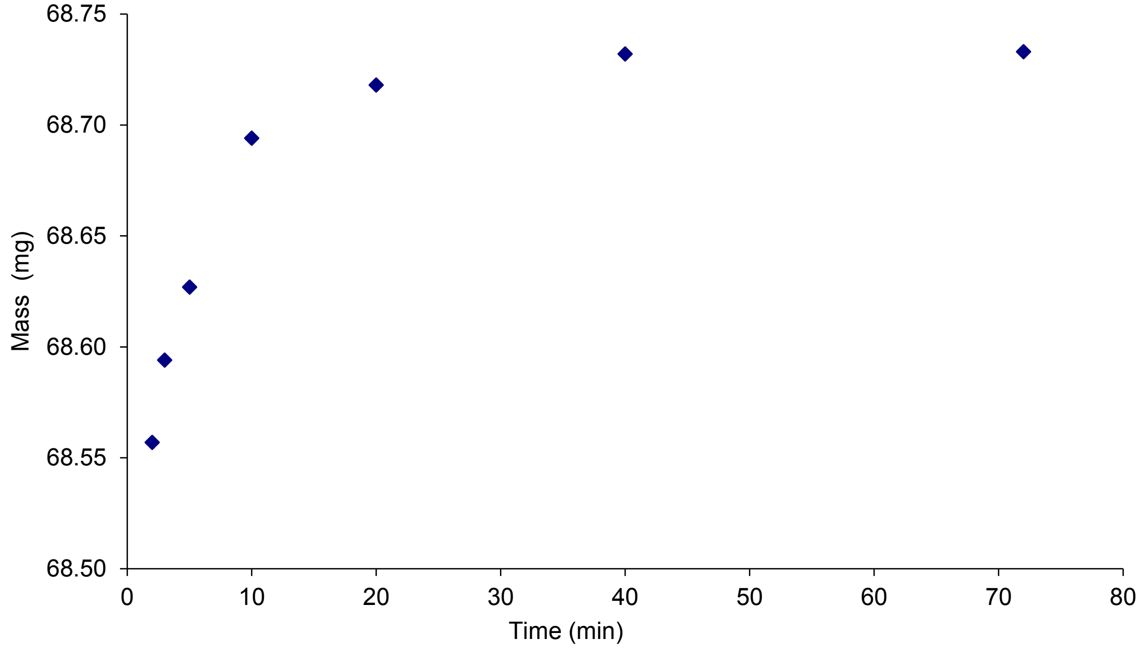


Figure 7. Rehydration curve for ABS (2-E5-6).

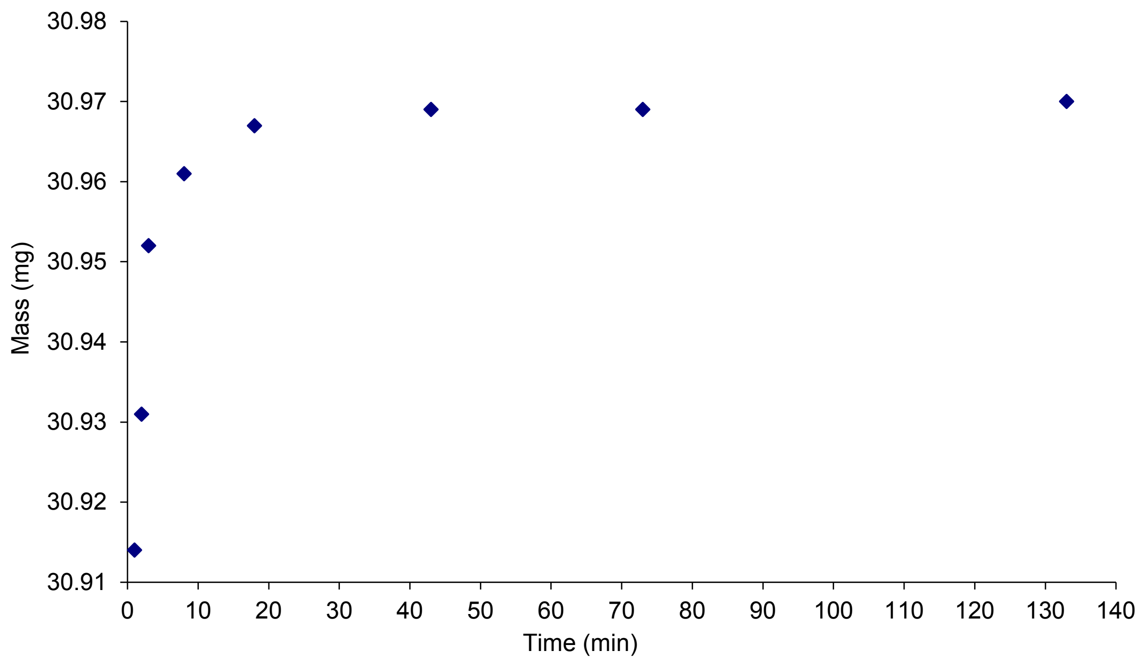


Figure 8. Rehydration curve for CA (2-E5-7).

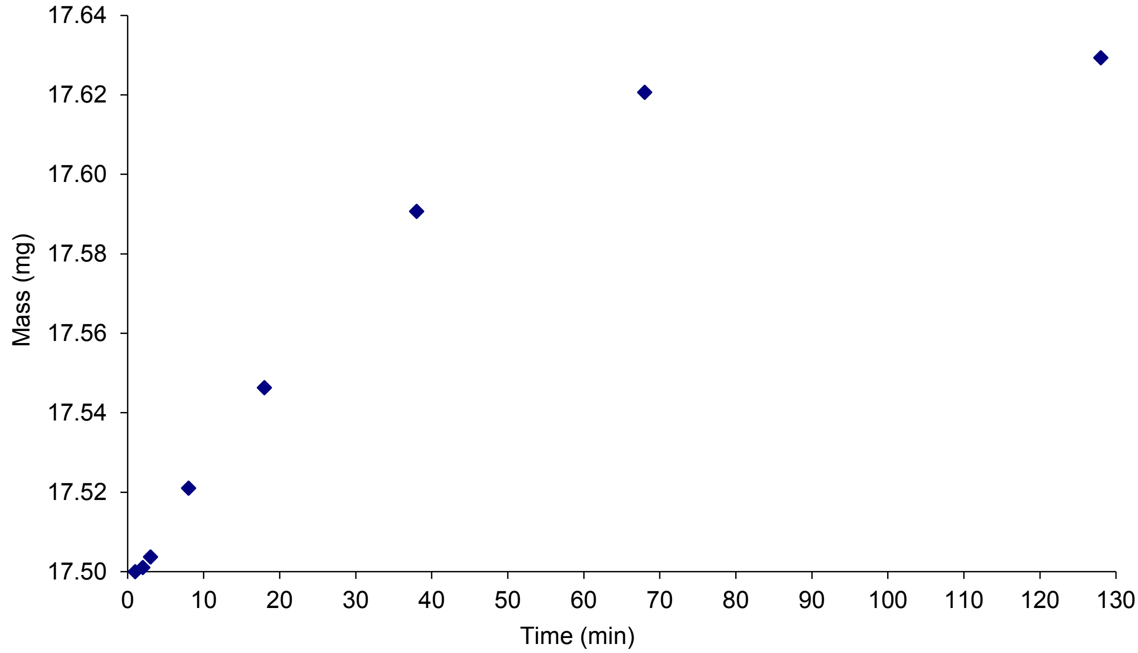


Figure 9. Rehydration curve for PPDT (2-E5-8).

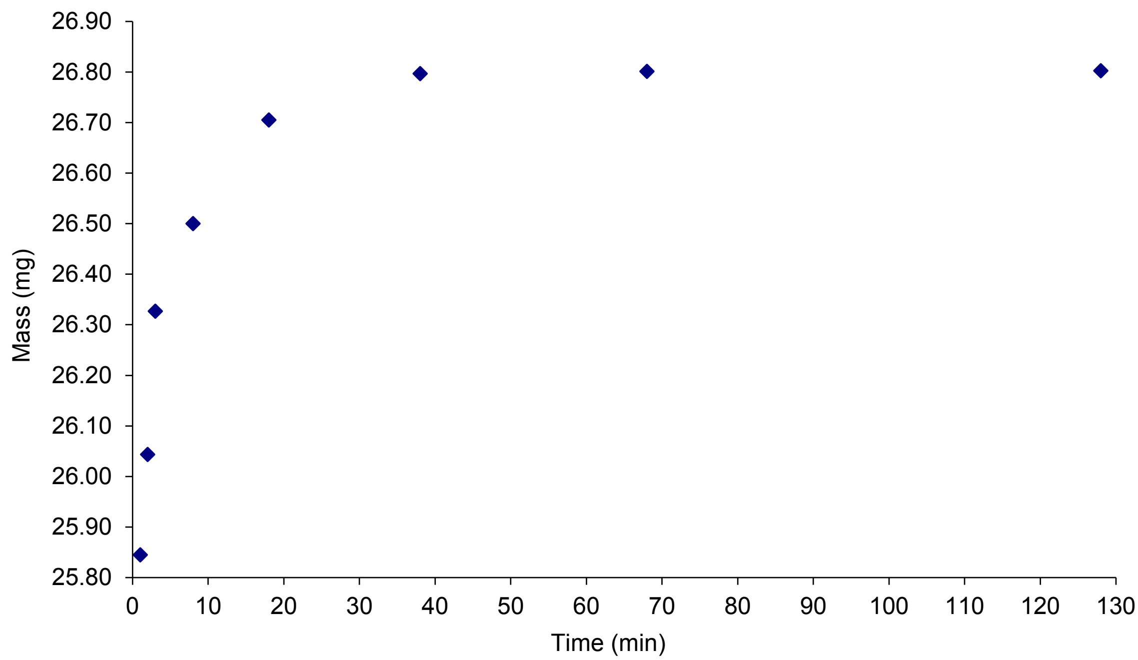


Figure 10. Rehydration curve for PE (2-E5-9).

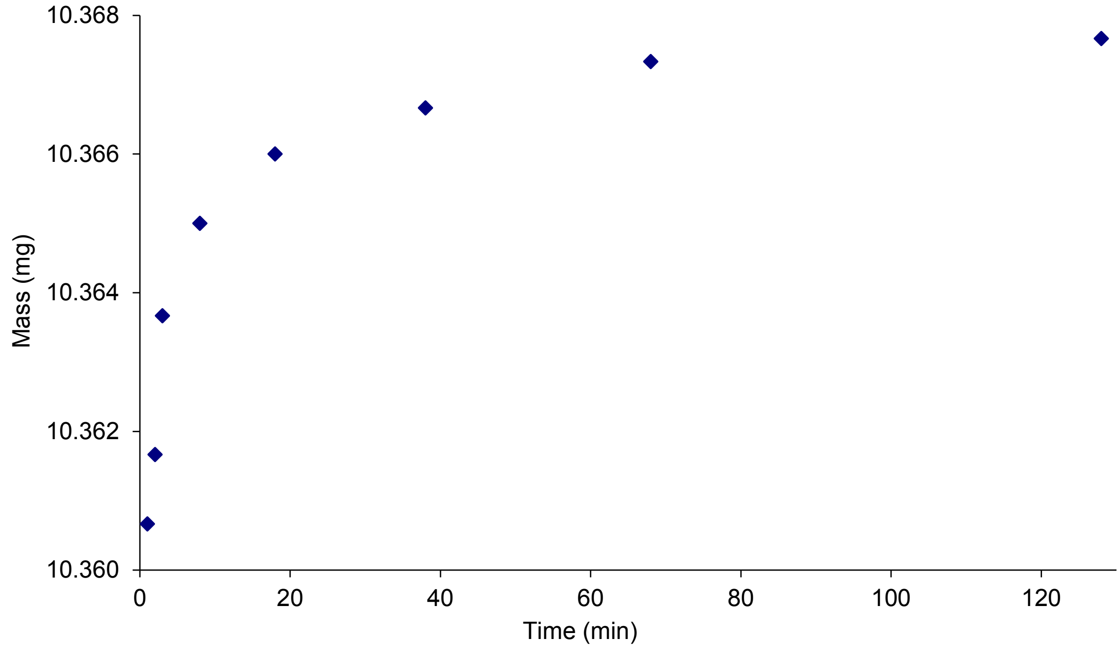


Figure 11. Rehydration curve for clear Tedlar (2-E5-10).

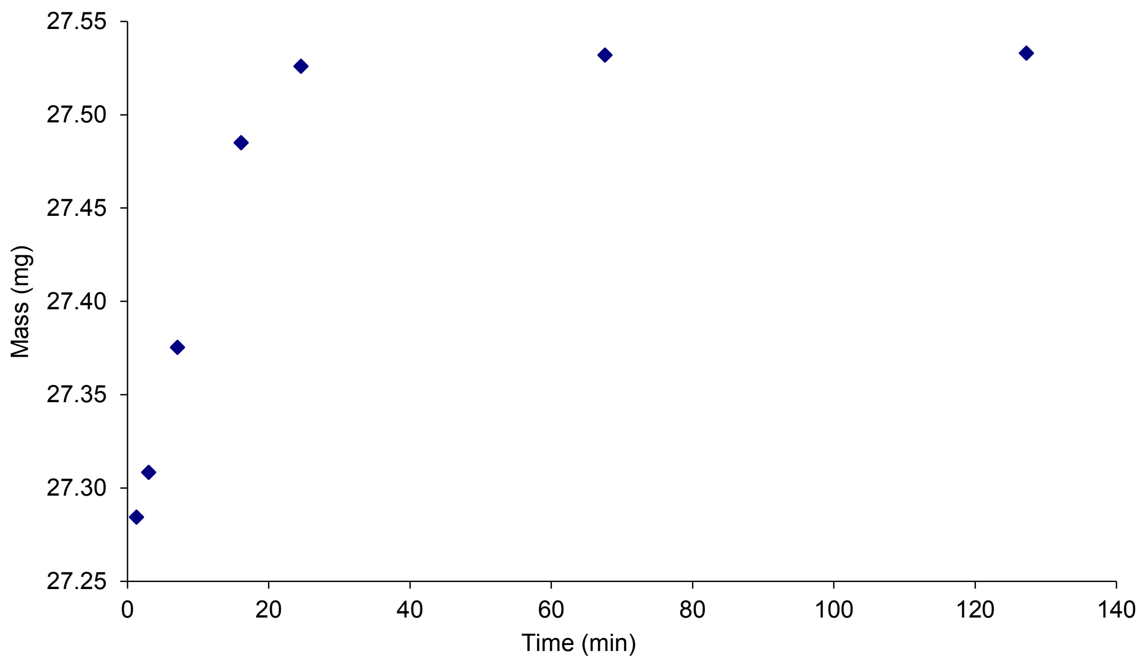


Figure 12. Rehydration curve for White Tedlar (2-E5-11).

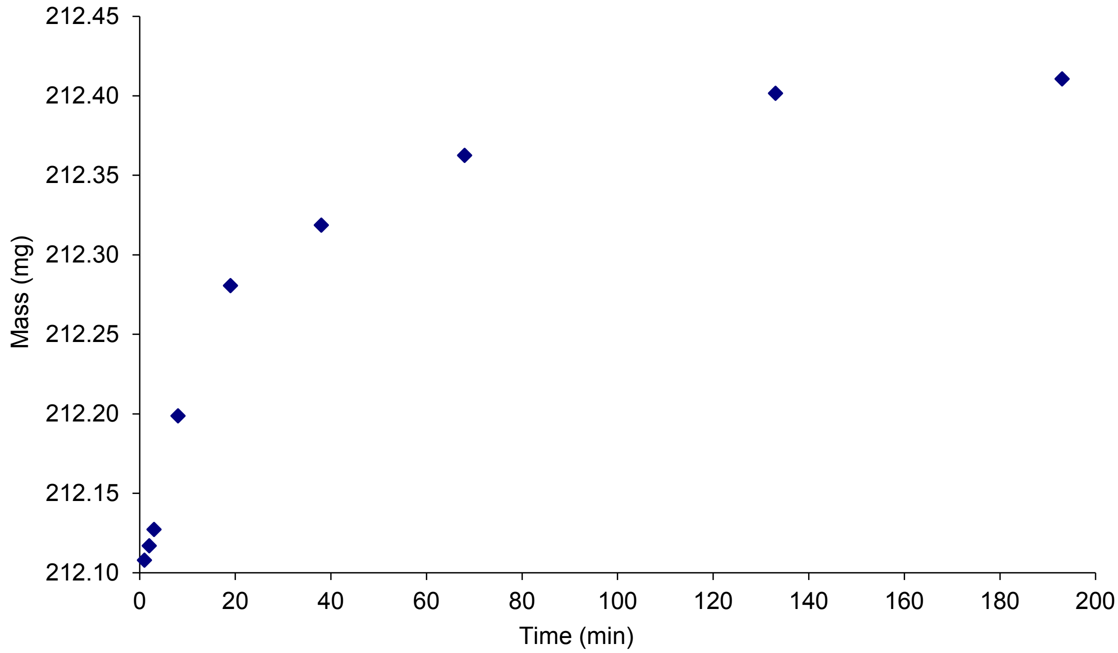


Figure 13. Rehydration curve for Delrin (2-E5-12).

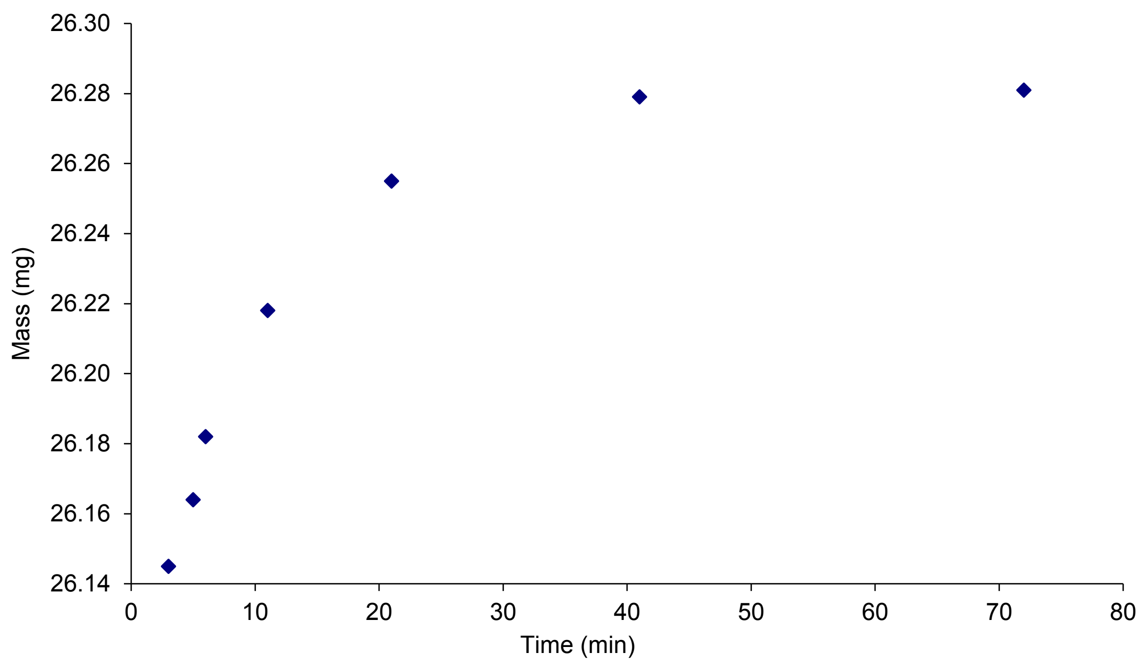


Figure 14. Rehydration curve for PAN (2-E5-13).

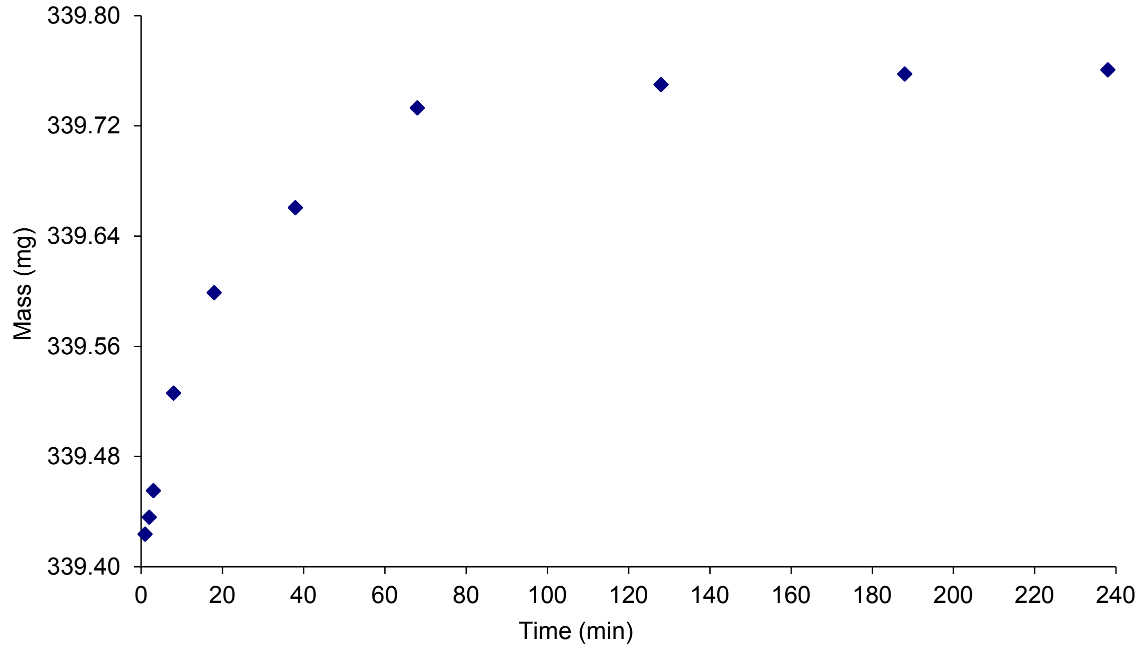


Figure 15. Rehydration curve for ADC (2-E5-14).

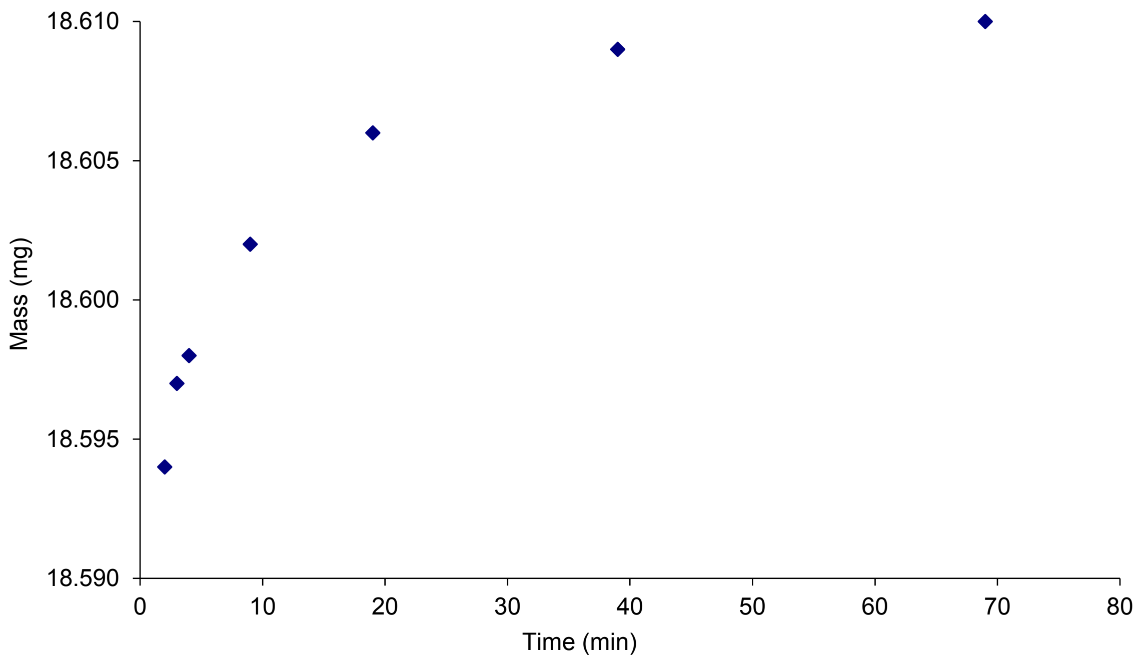


Figure 16. Rehydration curve for PS (2-E5-15)

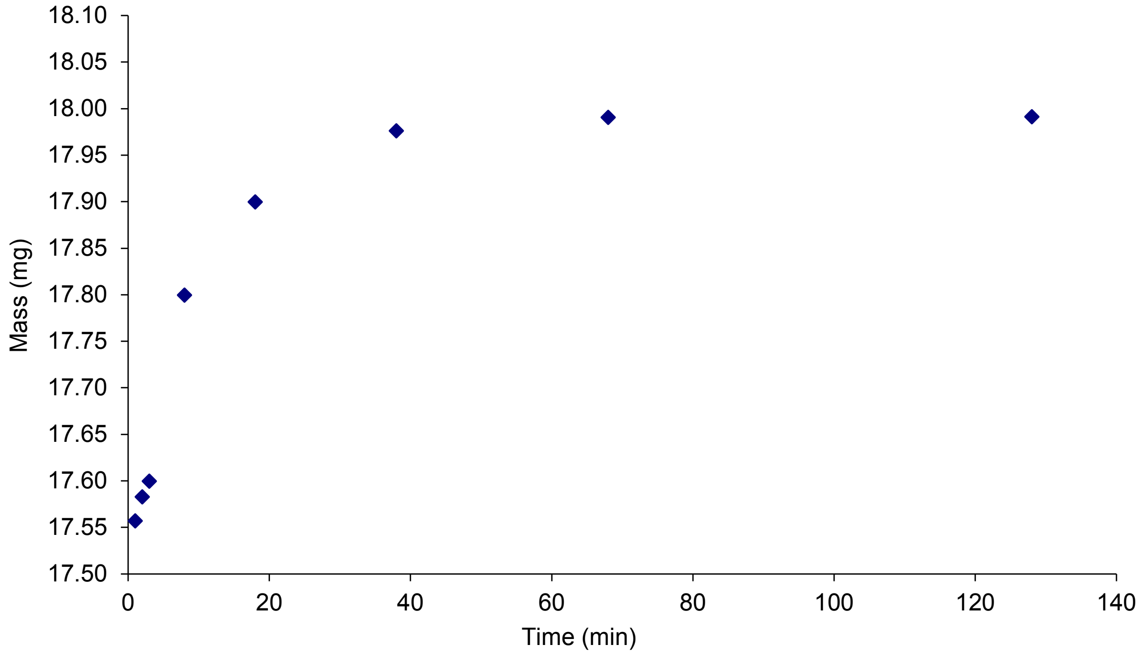


Figure 17. Rehydration curve for PMMA (2-E5-16).

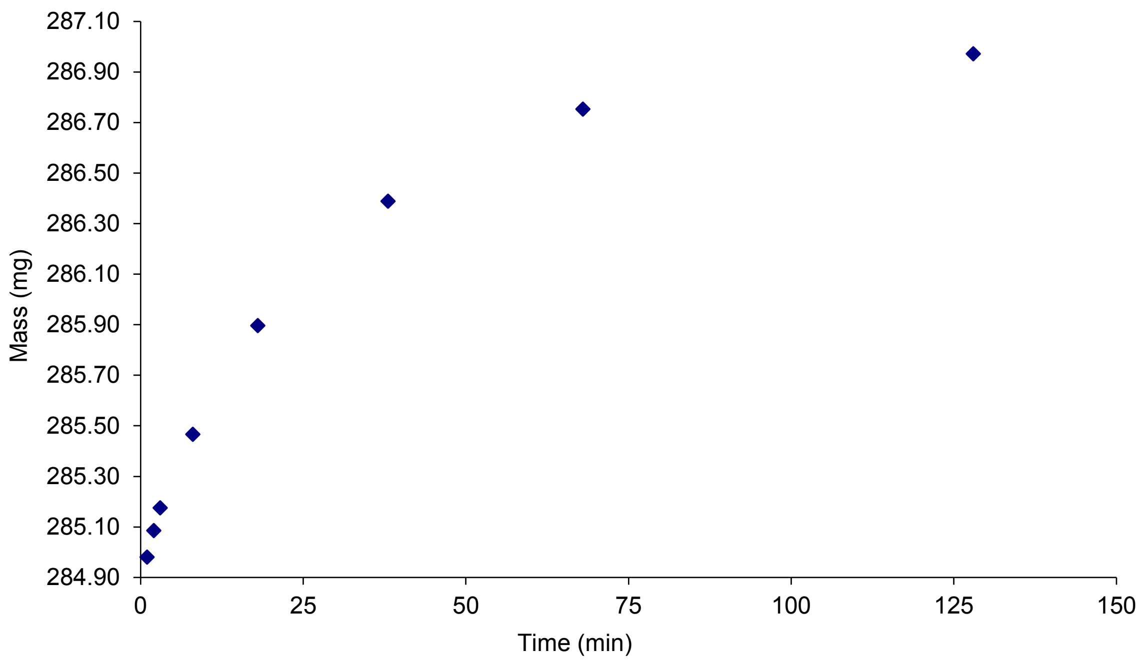


Figure 18. Rehydration curve for PEO (2-E5-17).

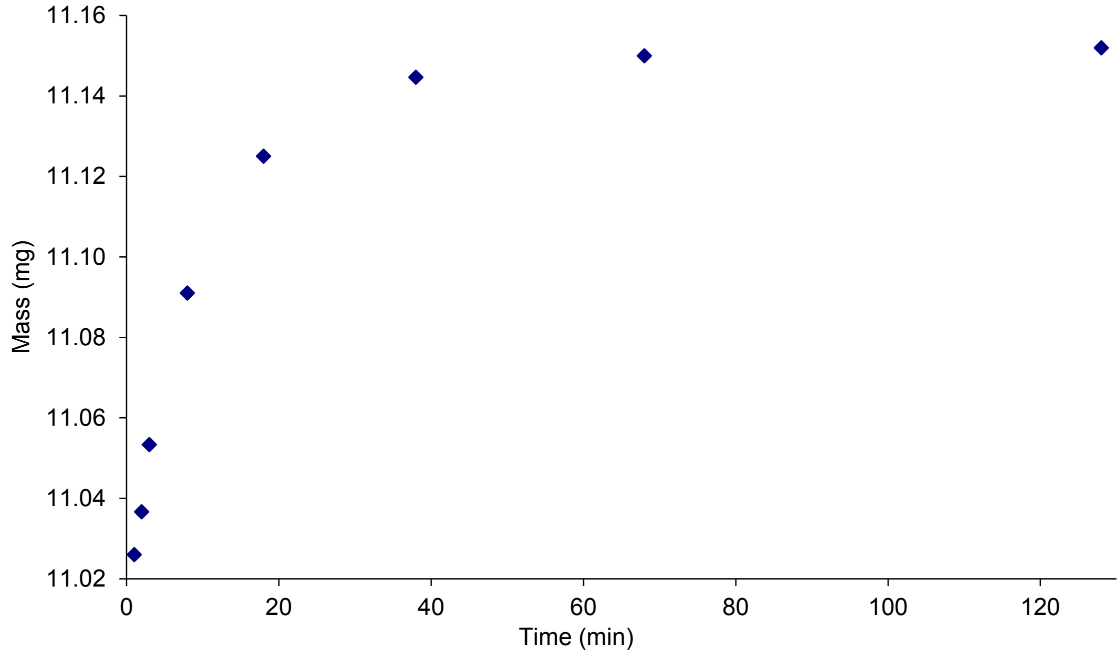


Figure 19. Rehydration curve for PBO (2-E5-18).

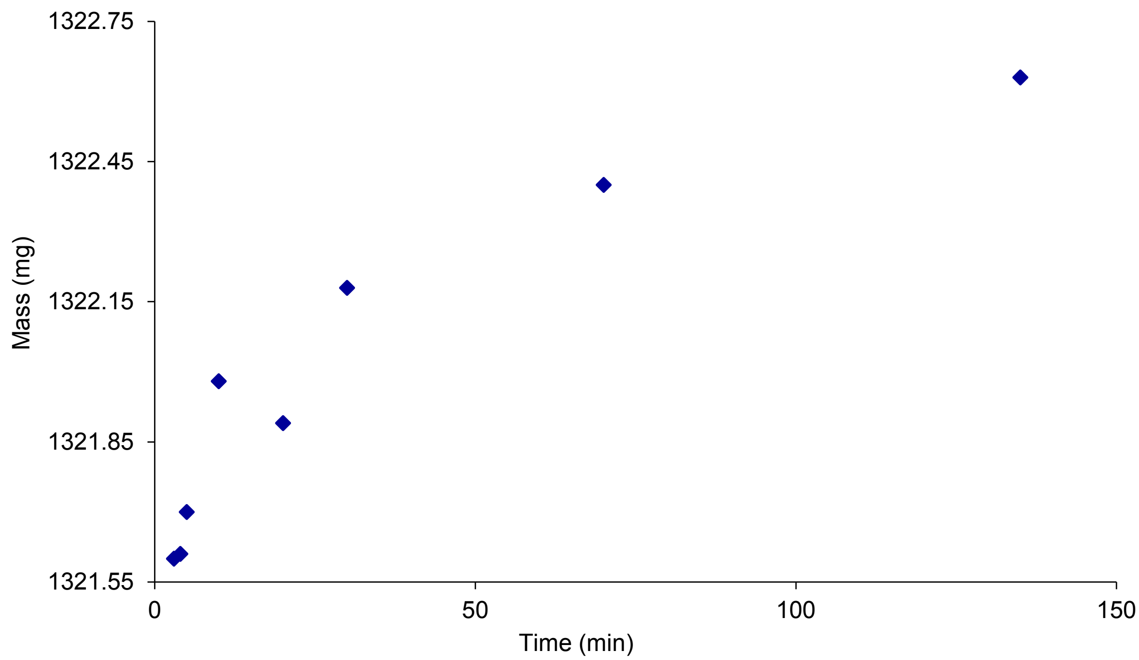


Figure 20. Rehydration curve for EP (2-E5-19).

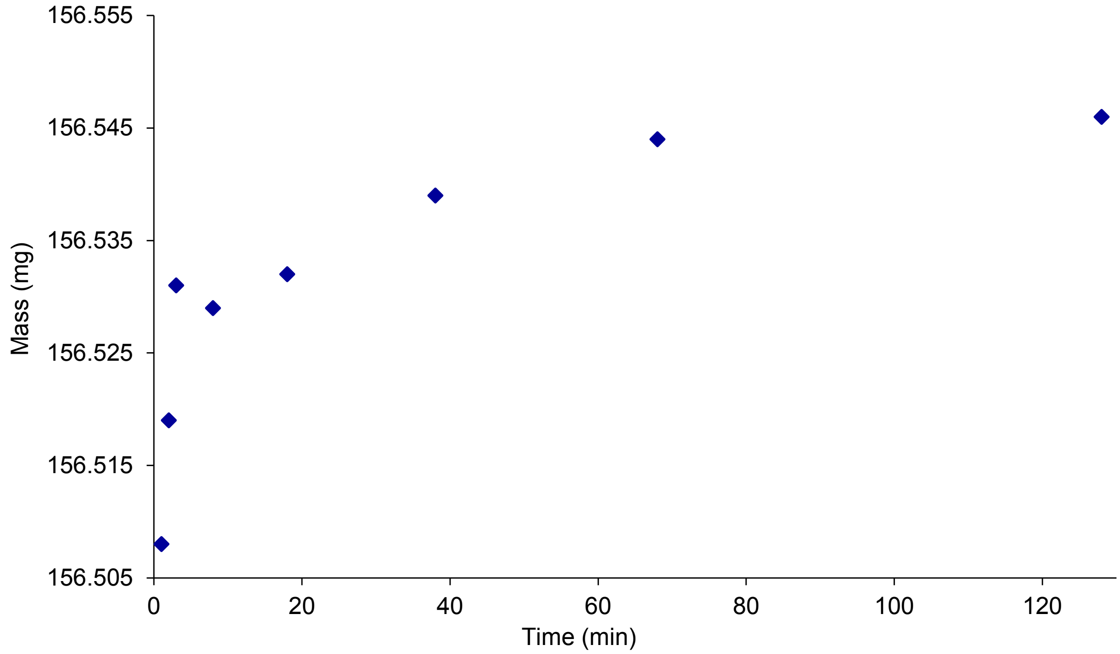


Figure 21. Rehydration curve for PP (2-E5-20)

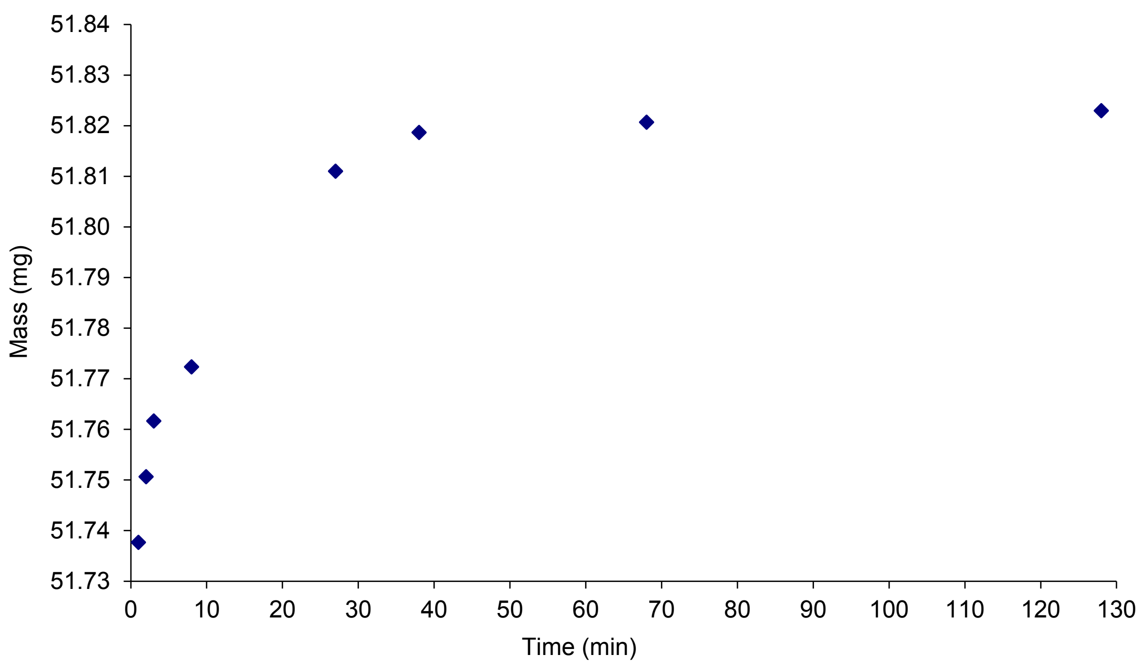


Figure 22. Rehydration curve for PBT (2-E5-21).

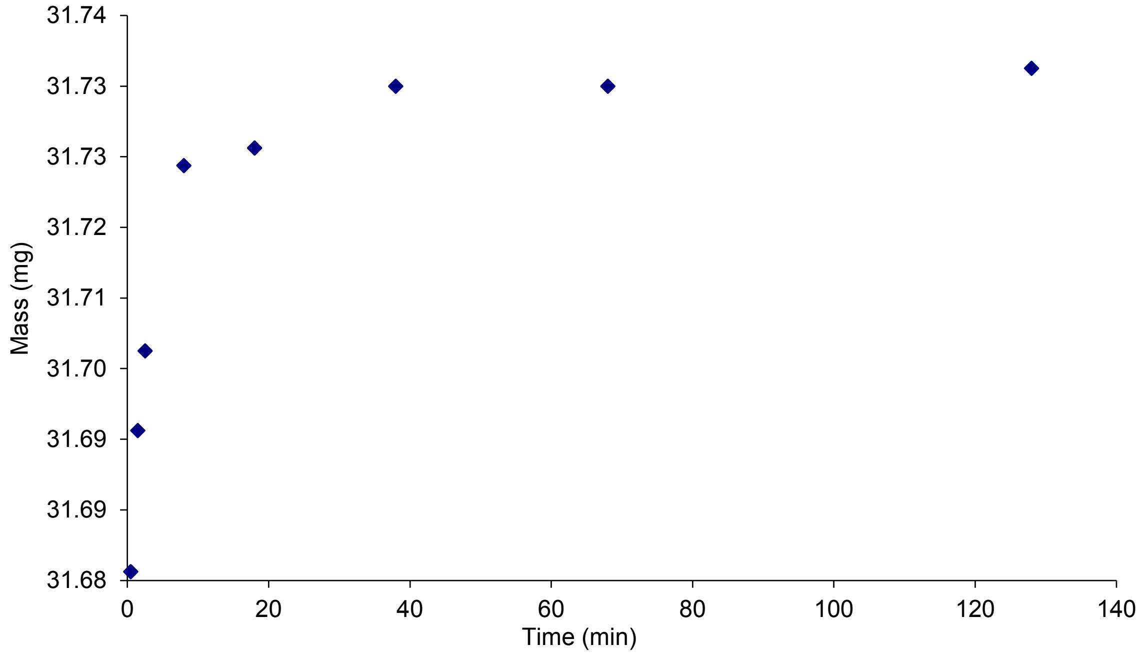


Figure 23. Rehydration curve for PSU (2-E5-22).

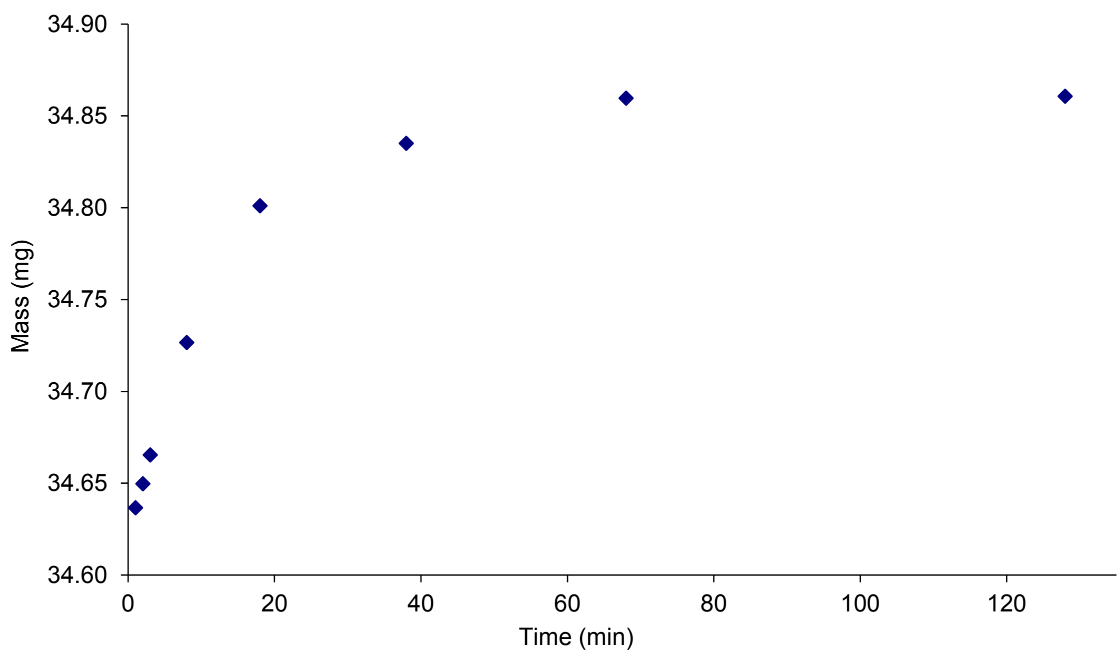


Figure 24. Rehydration curve for PU (2-E5-23).

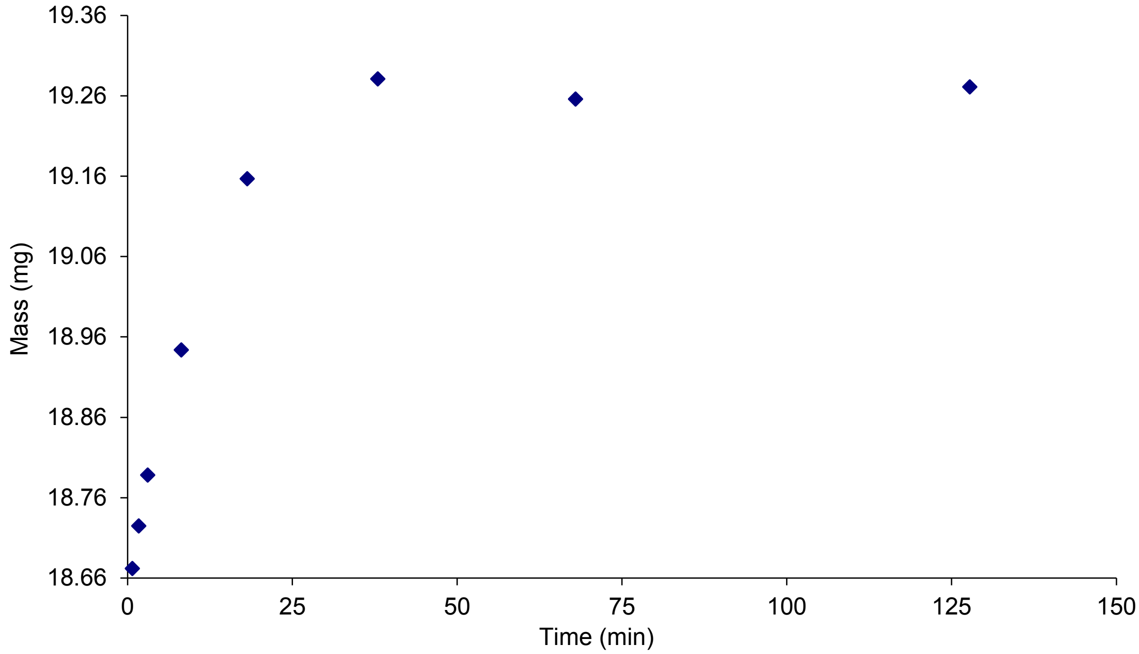


Figure 25. Rehydration curve for PPPA (2-E5-24).

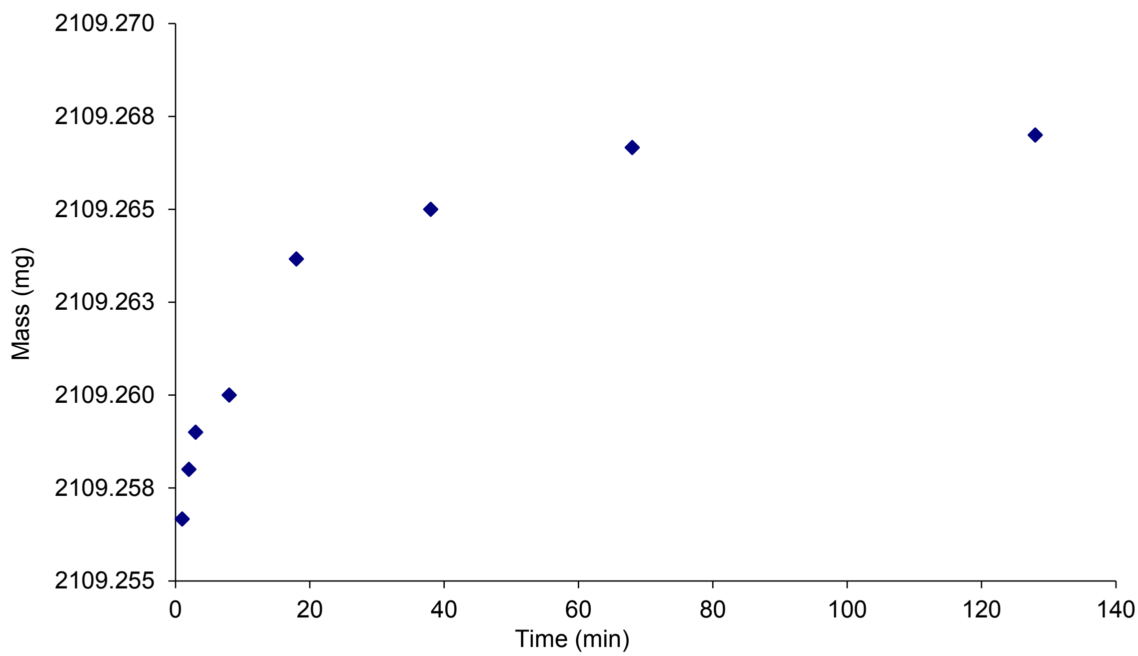


Figure 26. Rehydration curve for PG (2-E5-25).

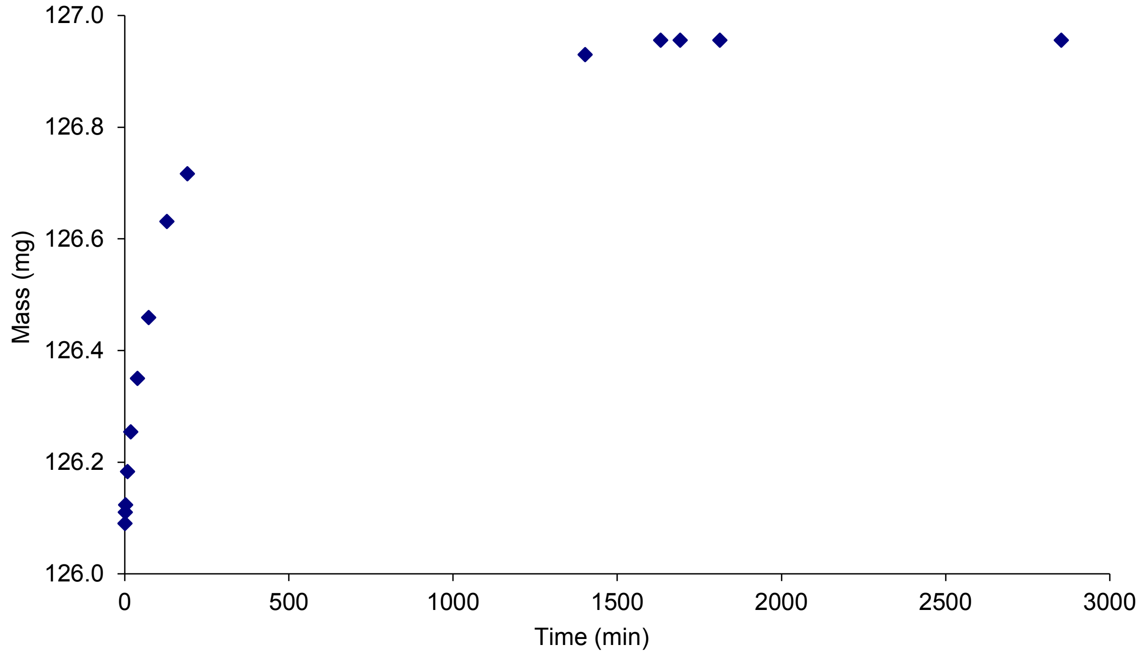


Figure 27. Rehydration curve for PEI (2-E5-26)

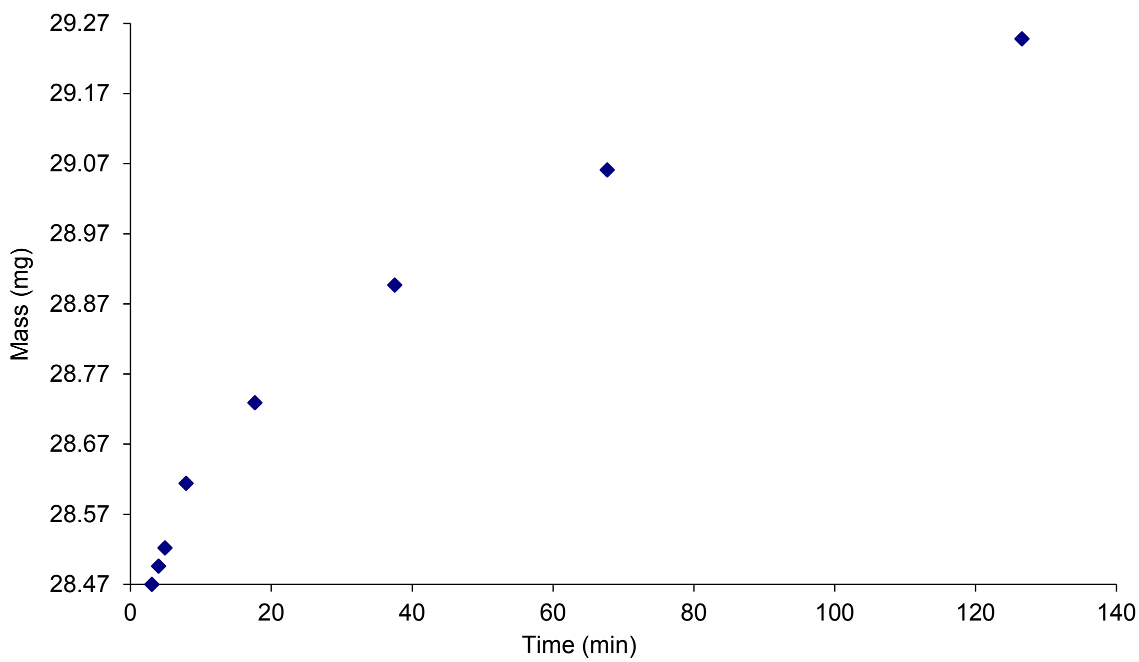


Figure 28. Rehydration curve for PA 6 (2-E5-27).

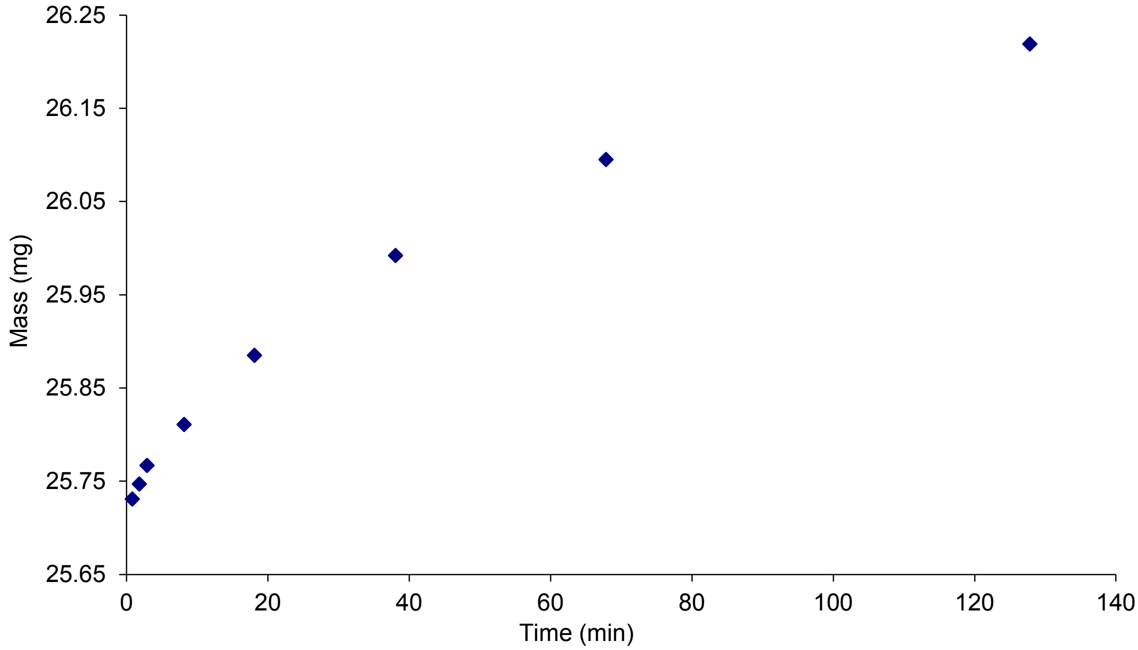


Figure 29. Rehydration curve for PA 66 (2-E5-28).

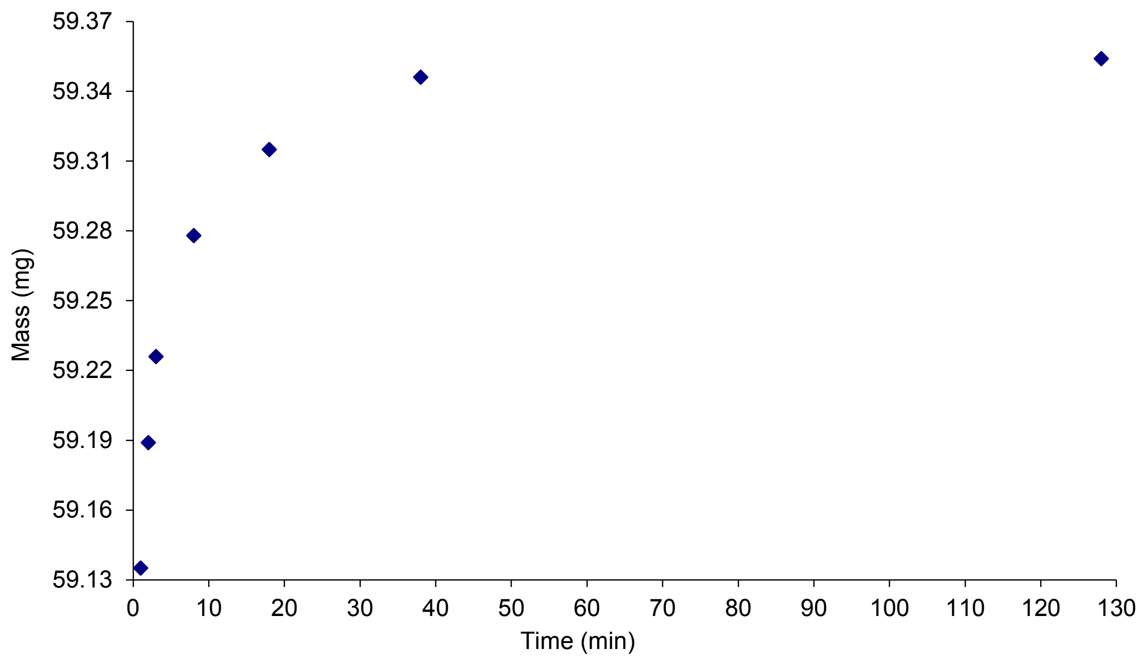


Figure 30. Rehydration curve for CP 1 (2-E5-29).

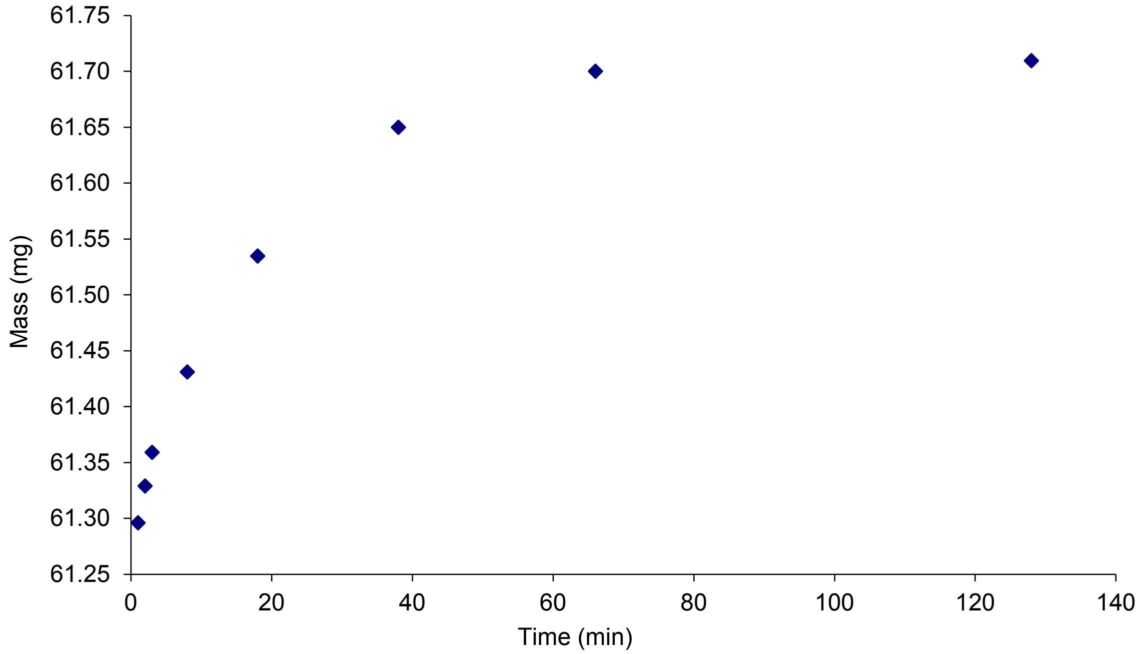


Figure 31. Rehydration curve for 5 mil Kapton H (2-E5-30 & 2-E5-33).

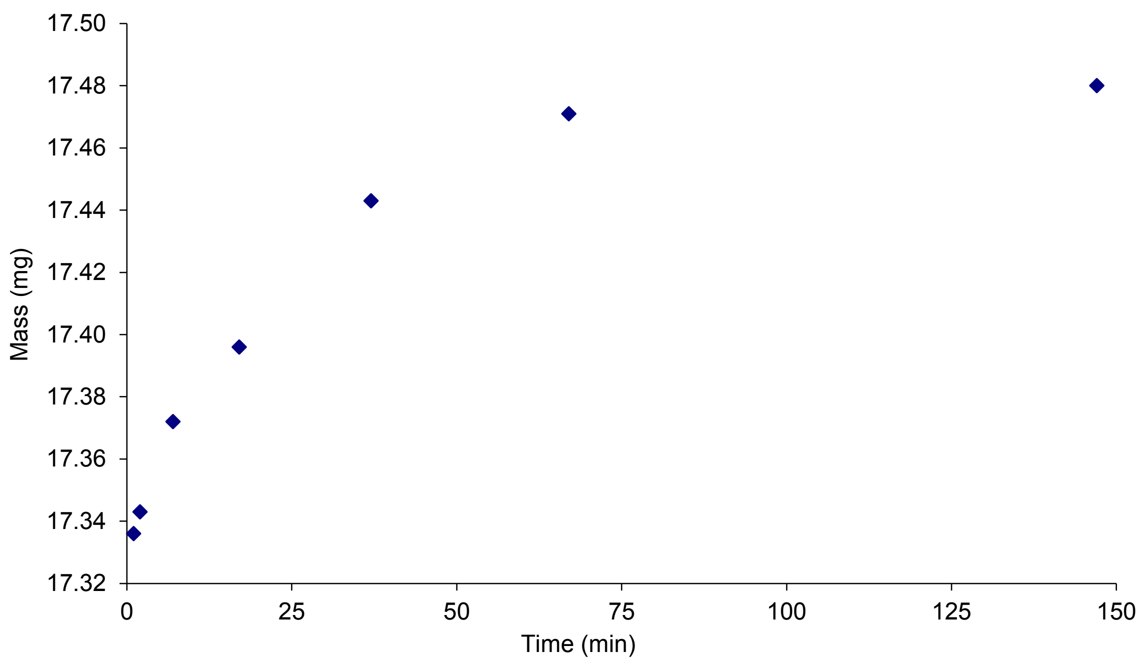


Figure 32. Rehydration curve for 2 mil Kapton H (not flown on MISSE 2).

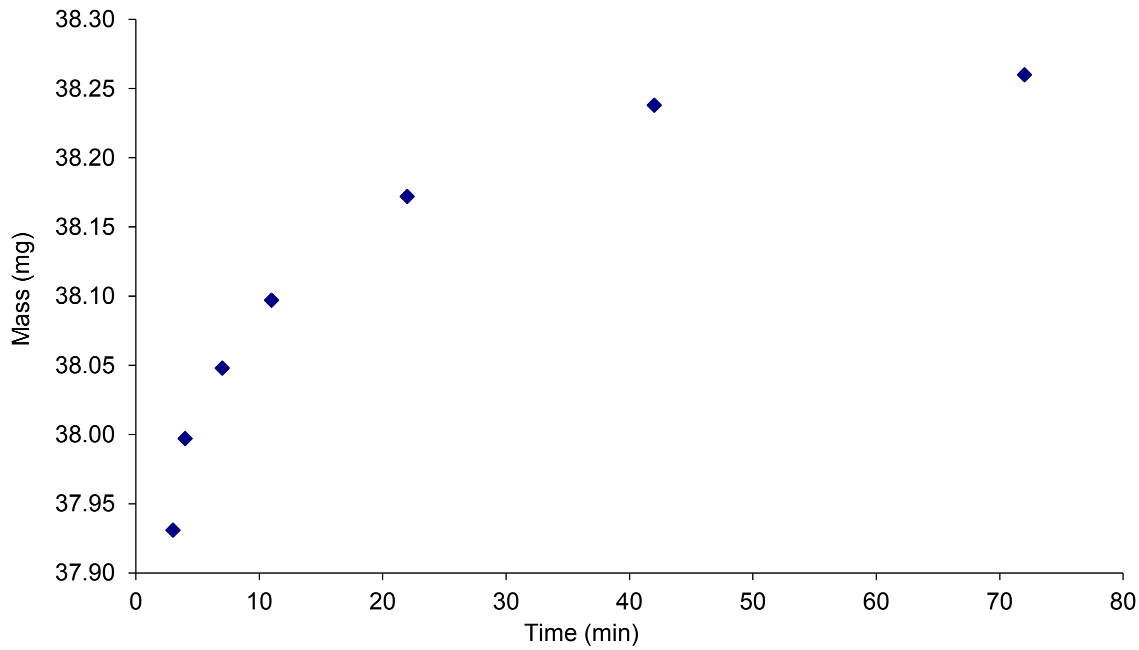


Figure 33. Rehydration curve for Kapton HN (2-E5-31).

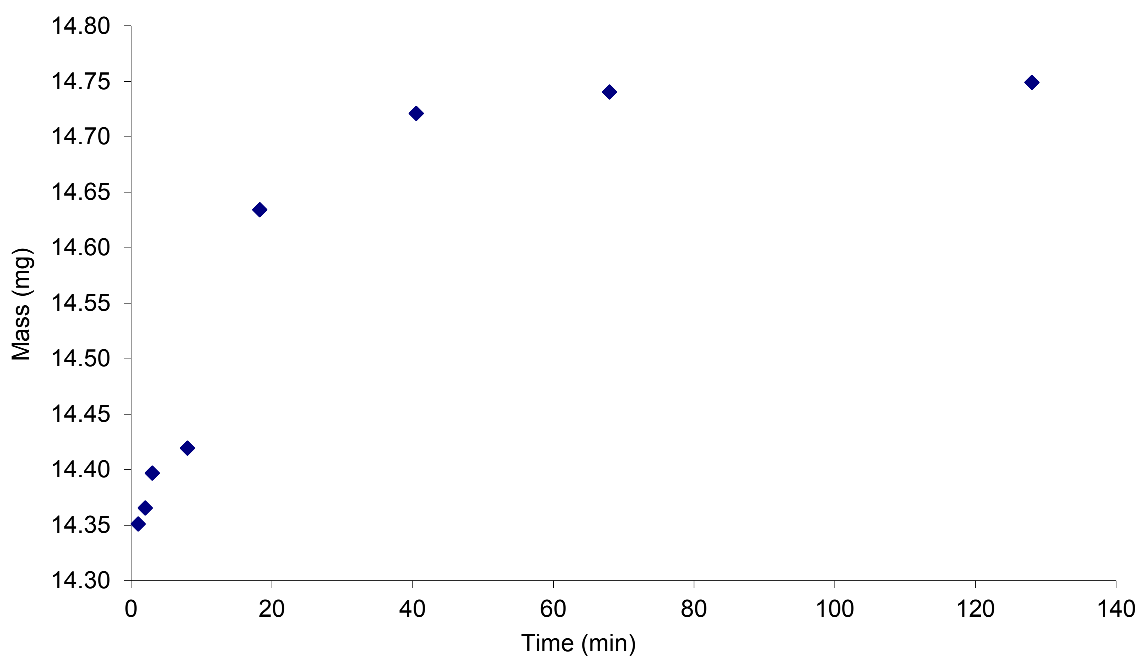


Figure 34. Rehydration curve for Upilex-S (2-E5-32).

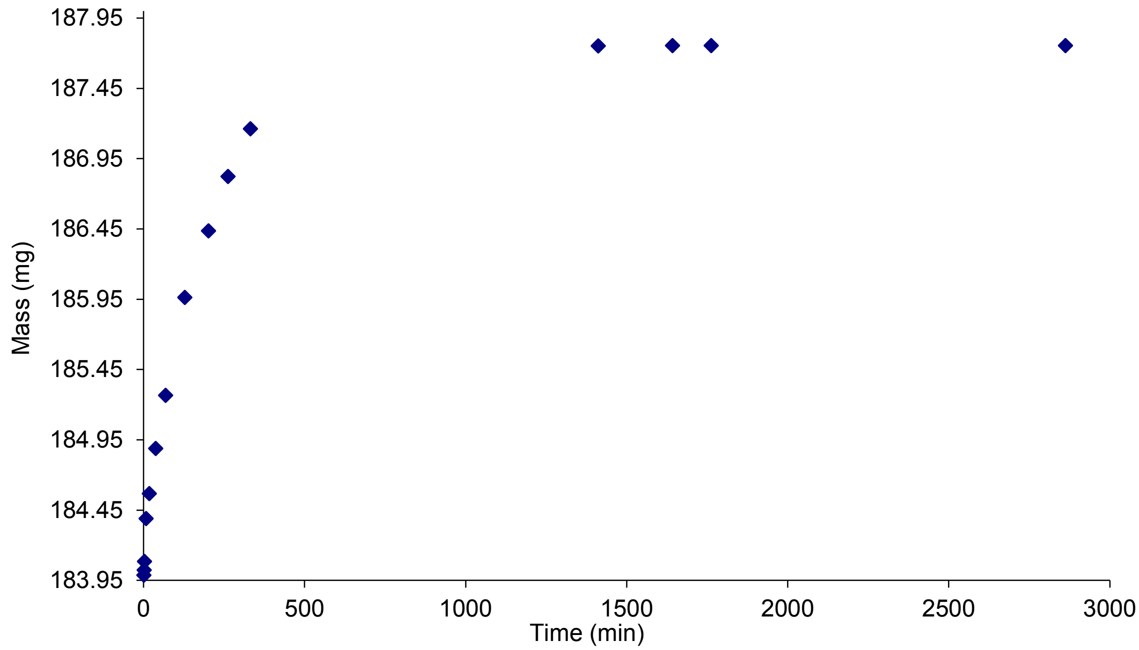


Figure 35. Rehydration curve for PMR-15 (2-E5-34).

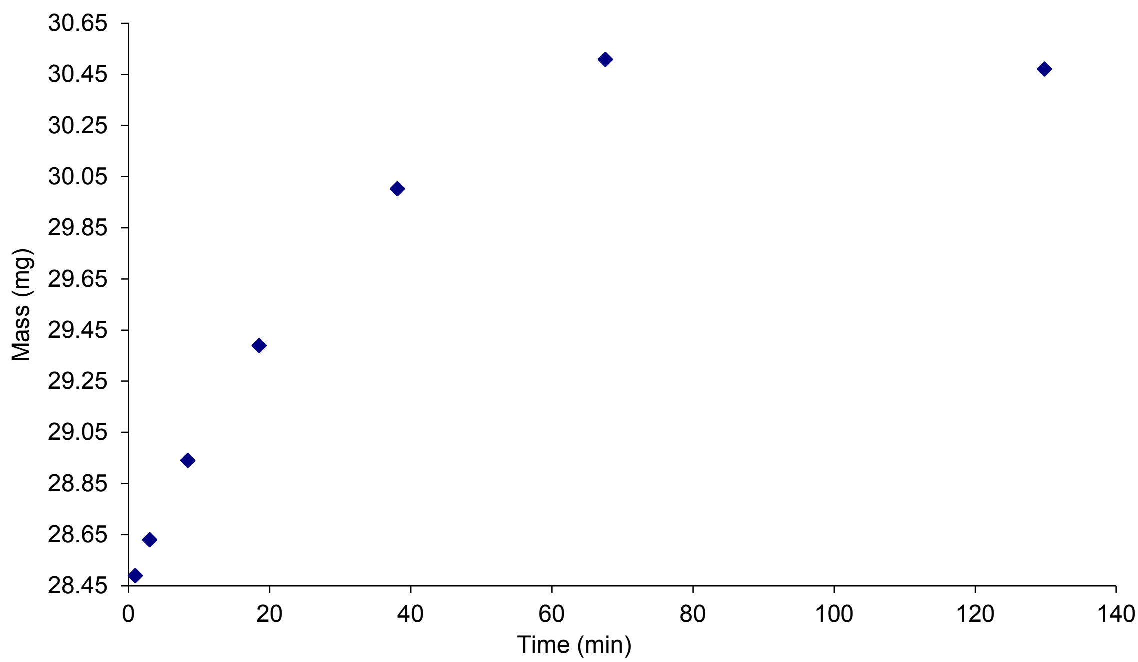


Figure 36. Rehydration curve for PBI (2-E5-35).

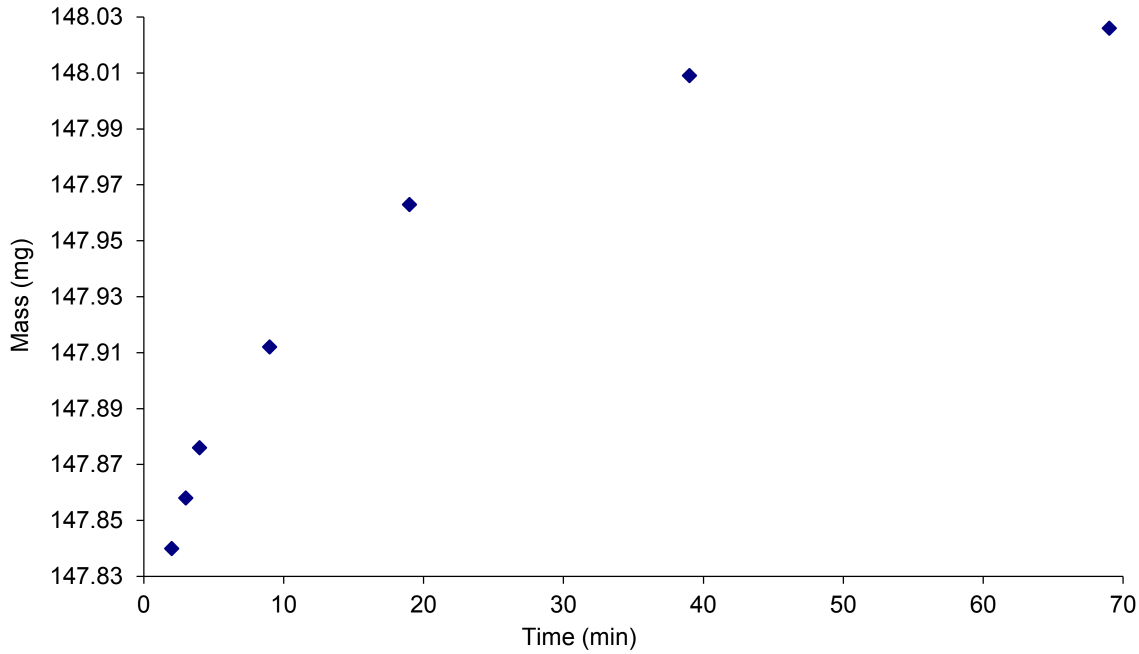


Figure 37. Rehydration curve for PC (2-E5-36).

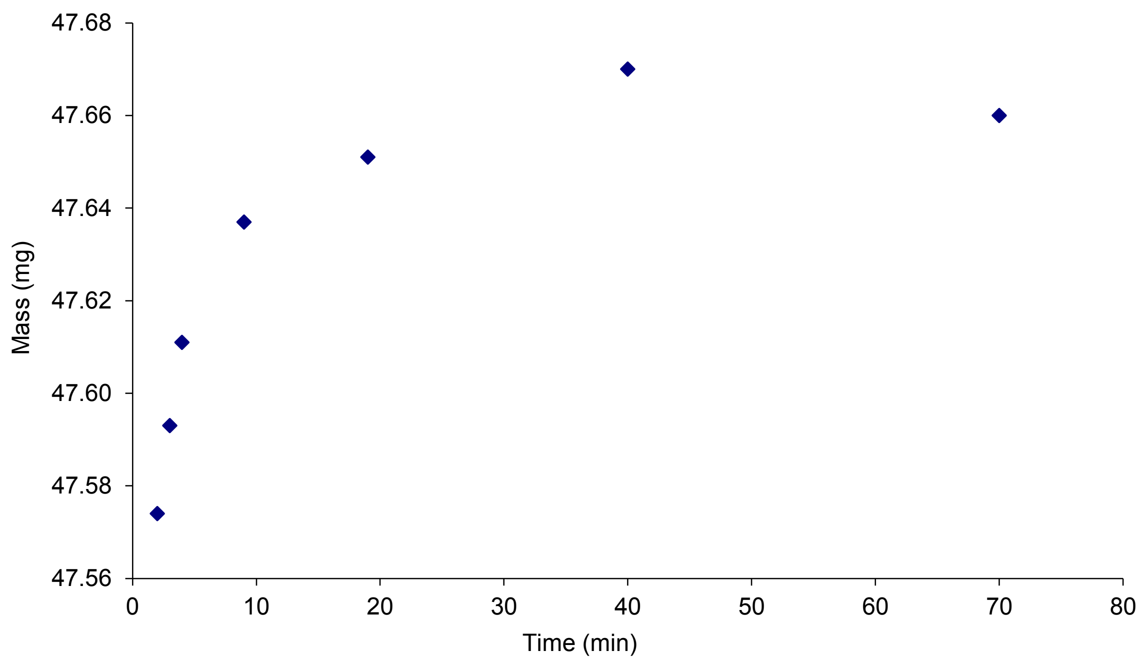


Figure 38. Rehydration curve for PEEK (2-E5-37).

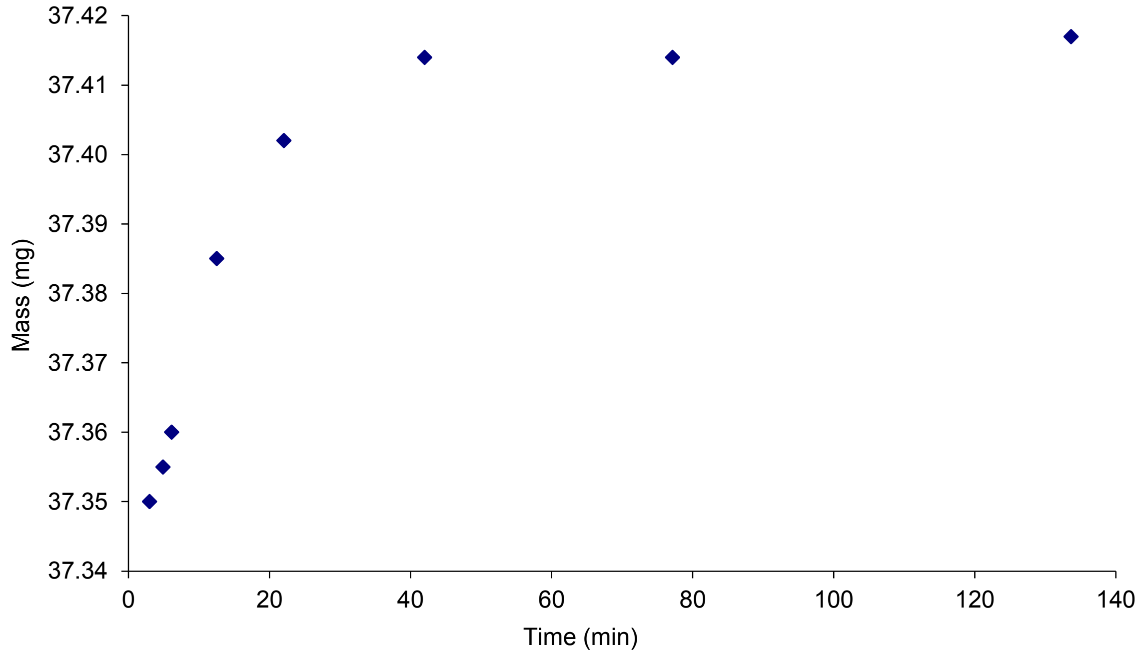


Figure 39. Rehydration curve for PET (2-E5-38).

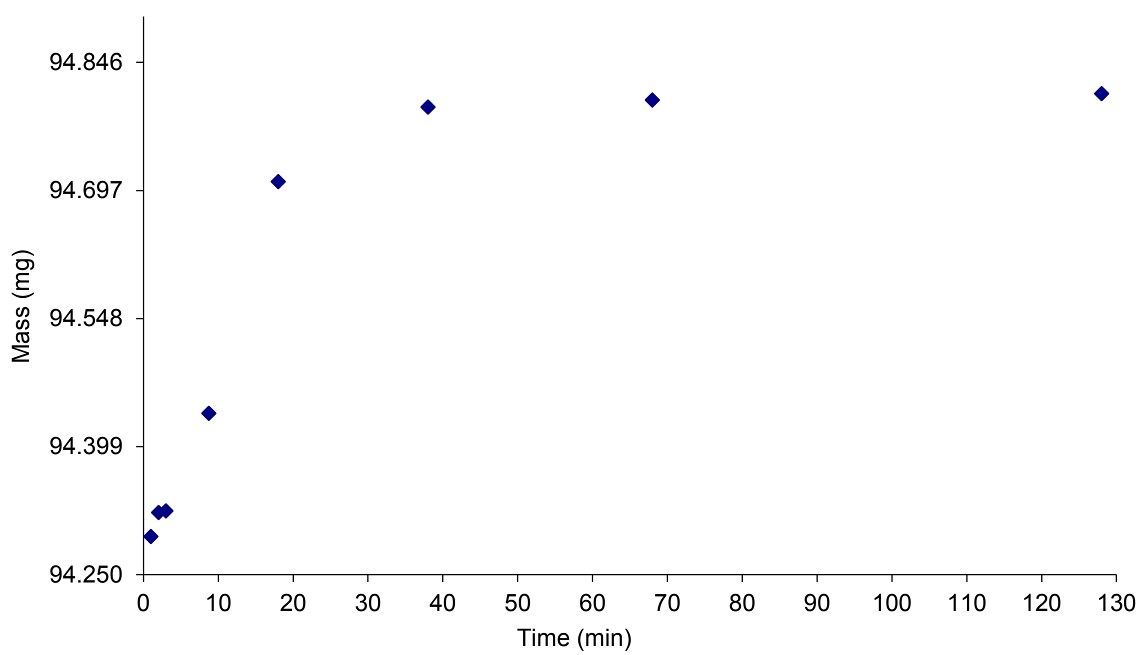


Figure 40. Rehydration curve for CTFE (2-E5-39).

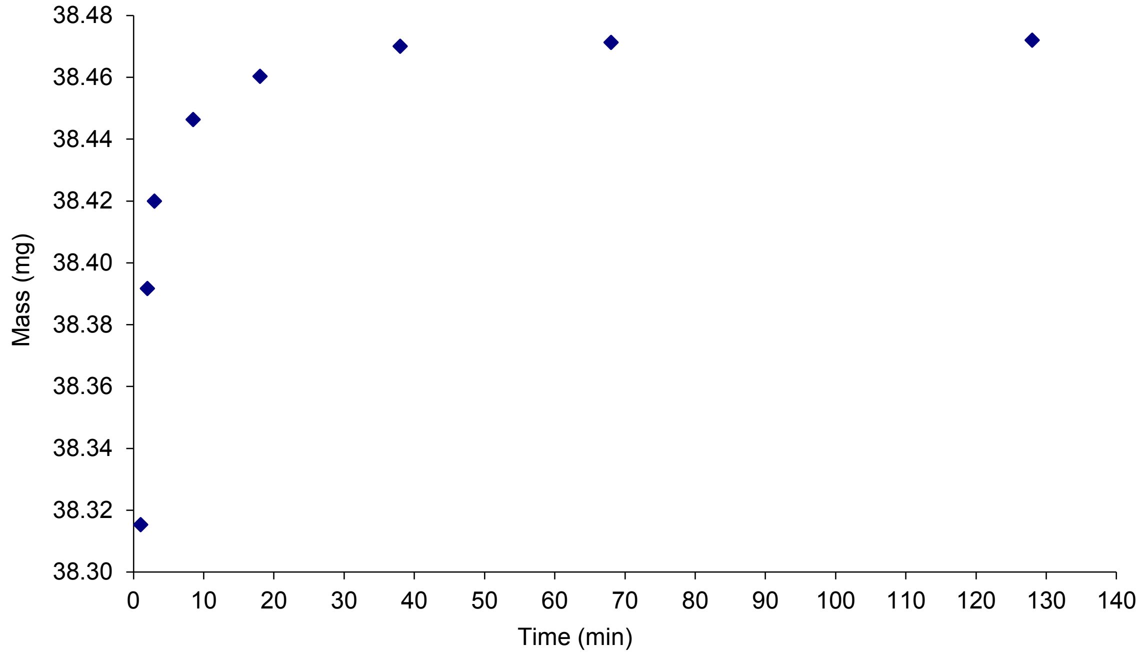


Figure 41. Rehydration curve for ECTFE (2-E5-40).

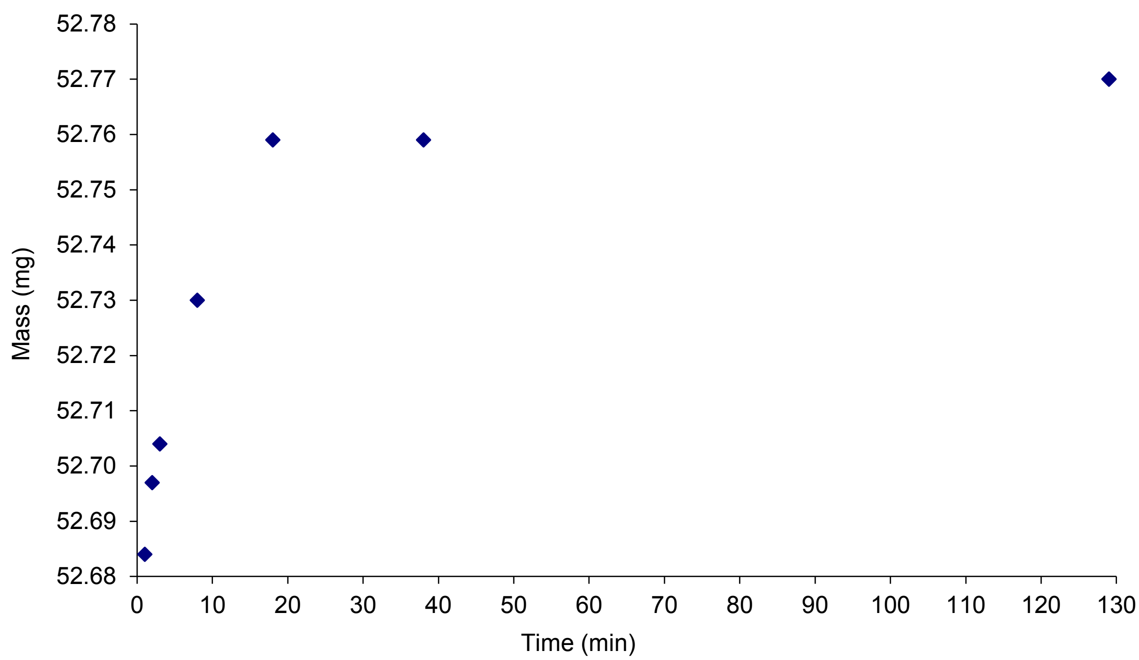


Figure 42. Rehydration curve for ETFE (2-E5-41).

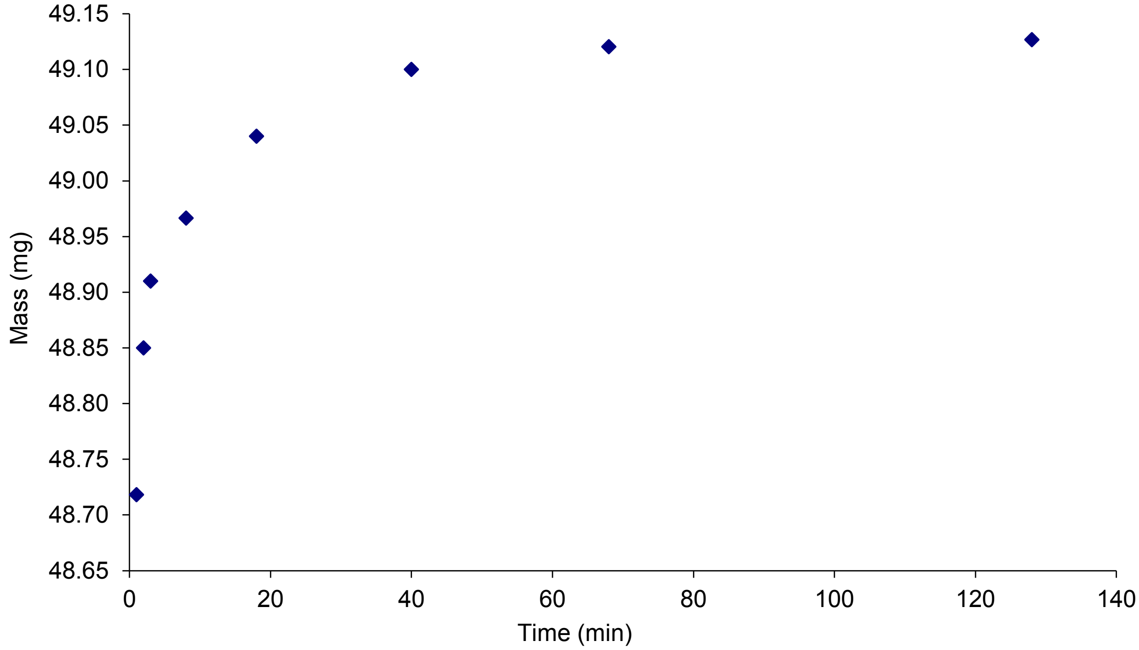


Figure 43. Rehydration curve for Teflon FEP (2-E5-42).

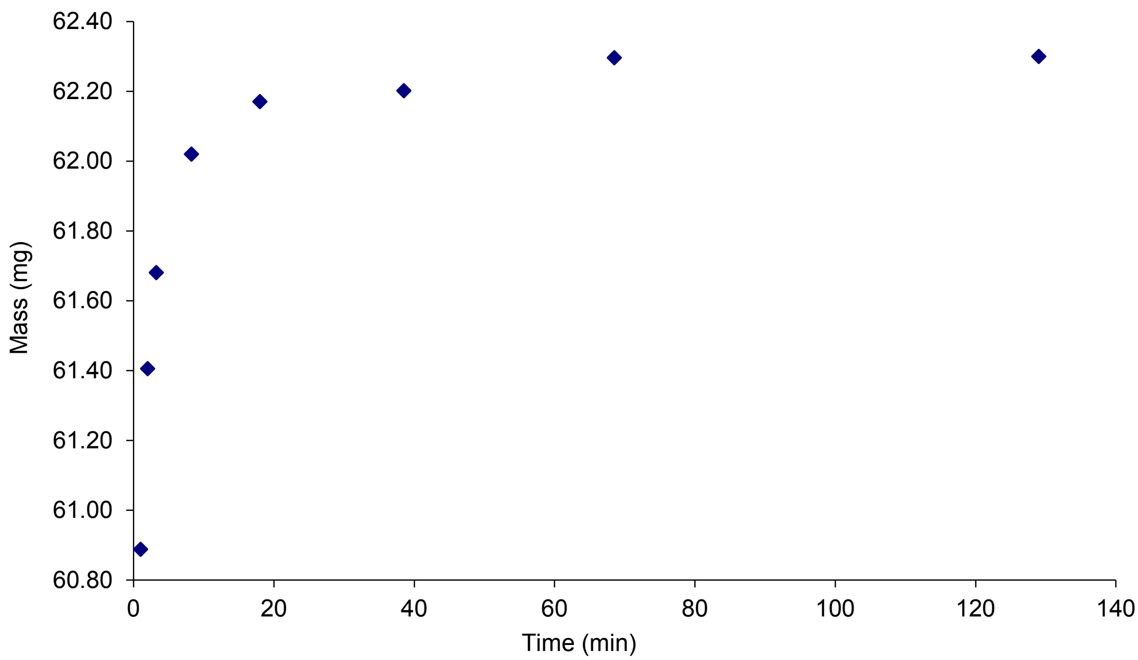


Figure 44. Rehydration curve for PTFE (2-E5-43).

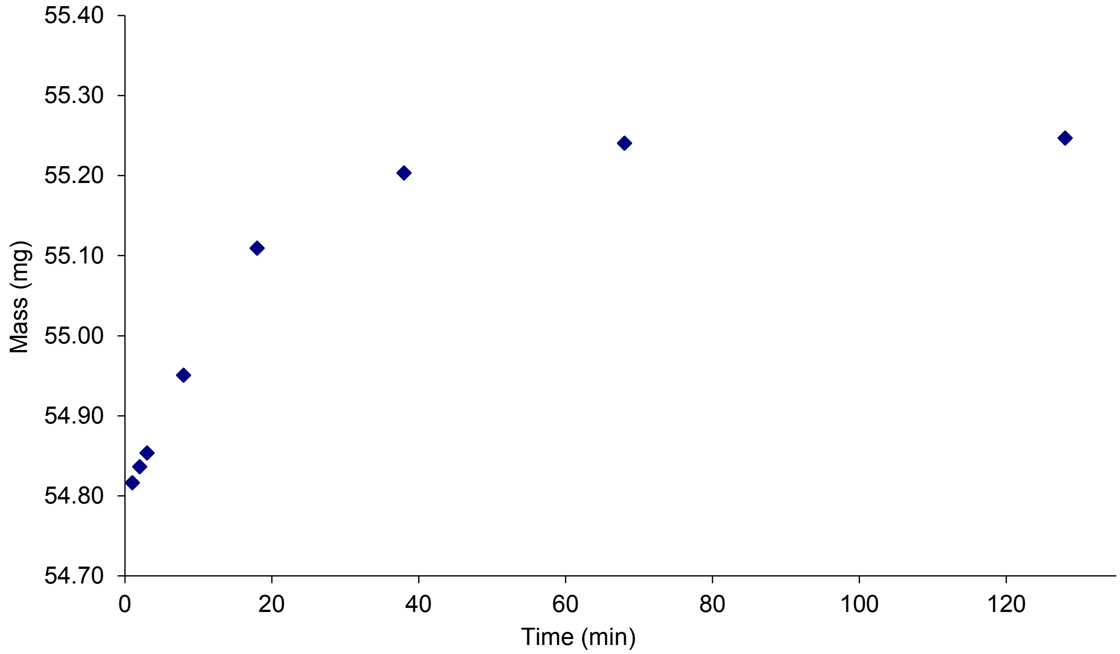


Figure 45. Rehydration curve for PFA (2-E5-44).

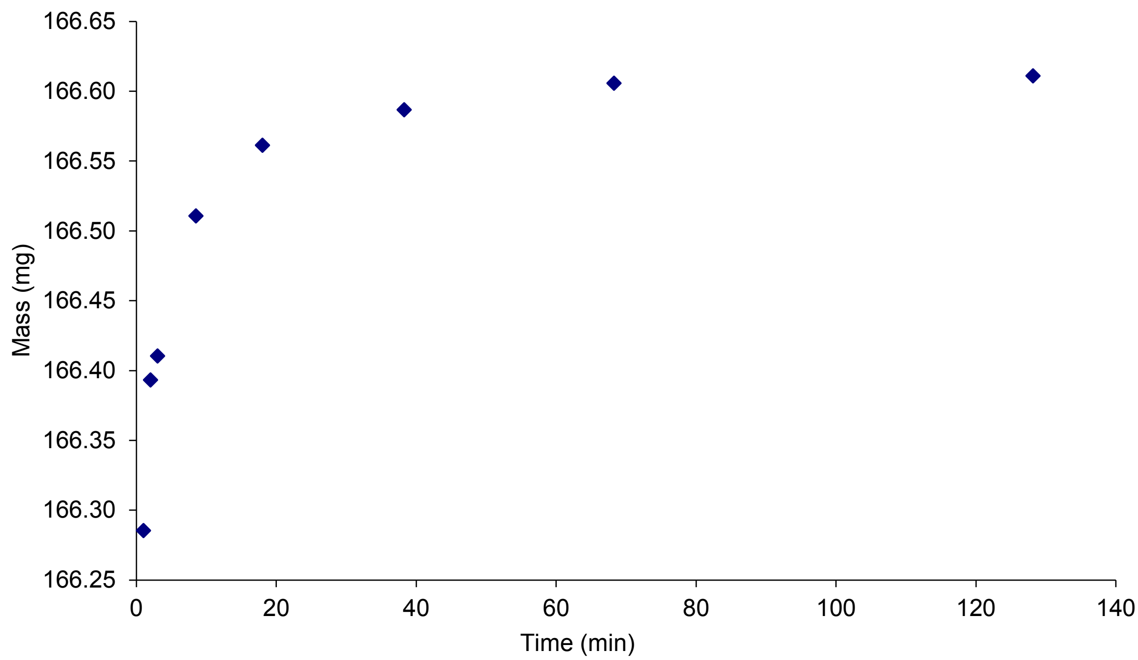


Figure 46. Rehydration curve for Teflon AF (2-E5-45).

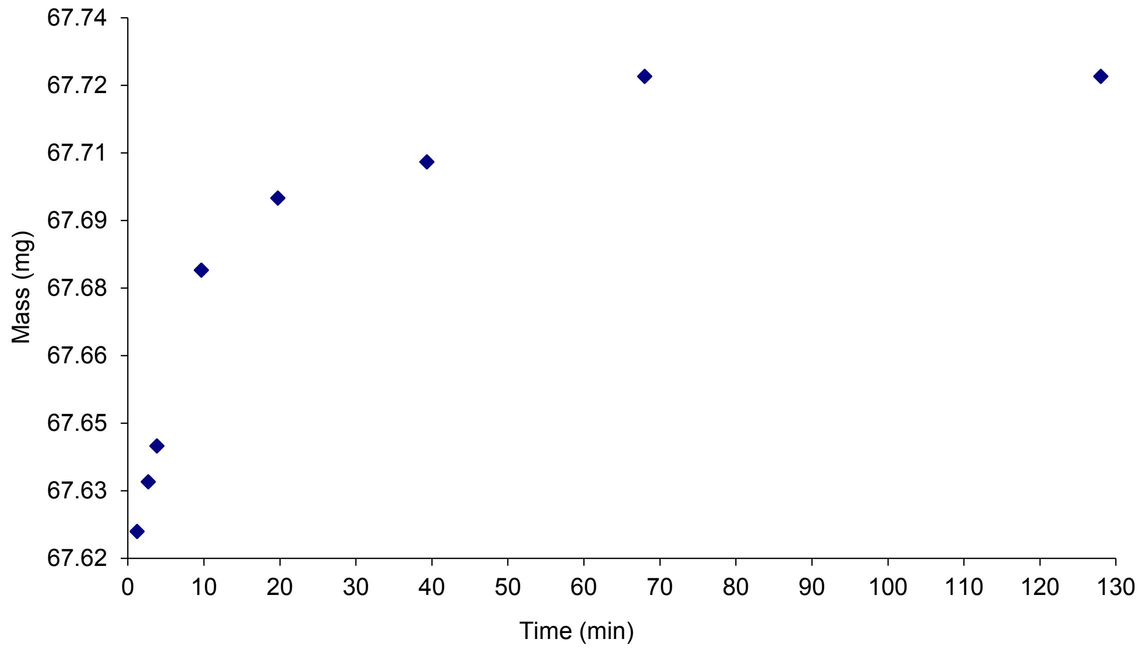


Figure 47. Rehydration curve for PVDF (2-E5-46).

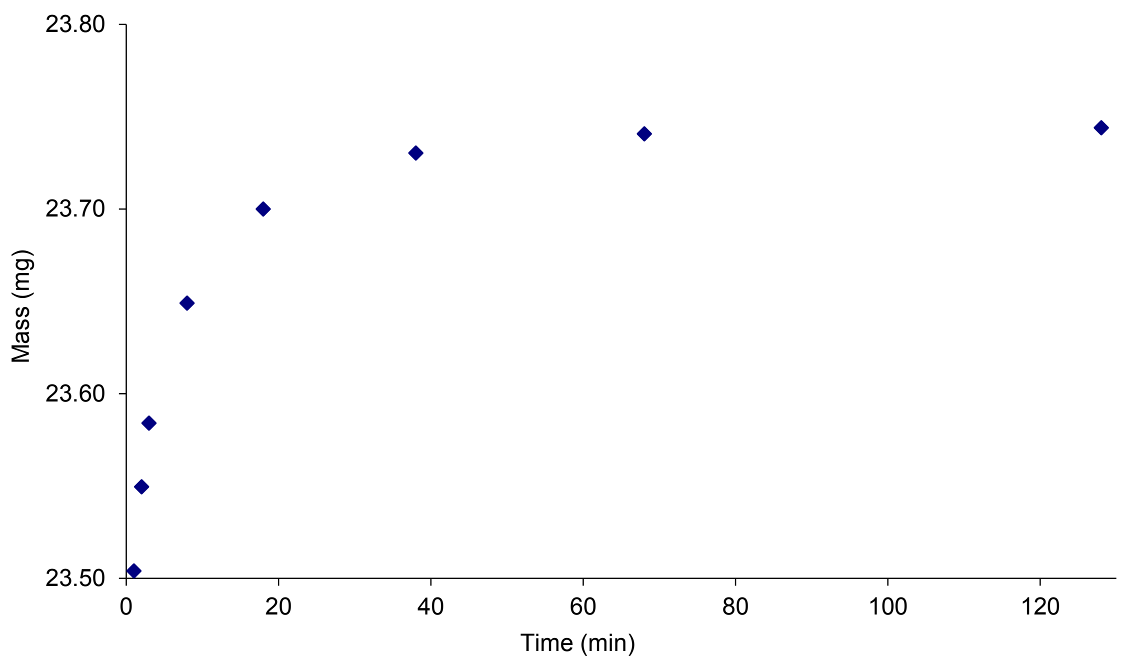


Figure 48. Rehydration curve for CN.

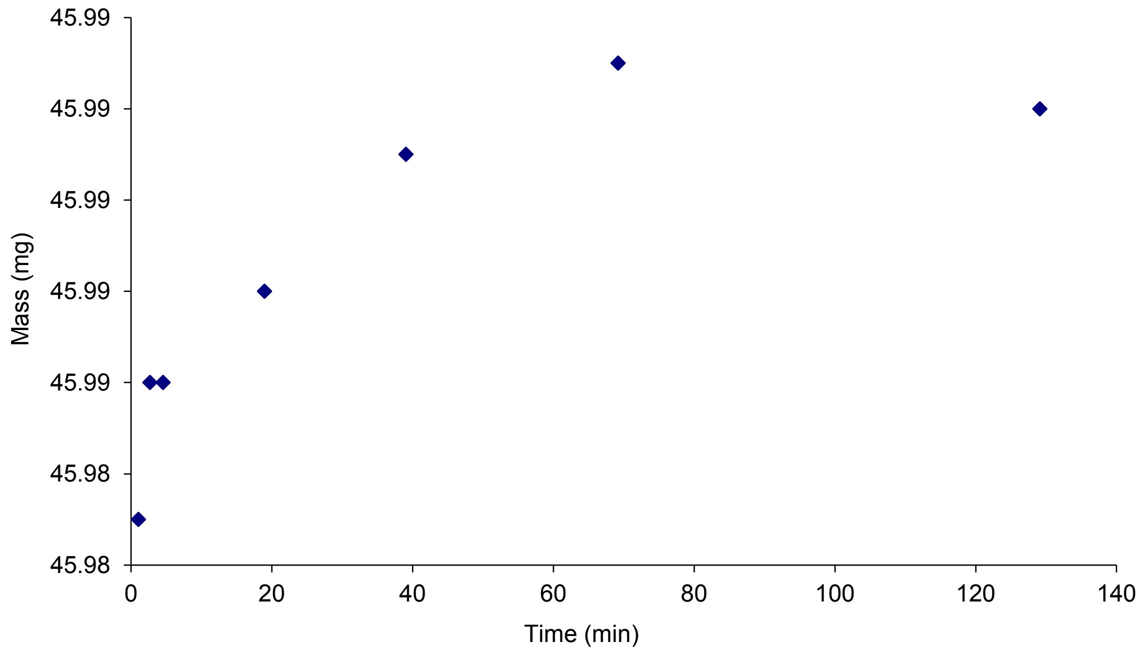


Figure 49. Rehydration curve for Saran.

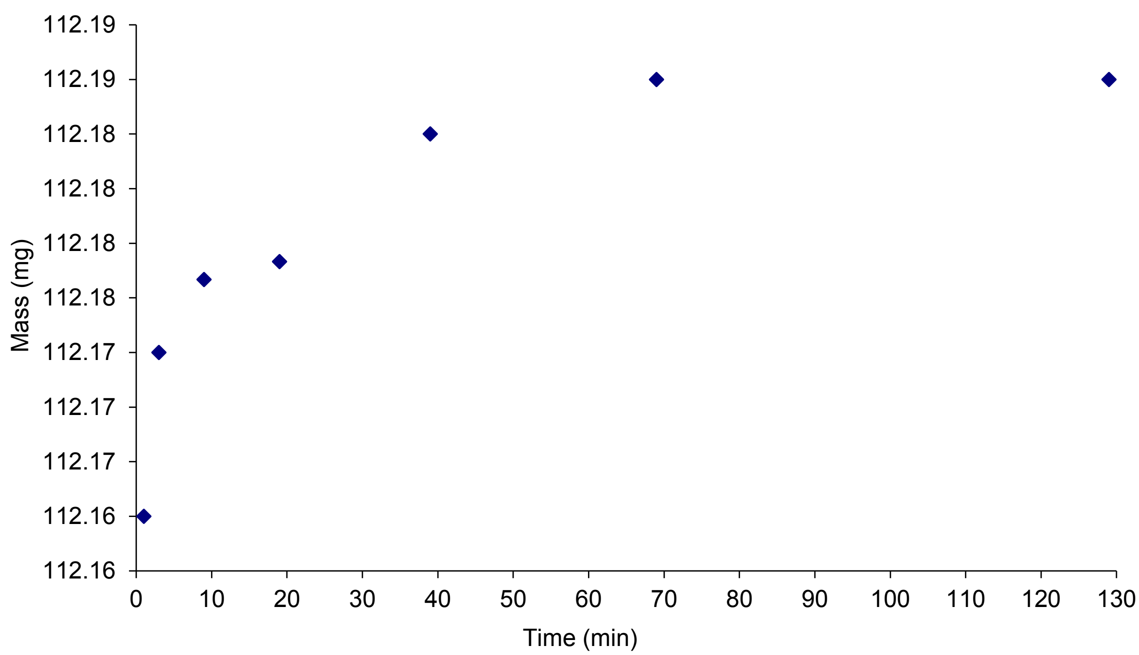


Figure 50. Rehydration curve for UHMWPE.

Using the data from the rehydration curves the pre-flight and post-flight mass procedures for the MISSE 2 PEACE Polymers experiment were developed. Based the data of the Open-Close Trials for Kapton H, it was concluded numerous samples could be dehydrated together with mass measurements made sequentially. The flight samples were dehydrated in a vacuum desiccator maintained at a pressure of 8.0 - 13.3 Pa (60-100 mTorr) with a mechanical roughing pump. Typically, five flight samples and their corresponding back-up samples were placed together in a desiccator (a total of 10 groups of samples). The sets of samples were placed in the desiccator in a particular order and left under vacuum for a minimum of 4 days.

Many of thin film polymers appear to have gained most of their mass within a couple hours based on the rehydration data. But, not all polymers were fully rehydrated in the time period that the data was collected. This was particularly true for both polyamide 6 (PA 6) and polyamide 66 (PA 66). Therefore, it was determined that the flight samples should be dehydrated for a minimum of 4 days (96 hours) to help ensure that the samples were fully dehydrated prior to the mass being obtained. The vacuum desiccator was put under vacuum immediately after a sample was removed to keep the additional samples dehydrated. The time at which the sample was first exposed to air was recorded along with the times at which it was weighed. A total of 3 mass readings were obtained and averaged. The total time it took to obtain the three readings, starting from the time air was let into the desiccator, was typically five minutes. Records of the following were kept: the sequence of sample weighing, the number of samples in each set, the time under vacuum prior to weighing, the temperature and humidity in the room, the time air was let into the desiccator and the time a sample was taken out of the desiccator, the time of each weighing and the mass. The same procedure and sequence was repeated with the same samples post-flight.

Conclusions

The primary objective of the MISSE 2 PEACE Polymers experiment was to determine the AO E_y of a wide variety of polymers exposed to the LEO space environment. The E_y values were determined based on mass loss measurements. Because many polymeric materials are hygroscopic, pre-flight and post-flight mass measurements were obtained using dehydrated samples. To maximize the accuracy of the mass measurements dehydration data for each of the polymers was desired. A comparison of dehydration and rehydration data showed that rehydration data mirrors dehydration data, and is easier and more reliable to obtain. In addition, Open-Close Trial tests were conducted and showed that multiple samples could be dehydrated and tested sequentially, as long as the desiccator was returned under vacuum as soon as a sample was removed.

Rehydration curves of 43 different polymers and pyrolytic graphite were obtained. The polymers displayed a wide range of moisture absorption, hence the hygroscopic nature of the polymers varied greatly. Some of the polymers, such as PP, PVDC and UHMWPE had very little moisture absorption ($\leq$ 0.032%). Pyrolytic graphite had negligible moisture absorption (0.001% mass increase). Fourteen samples had an increase in mass of greater than 1%. And, numerous samples had large moisture absorption ($\geq$ 2%) including PE, PMMA, PPPA, PA 6, PA 66, Upilex-S, PMR-15 and PTFE. The polymer with the greatest mass increase in the duration the data was collected was PBI with a total mass increase of 7.14%. Many of thin film polymers appear to have gained most of their mass within a couple hours based on the rehydration data. But, not all polymers were fully rehydrated in the time period that the data was collected. This information was used to determine the best pre-flight and post-flight mass procedures for the MISSE 2 PEACE Polymers experiment, including dehydrating the samples for a minimum of 96 hours prior to measuring the mass of the samples.

References

1. de Groh, K. K. Banks, B. A. McCarthy, C. E. Rucker, R. N. Roberts L. M. and Berger, L. A., "MISSE 2 PEACE Polymers Atomic Oxygen Erosion Experiment on the International Space Station," *High Performance Polymers 20 (2008) 388-409 (Rev).*
2. NASA Technical Handbook, *Spacecraft Polymers Atomic Oxygen Durability Handbook* (NASA-HDBK-6024), Revalidated 2017. Authors: K. K. de Groh, B. A. Banks and C. E. McCarthy.
3. DuPont, "DuPont Kapton Polyimide Film General Specifications," http://www.dupont.com/content/dam/dupont/products-and-services/membranes-and-films/polyimde-films/documents/DEC-Kapton-general-specs.pdf, accessed February 20, 2018.