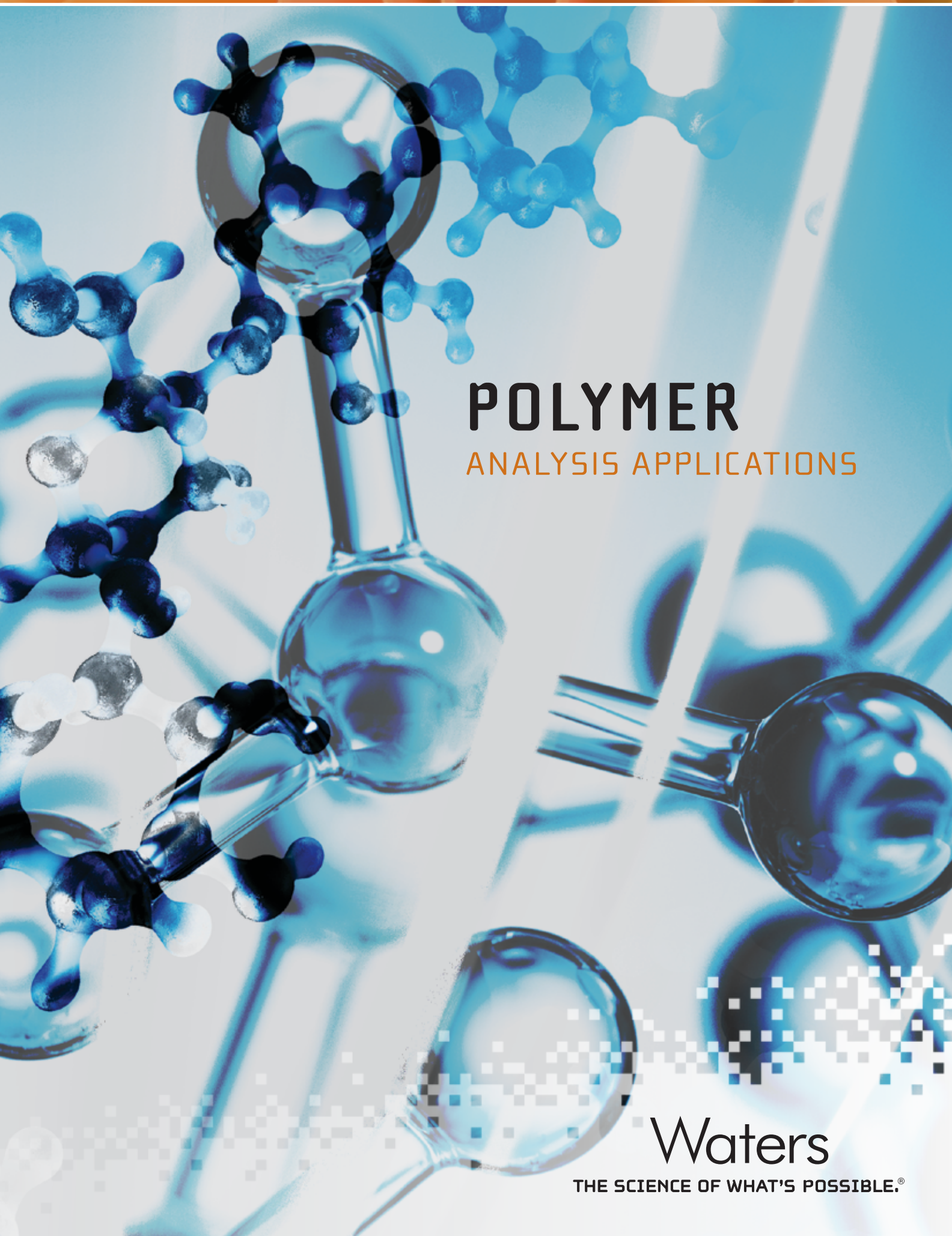

POLYMER

ANALYSIS APPLICATIONS

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ADVANCING POLYMER SCIENCE

INTRODUCTION

Today's polymer manufacturers operate within an increasingly dynamic market space that is fueled by intense competition, complex regulatory considerations, and a true resurgence in polymer development spurred by modern day chemistry. By leveraging the very latest analytical technologies, these science-based organizations are able to accelerate their pursuit of new product innovations, productivity enhancements, and corporate sustainability goals.

Waters unique portfolio of polymer analysis solutions offers capabilities that are simply unparalleled in the industry – allowing laboratories to not only better characterize complex polymer samples, but to improve operational

efficiency and asset utilization. With systems such as Advanced Polymer Chromatography™ (APC™), UltraPerformance Convergence Chromatography™ (UPC^{2}®), and High Definition Mass Spectrometry™, Waters is helping leading-edge scientists advance their understanding of the synthesis, architecture, and functional properties of polymers and polymer additives.

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SEPARATIONS
ADVANCED
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CHROMATOGRAPHY

Efficient Processing of Data for Polymer Analysis Using Empower 3 Software with GPC Option

Jeremy C. Shia, Mia Summers, and Kenneth J. Fountain

GOAL

To demonstrate the efficiency and simplicity of using Empower® Software to process GPC/APC data, calculate the molecular weight parameters, and effectively characterize polymer samples.

BACKGROUND

Empower Software is Waters' compliance-ready chromatography data software (CDS) package for advanced data acquisition, management, processing, reporting, and distribution. It is widely used in many analytical laboratories for applications ranging from pharmaceutical, chemical, food, and environmental analysis. In addition, it offers powerful processing options for gel permeation chromatography for polymer analysis. With recent technological advances in instrumentation, Waters® ACQUITY® Advanced Polymer Chromatography™ (APC™) System combined with the sub-3 µm particle column technology delivers unprecedented high resolution, chromatographic characterization of polymers, and particularly low molecular weight species, faster than ever before.

To illustrate the capabilities of Empower, a polysulfone sample was analyzed using Waters ACQUITY APC™ System with two columns connected in series. The molecular weight calibration was performed using a set of polystyrene standards with narrowly distributed molecular weights. The calibration data were processed and the curve was generated using Empower 3 Software with GPC option. Finally, the molecular weight parameters of this polysulfone sample were automatically measured against the polystyrene calibration curve to characterize the polymer.

A powerful and efficient tool to calculate molecular weight distributions and automatically generate characterization data for polymer samples.

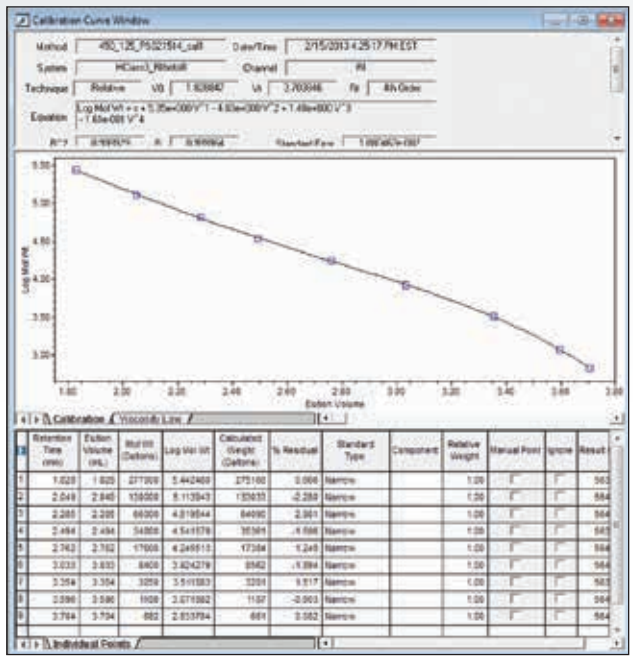

Figure 1. Calibration curve for polystyrene standards generated using Empower 3 Software with GPC option.

THE SOLUTION

There are two ways to calibrate GPC/APC systems: relative and universal. Relative calibration can be achieved by comparing the unknown to a well-characterized polymer with broad molecular weight distribution, or to a set of narrowly distributed polymers. This is typically based on data acquired from various detectors including but not limited to UV, ELSD, RI and CAD. Universal calibration requires the use of molecular weight sensitive detectors, such as a viscometer, low-angle light scattering detector (LALLS), or multi-angle light scattering detector (MALLS). Empower 3 Software with GPC option can accommodate all modes of calibration.

In this example, the calibration of the ACQUITY APC System is illustrated by analyzing a set of polystyrene standards with narrow dispersity. The molecular weights at peak maximum (Mp) of each polystyrene standard are utilized to establish the molecular weights relative to the retention time or retention volume. The creation of the processing method is easily performed using a processing method wizard, or customized integration events can be set manually. Once the data is automatically integrated and quantified, a calibration curve is generated. The polystyrene calibration curve plotting log Mp versus the retention volume is shown in Figure 1.

Once the calibration curve is generated, the sample is processed and molecular weight distributions are calculated and displayed in a conventional Empower data table, as shown in Figure 2. Further data processing using the GPC option in Empower 3 allows users to visualize polymer data in many ways, including molecular weight distribution plots where both dwt/d(logM) and % cumulative versus the slice log MW are displayed in the same graph, shown in Figure 3. Data may be exported, or a report containing any or all of the results (including molecular weights, chromatograms, distribution plots, and calibration curves), can be generated using an existing template or a customizable report template.

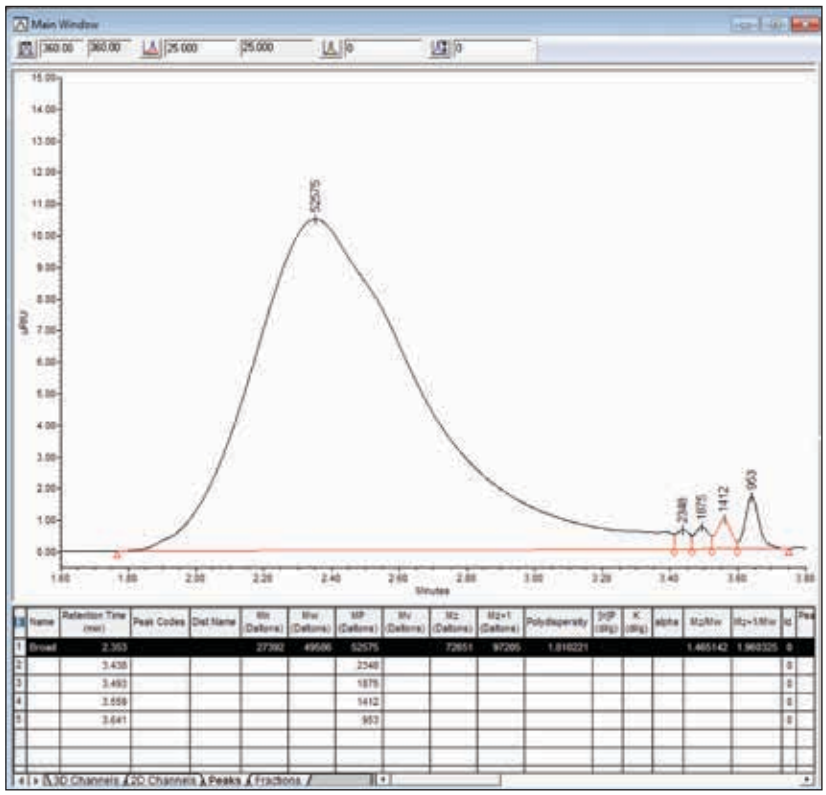

Figure 2. Chromatogram of polysulfone. The molecular weight parameters such as Mw, Mn, Mz, and polydispersity were calculated from a calibration curve generated using a set of narrow polystyrene standards.

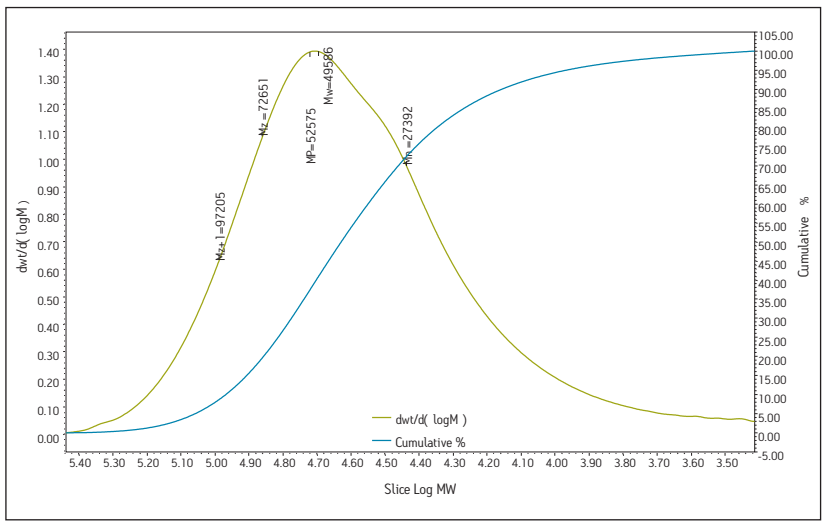

Figure 3. Molecular weight distribution plot of a polysulfone sample that was analyzed using APC XT 450Å and 125Å columns connected in series.

SUMMARY

A set of narrow polystyrene standards and a polysulfone sample were rapidly analyzed using the ACQUITY APC System and processed using Empower 3 Software with GPC option. A relative calibration curve was established based on the polystyrene standard injections, and the polymer was characterized by molecular weight distributions that were automatically calculated by the software. Empower 3 Software with GPC option has proven to be straightforward yet versatile for its capabilities to calculate molecular weight distributions and automatically generate characterization data for polymer samples. Combining the vast capabilities of Empower 3 Software with the GPC option with the analysis speed and resolution of the ACQUITY APC System results in a powerful and efficient tool for the effective characterization of new and existing polymers.

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High-Speed, High-Resolution Analysis of Low Molecular Weight Polymers Using the Advanced Polymer Chromatography (APC) System

Mia Summers and Michael O'Leary
Waters Corporation, Milford, MA, U.S.A.

APPLICATION BENEFITS

- Fast characterization of polymers without sacrificing performance.
- Improved resolution of low molecular weight oligomers compared to conventional GPC analysis.
- Improved calibration for higher measurement accuracy of low molecular weight oligomers compared to conventional GPC analysis.
- Rapid monitoring of polymers to enable earlier detection of changes during the product development process.

WATERS SOLUTIONS

ACQUITY® Advanced Polymer Chromatography™ (APC™) System

ACQUITY APC XT Columns

Waters® Polymer Standards

Empower® 3 CDS with GPC Option

KEY WORDS

Polymer, SEC, GPC, APC, polymer characterization, low molecular weight polymers, oligomers, epoxy resin

INTRODUCTION

Gel permeation chromatography (GPC) is a well-established, informative method for characterizing polymers. However, while a great amount of information can be obtained using this technique, there are inherent limitations to this type of analysis. Columns are frequently styrene-divinylbenzene based and require proper conditioning as well as operation under low back pressures to ensure long-term stability. Particles are typically larger (≥5 µm) and resolution is often compromised as a result. Smaller particle (<5 µm) columns are commercially available and improve the speed of GPC separations, but the speed is limited by their inherently low maximum operating pressures. In addition, the large system volumes of conventional GPC instrumentation require the use of large diameter columns to mitigate the system bandspreading, which can lead to a deterioration in resolution. Waters ACQUITY Advanced Polymer Chromatography (APC) System combines sub-3 µm hybrid particle columns, enhanced system stability, and the capability of accurate flow rates at higher pressures. Additionally, the low overall system dispersion can significantly affect resolution, especially for low molecular weight oligomers. Improved resolution in low molecular weight oligomer separations with shortened runtimes enables rapid monitoring of polymer process development, earlier detection of new polymeric species, and altogether faster commercialization of new polymer products.

In this application note, separations using the ACQUITY APC System will be compared to conventional GPC separations. Faster analysis, improved resolution, and the beneficial effect on calibration of low molecular weight oligomers using a low-dispersion system with sub-3 µm hybrid particle technology columns will be illustrated. The combination of these technologies allows more robust and precise determination of molecular weight parameters for low molecular weight polymer samples. Earlier identification of even subtle changes in a polymer can significantly speed up the development of polymers for chemical and biomaterial applications.

EXPERIMENTAL

Alliance® GPC System Conditions

Detection:	2414 RI
RI flow cell:	35 °C
Mobile phase:	THF
Flow rate:	1 mL/min
Columns:	Styragel 4e, 2 and 0.5, 7.8 x 300 mm (3 in series)
Column temp.:	35 °C
Sample diluent:	THF
Injection volume:	20 µL

ACQUITY APC System Conditions

Detection:	ACQUITY RI
RI flow cell:	35 °C
Mobile phase:	THF
Flow rate:	1 mL/min
Columns:	ACQUITY APC XT 200 Å and two 45 Å, 4.6 x 150 mm (3 columns in series)
Column temp.:	35 °C
Sample diluent:	THF
Injection volume:	20 µL

Data management

Empower 3 CDS

Samples

Waters Polystyrene Standards (100K, 10K, and 1K) at 1 mg/mL

Epoxy resin at 2 mg/mL

RESULTS AND DISCUSSION

To properly characterize polymers using SEC, it is important to generate a calibration curve using appropriate standards to establish the separation range with the columns being used. With long conventional GPC run times of up to one hour (or more), analyses of standards and samples can be quite time-consuming. Since the data generated for samples will be compared against the calibrated standards to determine molecular weight, the accuracy of the standard results is paramount in order to obtain accurate results for the polymer sample. In addition to the long run times inherent in GPC, the large extra-column volume of conventional GPC systems can result in peak bandspreading, reducing the resolution and thus accuracy of the calibration points. The lower dispersion ACQUITY APC System, delivers less bandspreading and the narrow standard peaks are much sharper, compared to the conventional GPC system, as shown in Figure 1. Additionally, combining the low-dispersion of the APC System with robust sub-3 µm APC Column Technology that supports higher flow rate and backpressures also improves resolution for the 1K polystyrene standard, and provides a five-fold reduction in analysis time.

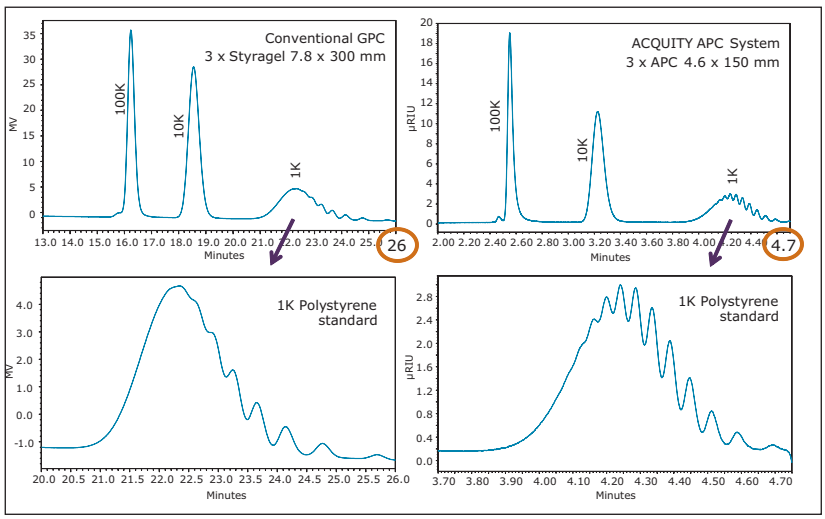

Figure 1. A comparison of run times and resolution for polystyrene standards (Mp: 100K, 10K, and 1K) on a conventional GPC system and the ACQUITY APC System.

The improved resolution delivered by the APC System results in additional identifiable peak molecular weights for the 1K polystyrene standard. Using molecular weight information that may be determined from the standard supplier or from measurements of the standard using external methods, the additional points can then be added to the calibration curve, shown in Figure 2, adding confidence to the sample results calculated relative to this curve.

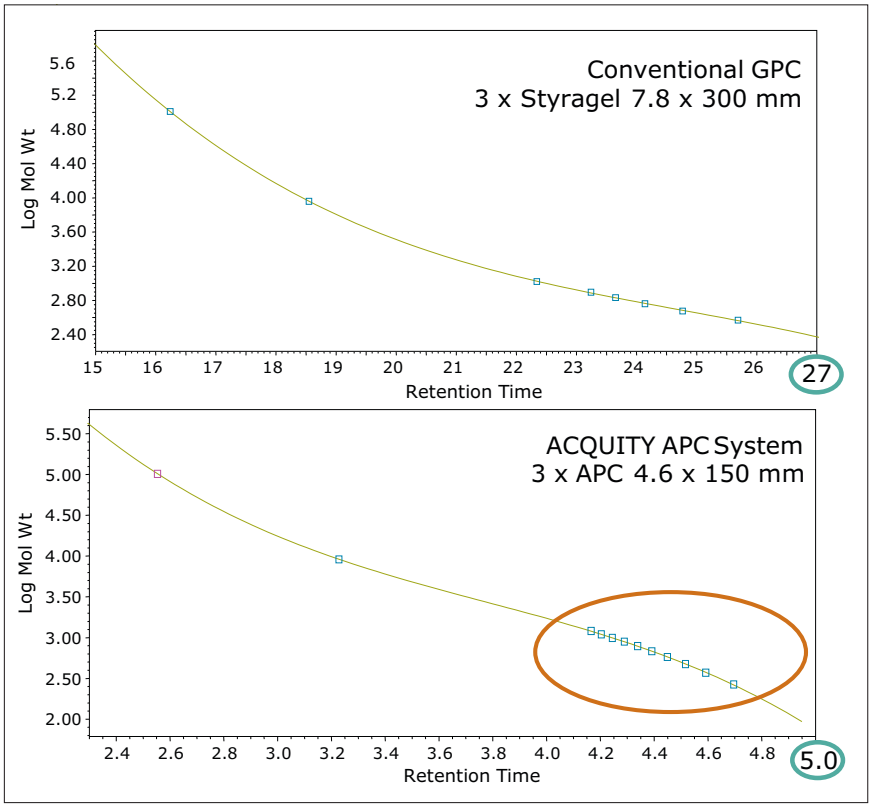

Figure 2. More points on the calibration curve for polystyrene standards (100K, 10K, and 1K) using the ACQUITY APC System, due to improved resolution of the 1K low molecular weight standard.

Typically, a series of standards are run to obtain the points in the calibration curve. With conventional GPC, the equilibration, preparation and analysis of each standard can take hours to days. As a result, the calibration may not be done frequently and results may be based on an 'old' calibration. With the ACQUITY APC System, equilibration is much faster due to the low system dwell volume and the run times are much shorter due to the use of smaller particles at higher flow velocity. Shortened run times allow the equilibration and calibration to be easily completed within one hour. Finally, with the additional resolution, fewer standards may need to be prepared and injected to obtain a robust curve that can be used for calibration.

When a sample is analyzed, the greater robustness of the calibration allows for higher confidence in the molecular weight determinations of the low molecular weight oligomers. The analysis of an epoxy resin sample relative to polystyrene calibration standards is shown in Figure 3. The result shows resolution of oligomers with a run time of less than five minutes using three ACQUITY APC XT 4.6 x 150 mm Columns in series.

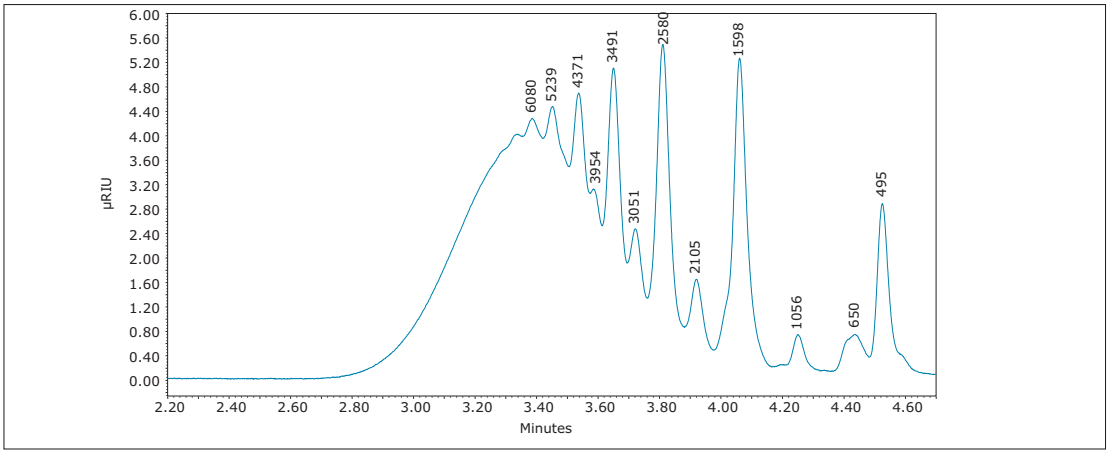

Figure 3. An epoxy resin sample in THF using three ACQUITY APC XT 4.6 x 150 mm Columns in series with ACQUITY RI detection. Resolution of low molecular weight oligomers (shown by peak molecular weights) was achieved in less than five minutes.

The fast run times with APC can benefit reaction monitoring in process development. Increased resolution can facilitate faster identification of changes to the polymer that may occur in synthesis applications or degradation studies. Earlier detection of process changes by monitoring various molecular weights can provide a better understanding of the polymers and expected properties. This can facilitate the development of new polymers and lead to more rapid commercialization.

CONCLUSIONS

The Advanced Polymer Chromatography System provides significant improvements over conventional GPC systems due to lower dispersion in the system and higher backpressure capabilities that allow the use of smaller, hybrid particles. By combining the APC System with advancements in column technology, improved resolution of low molecular weight oligomers is also realized, compared to conventional GPC. APC performance benefits include more robust calibrations, which are essential in generating accurate measurements for polymer characterization. The combination of speed and resolution improvements for low molecular weight polymers allows quick, reliable characterization of polymers in the development process, which can facilitate fast-tracking of new polymers to market.

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Solvent Flexibility for Size-Based Polymer Analysis Using the Advanced Polymer Chromatography (APC) System

Mia Summers, Jeremy Shia, Kenneth J. Fountain
Waters Corporation, Milford, MA, USA

APPLICATION BENEFITS

- Eliminates the need to dedicate and maintain multiple columns in different solvents.
- Fast re-equilibration of the APC™ System and columns for rapid solvent changeover.

WATERS SOLUTIONS

ACQUITY APC™ System

ACQUITY APC XT Columns

Waters® Ready-Cal Polymer Standards

Empower® 3 CDS

KEY WORDS

Polymer, SEC, GPC, APC, polymer characterization, solvent switching, THF, Toluene, DMF

INTRODUCTION

Gel-permeation chromatography (GPC) columns are commonly packed with gel-based stationary phases such as styrene-divinylbeneze or methacrylate polymers. These stationary phases require sufficient conditioning to allow the particles to swell to an appropriate size in the mobile phase solvent that is being used. To ensure proper performance of these columns, the particles are often packed in the mobile phase solvent (or solvent with similar properties) used in the application. Therefore, commercially-available columns of a particular pore size are frequently available for purchase in different solvents. This minimizes any loss of column performance due to changes in the particle properties, should a different mobile phase be used.

There are clear limitations to using gel-based packing materials in chromatographic analysis. Should a change in mobile phase solvent be required, polymer chemists must purchase a new column in the appropriate mobile phase or use an existing column, perform a lengthy equilibration and accept the potential for compromised column performance. In addition, gel-based stationary phases can suffer from mechanical instability at higher backpressures and must be used gently to ensure the particles do not collapse.

Waters Advanced Polymer Chromatography™ (APC) Columns for the analysis of polymers contain high-strength, sub-3 µm hybrid silica particles which are resilient to solvent changes. Since there is little to no swelling of the particle in different solvents, column performance is maintained across the use of many common mobile phases. The versatility of APC Columns enables polymer scientists to analyze their samples in the most appropriate solvent for their application, while minimizing the number of columns in the lab. Using the low-dispersion ACQUITY APC System in combination with robust APC Columns, high backpressures can be accommodated, allowing the use of faster flow rates. This results not only in significant time-savings for polymer sample analysis, but also in considerable resource savings through faster overall system equilibration and by using the same bank of columns for multiple applications.

EXPERIMENTAL

ACQUITY APC System Conditions

Detection:	ACQUITY® RI
RI flow cell:	35 °C
Mobile phase:	THF, Toluene, or DMF with 10mM LiCl
Flow rate:	1 mL/min
Columns:	ACQUITY APC XT 450 Å, 4.6 x 150 mm 2.5 µm (single) ACQUITY APC XT 450Å and 125Å, 4.6 x 150 mm 2.5 µm (in series)
Column temp.:	35 °C
Sample diluent:	THF, toluene, or DMF with 10 mM LiCl
Injection volume:	20 µL
Data management:	Empower 3 CDS

Sample preparation

Standards:	Waters Polystyrene ReadyCal Standards Kit (p/n WAT058931) at 1 mg/mL
Samples:	Polystyrene 180K narrow sample at 1 mg/mL in THF, poly(methyl methacrylate co ethyl acrylate in THF, poly(9,9 di-n-fluorenyl 2,7-diyl) in toluene, poly(bisphenol A co epichlorohydrin) in DMF with 10 mM LiCl

RESULTS AND DISCUSSION:

Traditional columns for polymer analysis commonly consist of polymeric stationary phases, such as polystyrene cross-linked with divinylbenzene. These require proper equilibration in the mobile phase to allow the particles to swell to their final size. As the particles swell, they are less stable and require gentle packing and running pressures to ensure long-term stability of the columns. Changing mobile phase solvents is generally discouraged, since the particles may swell differently in alternate solvents and alter the packing efficiency and long-term reproducibility of the columns. If a change in mobile phase solvent is required, a lengthy transfer and equilibration process is employed. The new solvent is typically run at very low flow rates, ramped up slowly to the operating flow rate, and flowed for an extended period of time to ensure thorough equilibration of the particles in the new mobile phase. Rather than perform this time-consuming procedure, new columns may be purchased and shipped in the mobile phase solvent of anticipated use. However, the necessity to purchase several columns, each in different solvents is cumbersome and expensive. Adding to the expense is the fact that columns are commonly connected in series for polymer analysis which means that multiple column sets in various solvents are needed for the analysis of polymers with different solvent requirements.

The use of hybrid silica particle columns in Advanced Polymer Chromatography (APC) allows chromatographers to select their ideal mobile phase for polymer analysis. Compared to polymeric stationary phases, hybrid silica particles are not prone to swelling and shrinking, allowing users to easily switch between different mobile phase solvents for reproducible results time after time. In addition, the use of high strength hybrid silica particles allows for high flow rates to be used, enabling chromatographers to take advantage of the faster runtimes, better peak shape, and resolution that the APC System offers.

To illustrate the solvent flexibility of the ACQUITY APC Columns, a comparison of the elution profiles for a narrow dispersity polystyrene sample across three mobile phases (THF, toluene, and DMF) is shown in Figure 1.

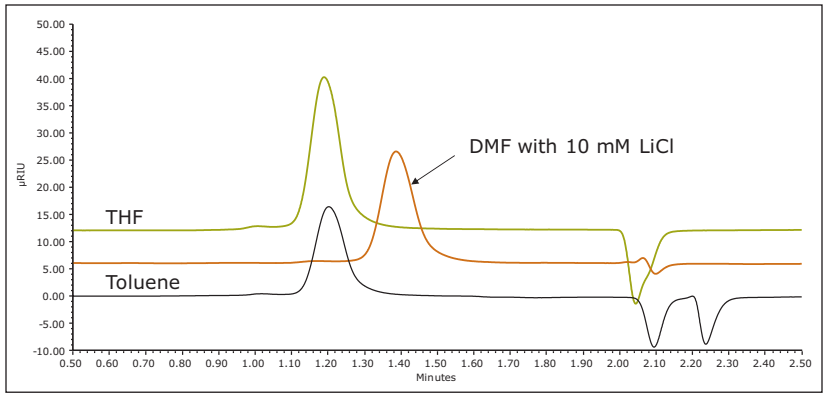


Figure 1. Comparison of elution of a polystyrene narrow sample using three different solvents (THF, toluene, and DMF) on an ACQUITY APC XT 450 Å 2.5 µm, 4.6 x 150 mm Column. Differences in elution times result from varying analyte characteristics in the different solvents.

For each solvent system, a calibration curve was generated using Waters ReadyCal Standards that were prepared in the respective solvents, shown in Figure 2.

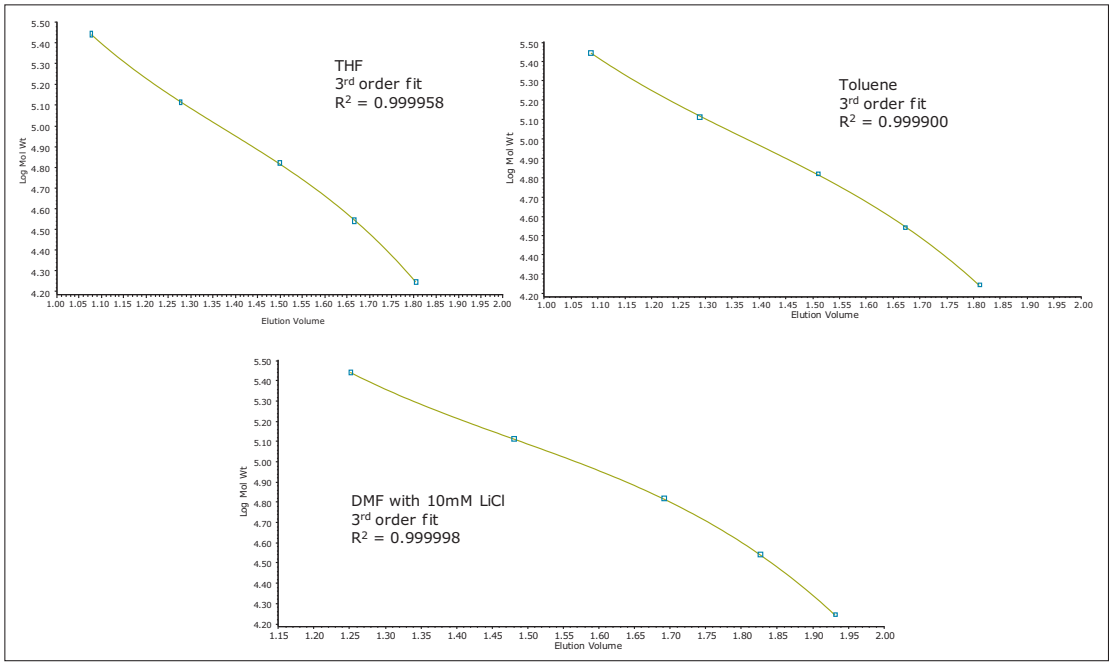


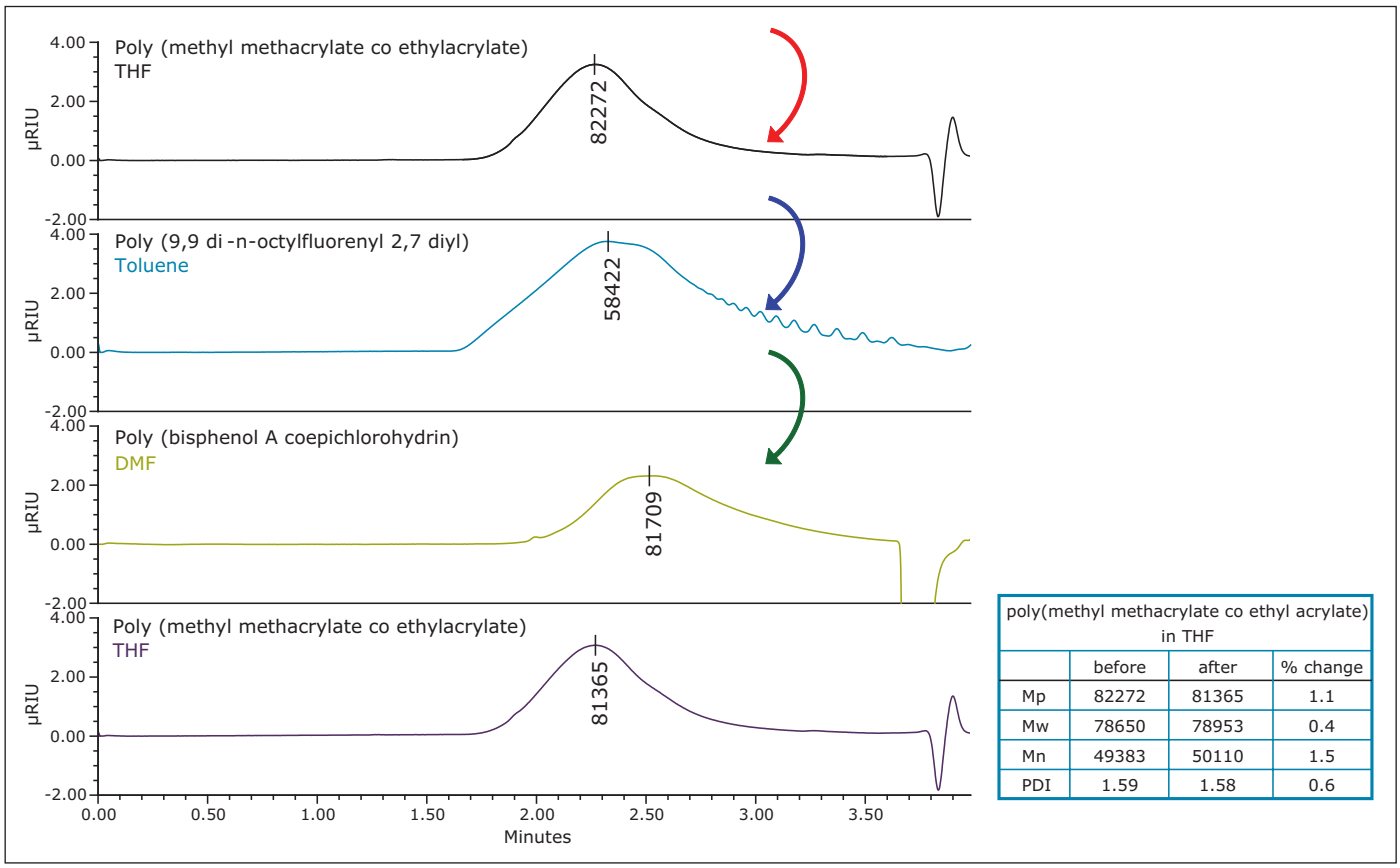
Figure 2. Comparison of polystyrene calibration curves (MW range: 17.6 K to 277 K) on the same ACQUITY APC XT 450Å 4.6 x 150 mm Column across different solvents (THF, toluene, and DMF) showing excellent fit in different solvents.

Solvent	Injection	Mw	Mn	PD
THF	1	170093	162305	1.05
THF	2	169765	162011	1.05
THF	3	170014	161989	1.05
	Average	**169957**	**162102**	**1.05**
	%RSD	**0.1**	**0.1**	**0.1**
Toluene	1	171228	167118	1.02
Toluene	2	170293	165109	1.03
Toluene	3	170771	166117	1.03
	Average	**170764**	**166115**	**1.03**
	%RSD	**0.3**	**0.6**	**0.3**
% Change compared to THF		**0.5**	**2.5**	**-1.9**
DMF	1	167856	163697	1.03
DMF	2	166593	161292	1.03
DMF	3	167501	163111	1.03
	Average	**167317**	**162700**	**1.03**
	%RSD	**0.4**	**0.8**	**0.4**
% Change compared to THF		**-1.6**	**0.4**	**-1.9**

Table 1. Comparison of Mw, Mn, and polydispersity (PD) measurements for a narrow dispersity polystyrene sample across three different solvents (THF, toluene, and DMF) on a single ACQUITY APC XT 450 Å 2.5 µm, 4.6 x 150 mm Column.

The narrow polystyrene sample was tested against the calibration curves and molecular weights (Mp, Mw, Mn) and polydispersity (PD) were calculated and compared for each solvent system, described in Table 1. All of the measurements showed good precision and accuracy on the ACQUITY APC System using the APC Column. For each molecular weight measurement, %RSD was <1 for triplicate injections and % change in molecular weight measurements of <3% were observed across the three different solvents systems used.

A separate example of the reproducibility of molecular weight results obtained for a polymer sample, after changing mobile phase solvents on the same bank of columns is shown in Figure 3. In this case, a two-column bank of 450 Å and 125 Å ACQUITY APC XT Columns in series was used. The columns were first equilibrated in THF and a sample of poly(methyl methacrylate co ethylacrylate) was tested to obtain molecular weight information including Mp, Mw, Mn, and polydispersity (PD), relative to a polystyrene calibration performed in THF. Next, using the same bank of columns on the ACQUITY APC System, the solvent was changed to toluene, primed, and equilibrated. A new polystyrene calibration was performed in toluene and a sample of poly (9,9 di-n-octylfluorenyl 2,7-diyl) was tested. The ACQUITY APC System and same column set were then changed to N,N-dimethylformamide (DMF) containing 10 mM LiCl for the analysis of poly(bisphenol-A co epichlorohydrin). Finally, the system was returned back to THF, a new polystyrene calibration was performed and poly(methylmethacrylate co ethylacrylate) was re-analyzed. Molecular weight results were compared before and after the solvent changeover. An overall difference of <2% was seen when comparing the results of poly(methylmethacrylate co ethylacrylate) in THF before and after the solvent changeover, demonstrating the high robustness of the particles after exposure to various solvent environments. Traditionally, this application may have taken days to complete, using multiple solvent-dedicated column sets. With the APC System, solvent changes can be performed in a matter of hours using the same set of APC Columns.



poly(methyl methacrylate co ethyl acrylate) in THF			
	before	after	% change
Mp	82272	81365	1.1
Mw	78650	78953	0.4
Mn	49383	50110	1.5
PDI	1.59	1.58	0.6

Figure 3. Repeatable analysis of poly (methyl methacrylate co ethylacrylate) on the APC system, using the same two APC 4.6 x 150 mm columns (450 Å and 125 Å) in series after switching solvents from THF to toluene to DMF and back to THF.

CONCLUSIONS

Changing solvents in polymer analysis is a seldom performed practice due to current limitations of gel-based stationary phases. However, the hybrid silica particles packed in APC Columns allow the use of different mobile phase solvents without concern of swelling and shrinking of particles. This results in a repeatable, robust analysis of polymers on the same columns, even after exposure to different solvent environments. Further, the low-dispersion, high backpressure capability of the APC System ensures fast equilibration of the column and system in the appropriate solvent. The ACQUITY APC System combined with ACQUITY APC Columns allows polymer scientists the versatility to rapidly analyze their polymers in the ideal solvent for their application without the cost of maintaining multiple columns sets.

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UPC²/MS for Characterization of Complex Oligomeric Materials

Baiba Čabovska and Michael O'Leary
Waters Corporation, Milford, MA, USA

APPLICATION BENEFITS

- ACQUITY UPC²® can analyze more thermally labile and higher molecular weight polymers than GC.
- ACQUITY UPC² is compatible with polar and non-polar polymers.
- Supercritical fluid mobile phase and sub-2-µm particle stationary phases shorten retention times for large molecular weight compounds.
- ACQUITY UPC² reduces the use of toxic solvents in comparison with normal phase LC.
- MS provides complimentary information to UV data, which can be useful for characterization of individual oligomers, impurity determination, and formulation analysis.

WATERS SOLUTIONS

ACQUITY UPC² configured with PDA and ACQUITY® SQD

ACQUITY UPLC® HSS Column

ACQUITY UPC² BEH Column

Empower® 3 CDS

KEY WORDS

Polymers, UPC², supercritical fluids, SFC, polystyrene, PMMA, convergence chromatography, oligomers

INTRODUCTION

The most common polymer analyses use gel permeation chromatography (GPC) to determine average molecular weight and polydispersity. However, when high resolution separations for individual oligomers are required to evaluate the material performance or understand polymer structure, other analytical techniques are used.[1-4] Low molecular weight polymers can be analyzed by liquid chromatography (LC), gas chromatography (GC), and supercritical fluid chromatography (SFC) among others. The choice of separation technique usually is defined by solubility, average molecular weight, and thermal stability of the polymer. Waters® UltraPerformance Convergence Chromatography™ (UPC²®), the next step in the evolution of SFC, offers several advantages for the separation of complex oligomeric materials. Due to the low viscosity of supercritical carbon dioxide in comparison with liquids, higher flow rates can be used, which results in shorter analysis times than LC. Convergence chromatography operates at lower temperatures than GC, which is beneficial for the analysis of thermally labile material. Furthermore, UPC² can separate higher mass, non-volatile oligomers than GC. Another advantage is the use of sub-2-µm particle columns which provide more theoretical plates and better resolution than traditional SFC. If the polymer has a chromophore, UV detection can be used. If information about isomer molecular weight is needed, a mass spectrometer (MS) can be used as the detector. UPC² can be interfaced with both UV and MS detectors.

The simplest types of polymers are addition polymers. They are formed by sequential addition of monomer units without a loss of any molecules. Condensation polymers are formed in a condensation reaction between two or more different monomers, where individual molecules bind together and expel a by-product such as water. During polymerization reactions the individual molecules can attach to each other not only linearly but can also form branched isomers. Due to their ability to form various isomers, their separation and characterization can be challenging. In addition, degradation products and by-products can be formed under polymerization conditions which need to be characterized. The performance of polymeric materials can be affected by the isomer and oligomer distribution.

In this application note, we investigated various addition polymers, polystyrenes (PS) and polymethylmethacrylates (PMMAs), to evaluate the separations range of UPC². This knowledge was then applied to the analysis of condensation co-polymers, bisphenol A- formaldehyde condensation polymer (PBAA) and poly[(phenyl glycidyl ether)-co-formaldehyde] (PGEF), using MS and UV detection.

EXPERIMENTAL

Sample preparation

All polymer samples were dissolved in tetrahydrofuran (THF) at a concentration of 10 mg/mL.

UPC² conditions

System:	ACQUITY UPC² with PDA and ACQUITY SQD
Mobile phase A:	CO_2 (food grade)
Mobile phase B:	0.3% ammonium hydroxide in methanol
Column temp.:	60 °C
Injection volume:	1.0 µL
MS ionization:	ESI (+ or - depending on sample)
MS scan range:	150 to 2000 *m/z*
Capillary:	1 kV
Cone:	25 V
Make-up solvent:	0.3% ammonium hydroxide in methanol
ABPR:	see specific sample
Flow rate:	see specific sample
Vials:	Clear Glass 12 x 32 mm Screw Neck Vial, 2-mL volume
Data management:	Empower 3 CDS

RESULTS AND DISCUSSION

Various molecular weight polystyrenes and PMMAs (Figure 1) were evaluated on sub-2-µm particle size columns for UPC². Figure 2 shows the separation of three different polystyrenes. Separation of all oligomers for PS-1000 and PS-1300 was achieved in less than 2.5 minutes. However, only partial separation for PS-2500 was attained. As molecular weight increases, the complexity of the polymer increases so that baseline resolution is no longer achieved.

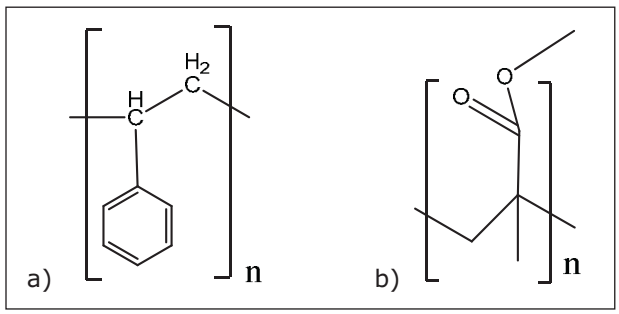

Figure 1. Structures for: a) polystyrene and b) PMMA.

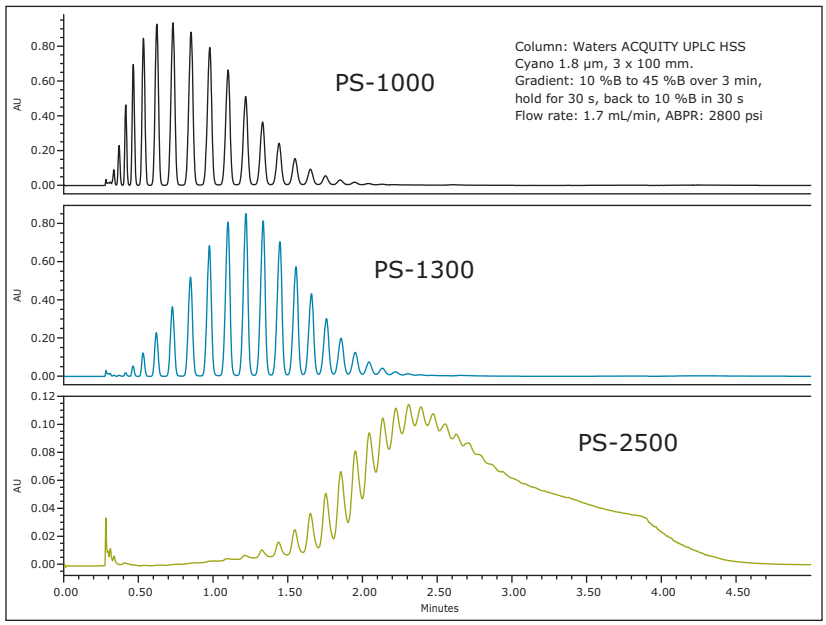

Figure 2. UV chromatograms showing separations for three different polystyrenes.

It was possible to resolve higher mass PMMA oligomers than polystyrene, as shown in Figure 3. As the average molecular weight of polymer increases, the retention time for complete elution goes up as well. The molecular weight range of polymers that can be analyzed by UPC^2 will depend on the solubility of the sample in CO_2, the type of polymer, and the length of run time the analyst is willing to accept for the separation to be achieved. Higher molecular weight polymers generally require a higher percentage of organic modifier to elute off the column. However, increasing the organic modifier percentage increases the back pressure. Keeping the back pressure within an acceptable range requires the flow rate to be decreased, which ultimately can extend the run time.

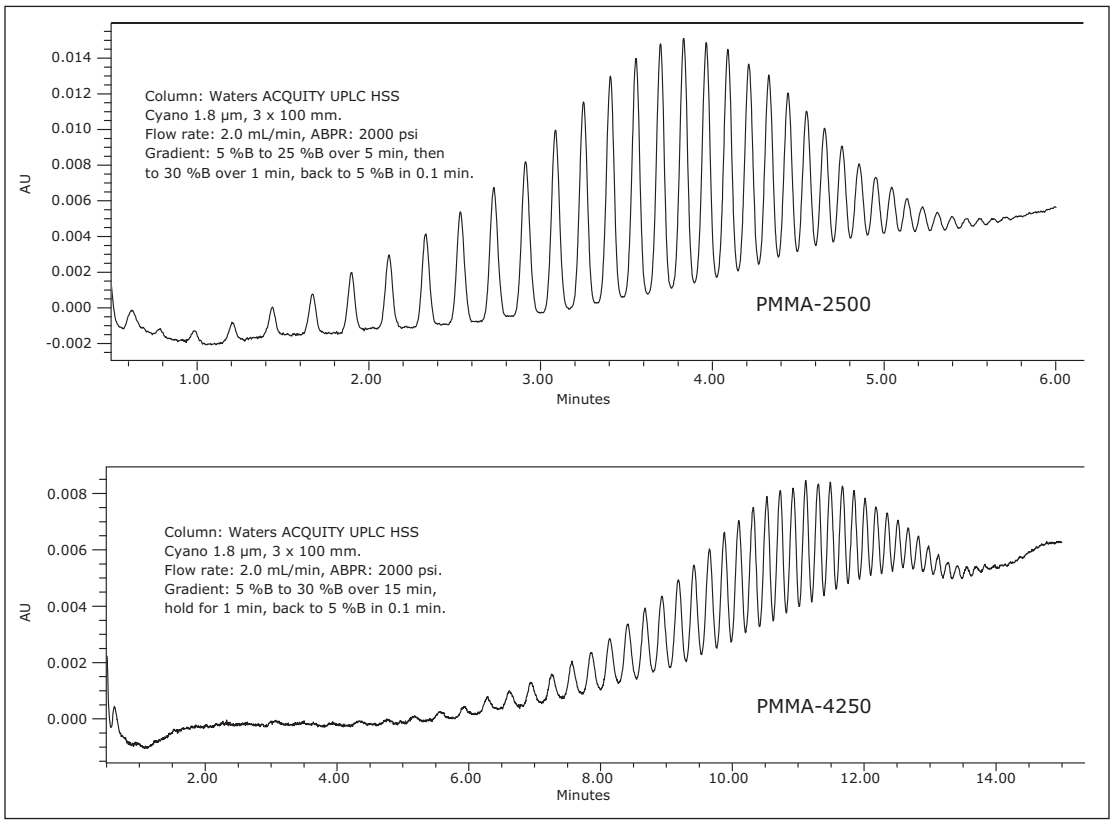

Figure 3. UV chromatograms for PMMA separation.

Case study 1

Examples of the value of UPC^2 in polymer analysis are demonstrated in the following two case studies. The first one involves the analysis of bisphenol A- formaldehyde condensation co-polymer (PBAA), shown in Figure 4. The co-polymer is formed by addition of polybisphenol A to formaldehyde and expelling a water molecule in the process. Analyzing PBAA, the expected dimer, trimer, and subsequent oligomer peaks were observed. However, an additional large peak was observed at the retention time of 0.7 minutes with *m/z* 227 (Figure 5). The starting compounds for the polymer were bisphenol A and formaldehyde. *m/z* 227 (ESI-) corresponds to the bisphenol A molecular ion $[M-H]^-$.

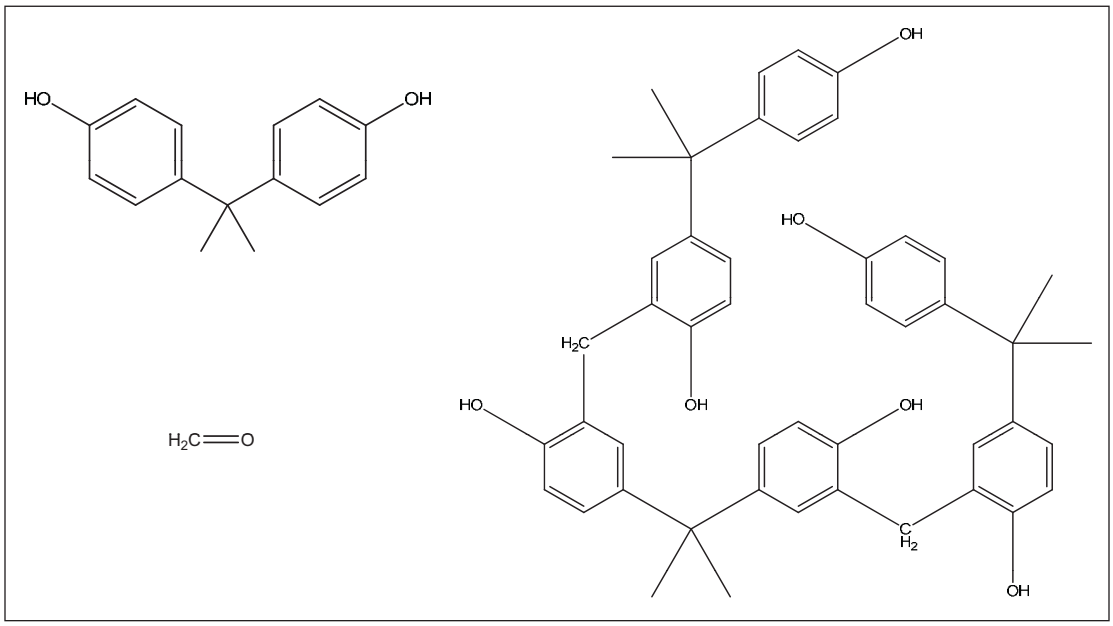

Figure 4. Structures for bisphenol A, formaldehyde, and a trimer of their co-polymer.

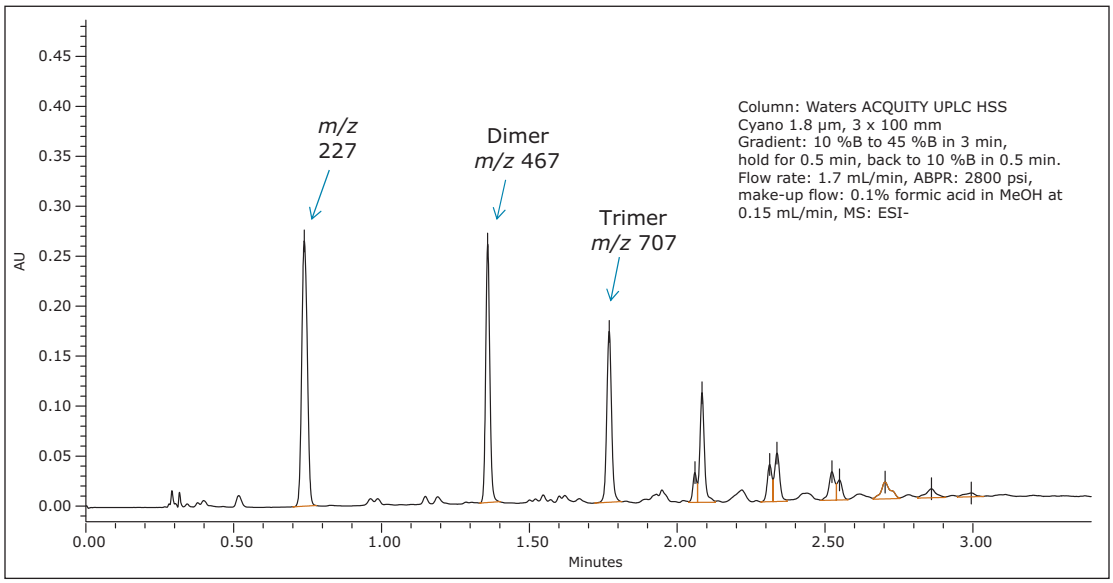

Figure 5. PBAA separation.

Confirmation of the unreacted bisphenol A was performed by UV and MS detection with an authentic standard (Figure 6). The retention time of bisphenol A standard corresponded to the unknown peak in the polymer sample. Also, the MS spectrum of bisphenol A matched the spectrum for the peak of interest. Additional confirmation was provided by the formic acid adduct also seen in the mass spectrum.

In this case, MS provided valuable information about an unreacted starting material in the polymerization reaction. This analysis method could be used in reaction monitoring to ensure complete utilization of the starting materials.

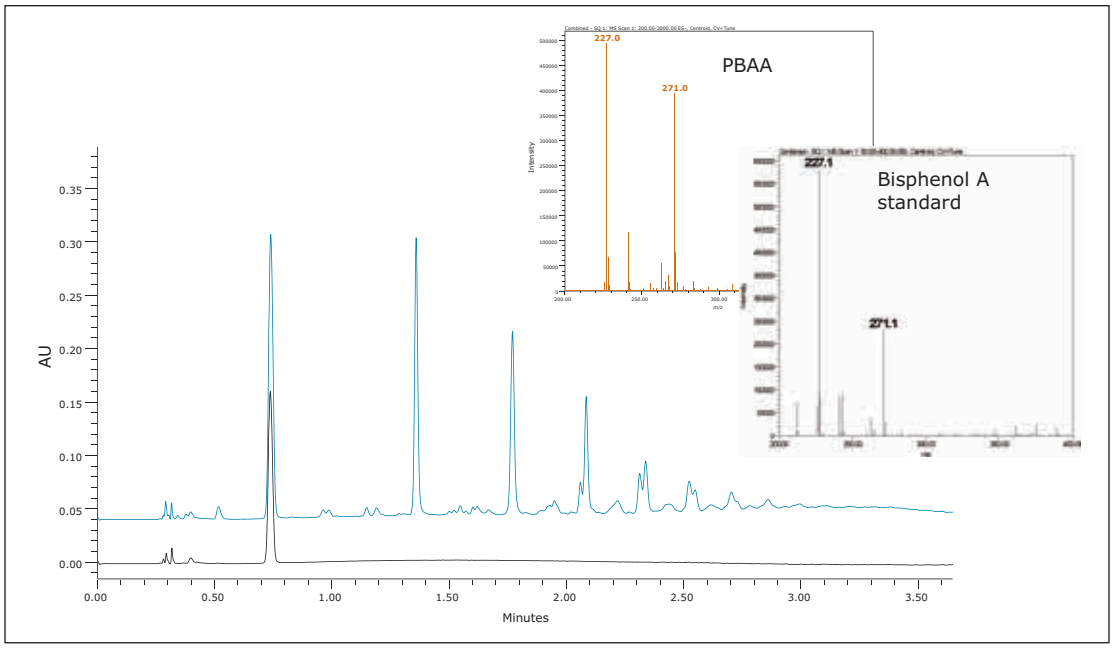

Figure 6. Confirmation for m/z 227 at the retention time of 0.7 minute. Black UV trace-bisphenol A standard 0.1 mg/mL, blue UV trace-polymer sample with unreacted bisphenol A.

Case study 2

The second test case involved analysis of poly[(phenyl glycidyl ether)-co-formaldehyde] (Figure 7). As shown in Figure 8, a separation for individual isomers was easily achieved for dimers. Based on the starting molecule's structure, there are three possible positions for the attachment of the next unit. For the dimer that means six different isomers can be present in the sample – only three were observed. For the trimers and subsequent oligomers, the possible structures increased exponentially. In the current separation, seven individual trimers were resolved.

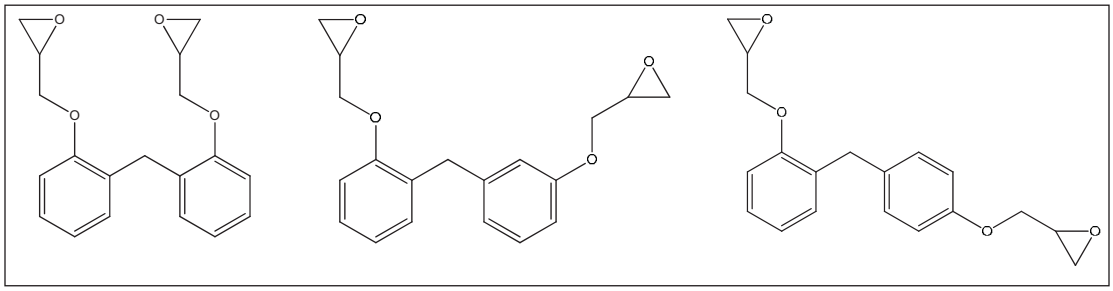

Figure 7. Representative structures for PGEF dimers.

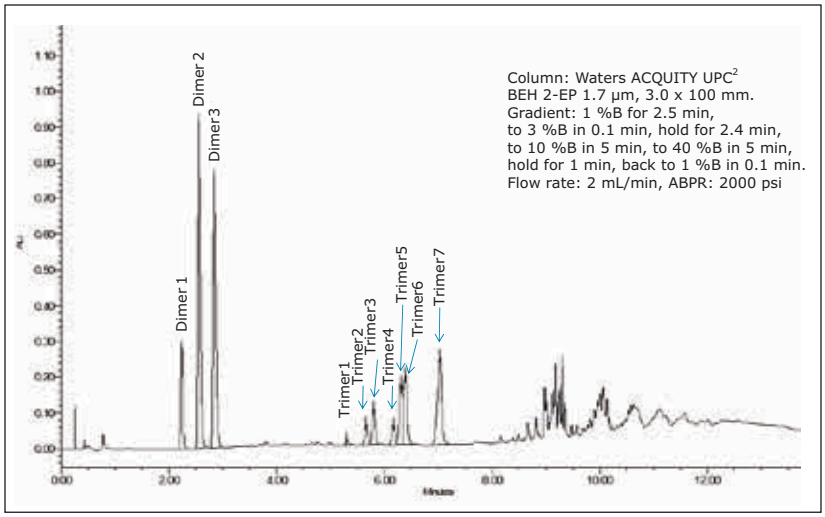

Figure 8. UV chromatograms for the separation of PGEF co-polymer.

When looking at the total ion chromatogram (TIC) from the same separation (Figure 9), additional peaks were seen between the dimers and trimers. The observed *m/z* ratios of the clusters were 404 and 402. These masses can result from changes in phenyl glycidyl ether with either loss of a glycidyl ether chain or with opening of an ether ring (Figure 10). Subsequent oligomers containing the described degradation units appeared between trimers and tetramers as well.

Since these degradation isomers were present in the sample at a much lower concentration than dimers and trimers, they would have been missed by UV detection.

In this case, UPC^2 with MS detection provided detailed information about isomers present in the polymer sample. Data about degradation products present in the sample allow adjusting of polymerization reaction conditions to avoid the loss or change of glycidyl ether chain. The analyst can isolate individual isomers and analyze by structural ID methods like NMR to identify the exact location of bonds if needed.

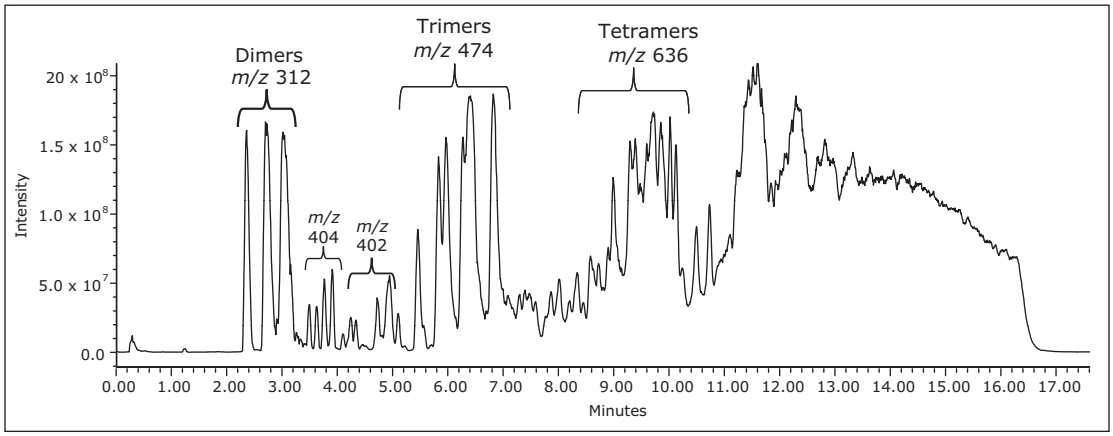

Figure 9. TIC for the separation of PGEF co-polymer.

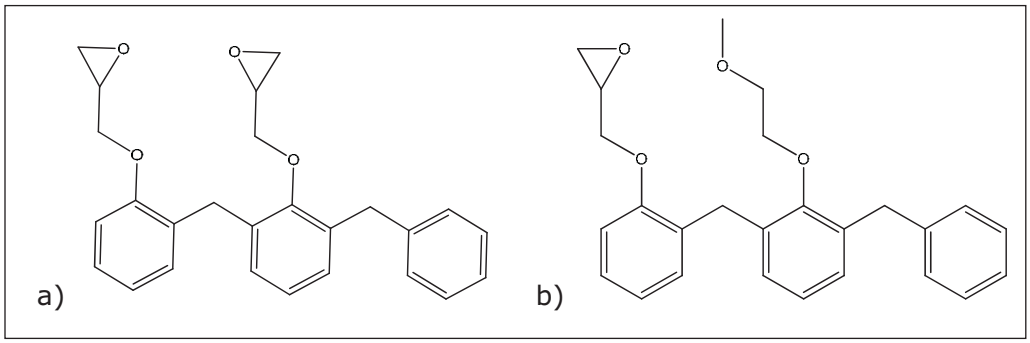

Figure 10. Proposed structures for a) m/z 402 and b) m/z 404.

CONCLUSIONS

UPC^2/MS is a very powerful tool for characterization of complex oligomeric materials. A wide selectivity space is beneficial for the separation of similar compounds like isomers of polymer oligomers. Additional advantages include compatibility with polar and non-polar polymers, lower analysis temperatures, and higher mass range than GC. The use of supercritical fluid mobile phase shortens retention times for large molecular weight compounds in comparison to LC. The addition of detection by MS provides complementary information to UV data, which can be useful for reaction monitoring, characterization of individual oligomers, impurity determination, and formulation analysis.

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ACQUITY UPLC/SQD ANALYSIS OF POLYMER ADDITIVES

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INTRODUCTION

Typical polymer additives include light and heat stabilizers, UV absorbers, antioxidants, fillers, plasticizers, biocides, colorants, and mold release agents. They are used for processing polymer resins and improving the properties of polymer and plastic products. Improper uses of additives can result in product failure. To ensure product quality, accurate and reliable polymer additive analysis methods are required.[1-5]

Recent discoveries indicate that some polymer additives appear to have carcinogenic and estrogenic properties.[6-8] Due to the widespread use of polymers for food packaging and medical devices, analysis of possible polymer additive leaching into food, medicine, and environment is needed. Typical separation time using conventional HPLC is approximately 20 to 40 minutes.[9-13]

This application note describes a three-minute method for identifying a mixture of 11 polymer additives using Waters® UPLC® with a bench top single quadrupole mass spectrometer, the ACQUITY UPLC® SQD System. ACQUITY UPLC employs high-pressure fluidic modules, novel small column particles and very low system volumes, resulting in greater separation efficiency, sensitivity, and speed. Designed to take full advantage of the UPLC technology, the ACQUITY® SQD Mass Spectrometer minimizes band spread of very narrow peaks to deliver improved spectral quality for compound identification. This has the advantage of providing polymer additive profiles in unknown polymer samples and examining polymer additive migration. The ability to quickly and unambiguously analyze the content of polymer additives can also facilitate workflow for analyzing polymer additive purity and troubleshooting in QC labs.

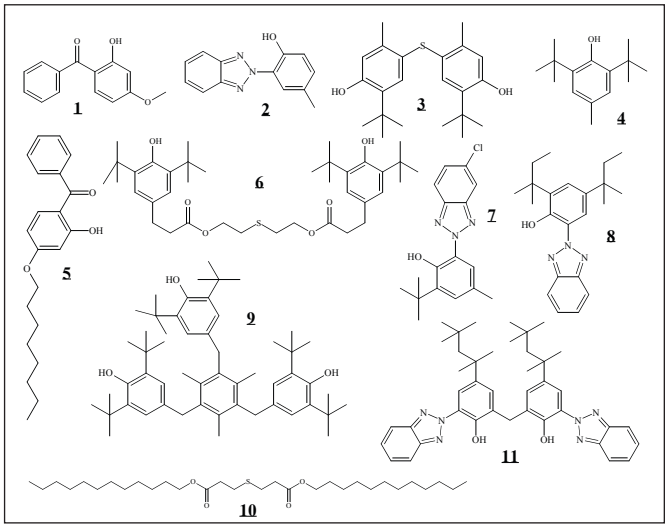


Figure 1. Chemical structures of polymer additives.

EXPERIMENTAL

Sample Preparation:

Analytes are Lowilite 20 **1**, [131-57-7]; Tinuvin P **2**, [2440-22-4]; Lowinox TBM6 **3**, [96-69-5]; BHT **4**, [128-37-0]; Chimassorb 81 **5**, [1843-05-6]; Irganox 1035 **6**, [41484-35-9]; Tinuvin 326 **7**, [3896-11-5]; Tinuvin 328 **8**, [25973-55-1]; Irganox 1330 **9**, [1709-70-2]; Irganox PS 800 **10**, [123-28-4]; and Lowilite 36 **11**, [103597-45-1]. **1-3**, **5**, and **6** were dissolved in CH_3CN to make 2 mg/mL stock solution. **4**, and **7-9** were dissolved in CH_3CN/DMSO (1:1 by volume) to make 1 mg/mL stock solution. **10** was dissolved in acetone to make 2 mg/mL stock solution. **11** was dissolved in toluene to make 2 mg/mL stock solution. The stock solutions were mixed and diluted with CH_3CN to give a test solution with 20 parts per million (ppm) of **1-11**.

UPLC System and Operation Conditions:

System:	ACQUITY UPLC/SQD Mass Spectrometer
Software:	MassLynx™ 4.1
Weak & strong wash:	CH_3CN (600 µL)
Seal wash:	90:10 Water: CH_3CN (5 min)
Column temp:	60 °C
Injection:	2 µL (full loop)
Column:	ACQUITY UPLC BEH C_{18} 2.1 x 50 mm
Mobile phase A:	H_2O
Mobile phase B:	CH_3OH

Gradient method:

Flow rate: 0.8 mL/min

Time (min)	%B	Curve
0	50	
2	100	6
3	100	6

Inlet pre-run method:

Flow rate: 0.8 mL/min

Time (min)	%B	Curve
0	100	
0.5	50	11
3	50	11

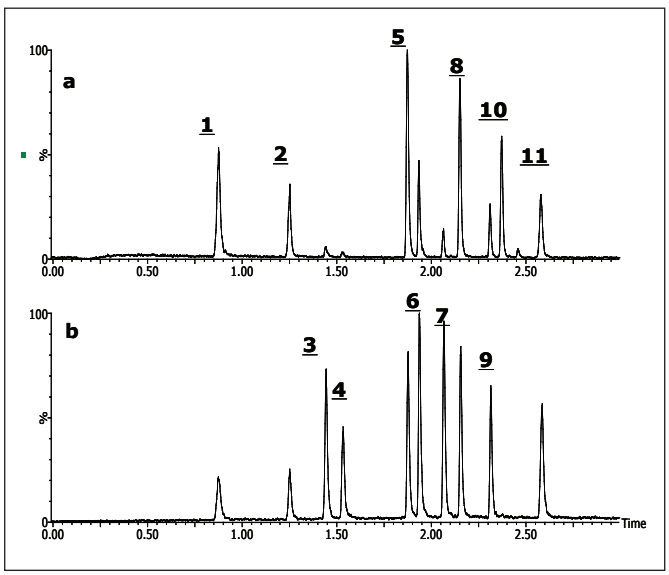
MS conditions

IonSABRE™ APCI Probe

Ionization mode:	APCI positive & APCI negative	
Corona (µA):	5.0	
Cone voltage:	+30, +50 V	-30, -70
Extractor:	+3 V	-3 V
Source temp:	150 °C	
APCI Probe temp:	500 °C	
Desolvation gas:	700 L/hr	
Cone gas :	20 L/hr	
Acquisition range:	100 to 780 m/z	

RESULTS AND DISCUSSION

Figure 1 shows the chemical structures of commonly used polymer additives (1-11). They were separated and identified in three minutes using the ACQUITY UPLC/SQD System with a 2.1 x 50 mm BEH C18 column. Figures 2a and 2b are the total ion chromatograms (TIC) of positive and negative atmospheric pressure chemical ionization (APCI) scans. The electronics of the ACQUITY SQD Mass Spectrometer enable rapid scanning (10,000 amu/sec) and polarity switching (20 msec) that allows detection of narrow peaks and provides mass spectra for chemical structure information in a single run. The chromatograms show that 11 polymer additives are separated with baseline resolution. Among them, seven polymer additives (1, 2, 5, 6, 8, 9, and 11) are easily detected by both positive and negative APCI, scans while polymer additives, 3, 4, and 7 have stronger peak signals with negative APCI scan. Polymer additive 10 is only observed by positive APCI mode. Acetonitrile and methanol were evaluated as the strong eluent. While 1-11 can be separated using H_2O/CH_3CN as the elution solution, H_2O/MeOH is the preferred mobile phase for obtaining better signals and spectra.



Figures 2a and b. TIC chromatograms of positive (a) and negative (b) APCI full scans at the cone voltages of +30 V and -30 V.

Figure 3 shows the extracted positive-ion mass spectra of **1, 2, 5, 8, 10,** and **11**. Figure 4 shows the extracted negative-ion mass spectra of **3, 4, 6, 7,** and **9**. The data indicate the value of APCI for the analysis of polymer additives. At a low cone voltage (30 V), the mass spectra have mostly pseudomolecular ions without notable fragmented and adduct ions. The mass spectra are easy to interpret and the observed m/z values match well with the theoretical intact molecular ions of additives (Table 1).

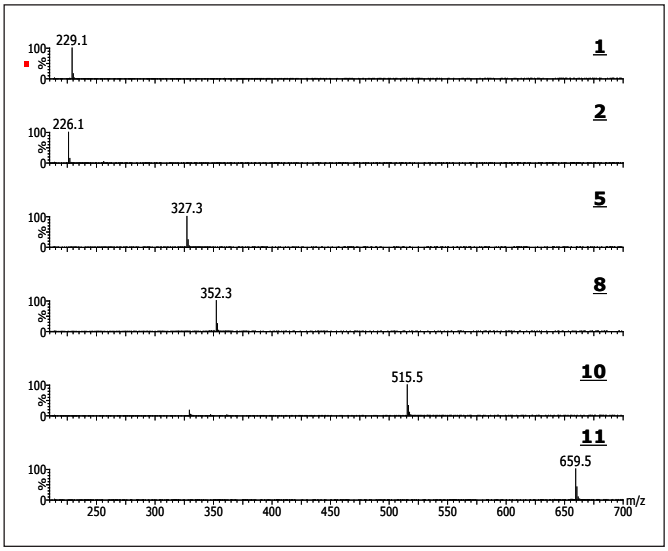


*Figure 3. Positive-ion mass spectra of **1, 2, 5, 8, 10,** and **11** at the cone voltage of 30 V.*

ID	Ret. Time (minute)	Compound	$[M+H]^+$	$[M-H]^-$
1	0.89	Lowilite 20	229.1	
2	1.26	Tinuvin P	226.1	
3	1.44	Lowinox TBM6		357.2
4	1.53	BHT		219.2
5	1.88	Chimassorb 81	327.2	
6	1.94	Irganox 1035		641.4
7	2.07	Tinuvin 326		314.1
8	2.16	Tinuvin 328	352.2	
9	2.31	Irganox 1330		773.6
10	2.38	Irganox PS 800	515.4	
11	2.59	Lowilite 36	659.4	

Table 1. Retention times and m/z of polymer additives.

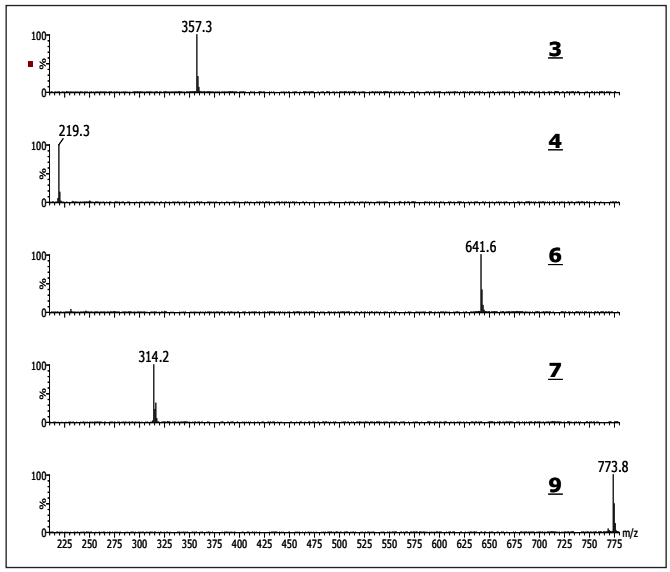
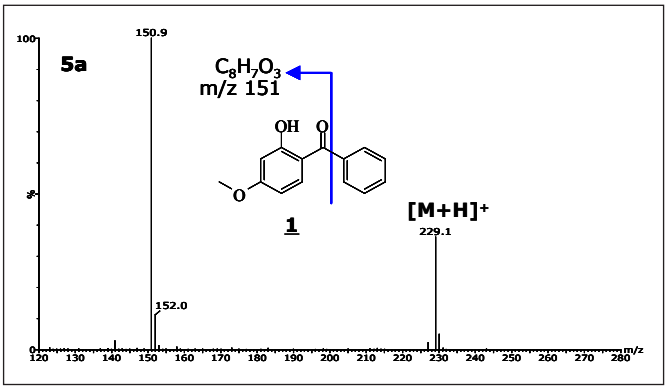
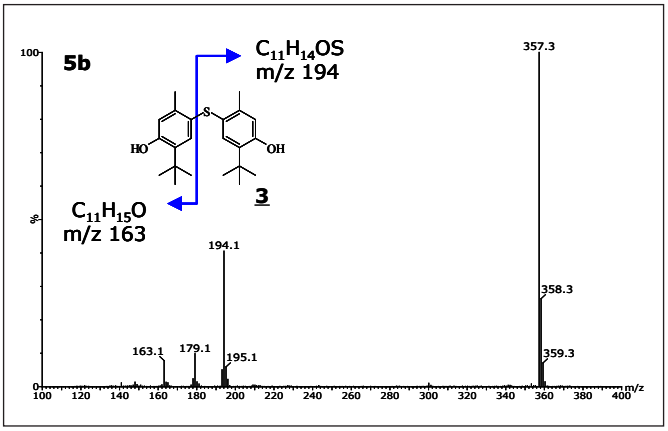
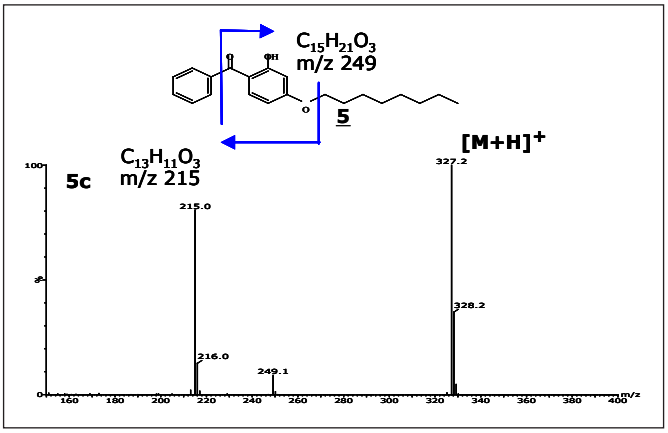


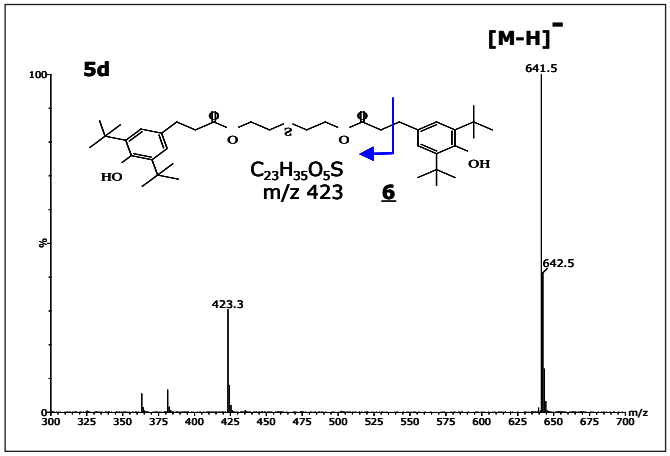
*Figure 4. Negative-ion mass spectra of **3, 4, 6, 7,** and **9** at the cone voltage of -30 V.*

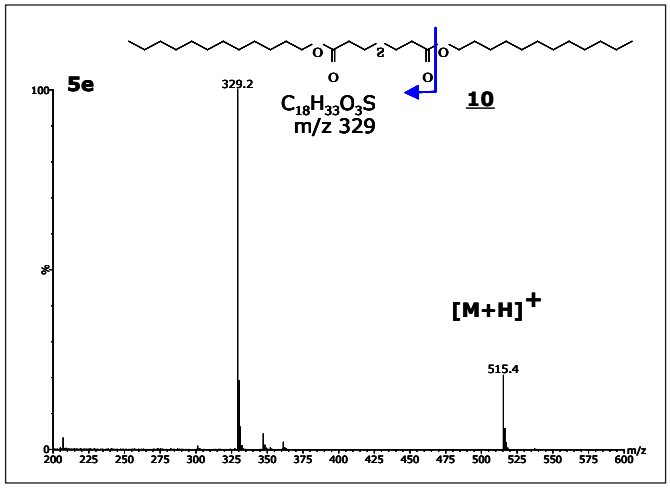
At higher cone voltages, the pseudomolecular ions of polymer additives can be fragmented to yield product ions and provide additional structure information. Figures 5 a-e are examples of extracted positive-ion and negative-ion spectra at cone voltages of +50 V and -70 V, respectively. The fragmented ions can be used to confirm the structures of polymer additives in unknown samples to prevent false identification.











*Figures 5a-e. Extracted mass spectra of **1, 5,** and **10** at cone voltage of 50 V; **3**, and **6** at the cone voltage of -70 V.*

CONCLUSIONS

The Waters ACQUITY UPLC with SQD Mass Spectrometer is an ideal system for the analysis of polymer additives. It provides a sensitive, baseline resolved separation of 11 polymer additives in three minutes. This high performance mass spectrometer with positive/negative switching enables optimal detection and confirms analyte identity in a single run. The system is seven times faster and consumes nine times less solvent than HPLC systems. This robust technology has broad applications in contract analytical labs, polymer product manufactures, government agencies, medical device manufacturers, and manufacturers of food plastics, wherever it is important to know the content of polymer additives and if those additives are leaching into products and the environment.

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ACQUITY UPLC with ELS and MS Detection: Polyetheramines

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Waters Corporation, Milford, MA, USA

APPLICATION BENEFITS

The ACQUITY UPLC® System the ELSD and single quadrupole MS detector provides a tool for the rapid differentiation, identification, and characterization of polyetheramines.

Quickly and reliably characterize polyetheramines and facilitate workflow:

- Certify lot-to-lot variations
- Quality control of raw materials
- New product development
- Product troubleshooting for both polyetheramine manufacturers and downstream users.

WATERS SOLUTIONS

ACQUITY UPLC System

ACQUITY UPLC ELS Detector

ACQUITY® SQ Detector

ACQUITY UPLC BEH Column

Empower® Software

KEY WORDS

Polyetheramine, polymer

INTRODUCTION

Polyetheramines have widespread demand in many applications including epoxy coatings, adhesives, sealants, coatings, inks and organic pigments, fuel and lubricant additives, herbicides and pesticides.[1] Commercial production of polyetheramines is based on the amination of polyols to form primary amines groups.[2,3,4]

The resulting products are mixtures of varying chain lengths with amine and hydroxyl terminal groups. Conventional chromatography for this class of compounds can be poorly resolved, time consuming, or lack robustness. Consequently managers supporting manufacturing, customers, and R&D rely on other analytical techniques that require higher levels of operator expertise.

This application note describes the analysis of a series of 220 to 1000 average molecular weight polyetheramines (Figure 1) using a Waters® ACQUITY UltraPerformance® LC® (UPLC) System with an evaporative light scattering detector (ELSD), a single quadrupole MS detector (ACQUITY SQD), and Empower Software. Polyetheramines present poor UV/VIS response because of the lack of strong chromophores. The ELSD provides an alternative detection mode to UV and the single quadrupole MS provides detailed molecular weight and structure. To compare the entire series, UPLC run time was extended to ten minutes for each product. The ability to quickly and reliably characterize polyetheramines can facilitate workflow in certifying lot-to-lot variation, quality control of raw materials, new product development, and product troubleshooting for both polyetheramine manufacturers and downstream users.

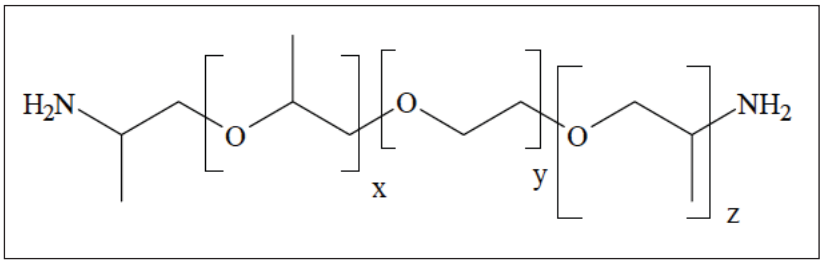

Figure 1. Generic structure of polyetheramine.

EXPERIMENTAL

UPLC conditions

LC System:	ACQUITY UPLC
Software:	Empower
Column:	ACQUITY UPLC BEH C18 2.1x 100 mm
Weak wash:	95:5 Water: CH_3CN (600 µL)
Seal wash:	90:10 Water: CH_3CN (5 min)
Mobile phase A:	0.05% TFA in H_2O
Mobile phase B:	0.05% TFA in CH_3C
Generic linear gradient:	4% B to 50% B in 10 min
Flow rate:	0.5 mL/min injection: 2 µL
Column temp:	50 °C

Note: A low dead volume MicroTee was used to split the flow to ELSD (80%) and ACQUITY SQD (20%).

ELSD parameters

Gain:	500	Nebulizer:	Cooler
N2 Gas pressure:	40 psi	Date rate:	20pt/s
Drift tube temp:	57°C	Time constant:	0.1

MS Conditions

MS System:	SQ Detector 2		
Probe:	ES+	ES capillary (kV):	3.2
Cone voltage:	35	Extractor (V):	2
RF Lens (V):	0.5	Multiplier	500
Source temp:	120 °C	Desolvation temp:	400 °C
Cone gas (L/hr):	50	Desolvation gas (L/hr):	750
LM resolution:	15.0	HM resolution:	15.5
Ion energy:	0.3	Scan range:	100 to 1200 Da
Scan time:	0.23 s	Inter-scan delay	0.1 s

RESULTS AND DISCUSSION

Table 1 lists the different polymer backbones and average molecular weights of the five commercial polyetheramine samples (1 to 5) that were analyzed. A polyethylene glycol (PEG) sample was included for comparison.

ID	Polyetheramine	Mw	mg/mL
1	NH_2-(PO/EO/PO)-NH_2	220	2.5
2	NH_2-(PO)-NH_2	400	2.4
3	NH_2-(PO/EO/PO)-NH_2	600	1.6
4	NH_2-(PO/EO/PO)-NH_2	900	2.9
5	CH_3-(EO/PO)-NH_2	1000	1.6
6	PEG	400	1.4

Table 1. Sample ID and concentration.(All the polymers were dissolved in water. EO is ethylene oxide units. PO is propylene oxide units. PEG is polyethylene glycol. Mw is the reported average molecular weight.)

Figure 2 shows ELSD chromatograms of polyetheramines 1 to 5 and PEG (6) from applying a 10 minute linear gradient method. Product peaks are well-resolved and symmetric within a 10 minute window, illustrating the benefits of UPLC with BEH column chemistry for the separation of polyetheramines. Under these elution conditions the retentions times of samples 1 to 6 differ significantly due to dissimilar relative hydrophobicities. Each product has a peak cluster or fingerprint that can be used for product identification. ELSD chromatograms are useful for QC, troubleshooting, customer support, and R&D. In new product development, this approach is also useful in monitoring the progress of chemical reactions based on polyetheramines.

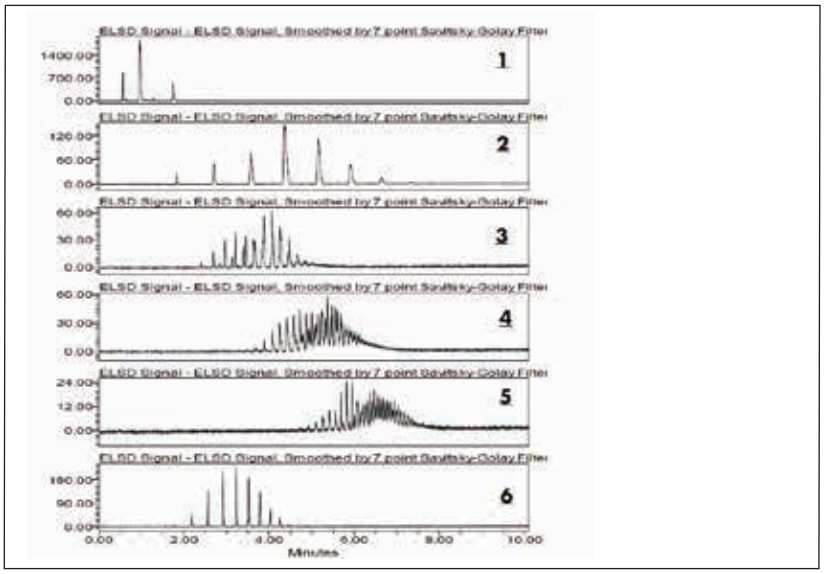

*Figure 2. ELSD chromatograms of **1 to 6** using a linear gradient method (4% to 50% B in 10 min).*

Applying other gradient methods resolves the polymer envelopes even further. The ELSD chromatograms of the higher MW polyetheramines 3 and 5 when applying more shallow gradient methods, are in Figure 3. The polymer envelopes are further resolved relative to Figure 2 and the chromatogram patterns suggest that both 3 and 5 contain multiple series of polymers.

Figure 4 shows an overlay of eight replicate injections of ES+ TIC (electrospray positive total ion current) chromatograms. Visual examination shows the overall reproducibility is excellent. Retention time reproducibility is another indicator of the robustness of UPLC with BEH column chemistry for this class of compounds. The ACQUITY SQ Detector can provide structural and molecular weight information about these series that the ELSD cannot.

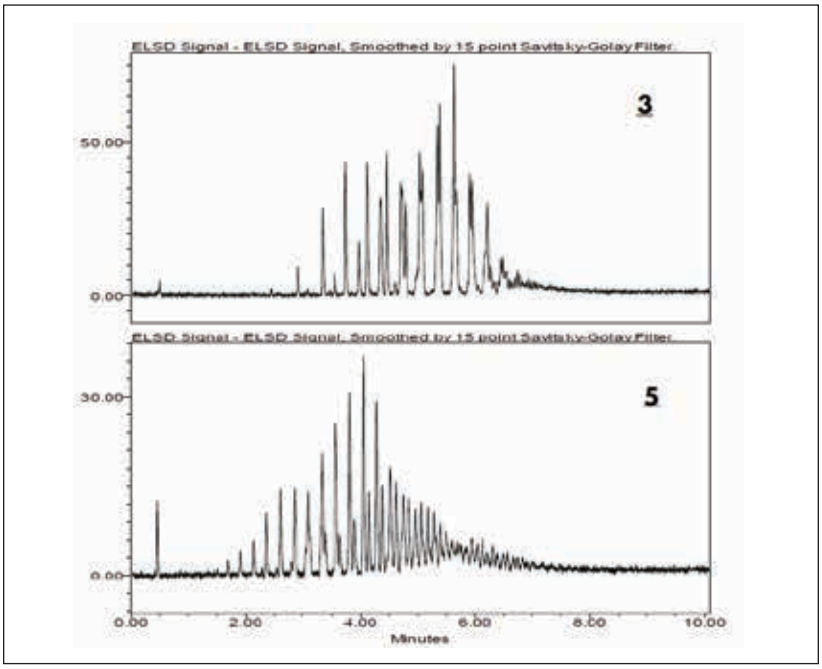

*Figure 3. ELSD chromatograms of **3** and **5** using other linear gradient methods (4% to 35% B in 10 minutes for **3**, 20% to 40% B in 10 minutes for **5**).*

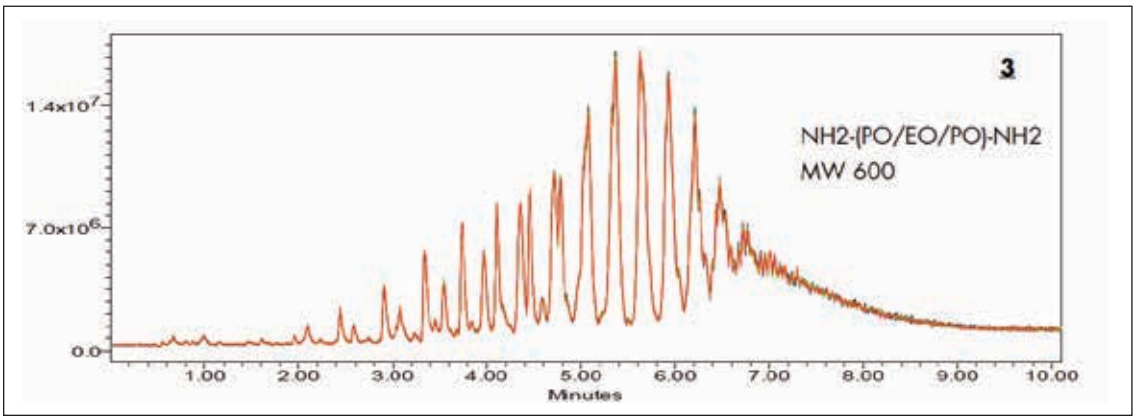

*Figure 4. Overlay ES+ TIC chromatograms of 8 replicate injections of **3** (4% to 35% B, 10-minute linear gradient).*

Figure 5 shows the extracted ES positive-ion mass spectra of 3 with peaks at retention times (min): 3.55, 3.74, 3.97, 4.11, 4.35, 4.46 and 4.71. Four series of polymer ions (3-ax, 3-bx, 3-cx, and 3-dx) with 44 Da (ethylene oxide unit) spacing can be recognized. Since 3 is tri-block polyetheramine (PO/EO/PO), the general structures of 3-ax, 3-bx, 3-cx, and 3-dx can be illustrated as follows:

3-ax = $NH_2CH(CH_3)CH_2$-(OCH_2CH_2)x-$[OCH_2CH(CH_3)]_2NH_2$;
where x = 5, *m/z* = 411; x = 6, *m/z* = 455; x = 7, *m/z* = 499; x = 8, *m/z* = 543

3-bx = $NH_2CH(CH_3)CH_2$-(OCH_2CH_2)x-$OCH_2CH(CH_3)NH_2$;
where x = 8, *m/z* = 485; x = 9, *m/z* = 529; x = 10, *m/z* = 573

3-cx = $HOCH_2CH_2$-(OCH_2CH_2)x-$OCH_2CH(CH_3)NH_2$;
where x = 7, *m/z* = 428; x = 8, *m/z* = 472; x = 9, *m/z* = 516

3-dx = $HOCH(CH_3)CH_2$-(OCH_2CH_2)x-$OCH_2CH(CH_3)NH_2$;
where x = 6, *m/z* = 398; x = 7, *m/z* = 442; x = 8, *m/z* = 486

These results demonstrate the utility of a single quadrupole mass spectrometer[5] combined with UPLC for lower MW polyetheramine characterization. For >2000 MW polyetheramines, an ACQUITY UPLC time-of-flight (ToF) MS system can provide characterization information. These experiments were outside the scope of this application note.

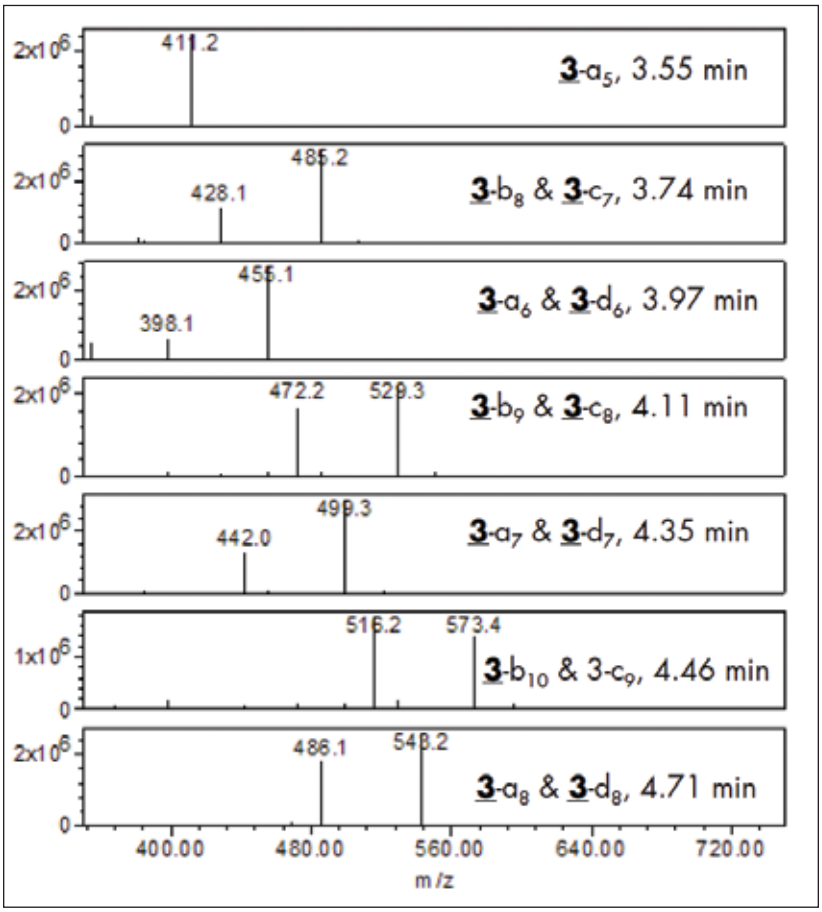

*Figure 5. Positive-ion mass spectra of peaks of **3** at retention time (min): 3.55, 3.74, 3.97, 4.11, 4.35, 4.46, and 4.71.*

CONCLUSION

The ACQUITY UPLC system with the ELSD and single quadrupole MS detector provides a tool for the rapid differentiation, identification, and characterization of polyetheramines. This is particularly important as these compounds lack a strong UV response. Reliable, reproducible comparisons of polyetheramines products are easily achieved when running fast gradients with ACQUITY UPLC BEH column chemistry and a simple mobile phase. Multiple benefits are derived from combining MS and ELS detection with UPLC separation. The retention time of ELSD chromatogram peaks are useful to fingerprint polymer components; whereas, the extracted mass spectra provide details about molecular weight for chemical structure elucidation. The resolution, separation speed and reproducibility of UPLC can benefit polyetheramine manufacturers and end-users. Applications include batch-to-batch product quality control and troubleshooting as well as monitoring the progress of new reaction products in product development.

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ACQUITY UPLC WITH PDA AND ELS DETECTION: POLYMER ADDITIVES

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APPLICATION BENEFITS

Two and a half minute analysis of a blend of 10 polymer additives using the Waters® ACQUITY UPLC® System with PDA and ELS detection and Waters Empower® 2 Software.

- Quickly and unambiguously identify polymer additives.
- Fast and reproducible analysis
- Easy to employ experimental conditions are suitable for R&D, analytical, and service laboratories involved in polymer/plastics development and production

WATERS SOLUTIONS

ACQUITY UPLC System with PDA and ELS Detection

Empower CDS Software

ACQUITY UPLC BEH Columns

KEY WORDS

HPolymer, plastic, resin, ABS, PC, PE, PP, PVC, Acrylic, polyacetal, polyamide, polyester, polystyrene, polyurethane, elastomer, rubber

INTRODUCTION

Polymer additives protect and enhance the performance of polymer and plastic products throughout the cycle of manufacturing, processing, storage and final applications. Products used every day such as fibers, textiles, furniture, sports equipment, packaging, wire and cable, consumer electronics, telecommunication equipment, automobiles, and airplanes are all made entirely or partially of polymers and plastics. Their widespread use results not only from the development of new polymer chemistry and resins but also from the advancement of polymer additives. A variety of additives are used in polymer resin processing to generate products with specific processing characteristics and functional properties, such as color, shape, and mechanical strength,as well as resistance to heat, flame, oxidation, aging, and light degradation.[1-2]

In manufacturing, a synergistic blend of polymer additives is incorporated into polymer and plastic products; small differences in the mixture can dramatically affect the characteristics of the products. To ensure that the intended amount of additive is in the polymer solution, accurate, reliable, and robust analytical methods are needed in QC and Central Analytical labs. Chromatographic techniques are the most widely used methods for the analysis of polymer additives. The typical separation time using conventional HPLC is approximately 20 to 40 minutes.[2-6]

This application note describes a two and a half minute analysis of a blend of 10 polymer additives using Waters® ACQUITY UPLC™ System with PDA and ELS detection and Empower 2 Software. With the built-in advanced mathematical algorithms, the polymer additives were quantitatively identified in a single run. The analysis is fast and reproducible. The ability to quickly and unambiguously analyze for polymer additives can facilitate workflow in quality control, new product development, deformulation of competitive polymer products, and product troubleshooting in the manufacturing of polymer additives as well as polymer and plastic products.

EXPERIMENTAL

UPLC Conditions

System:	ACQUITY UPLC PDA and ELS
Detectors:	
Software:	Empower 2
Weak wash:	CH_3CN (600 µL)
Strong wash:	CH_3CN (600 µL)
Seal wash:	90:10 Water: CH_3CN (5 min)
Column temp:	50 °C
Flow rate:	1 mL/min
Injection:	2 µL (full loop)
Detection:	PDA 210 to 500 nm
Sampling rate:	20 pts/s
Filter response:	0.1s
Column:	ACQUITY UPLC BE C_{18} 2.1x 50 mm
Mobile phase A:	0.05 v% of TFA in H_2O
Mobile phase B:	0.05 v% of TFA in CH_3CN
Linear gradient:	50% to 100%B in 1.4 min, hold for 1.1 min at 100%B

Note: Column equilibrated with 50%B for 2.5 min before each injection.

ELSD parameters

Gain:	500
Nebulizer:	Cooler
N2 Gas pressure:	40 psi
Date rate:	20 pt/s
Drift tube temp.:	57 °C
Time constant:	0.1

Sample preparation

Sample preparation analytes were Lowilite 20 (1), [131-57-7]; Lowinox TBM6 (2), [96-69-5]; Chimassorb 81 (3), [1843-05-6]; Irganox 1035 (4), [41484-35-9]; Tinuvin 326 (5), [3896-11-5]; Erucamide (6), [112-84-5]; Lowilite 27 (7), [3864-99-1]; Vitamin E (8), [10191-41-0]; Irganox PS 800 (9), [123-28-4]; and Lowilite 36 (10), [103597-45-1]. 1-4, and 8 were dissolved in CH_3CN to make 2 mg/mL stock solution. 5 and 7 were dissolved in CH_3CN/DMSO (1:1 by volume) to make 1 mg/mL stock solution. 6 was dissolved in acetone/DMSO (1:1 by volume) to make 1 mg/mL stock solution. 9 was dissolved in acetone to make 2 mg/mL stock solution. 10 was dissolved in $CHCl_3$ to make 2 mg/mL stock solution. The stock solutions were mixed and diluted with CH_3CN to give a working solution with 125 ppm of 1-10. Seven levels of calibration standards having 10, 15, 20, 25, 30, 35, and 40 ppm of 1-10 were prepared by dilution of the 125 ppm working solution with CH_3CN.

Note: Column equilibrated with 50%B for 2.5 min before each injection.

RESULTS AND DISCUSSION

Figure 1 shows the chemical structures of polymer additives (1-10): light stabilizers and UV absorbers (1, 3, 5, 7, and 10), antioxidants and heat stabilizers (2, 4, 8, and 9), slip and mold release agent (6). They are commonly used to improve the performance of polymer and plastic products based on the following resins: ABS, PC, PE, PP, PVC, Acrylics, Polyacetal, Polyamides, Polyesters, Polystyrene, Polyurethanes, Elastomers, and Rubbers.

A blend of the polymer additives (1-10) was separated in 2.5 minutes using the ACQUITY UPLC system with a linear gradient method.

Figure 2 is an overlay of seven replicate injections of PDA timed wavelength chromatograms. Visual examination showed that the overall reproducibilty was excellent. The chromatograms show that eight polymer additives were well-resolved by the gradient method. The additives Erucamide and Irganox PS 800 (6 and 9) did not have a strong UV chromophore and weren't observed. An unknown impurity in the Vitamin E (8) sample was found. Tables 1 and 2 show the retention times and peak area of each polymer additive observed in the seven replicate injections with statistical analysis results generated by Empower Software. The excellent % RSD results are good indicators of the robustness and suitability of UPLC with BEH Column chemistry for the analysis of polymer additives.

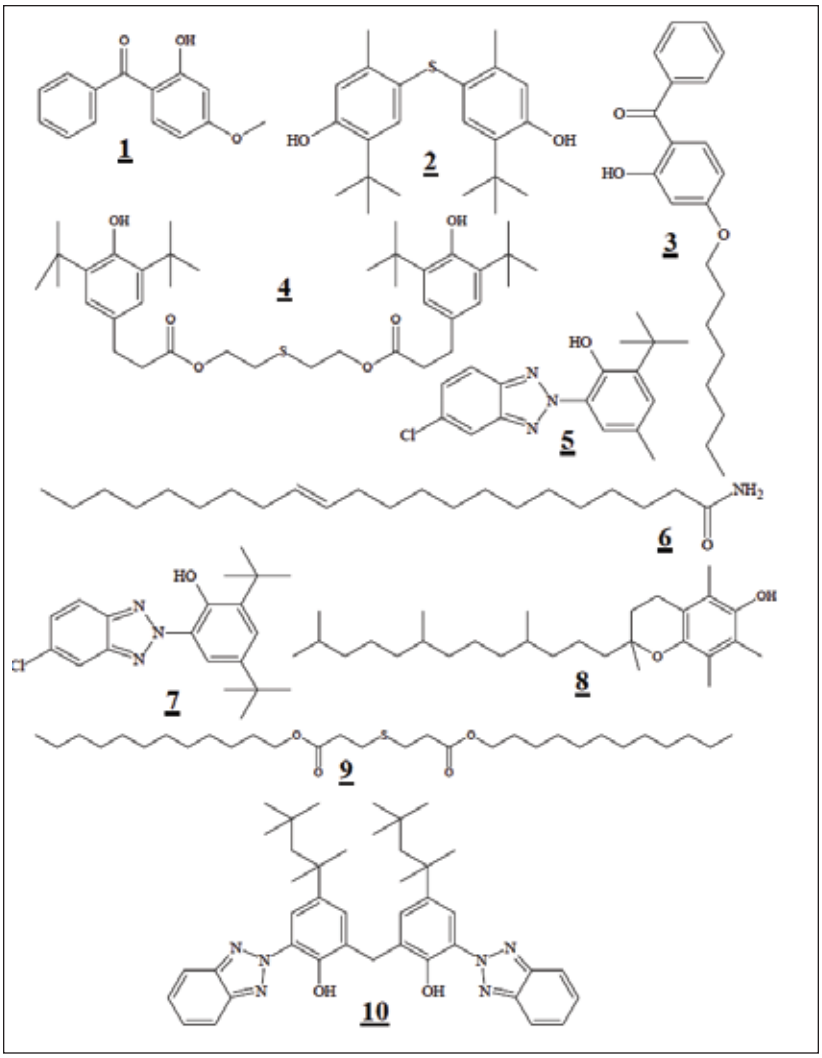

Figure 1. Chemical structures of polymer additives. Chemical names are in reference 10.

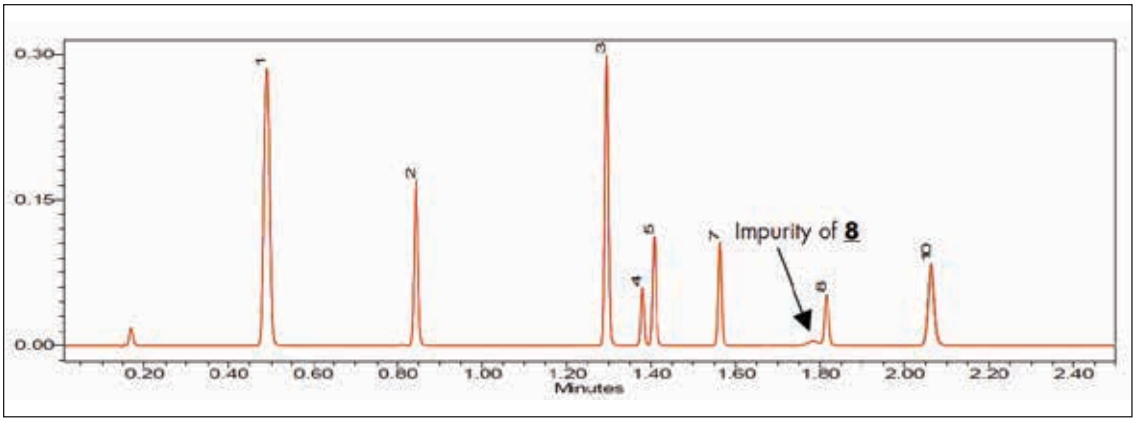

Figure 2. Overlay PDA timed wavelength chromatograms, retention time and peak tables of seven replicate injections of a blend of polymer additives sample containing 40 ppm of 1-10: (00 min, 320 nm, 0.6 min, 275 nm).

	1 (min)	2 (min)	3 (min)	4 (min)	5 (min)	7 (min)	8 (min)	10 (min)
1	0.490	0.843	1.295	1.379	1.408	1.561	1.815	2.063
2	0.490	0.843	1.294	1.378	1.406	1.562	1.814	2.061
3	0.490	0.844	1.295	1.380	1.408	1.561	1.815	2.062
4	0.490	0.843	1.294	1.379	1.407	1.562	1.815	2.062
5	0.490	0.844	1.295	1.379	1.408	1.561	1.815	2.062
6	0.490	0.844	1.295	1.379	1.407	1.561	1.815	2.062
7	0.490	0.844	1.295	1.380	1.408	1.563	1.816	2.064
Mean	0.490	0.843	1.295	1.379	1.407	1.562	1.815	2.062
Std. Dev.	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001
% RSD	0.07	0.05	0.04	0.04	0.04	0.05	0.04	0.05

Table 1. Component summary for retention time.

	1	2	3	4	5	7	8	10
1	267836	115147	176434	31584	68465	60975	39276	89901
2	268385	115152	176419	31765	68629	60937	38960	90615
3	268179	115335	176468	31478	68294	61050	39159	90031
4	267946	115169	176208	31460	68318	61092	38741	89953
5	268062	115090	176213	31482	68239	60838	38936	89671
6	268178	115058	176268	30975	67542	60974	38958	89741
7	268383	115191	176518	31568	68415	61157	38747	90225
Mean	268139	115163	176361	31473	68272	61003	38968	90020
Std. Dev.	207	88	128	243	347	106	197	320
% RSD	0.1	0.1	0.1	0.8	0.5	0.2	0.5	0.4

Table 2. Component summary for area.

Seven levels of calibration standards (10 to 40 ppm) were analyzed. With Empower's built-in advanced mathematical features, calibration curves were created from the standards and the quantities of analyte in each sample were calculated automatically. Figure 3 shows the calibration plots generated by Empower, using the peak areas versus the concentration. The linearity of the calibration curves was excellent with the R^2 values (residual sum of squares) above 0.9995. Table 3 shows a typical analysis results for peak identification and quantification using a blend of polymer additives as a sample. The last column shows all the results matching well with actual value (10 ppm). The data suggest that the UPLC system is well suited for the quantitative analysis of polymer additives in sub-ppm.

UV photodiode array (PDA) detection combined with Empower 2 Software enables a powerful range of detection and identity confirmation possibilities for chromatographic separations. Empower 2 provides the capability of creating a PDA library from pure component peaks in user chromatograms. The library matching and peak purity features can be used to confirm peak identities and to give added confidence that spectrally distinct peaks are not-coeluting. Using Spectral Contrast theory, Empower 2 quantitatively compares the shapes of UV spectra during library matching and peak purity analysis.[7-9] Figure 4 shows the UV spectra, extracted from PDA chromatograms of polymer additive standards, that were used to create a library with names and retention times.

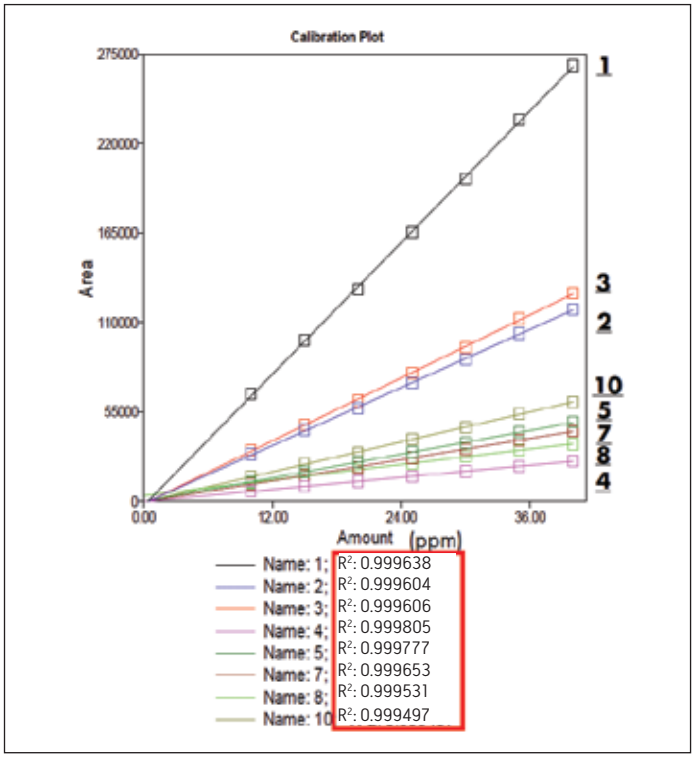

Figure 3. Calibration curves for polymer additives.

Table 3 is an example of a default Empower report table with PDA library matching peak purity results. In general, if the value of match angle is smaller than match threshold and the value of purity angle is smaller than purity threshold, the results indicate that the analyte is was separated and well-matched with the PDA library standard.

The data in Table 3 indicate that all the UV absorbing polymer additives except 8 were all separated and matched with PDA libraries. The values obtained form Empower indicate that peak 8 is not spectrally pure, perhaps suggesting co-euluting components. As indicated earlier in Figure 2 there was an overlap between the peaks of 8 and its impurity. Empower indicated this by returning a purity 1 angle greater than a purity 1 threshold.

To further characterize the impurity of 8, a longer BEH C18 column (2.1x100mm) might be used to optimize the sparation and mass spcetrometer added as a detector. These experiments are outside the scope of this application.

Figure 5 is an evaporative light scattering (ELS) chromatogram of a sample containing 40 ppm each of the additives (1-10). The chromatogram shows that nine (2-10) of the ten additives have significant response under the ELS detection conditions; the two non-UV absorbing additives was well separated from the others. The low ELS response of 1 is could be related to its volatility.

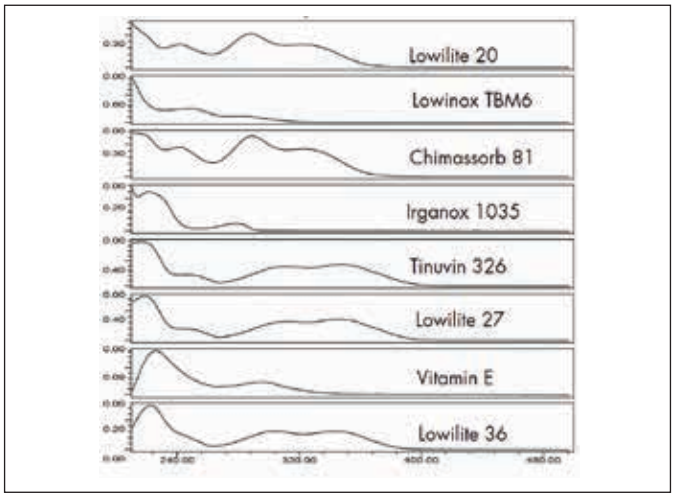

Figure 4. UV spectra of additives extracted from PDA data.

	Component	Match1 Spect. Name	Match1 Angle	Match1 Threshold	Purity1 Angle	Purity1 Threshold	Amount (ppm)
1	1	Lowilite 20	0.058	1.084	0.121	0.352	10.10
2	2	Lowinox TBM6	0.268	1.102	0.134	0.416	10.24
3	3	Chimassorb 81	0.054	1.072	0.110	0.349	10.22
4	4	Irganox 1035	1.215	1.069	0.769	1.104	10.13
5	5	Tinuvin 326	0.054	1.066	0.088	0.344	10.01
6	7	Lowilite 27	0.076	1.067	0.156	0.364	10.22
7	8	Vitamine E	4.054	1.382	0.811	0.768	9.95
8	10	Lowilite 36	0.083	1.113	0.197	0.435	10.07

Table 3. Peak identification and quantification.

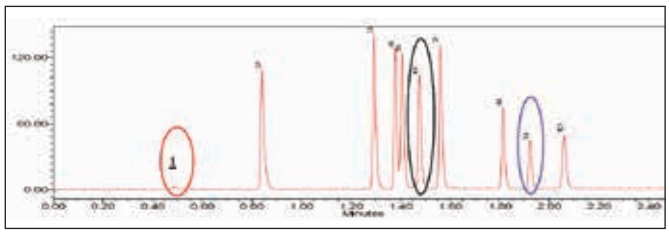

Figure 5. ELS chromatogram of polymer additives (40 ppm each of 1-10).

The ELS data fit well with quadratic equations. Figure 6 shows the typical quadratic calibration plots generated by Empower, using the peak areas versus the concentration of analyte. The R^2 values (residual sum of squares) for 6 and 9 are 0.998 and 0.997, respectively.

These results demonstrate the utility of combined PDA and ELS detectors with an ACQUITY UPLC System for analyzing polymer additives. With a single chromatographic run, all the UV and non-UV absorbing polymer additives can be analyzed simultaneously. Since many polymer additives lack a UV chromophore, an ELS Detector, in conjunction with PDA Detector, is well suited for this type of analysis.

CONCLUSIONS

Waters ACQUITY UPLC with PDA and ELS detectors is an ideal system for the analysis of polymer additives. It enables rapid, sensitive, baseline-resolved separations, and information rich data for a blend of polymer additives. All analytes cannot be detected using a single detection technique. By employing complementary detectors, more information per chromatographic run can be obtained, thus dramatically increasing productivity. With Empower Software, the data obtained from both PDA and ELS detectors can be analyzed simultaneously for polymer additive quantification. The PDA library matching and peak purity functions can be automated to add confidence in peak identification for UV absorbing analytes. The easy to employ experimental conditions are suitable for R&D, analytical, and service laboratories involved in polymer/plastics development and production. Additional applications of this methodology may include the evaluation of food and medicine contamination by polymer additives that migrate from packaging, medical tubing, and medical devices.

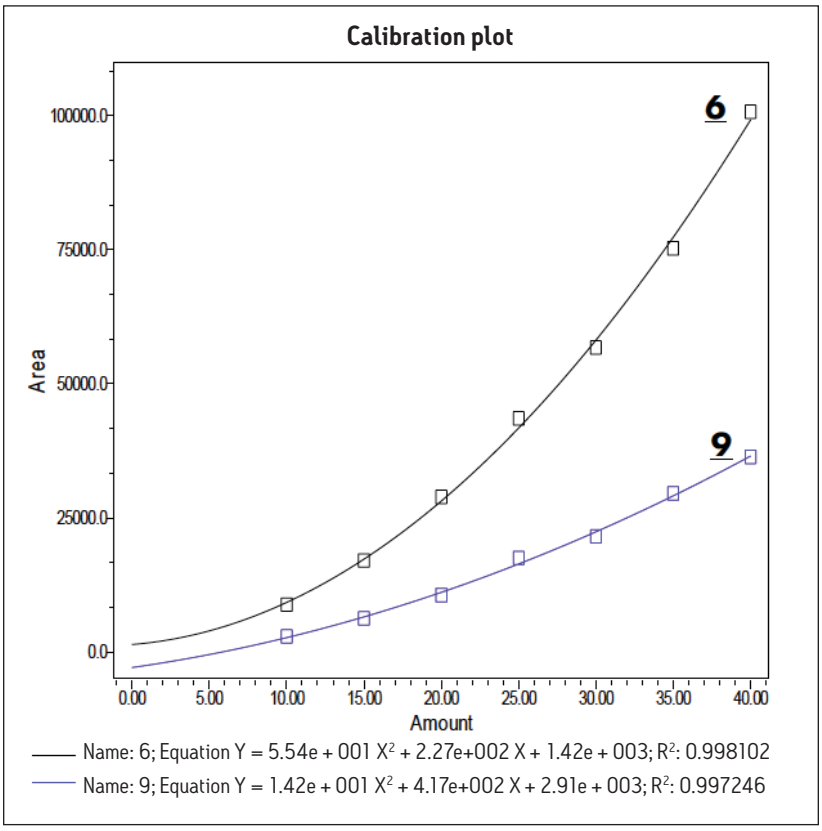

Figure 6. Calibration curves (quadratic fit) for ELS detector responses of 6 and 9.

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9. Empower\Help\Interpreting PDA Peak Purity Results.
10.

Peak no.	Trade name	CAS no.	Chemical name
1	Lowilite 20	[131-57-7	2-hydroxy-4-methoxy-benzophenone
2	Lowinox TBM6	[96-69-5	4,4' Thiobis (6-tert-butyl-m-cresol)
3	Chimassorb 81	1843-05-6	2-hydroxy-4-n-octoxybenzophenone (oxybenzone)
4	Irganox 1035	41484-35-9	Thiodiethylene bis[3-(3,5 -di-tert-butyl-4hydroxyphenyl)propionate]
5	Tinuvin 326	3896-11-5	2-(3,5-Di-tert-butyl-2-hydroxyphenyl)-5-chlorobenzotriazole
6	Erucamide	112-84-5	Ethoxylated tetramethyldecyndiol
7	Lowilite 27	3864-99-1	2- (2'-hydroxy-3',5'-di-t-pentylphenyl) benzotriazole
8	Vitamin E	10191-41-0	DL-alpha-Tocopherol
9	Irganox PS 800	123-28-4	Dilauryl 3,3'-thiodipropionate
10	Lowilite 36	103597-45-1	Methylenbis[6-(2H-benzotriazol-2-yl) -4-(1,1,3,3-tetramethylbutyl) phenol]

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Increasing the Chemical Information Obtained in a Polymer Industry Quality Control Environment with the SQ Detector 2

GOAL

To demonstrate the benefits of coupling the SQ Detector 2 and a Photo Diode Array (PDA) Detector to the ACQUITY UPLC® System, compared with using ACQUITY UPLC-PDA detection alone.

The SQ Detector 2 is a powerful, flexible tool for Quality Control laboratories.

BACKGROUND

Many Quality Control (QC) laboratories routinely use HPLC or UPLC® chromatographic separation coupled to analog detectors, such as a PDA Detector or a Refractive Index (RI) Detector. While such analysis techniques can provide valuable QC data, some components under investigation may not be detected. Physicochemical characteristics of certain compounds can prevent a sufficient response from being obtained.

Mass detection offers a powerful and flexible tool for the QC analyst, and can be used in conjunction with analog detectors. The ability to easily change the ion source on a mass detector means that a wide range of different classes of compounds, with different structures and properties, can be analyzed on a single instrument. Analytical parameters can be established to ensure the detection of all components of interest by acquiring unambiguous, non-selective data.

Quick and simple QC protocols can be implemented with a single quadrupole mass spectrometer, offering manufacturing companies valuable financial and time savings while maximizing return on investment.

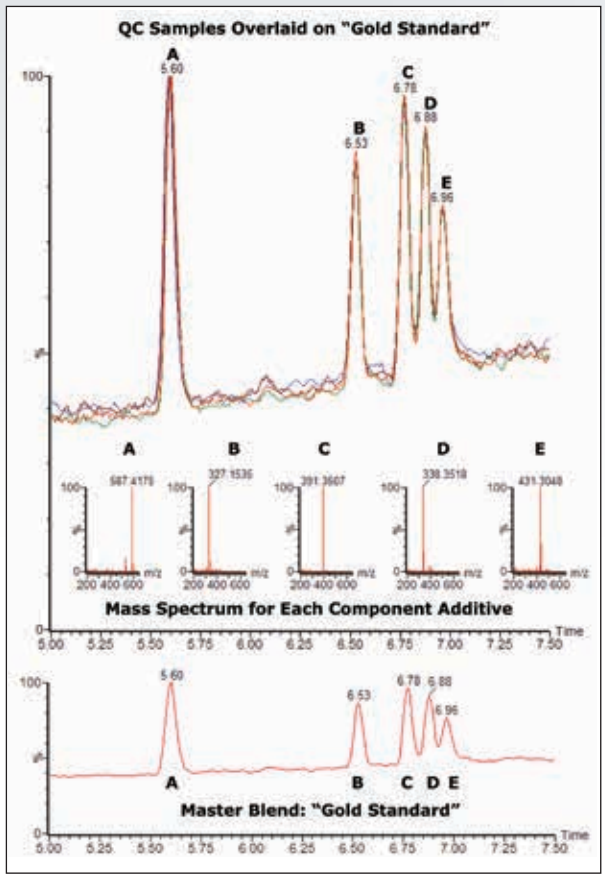

Figure 1. Molecular mass information can be obtained from mass spectra, along with chromatographic retention times and an overall batch fingerprint.

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THE SOLUTION

A Waters® SQ Detector 2 was coupled to an ACQUITY UPLC System. The SQ Detector 2 was fitted with an Atmospheric Pressure Photo Ionization (APPI) source. The APPI source offers an alternative to the more familiar ElectroSpray Ionization (ESI) or Atmospheric Pressure Chemical Ionization (APCI) sources that are also used with mass spectrometers. APPI is the ideal choice for analyzing compounds, such as polymers and polymer additives, because it is equally effective at ionizing low mass and high mass, polar and non-polar species. APPI is a complementary technique to ESI and APCI, offering complete flexibility for the QC analyst.

A blend of five polymer additives was analyzed to illustrate the benefits of using mass spectrometric detection compared with PDA detection. The blend was comprised of **A**. an antioxidant, Irganox 245; **B**. a UV absorber, 2-Hydroxy-4-(octyloxy)-benzophenone; **C**. a plasticizer, Diethylhexyl phthalate (DEHP); **D**. a slip agent, Erucamide; and **E**. an optical brightener, Uvitex OB.

Figure 1 shows a series of QC sample chromatograms overlaid on a master blend "Gold Standard" chromatogram. The Gold Standard represents the correct analytical profile of the polymer additive blend. Not only can analysts obtain retention time information and a characteristic fingerprint for the polymer additive blend, they can also acquire information about the molecular mass. The mass spectrum for each chromatographic peak shows unique information about each component of the blend.

Figure 2 shows a comparison between PDA data and mass spectrometric data for the five-component polymer additive blend. The data were acquired simultaneously, with the PDA Detector in line with the SQ Detector 2. The PDA Detector acquired data over the range 190 to 500 nm – while the SQ Detector 2 acquired data in full scan mode over the range *m/z* 50 to 800. Figure 2 shows that all five components were easily detected in the mass

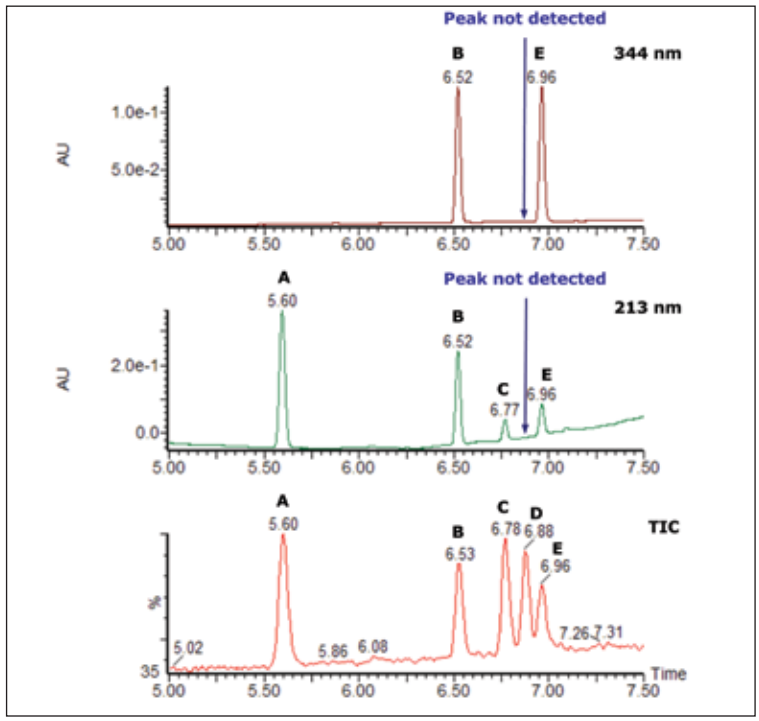

Figure 2. A comparison of PDA data with mass spectrometric data shows that component D, erucamide, was not detected by the PDA Detector, but was detected using the SQ Detector 2.

chromatogram; however, erucamide was not detected by the PDA Detector. No wavelength in the acquired range showed a response for erucamide.

SUMMARY

The SQ Detector 2 with an APPI source was successfully used to analyze a five-component polymer additive blend. A PDA Detector was included in line with the mass spectrometer.

Using an APPI source with the SQ Detector 2, a QC analysis method was developed that enabled the detection of all components of the polymer additive blend. The PDA Detector did not show a response for the slip agent erucamide. The SQ Detector 2 offers additional selectivity and flexibility to the analyst through the provision of alternative ion sources, proving a powerful tool to meet diverse analytical challenges in any QC environment.

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RAPID ANALYSIS OF 25 COMMON POLYMER ADDITIVES

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INTRODUCTION

Polymer additives are used to process and improve plastic product properties. The growth of plastic products around the world and concerns for their safe use and re-use have increased the demand for rapid and accurate analysis of additives in plastics, food, serum, and the environment.[1-5]

For product quality control, it is important to quantify additives and identify decomposition components to avoid product failure.[6-10] Using recycled plastics safely in food contact applications requires assessing residual polymer additive content[11] because additives and degradants can potentially migrate into food. Some additives have been linked with endocrine disruption raising health concerns when plastics are used for food packaging, medical devices, and toys.[12,13] The European Union Directive (2007/19/EC) regulates polymer additives in plastics used for food packaging. In the United States, California limits the concentration of certain phthalate additives in toys and child care articles (2007 October AB1108).

Most commonly, the analysis of polymer additives in a final product is performed using solvent extraction followed by high performance liquid chromatography. For QC, additive analysis can sometimes be performed in the uncured resin.

Typical analysis time using conventional HPLC is approximately 20 to 40 minutes.[14-19] This Technical Note describes a 3.5 minute run time method for characterizing 25 common polymer additives using Waters® ACQUITY UPLC® TQD system. TargetLynx™ Application Manager was set up to automate quantification.

This note illustrates application of the bench top tandem quadrupole mass spectrometer in full scan and MRM modes. An MS detector operated in full scan mode adds particular value when handling unknown polymer samples such as in competitive product analysis and patent infringement assessment. The benefit of constructing an MS/MS library for unambiguous identification of polymer additives as well as rapidly screening and quantifying targeted additives from complex standard mixtures is illustrated.

This single technique meets the requirements of a rapid, easy, unambiguous test when any combination of 25 common additives must be examined. The capability of using one methodology can facilitate workflow at QC labs, assist in competitive product deformulation, product troubleshooting, additive migration tests, and regulatory compliance. The testing method may help manufacturers avoid product recalls and liability litigation while protecting public health.

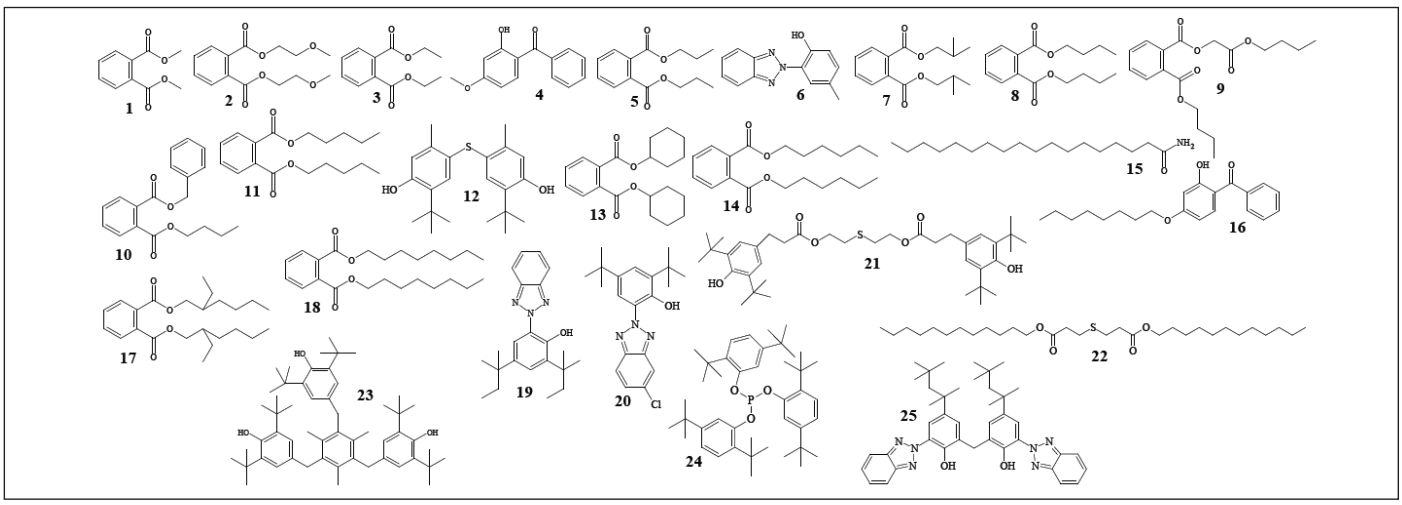


Figure 1. Chemical structures of polymer additives.

EXPERIMENTAL

Sample Preparation

Analytes are Phthalic acid dimethyl ester **1**, [131-11-3]; Phthalic acid bis(2-methoxyethyl) ester **2**, [117-82-8]; Phthalic acid diethyl ester **3**, [84-66-2]; Lowilite-20 **4**, [131-57-7]; Phthalic acid dipropyl ester **5**, [131-16-8]; Tinuvin-P **6**, [2440-22-4]; Phthalic acid diisobutyl ester **7**, [84-69-5]; Phthalic acid di-n-butyl ester **8**, [84-74-2]; n-butyl Phthalyl n-butyl glycolate **9**, [85-70-1]; Phthalic acid benzyl n-butyl ester **10**, [85-68-7]; Phthalic acid di-n-amyl ester **11**, [131-18-0]; Lowinox-TBM6 **12**, [96-69-5]; Phthalic acid dicyclohexyl ester **13**, [84-61-7]; Phthalic acid di-n-hexyl ester **14**, [84-75-3]; Stearamide **15**, [124-26-5]; Chimassorb-81 **16**, [1843-05-6]; Phthalic acid di(2-ethylhexyl) ester **17**, [117-81-7]; Phthalic acid di-n-octyl ester **18**, [117-84-0]; Tinuvin-328 **19**, [25973-55-1]; Tinuvin-326 **20**, [3896-11-5]; Irganox-1035 **21**, [41484-35-9]; Irganox-PS-800 **22**, [123-28-4]; Irganox-1330 **23**, [1709-70-2]; Irgafos-168 **24**, [31570-04-4]; and Lowilite-36 **25**, [103597-45-1]. **1-14**, **16-18**, and **21** were dissolved in CH_3CN to make 2 mg/mL stock solution. **15** was dissolved in isopropanol to make 2 mg/mL stock solution. **22** was dissolved in acetone to make 2 mg/mL stock solution. **19-20** and **23-25** were dissolved in toluene to make 2 mg/mL stock solution. The stock solutions were mixed and diluted with CH_3CN to make a working solution of the 25 polymer additives containing 60 ppm of **1-3**, **5**, **7** and **8**; 20 ppm of **4**, **6**, **9-14**, **16-18** and **21**; 10 ppm **23** and **25**; 6 ppm **15**, **19**, **20**, and **22**; 4 ppm **24** for full scan experiments. The working solution was further diluted with CH_3CN for MRM experiments.

UPLC System and Operation Conditions

LC system:	ACQUITY UPLC/TQD Mass Spectrometer
Software:	MassLynx™ v. 4.1
Weak & strong wash:	CH_3CN (600 µL)
Seal wash:	90:10 Water: CH_3CN (5 min)
Column temp:	60 °C
Injection:	2 µL (full loop)
Column:	ACQUITY UPLC BEH Phenyl 2.1 x 50 mm
Mobile phase A:	H_2O
Mobile phase B:	CH_3OH

Gradient Method

Flow Rate:	0.8 mL/min	
Time (min)	%B	Curve
0	40	
2.7	100	6
3.5	100	6

Inlet pre-run method

Flow rate:	0.8 mL/min	
Time (min)	%B	Curve
0	100	
0.5	40	11
3	40	11

TQD instrument tune page conditions

IonSABRE™ APCI Probe

Ionization mode:	APCI positive &	APCI negative
Corona (µA):	5.0	-5.0
Cone voltage:	+30 V	-30 V
Extractor:	+3 V	-3 V
Source temp:	150 °C	
APCI Probe temp:	500 °C	
Desolvation gas:	900 L/Hr	
Cone gas :	20 L/Hr	
Acquisition range:	180-800 m/z	

For full scan mode, the second quadrupole MS2 was tuned to unit resolution and used for data acquisition. For product ion scan mode, the mass resolution was tuned so that the precursor ion was resolved with a peak width at half height of 0.8 Da and product ions at half height of 0.6 Da. The product ion scan parameters, cone voltage, and collision energy for each polymer additives are listed in Table 1. For multiple reaction monitoring (MRM) scans, the mass resolution was adjusted so that the precursor and product ions were resolved with a peak width at half height of 0.85 Da. IntelliStart™ technology was used to optimize MRM scan parameters. Appendix 1 lists the MRM scan parameters for each polymer additive. Two MRM transitions were obtained for each additive; the primary transition was used for quantification and the secondary one was used for confirmation purposes. TargetLynx application manager was used for data processing.

RESULTS AND DISCUSSION

The chemical structures of polymer additives (1-25) in Figure 1 include plasticizers, light stabilizers, UV absorbers, antioxidants, heat stabilizers, slip, and mold release agents. These are commonly used to process and improve the performance of products made with the following polymer resins: PVC, ABS, PC, PE, PP, Acrylics, Polyacetal, Polyamides, Polyesters, Polystyrene, Polyurethanes, Elastomers, and Rubbers.

ACQUITY UPLC provides high separation efficiency, sensitivity and speed, and the rapid scanning (10,000 amu/sec) and polarity switching (20 msec) functions of the ACQUITY® TQD mass spectrometer allow detection of narrow peaks and provide both positive and negative mass spectra for chemical structure information in a single run. A blend of 25 polymer additives was separated in 3.5 minutes run time using a UPLC BEH Phenyl 2.1 x 50 mm column. Figure 2 shows the total ion chromatograms (TIC) of positive and negative atmospheric pressure chemical ionization (APCI) scans.

10 polymer additives (**4**, **6**, **12**, **16**, **19**-**21**, **23**-**25**) were detected by both positive and negative APCI scans while the remaining 15 were observed with only positive APCI scan. In positive APCI scan, **21** and **23** were severely fragmented and pseudomolecular ions were barely recognizable. In negative APCI scan, almost no fragmentation occurs for pseudomolecular ions of **21** and **23**, allowing identification with a high degree of confidence. An initial MS full scan provides rapid assessment of polymer additives in the analysis of unknowns in competitive polymer samples or troubleshooting product failures.

Table 1 lists peak ID, retention time, and m/z of the polymer additives. The high resolution power of UPLC®/TQD and the unique chemistry of BEH phenyl column baseline resolved the polymer additives with the exception of **4** and **5** which co-eluted in peak d;, **9** and **10** in peak h; **11** and **12** in peak i, and **19**; and **20** in peak p.

The TQD Mass Spectrometer enables determination of the most discriminating information for compound elucidation, molecular weight, and structural information so that co-eluted non-isomeric additives can be easily analyzed. Figures 3 and 4 show the extracted positive-ion mass spectra of peak p and peak i. The mass spectrum in Figure 3 has two peaks with m/z values of 352 and 358 which match well with the theoretical pseudomolecular ions of **19** and **20**. The mass spectrum in Figure 4 has several peaks. Using product ion and precursor ion scan functions of the TQD, the mass spectrum can be interpreted: m/z 219 is a CID fragment ion of pseudomolecular ion **11** (m/z, 307), and m/z 195 is a fragment ion of **12** (m/z, 359).

It is critical to have isomeric components chromatographically resolved for qualitative and quantitative analysis by LC/MS. The isomers **7**-**8** and **17**-**18** are well separated into four peaks f, g, n and o. Figure 5 shows the extracted positive-ion mass spectra of peak n and peak o. Each spectrum has two peaks, with the same pseudomolecular ion m/z 391. Product ion and precursor ion scan data confirm that m/z 279 is a CID fragmented ion of **17** while *m/z* 261 is a fragment ion of **18**.

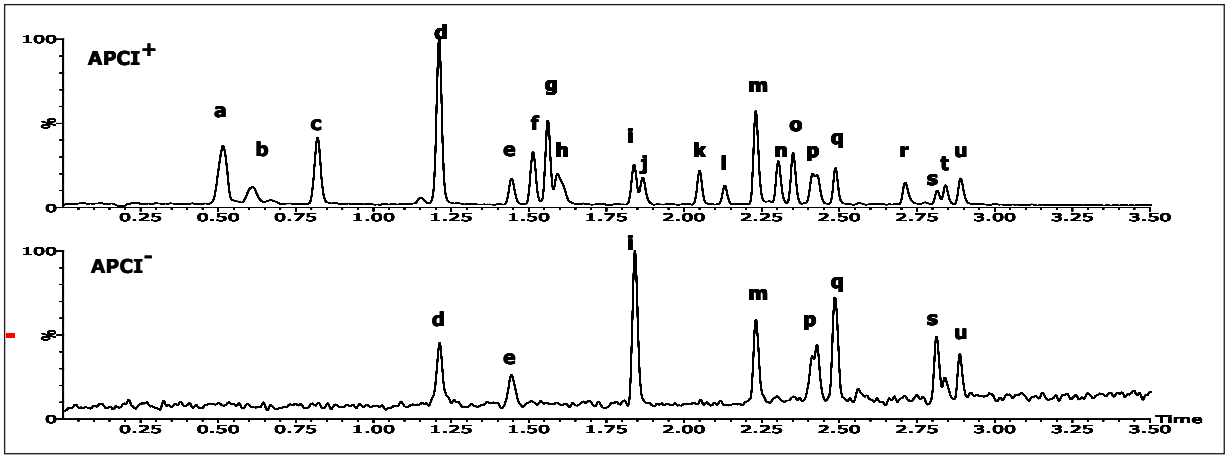


Figure 2. TIC chromatograms of a mixture of 25 polymer additives: positive and negative APCI full scans.

					Product ion scan parameters	
Peak ID	Polymer additives	Retention Time	$[M+H]^+$	$[M-H]^-$	Cone voltage (V)	Collision energy (eV)
a	**1**	0.52	195		30	7
b	**2**	0.62	283		14	6
c	**3**	0.82	223		12	7
d	**4**	1.21	229	227	30	15
d	**5**	1.22	251		18	7
e	**6**	1.45	226	224	30	17
f	**7**	1.51	279		20	7
g	**8**	1.56	279		20	7
h	**9**	1.60	337		20	6
h	**10**	1.62	313		20	7
i	**11**	1.84	307		20	7
i	**12**	1.84	359	357	30	15
j	**13**	1.87	331		20	9
k	**14**	2.05	335		20	8
l	**15**	2.13	284		30	25
m	**16**	2.23	327	325	30	17
n	**17**	2.30	391		20	8
o	**18**	2.35	391		20	8
p	**19**	2.41	352	350	30	22
p	**20**	2.43	358	356	30	22
q	**21**	2.49	643	641	40-	27-
r	**22**	2.71	515		30	12
s	**23**	2.81	775	773	45-	55-
t	**24**	2.85	647	645	30	35
u	**25**	2.90	659	657	30	19

Table 1. Product ion scan parameters, retention times, and m/z of polymer additives.

Figures 6A-Y show product ion MS-MS spectra of the polymer additives. Each polymer additive spectrum has a unique product ion pattern. Although phthalates **7** and **8** are isomers, they have quite different fragmentation patterns. Figure 6G shows that **7** has two additional product ion peaks (m/z 223 and 57) which are not observed in **8** (Figure 6H). Figures 6Q and 6R show that the phthalate isomers **17** and **18** also have very different product ion patterns. This indicates the usefulness of applying polymer additive libraries with product ion spectrum using UPLC/TQD data, molecular weight, and retention time for unequivocal identification of unknown samples.

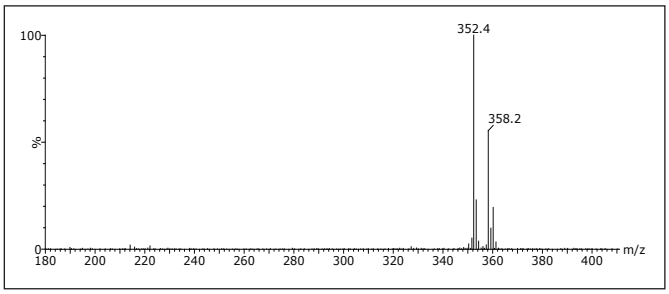


Figure 3. Positive ion mass spectra of Peak p, (19, and 20).

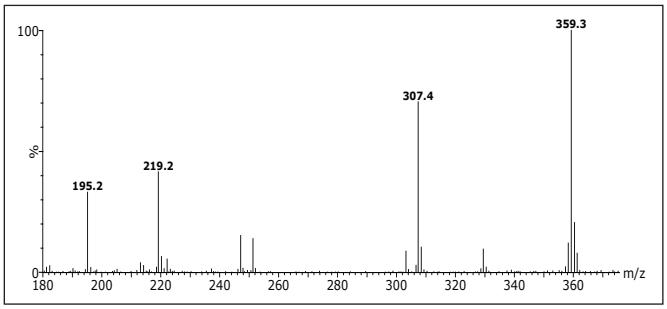


Figure 4. Positive ion mass spectra of Peak i, (11, and 12).

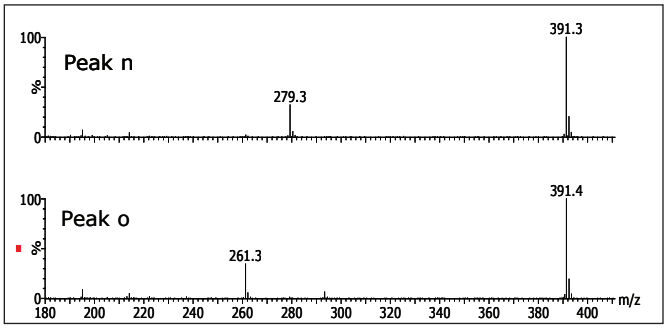
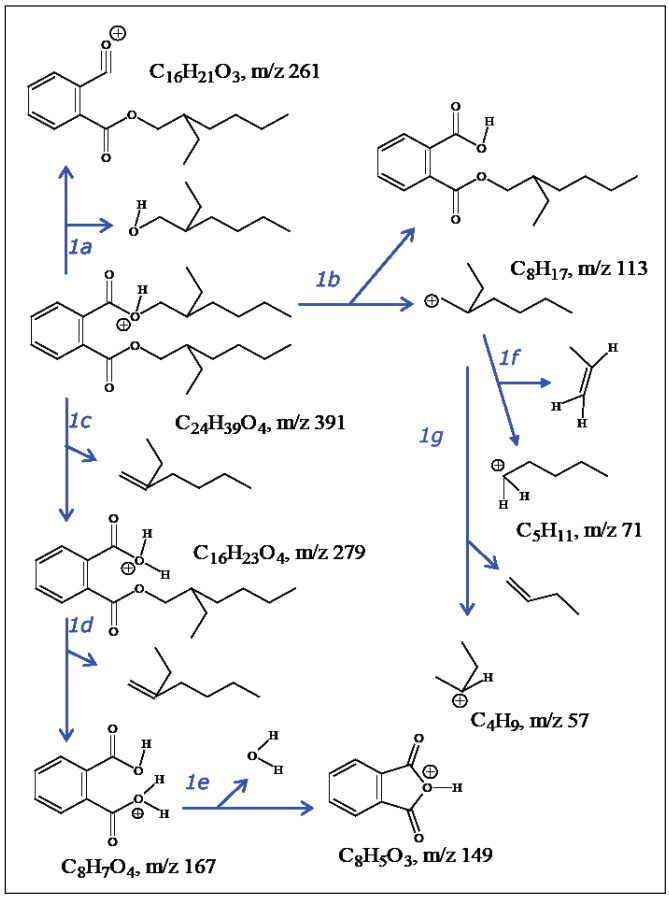


Figure 5. Positive ion mass spectra of peak n and o, (17, and 18).

The APCI MS-MS spectra of polymer additives can be interpreted using common fragmentation mechanisms of even-electron ions. For example, Schemes 1 and 2 elucidate the fragmentation pathways of pseudomolecular ions **17** and **21** for their major product ions. Using similar procedures, the fragmentation pathways of other polymer additives can also be elucidated (Figures 6A-Y).



Scheme 1. Proposed MS-MS fragmentation pathway of 17 [M+H] + adduct ion for the major product ions in figure 6Q: 1A. single bond cleavage with charge migration / alcohol loss, 1B. single bond cleavage with charge migration / neutral loss, 1C. multiple cleavages with charge retention / alkene loss, 1D. H-rearrangement, multiple cleavages with charge retention / alkene loss, 1E. cyclization/ water loss, 1F. and 1G. H-rearrangement, multiple cleavages with charge retention / alkene loss.

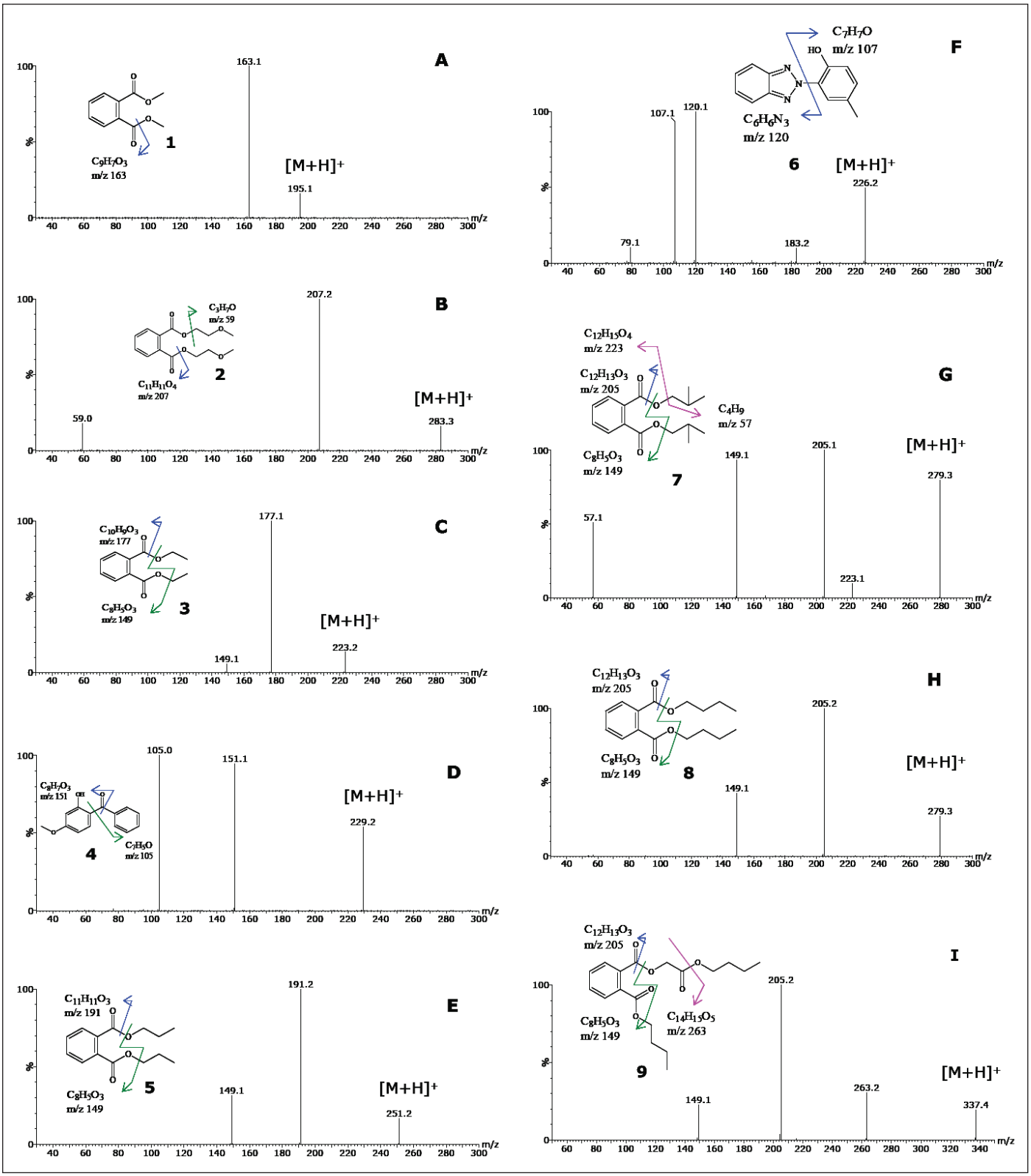


Figure 6A-I. Product ion MS-MS spectra of polymer additives.

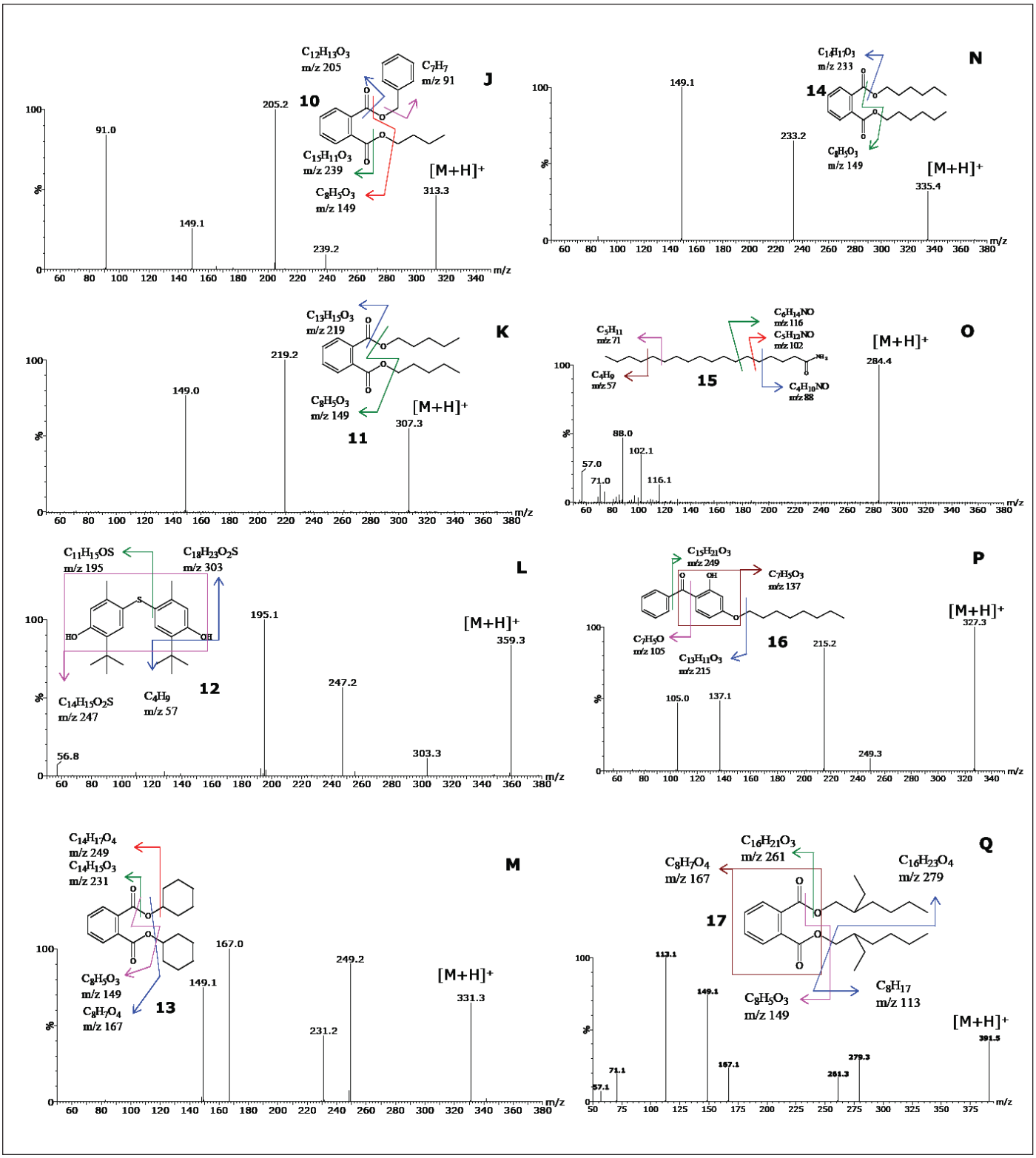


Figure 6J-Q. Product ion MS/MS spectra of polymer additives.

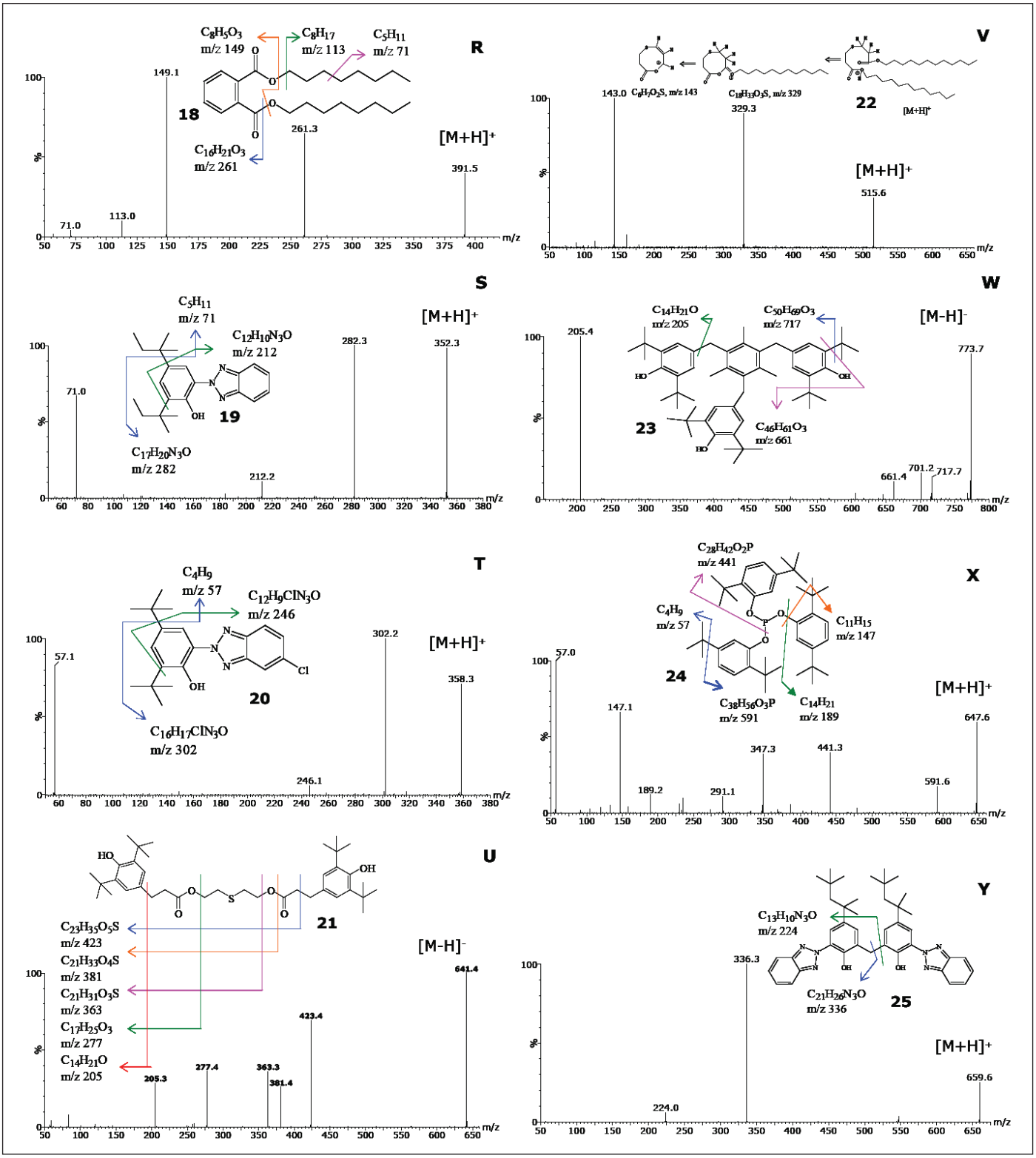
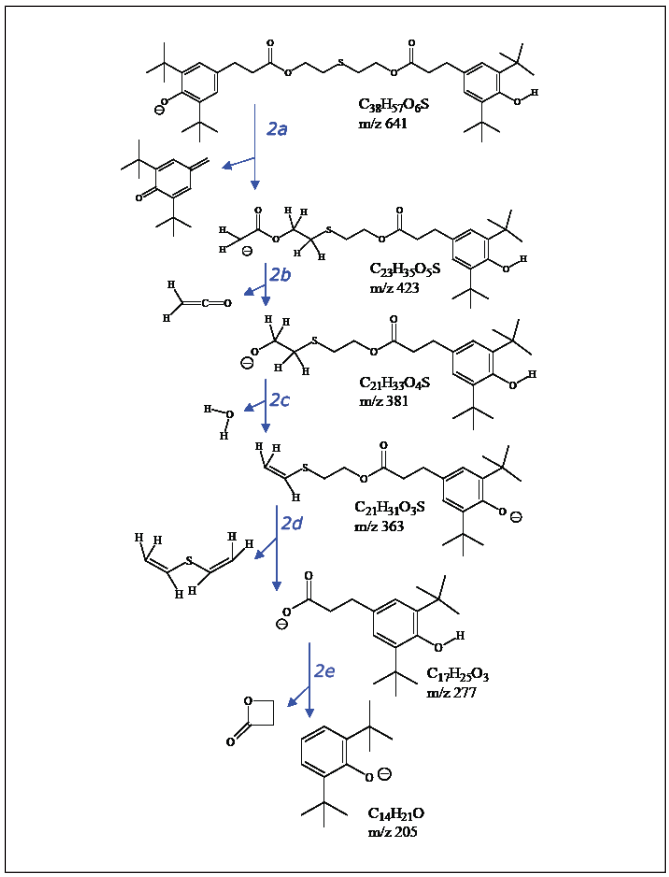


Figure 6R-Y. Product ion MS-MS spectra of polymer additives.

To rapidly screen and quantify known or target analytes from complex samples, the multiple reaction monitoring (MRM) scan function of the TQD mass spectrometer is typically used. The ACQUITY TQD incorporates IntelliStart technology for automatic system set-up as well as auto-tune functionality for optimizing MRM scan parameters. This provides an approachable interface for non-expert users to carry out MS-MS experiments with optimum operational performance. Appendix 1 contains two MRM transitions and typical scan parameters for each of the 25 polymer additives. Two MRM transitions were monitored for each additive. If two MRM transitions are chosen, then confirmation can be performed in a single run with quantification, assuming that the ion ratio between the two transitions is consistent for standards and samples.



Scheme 2. Proposed MS-MS fragmentation pathway of 21 [M-H]- adduct ion for the major product ions in figure 6Q: 2A. and 2B. Single bond cleavage with charge migration / neutral loss, 2C. H-rearrangement, multiple cleavages with charge retention / water loss, 2D. Multiple cleavages with charge retention / alkene loss, H-rearrangement, 2E. Cyclization with charge migration/ H-rearrangement.

The primary transition was used for quantification and the secondary one for confirmation. TargetLynx Application Manager Software was set up to automatically process data and report quantitative results including the ion ratio of the two MRM transitions for each additive. Figure 7 shows a typical TargetLynx browser display. This example shows the MRM transition chromatograms of dicyclohexyl phthalate, **13** (20 pg/µL) with a calibration curve (5 pg/µL to 625 pg/µL). The correlation coefficient of the calibration curve is > 0.9998.

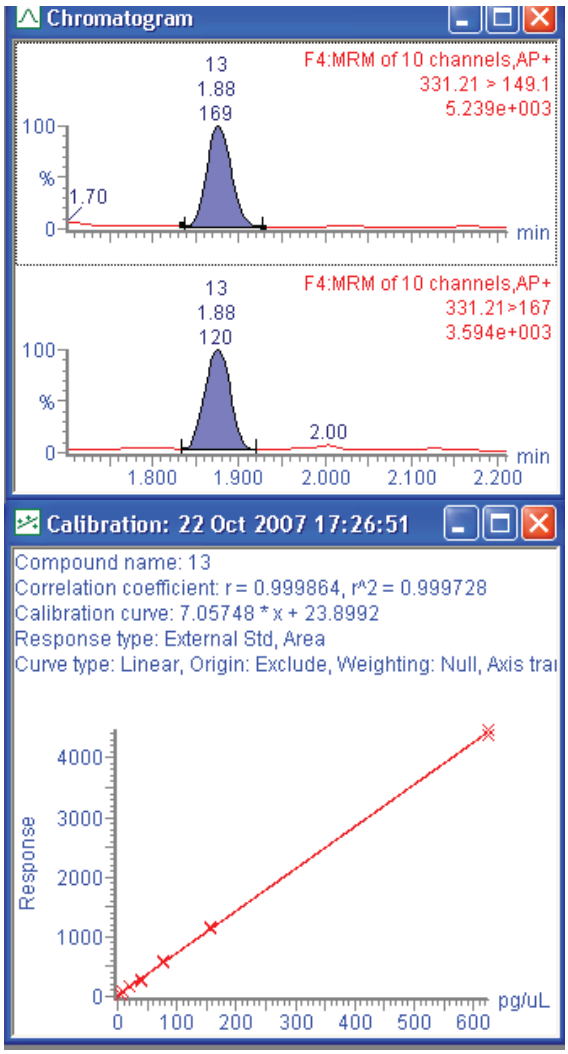


Figure 7. MRM transition chromatograms of dicyclohexyl phthalate 13 (20 pg/µL) and calibration curve.

CONCLUSION

Waters ACQUITY UPLC TQD System is ideal for analyzing polymer additives in complex samples. With the methodology provided here, an analyst can screen, identify, and routinely quantify 25 common polymer additives at ppb levels. The run time is seven times faster and consumes nine times less solvent than conventional HPLC systems.[1,2,5,13,18] The technology is robust and user friendly, making it easy to implement in labs with expert and non-expert users alike. Automating result reports with TargetLynx can further enable rapid screening and quantitation of regulated and non-regulated additives. This is suitable for multiple environments including contract analytical labs, polymer product labs, government agencies, medical device, and food packaging manufacturers. The ACQUITY UPLC TQD can help you obtain answers whenever it is important to analyze known or unknown polymer additives.

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Polymer additives	MRM transitions	Dwell time (s)	Cone voltage (V)	Collision energy (eV)
1	195.1>77.1	0.020	15	30
	195.1>163.1			10
2	283.2>59.1	0.020	15	14
	283.2>207.2			6
3	223.1>149.1	0.020	15	16
	223.1>177.2			6
4	229.1>105.2	0.025	30	20
	229.1>151.2			16
5	251.1>149.1	0.025	15	14
	251.1>191.2			8
6	226.1>107.1	0.015	35	22
	226.1>120.1			20
7	279.2>57.2	0.015	20	12
	279.2>149.1			12
8	279.2>149.1	0.015	20	12
	279.2>205.1			8
9	337.2>149.1	0.015	15	14
	337.2>205.2			8
10	313.2>91.1	0.015	15	22
	313.2>205.2			8
11	307.2>149.1	0.015	15	14
	307.2>219.1			6
12	359.2>139.0	0.015	20	22
	359.2>195.1			18
13	331.2>149.1	0.015	15	24
	331.2>167.0			12
14	335.2>149.1	0.015	15	12
	335.2>233.1			8
15	284.4>88.2	0.015	45	20
	284.4>102.1			20
16	327.2>105.0	0.010	40	28
	327.2>137.0			28
17	391.2>149.1	0.010	15	26
	391.2>167.0			14
18	391.2>149.1	0.010	15	26
	391.2>261.2			8
19	352.2>71.1	0.010	50	26
	352.2>282.2			24
20	358.2>57.1	0.010	45	32
	358.2>302.1			24
21	641.5>83.1	0.025	-45	-42
	641.5>381.4			-28
22	515.4>143.1	0.015	30	20
	515.4>329.2			14
23	773.5>205.3	0.030	-60	-55
	773.5>717.5			-55
24	647.5>57.1	0.015	70	46
	647.5>147.2			50
25	659.4>265.2	0.015	45	45
	659.4>336.3			24

Appendix 1. MRM scan parameters for polymer additives.

SEPARATIONS

SUPERCRITICAL FLUID EXTRACTION

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Streamlining Current Approaches for Extractable Analysis Utilizing Waters MV-10 ASFE and ACQUITY UPC² Systems

Baiba Čabovska, Andrew Aubin, and Michael D. Jones
Waters Corporation, Milford, MA, USA

APPLICATION BENEFITS

- SFE offers greater flexibility than microwave extraction and represents a substantial savings in solvent consumption and run time when compared to Soxhlet extraction
- UPC²™ enhances extractables analysis by streamlining the workflow

WATERS SOLUTIONS

ACQUITY UPC² System configured with PDA and SQD Detection

MV-10 ASFE™ System

Empower™ 3 Software

KEY WORDS

Extractables, SFE, UPC², supercritical fluid, convergence chromatography

INTRODUCTION

Analysis of extractables in the pharmaceutical and food packaging industries is well established.[1-3] Analytical workflows can incorporate various techniques. Similarly, the evaluation of container closure systems can include various extraction techniques. The ACQUITY UPC²™ System streamlines the analytical workflow by providing flexibility with various common solvent systems resulting from extraction procedures.[4] While supercritical fluid plays a key role in improving analytical workflow, the question is raised: "Can the sample extraction process be streamlined to utilize one technique, namely a supercritical extraction process?"

Several techniques can be used to prepare sample extracts in the extractables analysis process. Typically, either a Soxhlet, microwave, or supercritical fluid extraction (SFE) are performed. The extraction solvents must cover a wide range of polarities to ensure that non-polar and polar analytes are extracted from packaging material. The Soxhlet apparatus can be a very attractive option due to its relatively inexpensive setup. However, when the price of extraction solvents and their waste disposal is considered, microwave and SFE offer cost saving benefits including reduced solvent consumption and waste disposal, as well as valuable reduction in analysis time.

In this application, four different types of packaging material were extracted including: high density polypropylene pill bottle (HDPE), low density polypropylene bottle (LDPE), ethylene vinyl-acetate plasma bag (EVA), and polyvinyl chloride blister pack (PVC). Following extraction, the resulting solutions were rapidly screened for 14 common polymer additives using an UltraPerformance Convergence™ Chromatography (UPC²) System with PDA and single quadrupole (SQD) mass detection. Microwave and Soxhlet were used to separately prepare IPA and hexane extracts, while different concentrations of IPA were used as the co-solvent for SFE extractions. Here, the extraction profiles of the different techniques are compared.

EXPERIMENTAL

Method conditions

UPC² Conditions

System:	ACQUITY UPC² with PDA and SQD Detection
Column:	ACQUITY UPC² BEH 2-EP 3.0 x 100 mm, 1.7 µm
Modifier:	1:1 methanol/ acetonitrile
Flow rate:	2 mL/min
Gradient:	1% B for 1 min, to 20% over 2.5 min, hold for 30 s, re-equilibrate back to 1%
Column temp.:	65 °C
APBR:	1800 psi
Injection volume:	1.0 µL
Run time:	5.1 min
Wavelength:	220 nm
MS scan range:	200 to 1200 *m/z*
Capillary:	3 kV
Cone:	25 V
Make-up flow:	0.1% formic acid in methanol, 0.2 mL/min
Data management:	Empower 3 Software

Sample description

Microwave Extractions

The samples of HDPE, LDPE, EVA, and PVC (2 g) were cut into 1x1 cm pieces and subsequently extracted in either 10 mL of isopropanol or 10 mL of hexane for 3 h at 50 °C.

Soxhlet Extractions

Soxhlet extractions were performed by placing cut pieces (roughly 1x1 cm) of material (3 g for PVC, 5 g for HDPE, LDPE, or EVA) into a Whatman 33 x 94 mm cellulose extraction thimble. The thimble was then placed in a conventional Soxhlet extraction apparatus, consisting of a condenser, a Soxhlet chamber, and an extraction flask. Approximately 175 mL of extraction solvent (either hexane or IPA) was added into the Soxhlet apparatus. All samples were extracted with the hot boiling solvent mixture for 8 h. Upon completion, the extraction solvent was reduced to near dryness and reconstituted in 15 mL of either hexane or IPA. Prior to analysis, extracts were filtered through a 0.45-µm glass fiber syringe tip filter to remove any particulates.

SFE

Supercritical fluid extraction (SFE) was performed using a Waters® MV-10 ASFE System. For each SFE experiment, cut pieces (roughly 1x1 cm) of material were loaded into 10-mL stainless steel extraction vessels (2 g for PVC, 3 g for HDPE, LDPE, or EVA). Two distinct extractions were performed on each material. The first used 5.0 mL/min carbon dioxide plus 0.10 mL/min IPA, the second used 4.0 mL/min carbon dioxide plus 1.0 mL/min IPA. All extractions were performed at 50 °C and 300 bar back pressure using a 30-min dynamic, 20-min static, and 10-min dynamic program that was repeated twice. IPA was used as a makeup solvent at 0.25 mL/min. For high IPA extractions, following the extraction process, collected solvent (a mixture of the co-solvent and make-up solvent) was reduced to near dryness and reconstituted in IPA (10 mL for PVC, 9 mL for HDPE, LDPE, and EVA). For low IPA extractions, the collected solvent was brought up to volume accordingly. Prior to analysis, extracts were filtered through a 0.45-µm glass fiber syringe tip filter to remove any particulates. Total extraction time per sample was 2 h.

RESULTS AND DISCUSSION

Comparing the duration of the extraction processes, Soxhlet extracted each sample individually for 8 h. Microwave could accommodate up to 16 samples simultaneously over a 3-hour extraction. The SFE process took 2 hours per sample with up to 10 samples loaded onto the sample tray. Even if more Soxhlet apparatus were used simultaneously, the total extraction time would still significantly exceed microwave or SFE extraction times.

In terms of solvent usage, Soxhlet required up to 175 mL of solvent, followed by evaporation to reduce sample volume. Microwave used 10 mL of solvent that could be dried down if improvements in sensitivity are needed. SFE offered the greatest flexibility in sample pre-concentration. Under low IPA extraction conditions, the final volume collected was approximately 5 mL, and brought up to volume to have the concentration of the sample comparable to microwave and Soxhlet samples. Under high IPA extraction conditions, the total volume collected was ~30 mL, which had to be evaporated to obtain the final concentration.

The fewest number of extractables were observed in the PVC and EVA samples analyzed after microwave extraction. The most extractables were observed using either hexane or IPA extract in the LDPE sample, as shown in Figure 1.

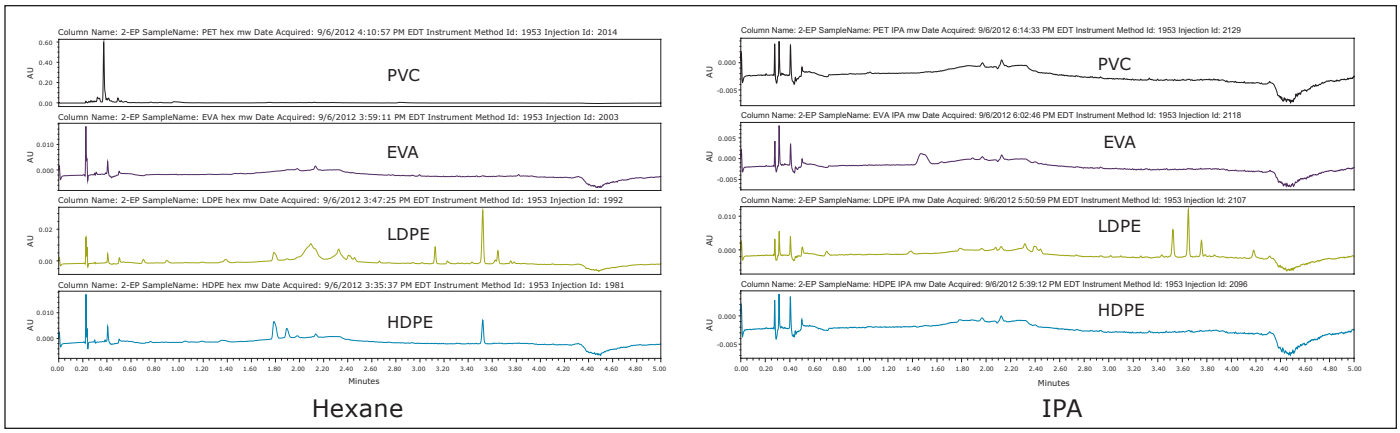

Figure 1. Hexane and IPA extracts using the microwave extraction technique.

Using Soxhlet extraction, several additional peaks were observed in the PVC chromatograms, as shown in Figure 2, which were not visible following microwave extraction. The observable differences are possibly due to the longer extraction times and higher extraction temperature used in Soxhlet extraction.

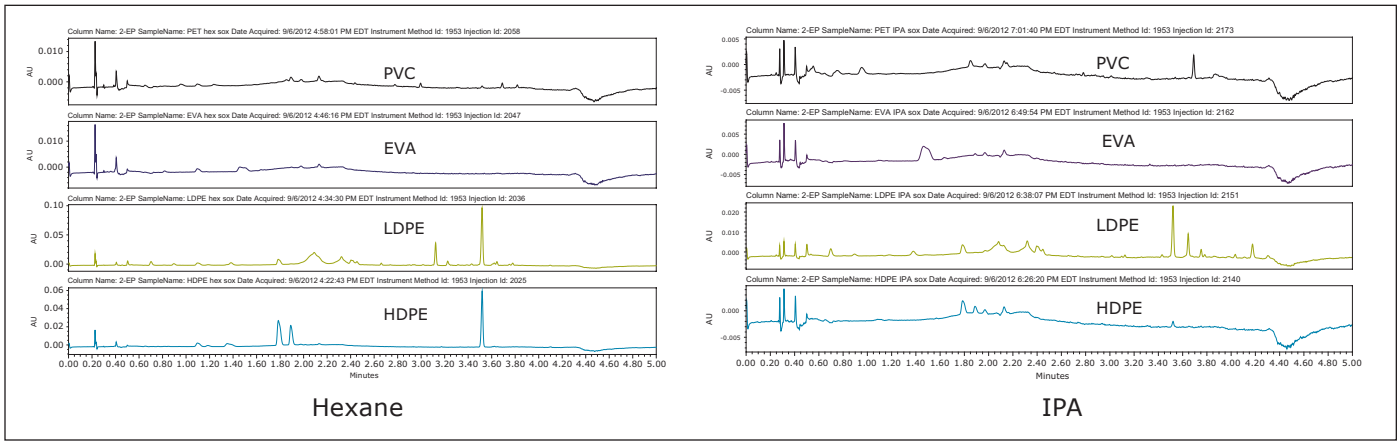

Figure 2. Hexane and IPA extracts using the Soxhlet extraction method.

Visually comparing SFE extraction profiles with the other two techniques, SFE extracted similar amounts of analytes as Soxhlet, and a greater amount than microwave extraction of PVC, as shown in Figure 3. High IPA extracted higher amounts in LDPE than the lower percentage in the IPA extraction experiment. This illustrated the flexibility and ease of adjusting to determine the optimal percentage of modifier needed for each plastic material to achieve a successful extractables analysis.

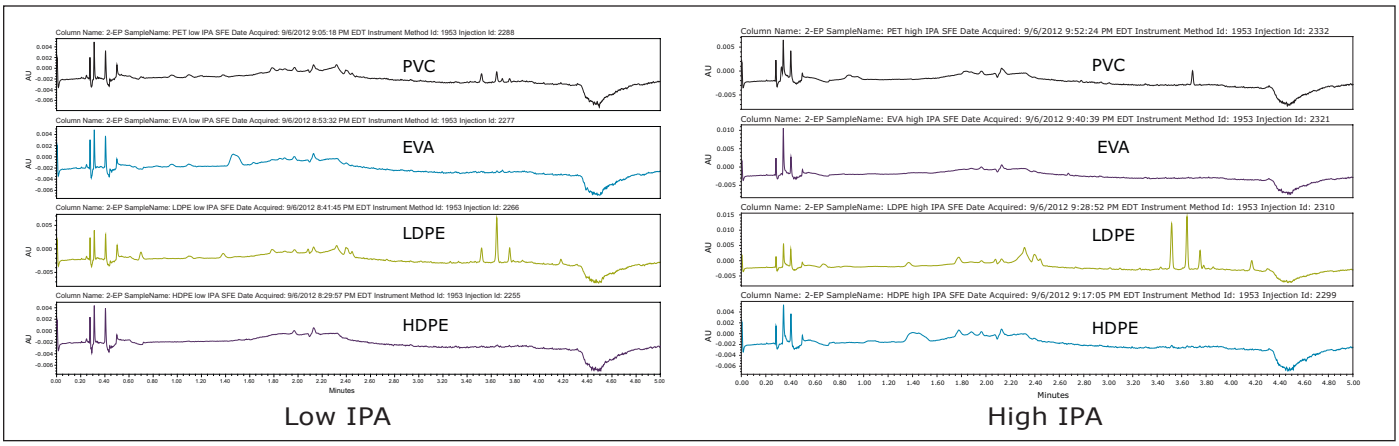

Figure 3. SFE extracts with low and high volumes of IPA co-solvent.

All extraction techniques using IPA as the solvent produced similar chromatographic profiles for the LDPE sample, as seen in Figure 4. Concentration of the extractables can be increased by extended extraction times, higher temperature in microwave and Soxhlet extractions, or a higher level of IPA in the case of SFE. Hexane extractions were not performed by SFE since CO_2 is a non-polar solvent with similar chemical properties to hexane; therefore, comparable results were expected.

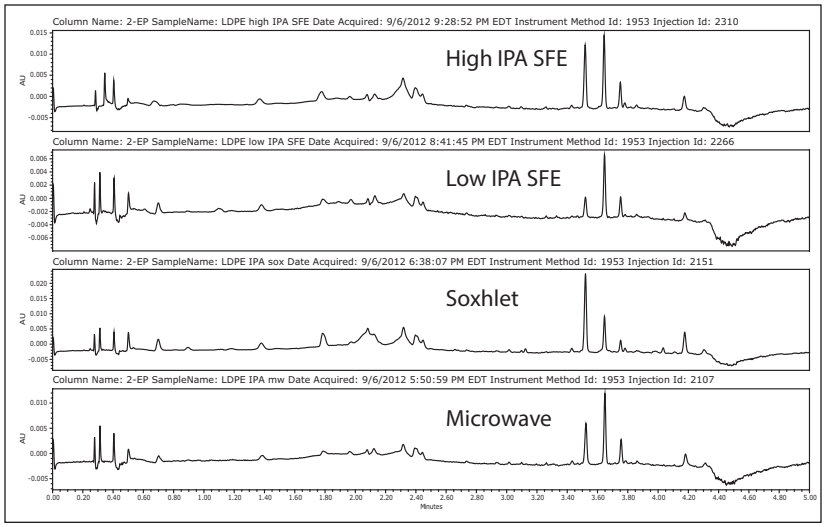

Figure 4. IPA extracts for LDPE.

Examples of identified compounds in LDPE hexane extracts are shown in Figure 5.

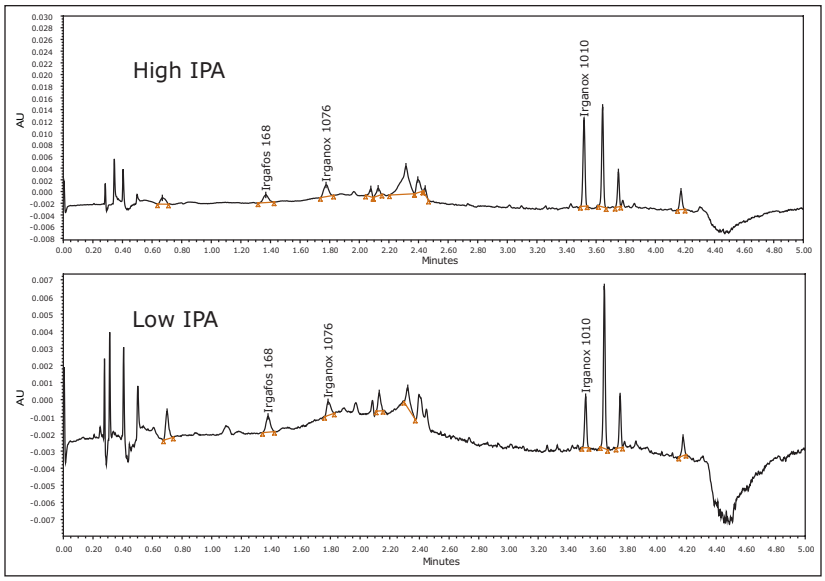

Figure 5. Identified extractables in LDPE, SFE extracts.

In summary, all of the techniques are comparable in terms of types of compounds extracted. However, it was determined that SFE offers many advantages over other extraction techniques when time and resources are important. The MV-10 ASFE System is software controlled, providing automated method development. There can be up to four co-solvents available for use, and various percentages and extraction times can be set in the methods. Soxhlet and microwave require manual solvent changes for each step in method development, which is quite time-consuming when conducting a quality by design (QbD) study.

CONCLUSIONS

SFE provided 80% to 97% savings in solvent consumption, and a 75% savings in extraction time compared to Soxhlet extraction. The software controlling SFE allowed automated method development to determine the optimal percentages and choices of extraction co-solvent. In addition, SFE provided flexibility in sample pre-concentration compared to microwave extraction.

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Characterizing Polymer Folding Patterns Using Ion Mobility Mass Spectrometry

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[1] Waters Corporation, Manchester, UK
[2] University of Mons, Belgium

APPLICATION BENEFITS

- Rapid data collection
- Polymer size investigation
- Limited laboratory consumable requirements

WATERS SOLUTIONS

SYNAPT® G2 HDMS™

MassLynx® Software v. 4.1

DriftScope™ v. 2.2

KEY WORDS

Ion mobility spectrometry (IMS), polymer characterization, folding patterns, poly ethylene glycol (PEG), poly propylene glycol (PPG), polylactide (PLA), co-polymers

INTRODUCTION

Many analytical techniques are used by the polymer industry, for example gel permeation chromatography (GPC) with refractive index (RI) detection and nuclear magnetic resonance spectroscopy (NMR). Each technology provides complementary information about a sample, such as average molecular weight, molecular weight distribution, monomer units, and end group composition.

These chemical properties (composition and mass parameters) are measured because they have an effect on the physical properties of polymers, and therefore their use in various applications. These traditional techniques cannot be used to determine 3D structure, which is greatly influenced by the flexibility of the polymer chain. It is predicted that the 3D structure of a polymer will have functional importance as synthetic polymers become increasingly sophisticated.[1,2] There is a close relationship between structural architecture and macroscopic properties.

The demand to accurately characterize this new functionality is likely to rise as polymers are increasingly used in highly regulated industries. Applications such as food contact materials and cosmetics are already attracting the attention of regulatory bodies.[1]

This application note demonstrates how a polymer can be differentiated and characterized using Ion Mobility Spectrometry-Mass Spectrometry (IMS-MS) based on its flexibility and structure. The technique is rapid and requires very little sample preparation.

EXPERIMENTAL

Samples

The copolymers were first dissolved in 50:50 acetonitrile:water before further dilution to produce the following:

10 ppm PEG-r-PPG in 50:50 acetonitrile:water.

10 ppm PEG-b-PPG-b-PEG in 50:50 acetonitrile:water.

The polylactide sample was first dissolved in acetonitrile before further dilution to produce the following:

200 ppm polylactide and 20 ppm sodium iodide in acetonitrile .

MS Conditions

MS system:	SYNAPT G2 HDMS
Ionization mode:	ESI positive
Infusion rate:	10 µL/min
Scan time:	1 sec
Extraction cone:	5.0 V
Desolvation temp.:	200 °C
Cone gas:	Nitrogen, 20 L/hr
Desolvation gas:	Nitrogen, 600 L/hr

Sample	Capillary (kV)	Sample cone (V)	Source temp (°C)
PEG-b-PPG-b-PEG	2.5	100	120
PEG-r-PPG	2.5	100	120
Polylactide	3.1	50	80

RESULTS AND DISCUSSION

Waters® SYNAPT G2 HDMS is an orthogonal acceleration quadrupole Time-of-Flight (ToF) mass spectrometer with an integrated Triwave® device that is capable of differentiating ions using mobility separation. Ions are guided from the ion source through the quadrupole to the mobility cell, and finally the ToF analyzer. The order of the technology within the instrument allows true MS/MS analysis to be carried out, if required, before ions are separated in the T-Wave™ ion mobility separation region according to their size, shape, and charge state. Finally, the ToF analyzer measures the mass-to-charge ratio of the separated ions.

When polymers are analyzed by mass spectrometry, generally the analyst is looking for a series of ions in the data that are caused by the polymer increasing in mass due the addition of monomer units. This gives a polymeric ion distribution. When mobility separation is also performed we look for a series of ions in a 3D data set. Figure 1 shows the polymer structures analyzed as part of this study.

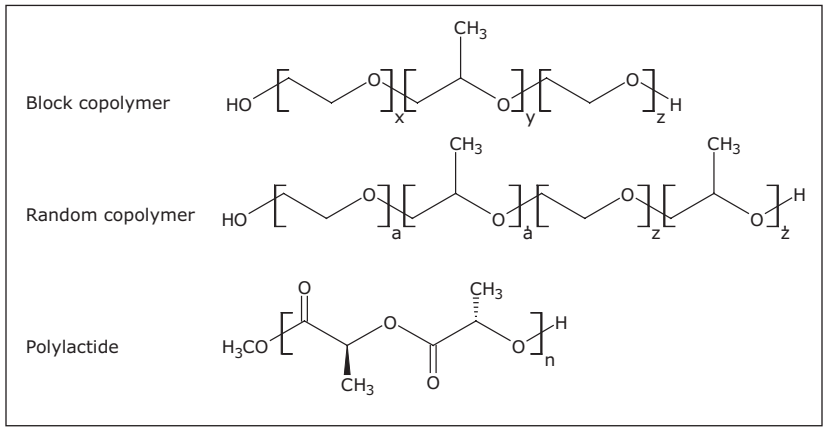

Figure 1. Polymer structures analyzed.

Figure 2 shows two mobility plots. The mass to charge ratio is on the x-axis, drift time on the y-axis, and ion intensity is represented by color. Both samples are copolymers containing PEG and PPG repeat units with an average molecular weight of approximately 2000 Da. Figure 2a presents the IMS data obtained for the block copolymer ions, the area with the highest ion intensity runs roughly diagonally across the plot. Figure 2b presents the IMS data when the random copolymer ions are analyzed. In the copolymer far greater bends, or kinks, are observed in the ion series.

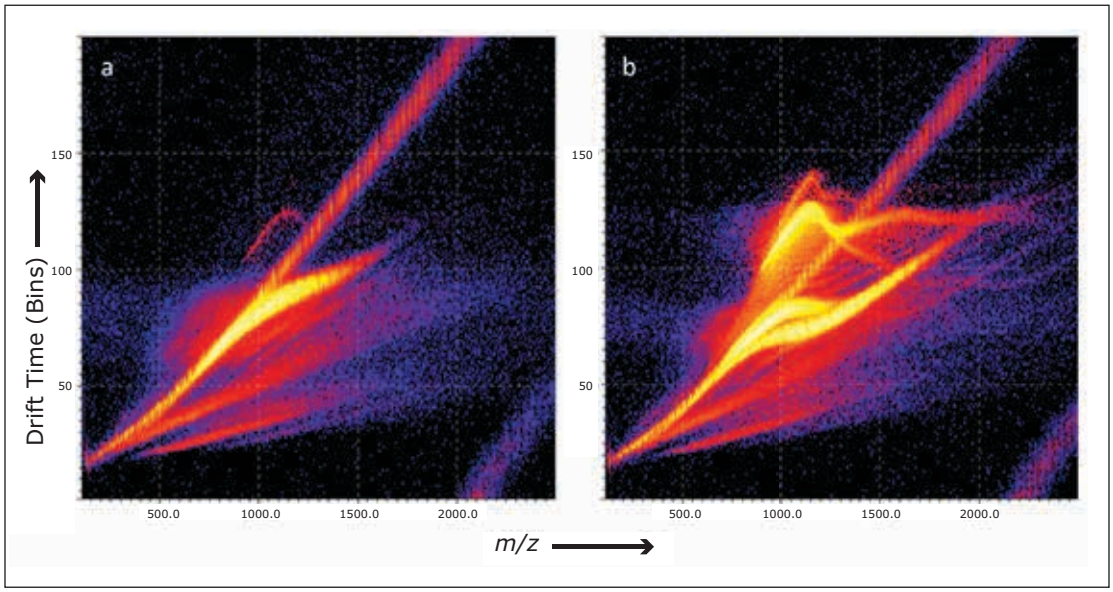

Figure 2. Mobility plots of two copolymers of PEG and PPG. a. block copolymer, and b. random copolymer.

If we observe a roughly straight diagonal line in the mobility plots, this tells us that as the polymer increases in mass, there is a predictable relationship with its collision cross section area. A bend, or a kink, in the ion series indicates that as the polymer increases in mass, the 3D arrangement of the polymer chain changes and possibly folds back on itself which is ultimately dictated by the cationizing species(s).[2]

A simple comparison of both spectra shown in Figure 2 allows us to very quickly differentiate between the random and block copolymer. The random copolymer has many more isomers, therefore it is reasonable to expect more conformers for a given *m/z* with a variety of shapes and sizes. With some copolymers it may even be possible to use the mobility separation to isolate a series of related ions.

Recently, academic research has been carried out on ionized polylactides in the gas phase. The aim of this work was to establish the presence of folding of multiply charged ions and the degree of polymerization at which the folding occurs, for given charge states. Figure 3 shows a graph from *Chemistry A European Journal*.[3] The authors produced both theoretical and experimental collision cross section areas for doubly and triply sodiated polylactide. The experimental values were obtained using a linear drift tube (University of Lyon, Dr. Ph. Dugourd).

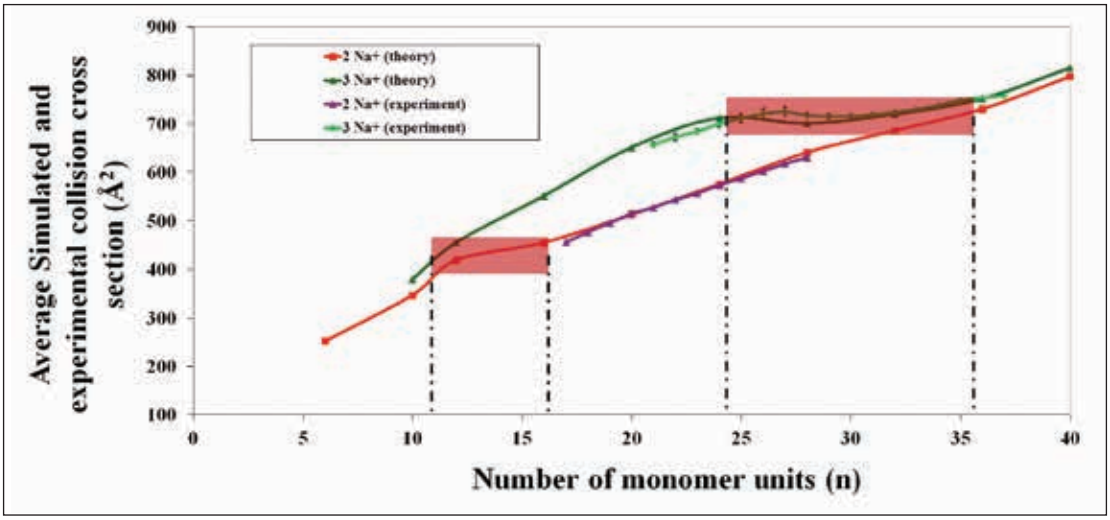

Figure 3. Graph showing average collision cross section area against number of monomer units for doubly and triply sodiated polylactide. Graph from Chem. Eur. J. and reproduced with thanks.[3]

The authors determined that doubly charged polylactide folds between 12 and 16 monomer units, and between 24 and 36 monomer units when triply charged. This information was confirmed by the theoretical 3D structures for these polymer ions. Figure 4 shows a snapshot for the 3D calculated structure of the sodiated 28-mer triply charged polylactide.

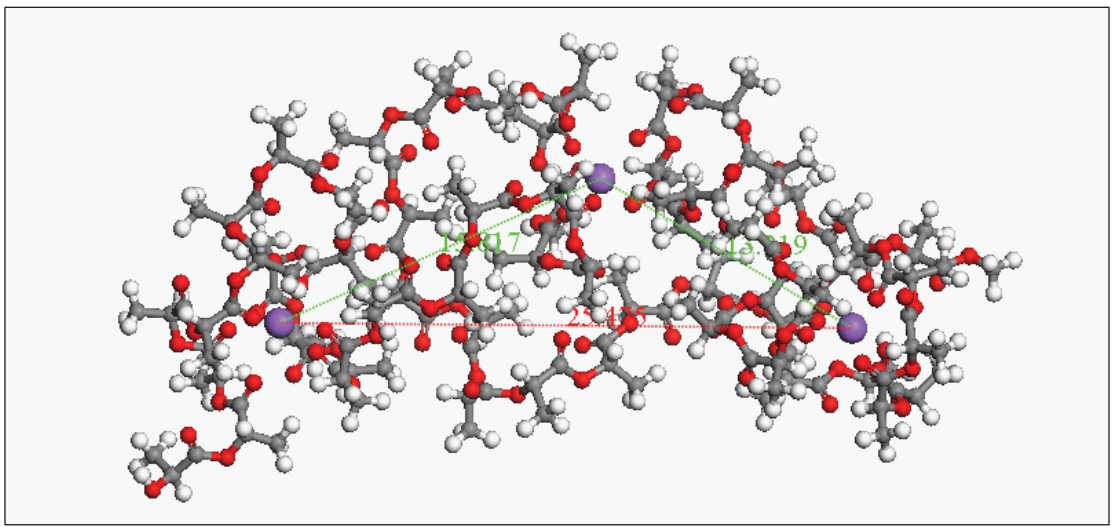

Figure 4. 3D representation calculated by the authors for the triply charged 28-mer polylactide. Image from Chem. Eur. J. and reproduced with thanks.[3]

Similar experiments were performed using SYNAPT G2 HDMS with ion mobility functionality enabled. Figure 5 a shows the full mobility plot with the charge state of the two main ion series labeled. Figure 5 b is a zoomed image of the area of interest. Three ions of particular interest have been highlighted and labeled with their degree of polymerization (DP). These are the ions where the significant folding occurs and this is consistent with the published research performed on a linear drift tube.[3] The increased sensitivity of the SYNAPT G2 HDMS provided additional information allowing the identification of two successive folding patterns for the triply charged ions.

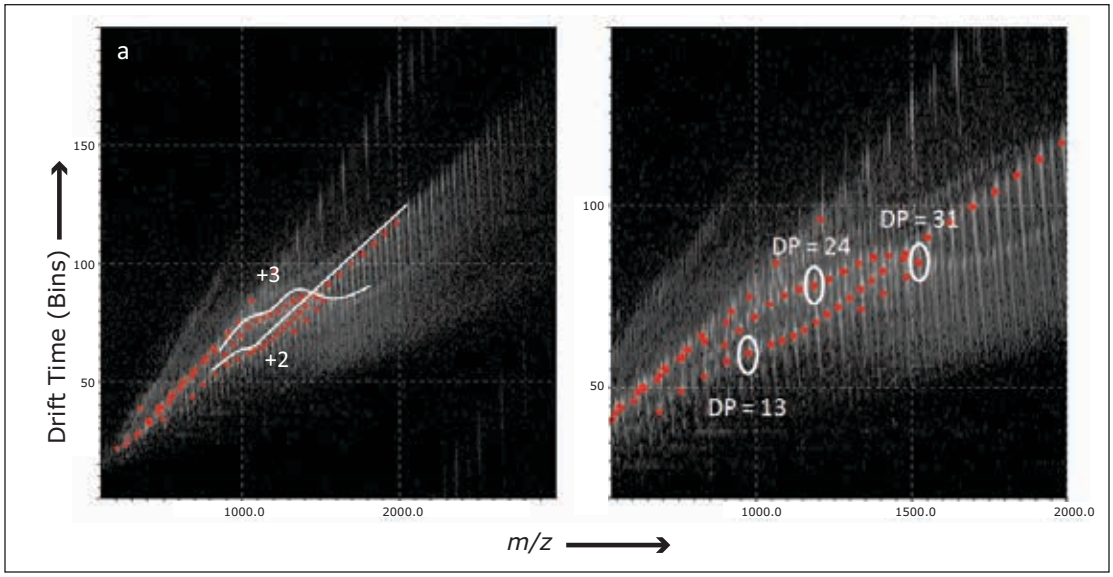

Figure 5. Mobility plots from Waters SYNAPT G2 HDMS of sodiated polylactides. a. Shows the full mobility plot with the charge state of the two main ion series labeled, and b. a zoomed image of the area of interest.

CONCLUSIONS

A selection of polymers and copolymers were analyzed on the SYNAPT G2 HDMS with ion mobility enabled. The ions were separated according to their size, shape, and mass to charge ratio. This information can be used to characterize a polymer's flexibility and 3D structure, measurements that cannot be made by traditional techniques or other commercially available mass spectrometers.

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Delivering Accurate Collision Cross Section Measurements with SYNAPT High Definition Mass Spectrometry (HDMS)

Kirsten Craven

GOAL

To demonstrate that any appropriate calibrant can be used for determining collision cross section (CCS) measurements on a SYNAPT® HDMS® System, providing a completely flexible approach for polymer characterization.

The SYNAPT HDMS with travelling wave ion mobility spectrometry (T-Wave™ IMS) capabilities provides a straightforward approach to CCS calibration and measurement.

BACKGROUND

Polymeric materials are becoming increasingly sophisticated to meet the demanding requirements of new industrial applications. In addition to a polymer's bulk physical properties, it has been predicted that 3D shape may have functional importance in the future.[1] Therefore, it is reasonable to assume that the ability to measure CCS to confirm theoretical calculations of a polymer's 3D arrangement will gradually become more important.

Waters® SYNAPT HDMS System uses T-Wave IMS to provide a simple, reliable, and rapid approach to measuring CCS values. The mobility cell within the instrument must be calibrated to carry out these measurements. A popular calibrant is polyalanine. The singly protonated ions have CCS values between 89 and 276 Å^2, for molecules with between 3 and 19 repeat units. These values have been taken from a widely referenced source, Professor David Clemmer's Group at Indiana University, USA.[2] Accurate CCS results require the analyte to be within the calibration range, and the ions must have the same charge state.

Some polymeric materials are relatively large, and multiple charging is common with electrospray ionization. So, what are the options if your sample doesn't fit within the polyalanine calibration?

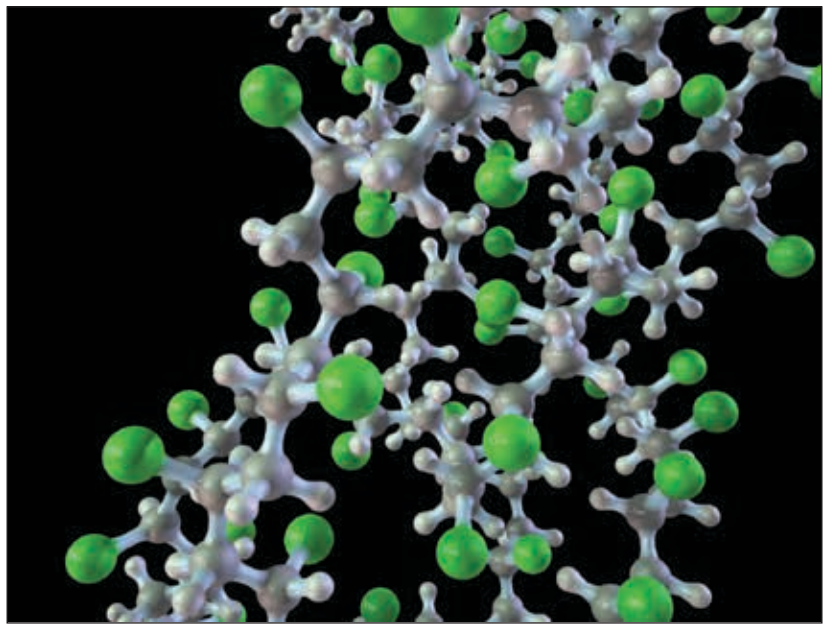

Figure 1. Polyvinyl chloride model.

THE SOLUTION

DriftScope™ Software was created by Waters® to allow visualization and interpretation of ion mobility data, and it includes the ability to automatically calculate CCS values. A known substance needs to be infused under the same instrument parameters as the sample. The software requires a "csv" file for the calibrant, containing a list of *m/z* and respective Å^2 values, to be imported into the software to create a calibration file. This means that any calibrant can be chosen assuming it meets a few simple requirements: the CCS values are known, the range of CCS values are appropriate for the analyte, and the charge state of the ions are the same.

The Clemmer Group's database of CCS values covers a range of peptides, proteins, and oligonucleotides with a variety of charge states. To demonstrate that any appropriate calibrant can be chosen, the following two substances from Clemmer Group's database where purchased, polyalanine and polylysine. Each sample was run under the same conditions to allow CCS values to be measured for both compounds, using the other as a calibrant. Figure 2 shows the graph of results. The CCS values measured had errors between +3% and -2%, well within the ±5% error generally quoted for these measurements on the SYNAPT.

If polyalanine is not an ideal calibrant, due to the range of CCS values, an alternative can be found in published literature. Polymers, such as polyethylene glycol and poly methyl methacrylate, have been characterized in detail.[3,4] CCS value for multiply charged polyalanine have also been published.[5]

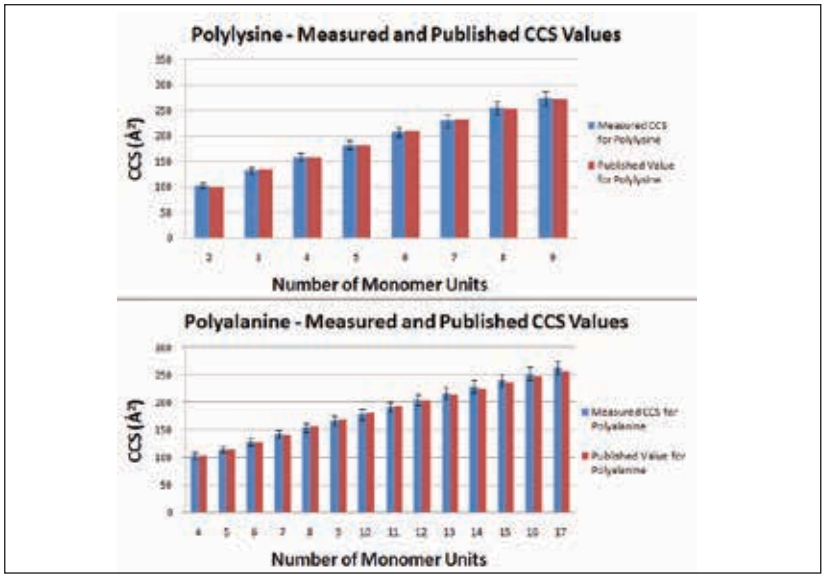

Figure 2. Measured and published CCS values for polyalanine and polylysine.

SUMMARY

This study has demonstrated flexibility for calibrating the SYNAPT HDMS ion mobility cell for CCS measurements. The requirements for a calibrant are limited to the following: the CCS values must be known, the calibration range is appropriate, and the charge state of the calibrant and sample are the same.

It has been predicted that, as polymers become increasingly sophisticated, their 3D arrangement will become important. Theoretical experiments are required to predict the most likely spacial arrangement of these molecules. Currently, ion mobility is the only methodology that can confirm these calculations.

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Using Ion Mobility Mass Spectrometry to Separate Homopolymer Mixtures

GOAL

To separate a mixture of two homopolymers using ion mobility mass spectrometry on Waters® SYNAPT® G2 HDMS.™

BACKGROUND

Mass spectrometry is a powerful tool for the polymer industry as it can be utilized to provide a range of vital information, including macromolecular connectivity, end group information, identification of monomer repeat units, and average molecular weight. This information can be used to indicate the manufacturing process used and the physical properties of the polymer.[1]

Synthetically manufactured polymers contain a range of molecular weight molecules, therefore many ions are observed when they are analyzed by mass spectrometry. If there are two homopolymers present it may become increasingly difficult to interpret the data due to the overlap of polymer ion series, especially if multiple charging has occurred. The additional orthogonal separating power offered by ion mobility (IM) provides a valuable tool for analysts. Figure 1 shows a mass spectrum and IM drift time plot of a polymer mixture containing poly ethylene glycol (PEG) and poly methyl methacrylate (PMMA).

The SYNAPT G2 HDMS with ion mobility functionality allows the separation of polymer mixtures.

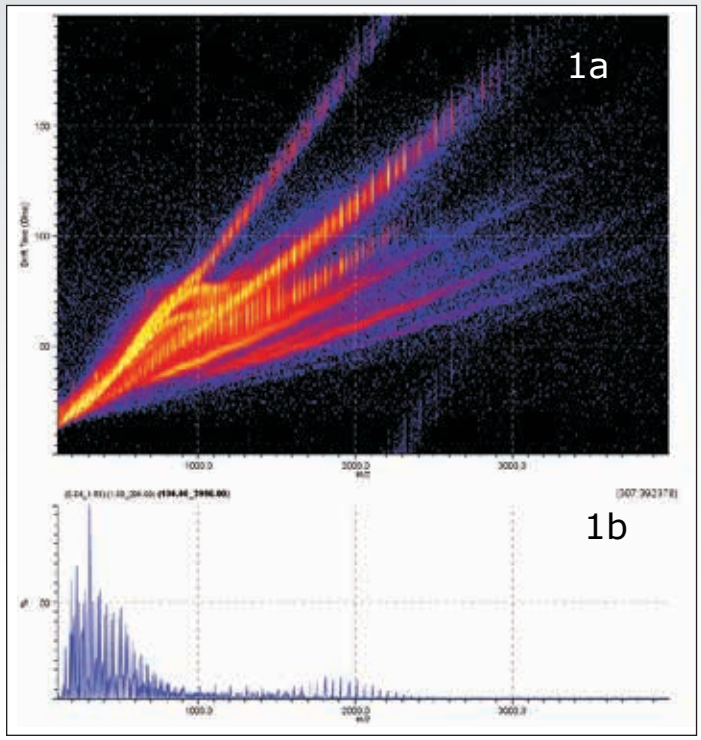

Figure 1. DriftScope data of 20 ppm PMMA 4000 and 20 ppm PEG 3000. (1a) IM drift time plot and (1b) mass spectrum.

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THE SOLUTION

Data were collected by infusing a sample containing a mixture of two polymers, poly methyl methacrylate (PMMA) 4000 and poly ethylene glycol (PEG) 3000, into Waters SYNAPT G2 HDMS with electrospray ionization and ion mobility enabled.

A high cone voltage was set to reduce multiple charging of the polymers making a doubly charged series of PMMA *m/z* 2000 relatively simple to identify. Confident identification of the PEG present would be very difficult without the mobility data due to the overlap of PEG and PMMA ion series, the complexity of which was increased due to multiple charging.

DriftScope™ Software was used to view the mobility data. Within DriftScope, a tool was utilized that allows data points to be selected and interpreted separately from the whole data set. Peak detection on the drift time plot was also used, identifying ions over a selected threshold, making it easier to identify ion series. Figure 2 shows the IM drift time plot and extracted spectra of PEG and PMMA. Highlighted are the areas within the mobility data that have been selected to generate the two spectra, confirming the presence of two polymers.

If additional confirmation or structural information is required, collision energy can be applied both before and/or after the mobility cell allowing true MS/MS analysis to be carried out.

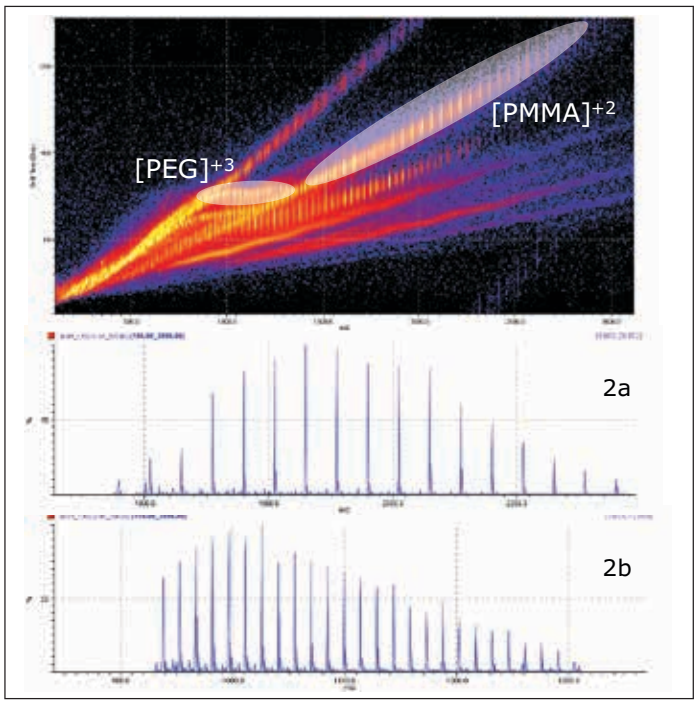

Figure 2. IM drift time plot of the polymer mixture. Highlighted are the select data points used to generate the two spectra shown (2a) PMMA 4000 and (2b) PEG 3000.

SUMMARY

The SYNAPT G2 HDMS offers robust exact mass data and orthogonal separation by ion mobility. This separates molecules by their shape, size, conformation, and mass-to-charge ratio. This is a powerful tool when analyzing complex samples such as polymer mixtures.

DriftScope Software has many tools to help analysts interrogate complex data, including multiple ways to view the data and peak detect ions, allowing ion series and related ions to be more easily identified. Selected data can be extracted and viewed in isolation to reduce the complexity, increase confidence, and allow faster data interpretation.

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Identifying Leachables and Extractables from Packaging Materials

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[2]Mannkind Corporation, Danbury, CT, USA

APPLICATION BENEFITS

- Facilitates the daunting task of identifying unknown compounds in any field that deals with structural elucidation, such as Pharmaceutical, Chemical Material, and Food industries.
- Provides a workflow for the systematic identification of extractables.
- The same workflow applies to either GC or UPLC with QTof.

WATERS SOLUTIONS

Xevo® G2 QTof Mass Spectrometer

Atmospheric Pressure Gas Chromatography (APGC)

MassLynx™ Software

MS^E Technology

MassFragment™ Sofware

KEY WORDS

Extractables, leachables, resins, monomers and oligomers, plasticizers, stabilizers, fillers, coloring agents, antioxidants, antistatic agents, elemental composition

INTRODUCTION

The Pharmaceutical industry is required by the U.S. FDA to demonstrate that no toxic or harmful substances migrate from packaging materials into a drug during its expected product shelf life.[1-5] Similarly, in the Food and Cosmetics industries, there is significant interest in the investigation of packaging leachables present in their products. By definition, extractables are compounds that are extracted from packaging or device components under controlled extraction conditions. Leachables are compounds that migrate from the packaging into the product during its normal shelf life. In the ideal case, leachables are a subset of extractables. If a thorough and accurate identification – or at least compound class identification of all potential contaminants is not performed, it can lead to product recall, financial losses, and/or brand alienation for the company.[6]

The initial investigation, called a controlled extraction study, involves some type of solvent extraction, typically a reflux, microwave, or supercritical fluid extraction.[7] The solvents chosen must cover a wide range of polarities to ensure that non-polar and polar analytes are extracted. The analytical techniques employed for analyzing extracts must be comprehensive to cover as many analytes as possible including GC-FID-MS (volatiles) and LC-UV-MS (non-volatiles).[5]

The challenge with the compounds observed in a controlled extraction study is their identification. Resin manufacturers rarely provide a complete list of all the additives in polymers used for packaging. The original ingredients can degrade or undergo chemical changes during the manufacturing process. Also, the resin manufacturer may not be aware of possible contaminants present within the compounds. Typical extractables include monomers and oligomers from incomplete polymerization reactions; plasticizers, stabilizers, fillers, coloring agents, antioxidants, and antistatic agents, as well as their degradants. Additionally, residues from detergents and mold release agents that can be present on the resin after the molding process.

EXPERIMENTAL

Sample preparation

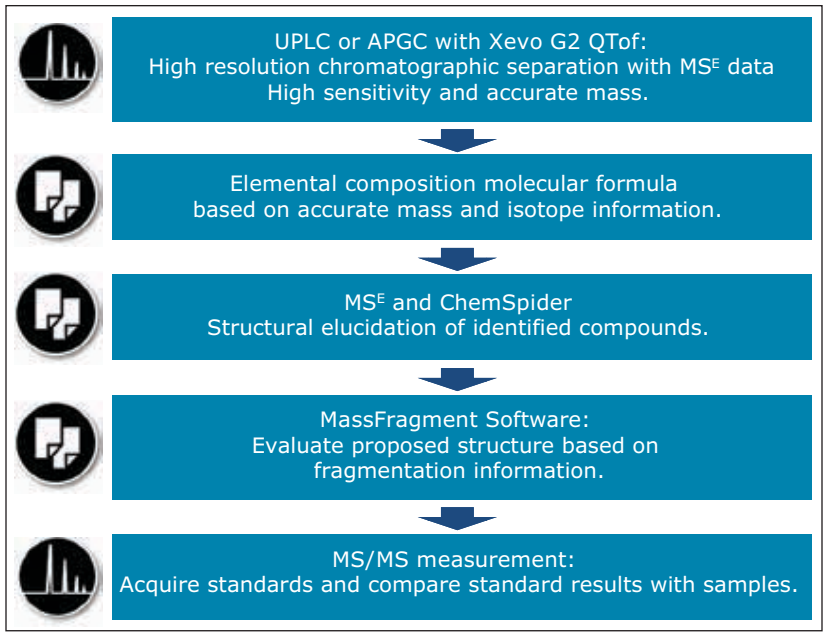
Samples were prepared by microwave extraction. The samples of polypropylene and nylon (2 g) were extracted in 10 mL of isopropanol for 3 h at 70°C. After the extraction the supernatant was transferred to the GC vials.

MS CONDITIONS

MS System:	Xevo G2 QTof with 7890A GC
Column:	HP1-MS, 30 m x 0.32 mm, 1.0 µm film
Carrier gas:	He at 2 mL/min
Temp.:	35 °C for 5 min, 20 °C/min to 320 °C, hold 20.75 min
Injection port:	300 °C
Injection type:	1 µL splitless, 1 min purge
Makeup gas:	N_2 at 500 mL/min
Scan range:	50 to 1,000 Da
Collision ramp for MS^E:	15 to 25 eV
Data management:	MassLynx v. 4.1 Software

Many of the analytes obtained from single quadrupole GC/MS data can be identified using commercially available libraries, such as NIST. However, a difficulty arises for volatiles analysis when the compound of interest is not listed in the library, or when the sensitivity of a single quadrupole MS is not sufficient for a positive identification. Therefore, additional techniques, such as Atmospheric Pressure Gas Chromatography (APGC) and Quadrupole Time-of-Flight (QTof) described in this application note, are beneficial.[8] Due to the absence of libraries for LC/MS data accurate mass data would vastly facilitate the non-volatile analysis. For both volatile and semi-volatile analysis performed here, MS^E data, acquisition on a quadrupole time of flight mass spectrometer, with commercially available structural elucidation tools proves to be valuable for identification of the unknown compounds.

Workflow



RESULTS AND DISCUSSION

Two widely available polymer materials were chosen for this study: polypropylene and nylon. In this application note, the identification of three different types of extractables is shown: an antioxidant, a monomer and a degradant of a monomer.

In the polypropylene sample, a peak (Peak A) was observed at a retention time of 26.3 min, as shown in Figure 1. Performing elemental composition analysis on the accurate mass APGC spectrum, shown in Figure 2, suggested a molecular formula of $C_{43}H_{63}O_3P$, as shown in Figure 3. The elemental composition software calculates the possible molecular formulas for the observed mass and also uses the isotope pattern algorithm to match the observed pattern with the theoretical one for each candidate molecular formula. In this case, there are two choices shown for the ion with the second being a closer match if only mass difference is considered. However, the combination of mass difference and isotope fit brings the correct one to the top of the list.

The APGC analysis was performed under dry source conditions,[9] which promotes molecular ion ($M^{\cdot+}$) formation ahead of the protonated adduct ($[M+H]^+$). It is interesting to note that under high energy collision conditions the molecular ion fragments more easily than the protonated adduct; therefore the difference in the base peak was observed (646.4 versus 647.4) between the two channels, shown in Figure 2.

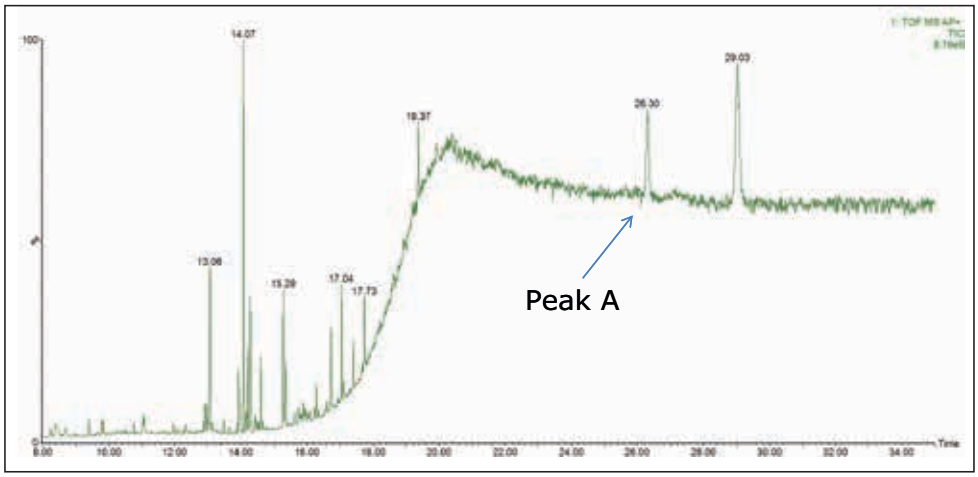


Figure 1. Polypropylene TIC.

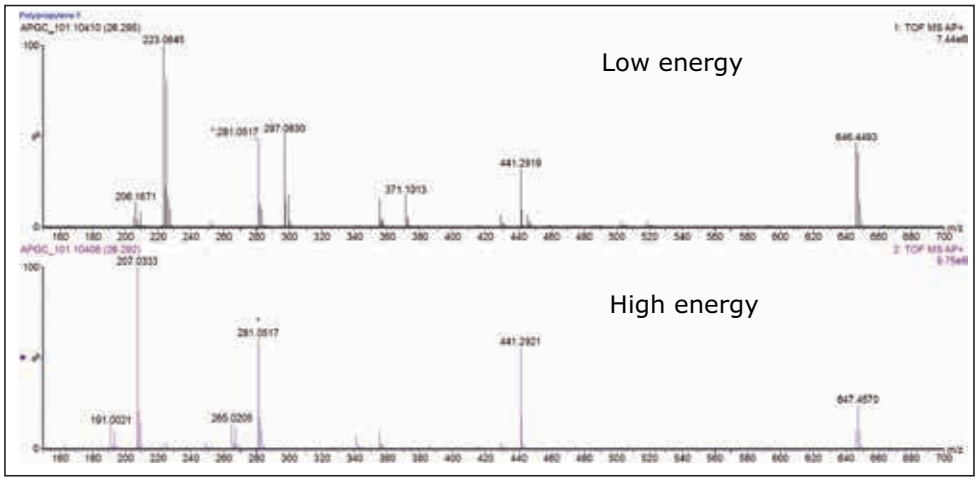


Figure 2. High and low energy spectra for Peak A.

Single Mass Analysis
Tolerance = 3.0 mDa / DBE: min = -1.5, max = 50.0
Element prediction: Off
Number of isotope peaks used for i-FIT = 3
Monoisotopic Mass, Odd and Even Electron Ions
265 formula(e) evaluated with 2 results within limits (up to 50 best isotopic matches for each mass)
Elements Used:

Mass	Calc. Mass	mDa	PPM	DBE	Formula	i-FIT	i-FIT Norm	Fit Conf %	C	H	O	P
646.4493	646.4515	-2.2	-3.4	12.0	C42 H63 O3 P	224.4	0.182	83.35	42	63	3	1
	646.4503	-1.0	-1.5	-1.0	C31 H66 O13	226.1	1.793	16.65	31	66	13	

Figure 3. Elemental composition data for Peak A.

Performing a search of the proposed elemental composition formula in ChemSpider gave Irgafos 168, shown in Figure 4, as the top answer when sorted by "# of References", as described by Little, *et al.*[10] Irgafos 168 is a trisarylphosphite processing stabilizer and protects the resin polymer, such as polypropylene, against oxidation during resin synthesis.

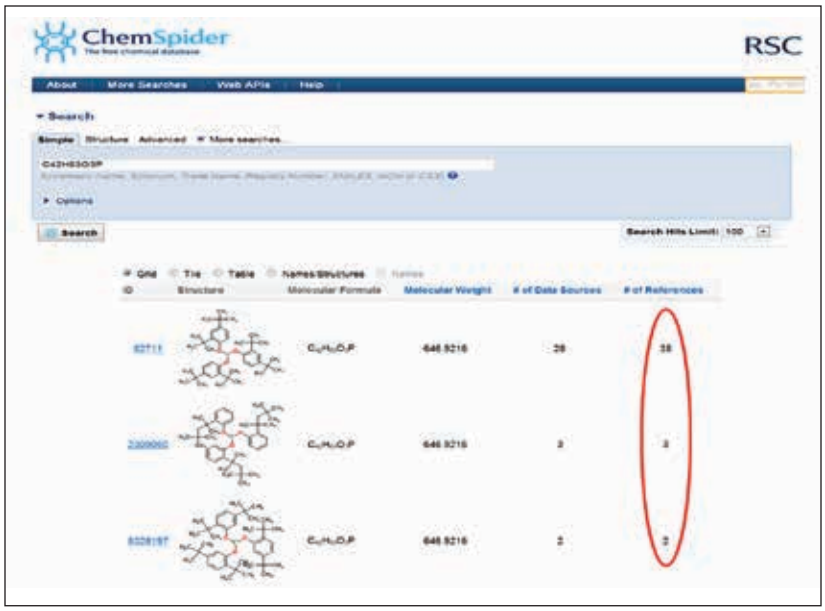


Figure 4. ChemSpider search for $C_{42}H_{63}O_3P$, first match is Irgafos 168. The search hits are ordered by number of references and data sources.

Confidence in the identification was increased when another structural elucidation tool, Waters® MassFragment Software, was able to match several fragments observed in the high and low energy spectra to major fragment ions of Irgafos 168, as shown in Figure 5. MassFragment identifies bonds in precursor structure and then assigns a score based on the type and likelihood of the bond breakage. In addition, the number of bonds broken is listed. The lower the score (*e.g.* S:1.0, B:1.0 vs. S:4.5, B:2.0) the more probable the appearance of the fragment substructure.

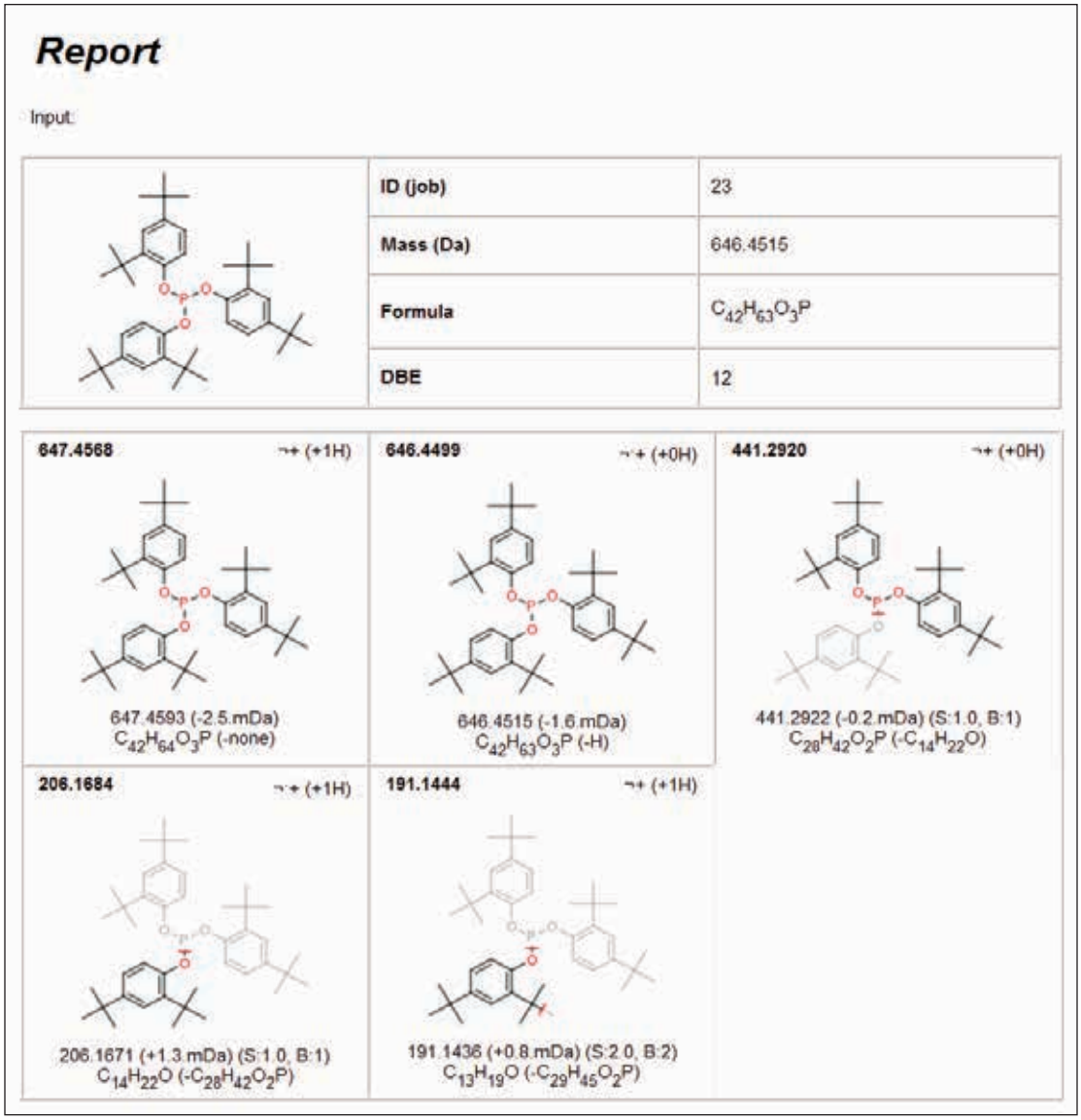


Figure 5. MassFragment Software report for confirmation of Irgafos 168.

The next step in this workflow is to purchase a standard and compare the retention time and fragmentation pattern with the sample.

Laurin lactam is a known starting material for the manufacturing of nylon. In the nylon extract the laurin lactam monomer (Peak B) is observed at a retention time of 15.93 minutes, as shown in Figure 6. The identity of the peak was confirmed by molecular formula and MassFragment following the workflow described in the previous example. A smaller peak is observed at a retention time of 16.07 minutes (Peak C). The measured mass is consistent with a molecular formula of $C_{12}H_{21}NO$, shown in Figure 7, which indicated that the peak was likely a laurin lactam degradant with an extra double bond in the molecule (laurin lactam monomer is $C_{12}H_{23}NO$). The parent ions in each spectra were confirmed by the presence of the in-source dimers (2M+H). For laurin lactam the observed dimer has *m/z* 395.3652 and for the degradant it is *m/z* 391.3324.

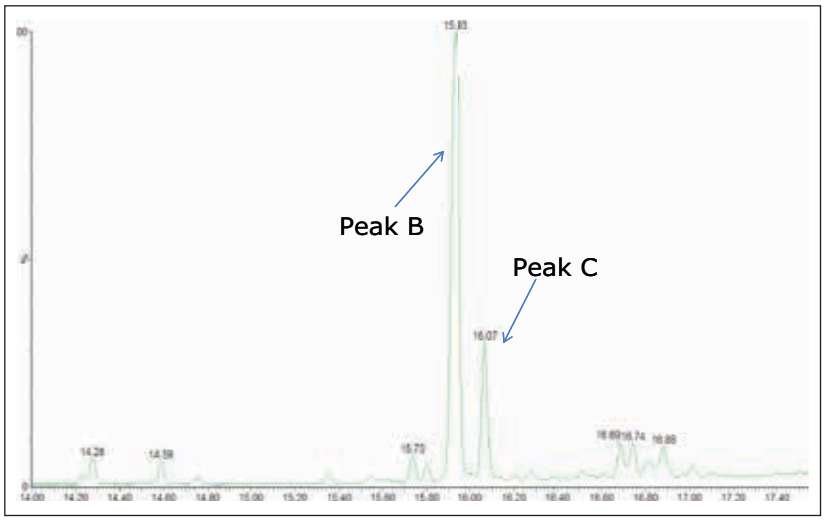


Figure 6. TIC for nylon extract.

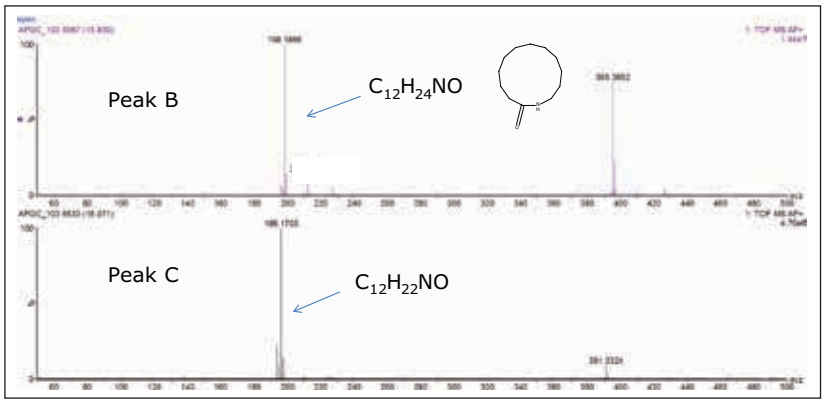


Figure 7. Spectra and molecular formula $[M+H]^+$ for Peaks B and C.

The ChemSpider search for $C_{12}H_{23}NO$ showed laurin lactam as the second top choice. The search of $C_{12}H_{21}NO$ did not provide any appropriate match based on the known compounds in the polymer.

Since a standard of this degradant is not likely to be available, the Xevo G2 QTof data allowed the assignment of a structure to this compound. It is not possible to determine the exact location of the double bond on the laurin lactam ring. However, in these types of studies it is not always necessary to determine an exact structure. It is sufficient if the compound's class has been identified. It was clear that the degradant is related to laurin lactam, therefore its toxicological profile was expected to be similar.

CONCLUSIONS

- Xevo G2 QTof is a valuable tool in the identification and structural elucidation of extractables. MS^E functionality allows simultaneous acquisition of precursor and fragment ions. Accurate mass and fragmentation information assists in the assignment of structures for many unknown compounds.
- Elemental composition and Mass Fragment Software provide the analyst with additional resources in cases when compounds of interest are not found in commercially available libraries.
- The workflow described can facilitate the daunting task of identifying the unknowns in any field that deals with structural elucidation, such as Pharmaceutical, Chemical Material, and Food industries.
- The fragments, the most likely molecular formula, and some chemical intuition based on ingredients known to be present can often provide a likely structure. In the extractable field a likely structure is often sufficient since the goal is to establish a safety threshold.

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Structural Confirmation of Polymeric Material Using MS/MS and Fragmentation Mechanisms

Kirsten Craven,[1] Michael McCullagh,[1] Pascal Gerbaux,[2] and Julien De Winter[2]
[1] Waters Corporation, Manchester, UK
[2] University of Mons, Belgium

APPLICATION BENEFITS

- Rapid data collection
- Exact mass elemental composition
- Polymeric architecture confirmation

INTRODUCTION

Polymeric materials are abundant in modern society covering a broad range of applications in industries such as automobiles, textiles, packaging, medical, and pharmaceutical, to name a few. This increasing complexity in applications has driven the need to produce highly complex polymeric materials. Full characterization of a sample has become a vital part of the development process.

Mass spectrometry can be used to answer many questions regularly asked by polymer scientists, including identifying end groups, back bone architecture, and repeat unit chemistry. A single-stage mass spectrometry experiment can provide information about the molecular weight of polymers and polymeric dispersity. Performing a dual-stage mass spectrometry experiment (MS/MS) while inducing fragmentation provides an extra layer of information regarding the architecture of the polymer and more detail about the end groups.[1]

Confirming the architecture of a polymer is important because it impacts its physical properties, such as density, strength, viscosity, and glass transition temperature. The physical properties of a polymer directly affect its applications.

Polylactides have recently attracted increased attention from both academic and industrial researchers due to their bio-compatible and bio-degradable nature. This application note uses polylactide to demonstrate how MS/MS fragmentation patterns can be used to help determine the backbone architecture of a polymer.

WATERS SOLUTIONS

Xevo® G2-S Q-Tof™

MassLynx® Software

KEY WORDS

Polymer analysis, fragmentation mechanisms, confirmation of backbone structure, polylactide, PLA

EXPERIMENTAL

Sample Description

The sample was first dissolved in acetonitrile before further dilution and the addition of lithium chloride to produce the following:

90 ppm polylactide and 10 ppm lithium chloride (in acetonitrile).

MS conditions

Mass spectrometer:	Xevo G2-S Q-Tof
Ionization mode:	ESI positive
Infusion rate:	10 µL/min
Scan time:	1 s
Capillary voltage:	3.0 kV
Sample cone:	45 V
Extraction cone:	5.0 V
Source temp.:	120 °C
Desolvation temp.:	200 °C
Cone gas:	Nitrogen, 20 L/h
Desolvation gas:	Nitrogen, 800 L/h

LockSpray conditions

Compound:	Leucine enkephalin
Mass:	*m/z* 556.2771
Flow rate:	20 µL/min
Capillary voltage:	3 kV
Collision energy:	6.0 V

RESULTS AND DISCUSSION

Figure 1 shows the structure of the polylactide repeat unit, which has a nominal mass of 144 Da, and the end groups for this sample. The first step in this experiment was to collect an MS spectrum, allowing the most appropriate ion to be selected for MS/MS analysis. The precursor ion selected was *m/z* 903. Both the MS and MS/MS spectra are shown in Figure 2.

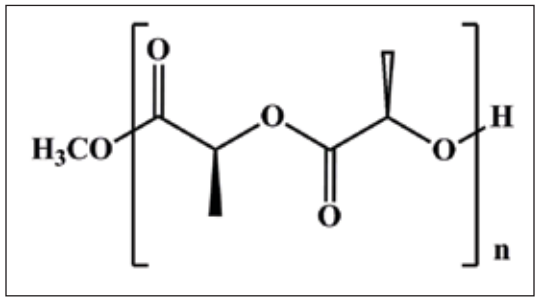

Figure 1. Polylactide repeat unit and end groups.

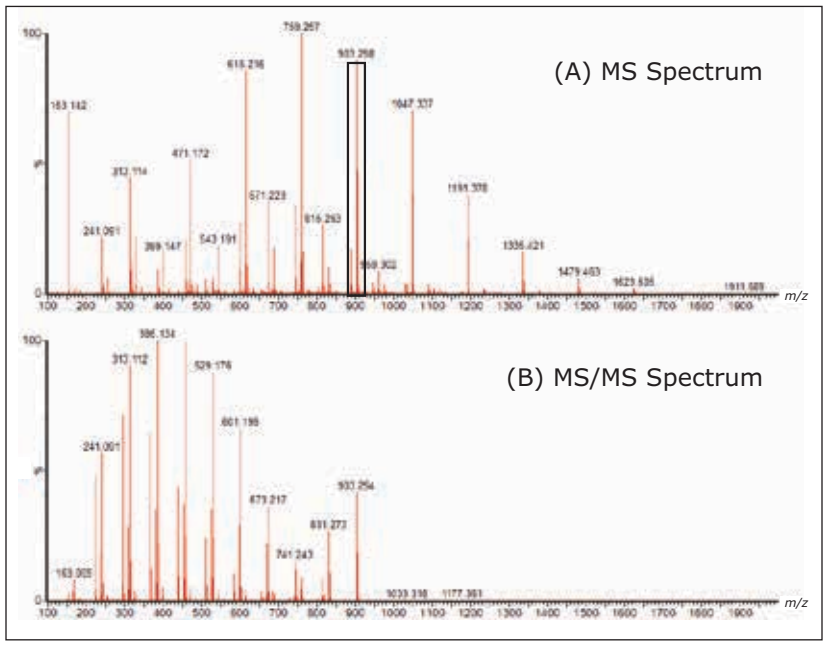

Figure 2. (a) MS spectrum of lithiated polylactide, the ion at m/z 903 has been highlighted, (b) MS/MS spectrum showing the fragment ions from the m/z 903 precursor ion.

Closer interpretation of the MS/MS spectrum shows three series of ions, each 72 mass units apart. Figure 3 shows each series labeled with a circle, a square, or a triangle. Understanding the fragmentation mechanisms that occur to create these ions is extremely important as it allows the scientist to determine the polymer architecture. The exact mass data that is generated can help guide this process by providing possible elemental compositions.

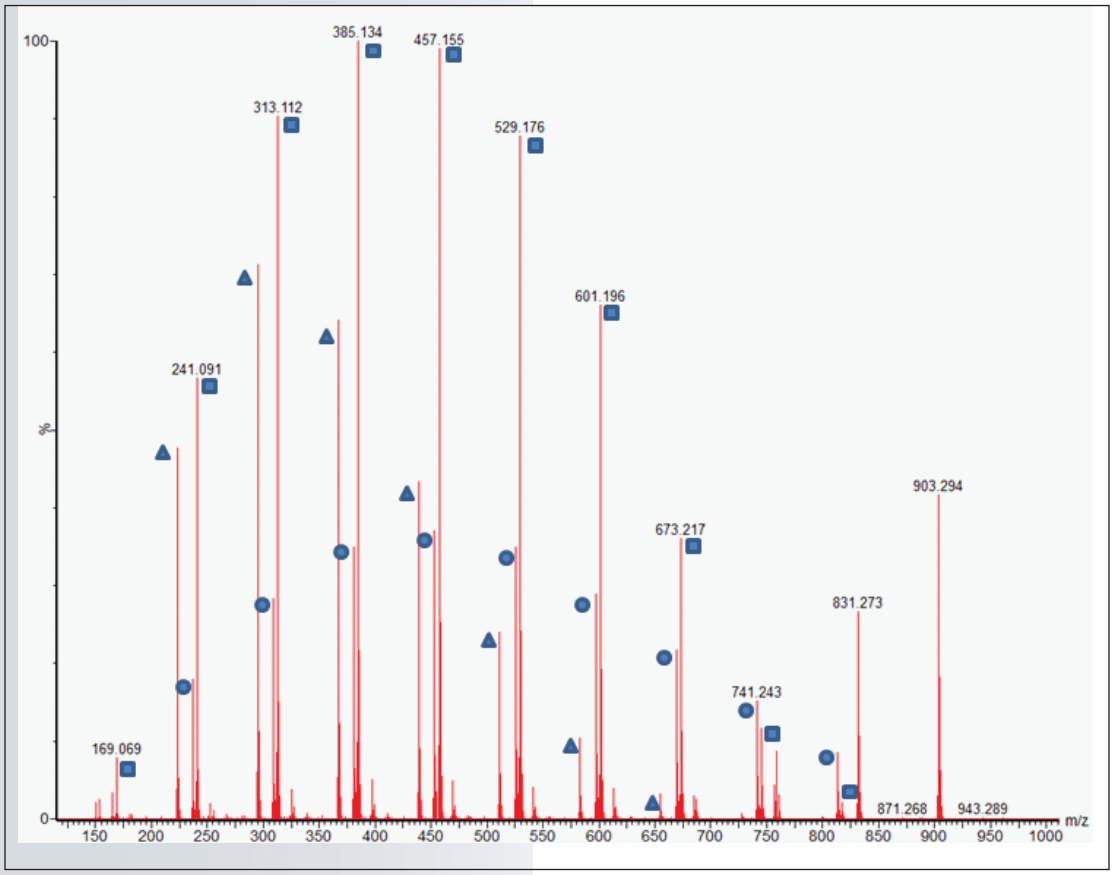

Figure 3. MS/MS spectrum of lithiated polylactide. Three ion series have been identified and labeled with a circle, a square, or a triangle.

Figure 4 proposes a fragmentation mechanism responsible for the initial 86-mass unit loss and consecutive 72-mass unit losses (labeled with a square). This pattern is consistent with the loss of the initiating end group from a linear polylactide. This polymer was synthesized by ring opening polymerization using methanol as the initiator.

Figure 5 shows a very similar fragmentation mechanism; however, this time the polymer is losing the terminating end group (ion series labeled with a circle). Again, this mechanism is consistent with a linear polymer. This is confirmed by a single 90-mass unit loss as a branched polymer would lose multiple 90-mass units. Finally, Figure 6 proposes two fragmentation mechanisms that are responsible for the series labeled with a triangle, which is caused by both end groups being lost.

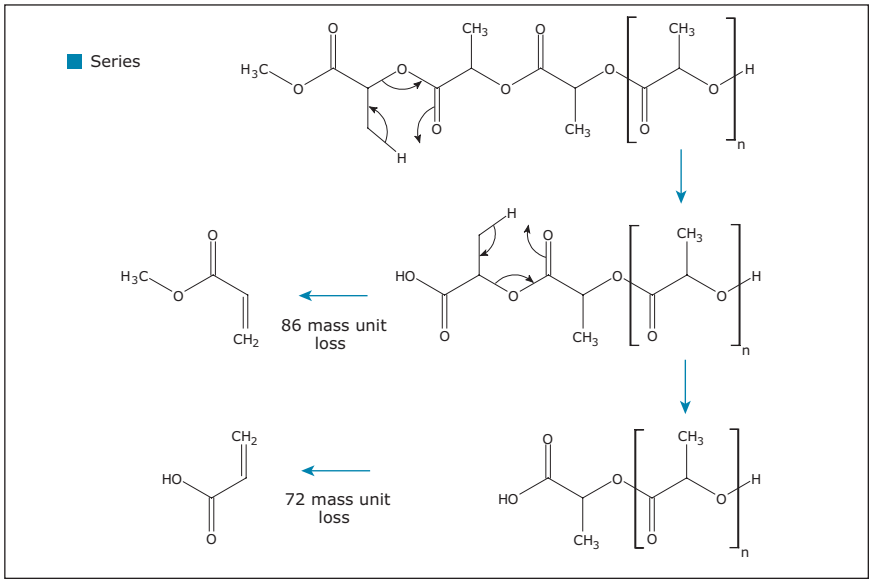

Figure 4. The fragmentation mechanism responsible for the initial 86-mass unit loss and consecutive 72-mass unit losses.

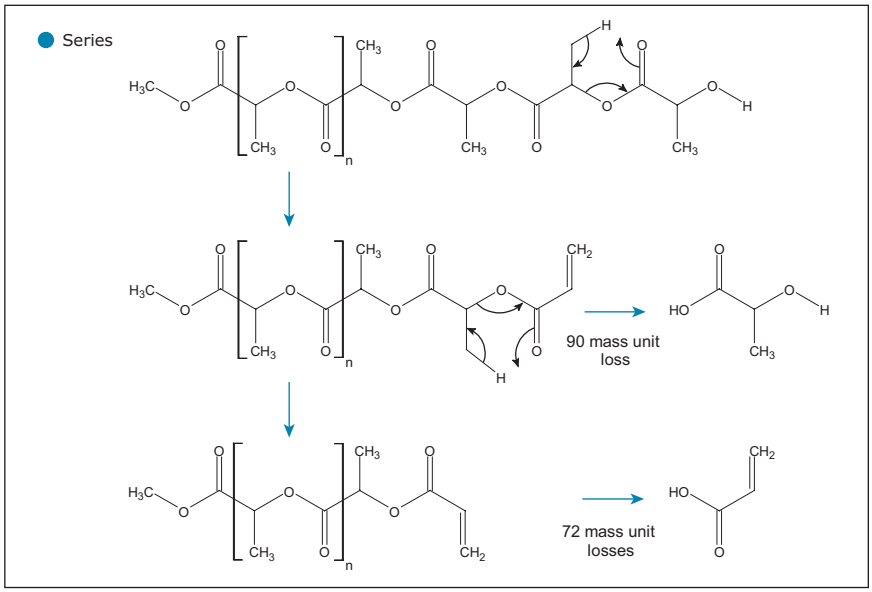

Figure 5. The fragmentation mechanism responsible for the initial 90-mass unit loss and consecutive 72-mass unit losses.

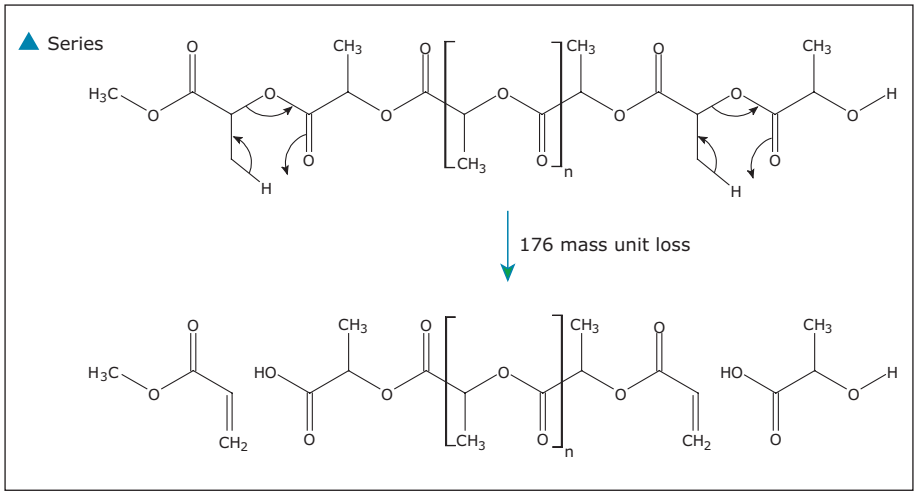

Figure 6. The two fragmentation mechanisms responsible for a total of 176-mass unit loss.

The fragmentation pattern that was observed is consistent with that published in scientific literature.[2]

Interpretation of the MS/MS results and an understanding of fragmentation pathways allow us to confirm that the sample is a linear polylactide. Knowing the architecture of the polymer is of great value. It can confirm the target compound has been synthesized, thereby determining if the product can be used for the desired application.

CONCLUSIONS

- The Xevo G2-S Q-Tof was successfully used to collect MS and MS/MS data on a polylactide sample.
- This information was used to propose the architecture of a polymeric material. A measurement that is vital to the industry to confirm the target compound has been produced.
- This application note demonstrates an approach that is appropriate for many polymer systems.

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Reliable End Group Determination for Polymers Using PMMA as a Model

Kirsten Craven
Waters Corporation, Manchester, UK

APPLICATION BENEFITS

- MS/MS analysis for increased confidence
- Information about the end groups can help guide further chemical modifications
- Elemental Composition functionality to aid decision-making

WATERS SOLUTIONS

Xevo® G2 QTof

MassLynx™ Software

KEY WORDS

Polymer analysis, end group determination, Poly Methyl Methacrylate (PMMA)

INTRODUCTION

Polymers have incredibly diverse applications including paints, cosmetics, plastics, textiles, and food packaging. This range of applications requires a broad spectrum of properties that can be created by varying many aspects of the polymer, such as chain length, terminating and initiating end groups, polymer chemistry, cross linking, and the inclusion of additives during the manufacturing process.

In recent years, Electrospray (ESI) and Matrix Assisted Laser Desorption Ionization (MALDI) have become increasingly important for the analysis of polymers. These ionization techniques within mass spectrometry have allowed information to be collected on a range of polymer properties including end group analysis, backbone structure, and in some cases average molecular weight.[1,2]

The ability to accurately and reliably carry out end group analysis provides valuable information to both polymer manufacturers and polymer research scientists. Information about the end groups can be used to indicate the synthetic process followed and guide how further chemical modifications can be carried out.[3]

Some synthetic polymers, such as poly ethylene glycol, will ionize in ESI mode with the right settings by simply dissolving and infusing. Other polymers become much easier to analyze if they are mixed with a salt before analysis so that the polymer becomes cationized (gains a charge by bonding with the cation from an added salt). The fragmentation pattern of the polymer can be affected by the specific cation present,[2] and hence the structural information that can be gained from an MS/MS experiment.

This application note describes how Waters® Xevo G2 QTof can be used to determine polymer end groups, using Poly Methyl Methacrylate (PMMA) as a model example. The Xevo G2 QTof is a hybrid Quadrupole Time-of-Flight mass spectrometer. The quadrupole allows precursor ions to be selected for fragmentation, which provides the analyst with additional structural information, a cleaner spectrum, and increases confidence in the origin of the ions detected.

EXPERIMENTAL

Samples

Three separate solutions were prepared of PMMA 4000, LiCl, and NaI, each at 1.0 mg/mL in methanol. These solutions were mixed and diluted to make the following:

100 ppm PMMA 4000 and
100 ppm LiCl in methanol

100 ppm PMMA 4000 and
100 ppm NaI in methanol

MS conditions

MS system:	Xevo G2 QTof
Ionization mode:	ESI+
Analyzer:	Resolution mode
Infusion rate:	10 µL/min
Acquisition rate:	1 spectrum/sec
Capillary voltage:	2.5 kV
Sample cone:	150 V
Extraction cone:	4.0 V
Source temp.:	150 °C
Desolvation temp.:	200 °C
Cone gas:	Nitrogen, 20 L/hr
Desolvation gas:	Nitrogen, 600 L/hr

LockSpray™ conditions

Compound:	Leucine enkephalin
Mass:	*m/z* 556.2771
Flow rate:	20 µL/min
Capillary voltage:	3.0 kV
Collision energy:	6.0 V

RESULTS AND DISCUSSION

Figure 1 shows PMMA 4000 cationized with Li^+ and PMMA 4000 cationized with Na^+. Both singly and doubly charged ions are present in both spectra. The inserts show two ion clusters in more detail, the 0.5 *m/z* difference between the isotopes confirms this is a doubly charged species. We can see the majority of PMMA is present as $[M + 2Li]^{2+}$ and $[M + 2Na]^{2+}$.

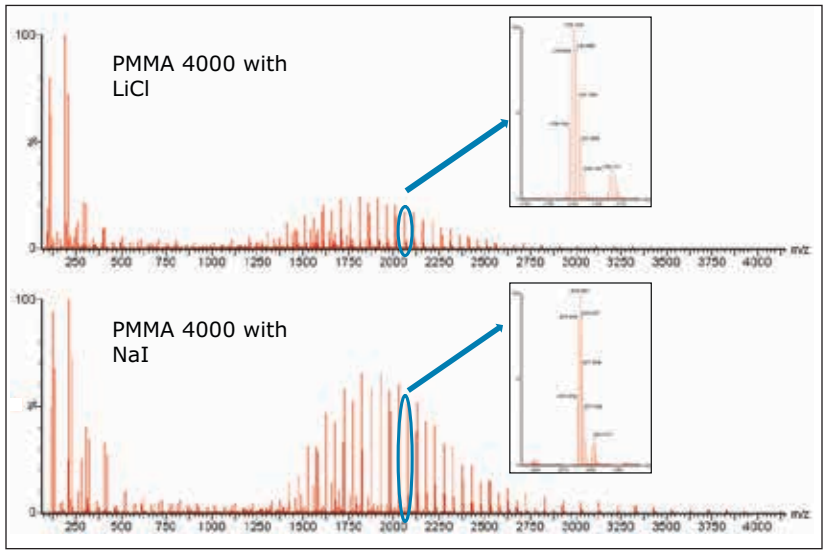

Figure 1. PMMA 4000 cationized with Li^+ (upper spectrum) and PMMA 4000 cationized with Na^+ (lower spectrum).

MS/MS experiments were carried out on the abundant oligomeric ions of the 38-mer for both the lithiated and sodiated PMMA, with *m/z* 1910 and 1926 respectively. The spectra from the MS/MS experiments are shown in Figure 2.

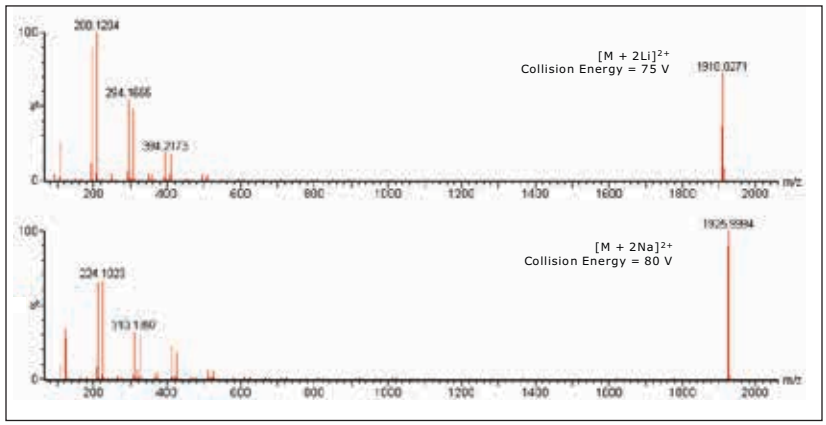

Figure 2. MS/MS spectra for PMMA 4000. The precursor ions chosen were m/z = 1910 and 1926, for lithiated and sodiated ions respectively.

MS/MS results for the lithiated and sodiated PMMA show the same trend, each having two series of ions 100 *m/z* units apart. Figure 3 shows the PMMA monomer repeat unit, which has a mass of 100 Da. The sodiated results are 16 *m/z* units higher than the lithiated, which is consistent with the mass difference between the two cations.

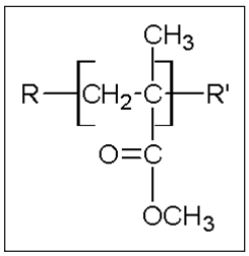

Figure 3. PMMA monomer repeat unit.

The results for lithiated PMMA have been considered in more detail using an option within MassLynx Software called Elemental Composition (EleComp). EleComp can be found in the Tools dropdown list in the Spectrum window. Figure 4 shows the EleComp results for masses above 15% relative abundance within the selected portion of the spectrum. EleComp has calculated possible formulae that could create ions of these masses. The results show that the ions of interest are within 1 mDa of the theoretical exact mass.

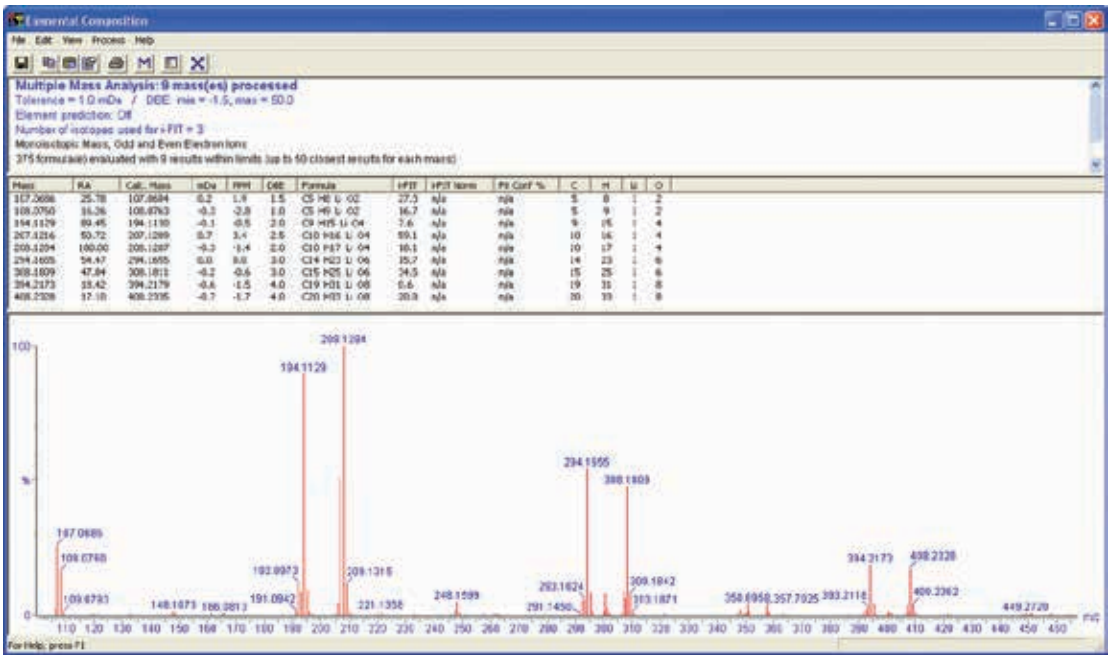

Figure 4. Elemental Composition results for lithiated PMMA (38-mer) analyzed in MS/MS mode. Results for masses above 15% relative abundance within the selected portion of the spectrum are displayed.

With this information it is possible to propose the structure, shown in Figure 5. Nomenclature for the fragments has been taken from the Proceedings of the 54th ASMS Conference.[4]

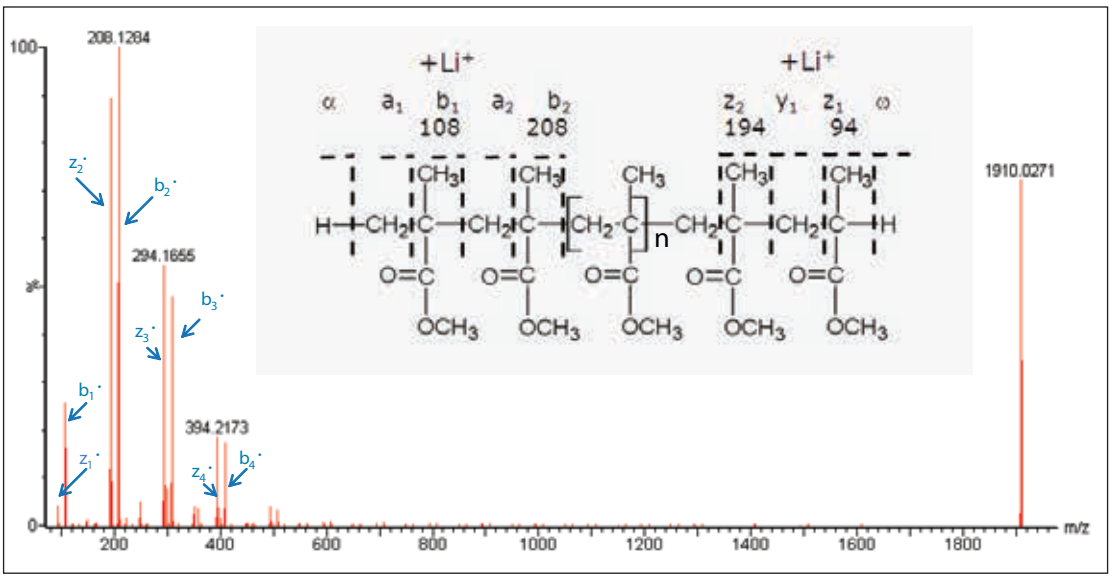

Figure 5. Proposed structure for PMMA end groups with corresponding spectrum.

CONCLUSIONS

- Data from the Xevo G2 QTof were successfully used to propose the end group structure for PMMA 4000, using an approach that is appropriate for many polymer systems. This is a very valuable measurement for the industry as it can indicate the synthetic process followed and guide how further chemical modifications can be carried out.
- Operating the QTof in MS/MS mode provides the analyst with additional structural information, a cleaner spectrum, and increases confidence in results.
- The Elemental Composition tool within MassLynx Software quickly provides the analyst with automated formulae information.

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3. G Montaudo and R Lattimer. Mass Spectrometry of Polymers. Boca Raton: CRC Press LLC; 2002. 68 p.
4. A T Jackson, R P Lattimer, P C Price, W E Wallace, M J Polce, C Wesdemiotis. Proposal for a common nomenclature of fragment ions in the mass spectra of synthetic polymers. Proceedings of the 54th ASMS Conference on Mass Spectrometry and Allied Topics, Seattle, WA, May 28-June 1, 2006.

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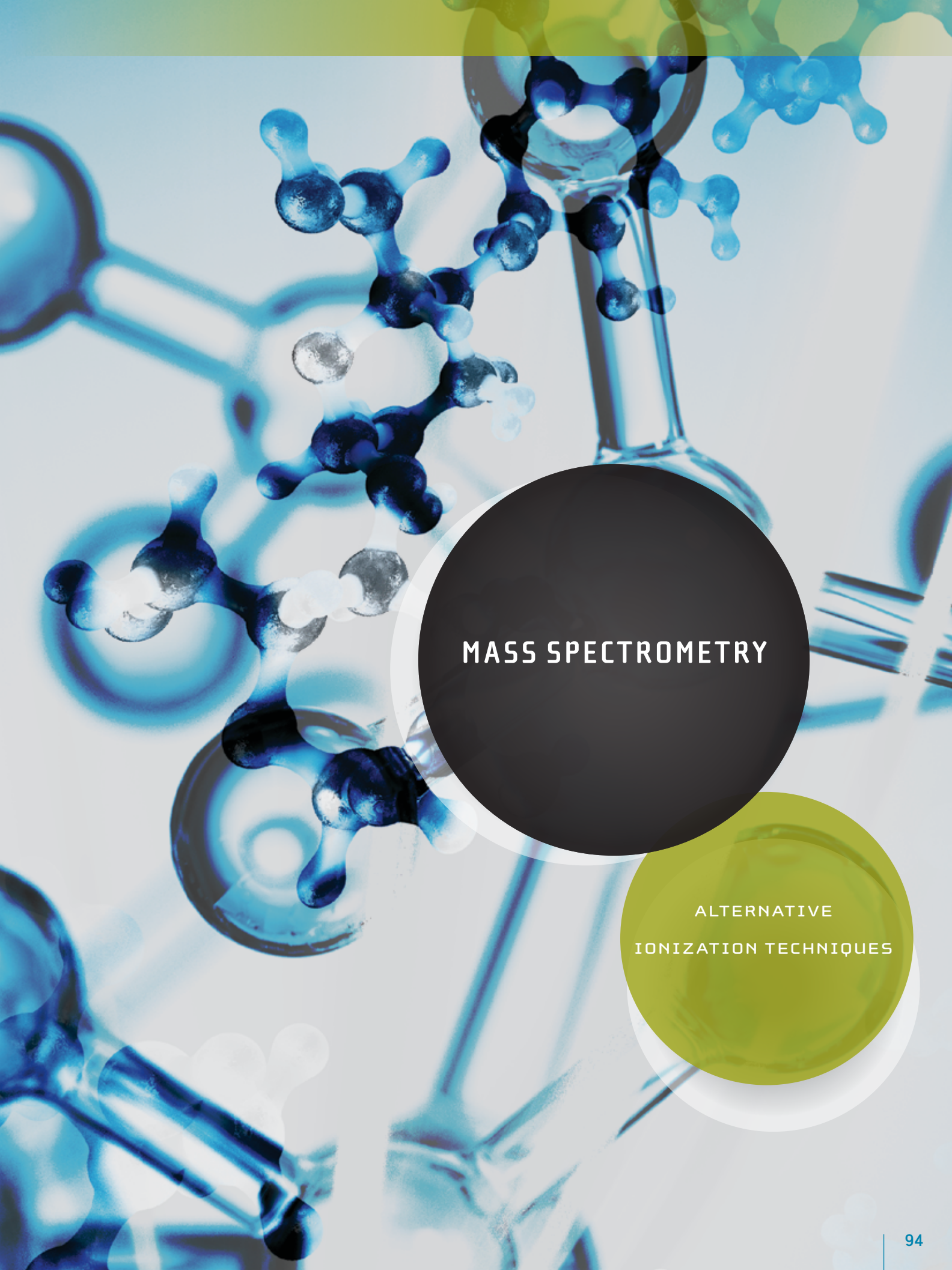

MASS SPECTROMETRY

ALTERNATIVE IONIZATION TECHNIQUES

Xevo TQD and Atmospheric Pressure Photo Ionization (APPI) for the Detection of Diverse Polymer Additives

GOAL

To demonstrate the applicability of Atmospheric Pressure Photo Ionization (APPI) with the Xevo® TQD for the analysis of a range of widely used polymer additives.

BACKGROUND

In their day-to-day activities, analytical laboratories encounter a wide range of structurally diverse molecules with varying physicochemical properties. The ability to rapidly, easily, and accurately analyze all these molecules using a single instrument platform offers analytical businesses the opportunity to streamline their workflows and affords a valuable competitive advantage.

The Xevo TQD MS is equipped with Waters® universal Xevo source housing. This provides analysts with quick and simpleaccess to diverse interface technologies with which to approach their daily analytical challenges. Along with APPI, other techniques include Atmospheric Pressure Gas Chromatography (APGC), Atmospheric Pressure Solids Analysis Probe (ASAP), combined ElectroSpray-Atmospheric Pressure Chemical Ionization (ESCi®), or NanoFlow™ Technologies.

Many industries, including the polymer and petrochemical industries, frequently encounter molecules that cannot easily be ionized using the typical technique of choice for mass spectrometry, ElectroSpray Ionization (ESI). However, APPI is well suited for the analysis of diverse molecular structures,

The Xevo TQD with flexible source options, such as APPI, offers comprehensive compound coverage for diverse routine analyses.

and it is particularly applicable to highly organic, non-polar species. APPI is the ideal choice for analyzing compounds, such as polymers and polymer additives, and it is equally effective at ionizing low mass and high mass species.

THE SOLUTION

A Xevo TQD Mass Spectrometer fitted with an APPI source, coupled to an ACQUITY UPLC System were used for the simultaneous analysis of 10 different polymer additives. The Xevo TQD was operated in MRM mode to ensure maximum sensitivity and selectivity for the compounds of interest.

The ionization process in APPI can be enhanced by a substance known as a dopant. The dopant is usually an organic solvent that is readily ionized by the vacuum-UV lamp, which can then react to ionize the analyte of interest. In this analysis, the dopant was acetone, which was incorporated into the mobile phases.

The additives analyzed include an anti-static agent, a clarifying agent, a plasticizer, a PVC softener, an optical brightener, UV absorbers, and antioxidant stabilizers. Their molecular masses ranged from 226 Da for Tinuvin P, to 647 Da for Irgafos 168. The MRM data were processed using TargetLynx™ Application Manager. Figure 1 shows the chromatograms obtained for the simultaneous analysis of a mix of the 10 polymer additives. We can clearly see good responses for every compound, indicating that they all were readily ionized using APPI.

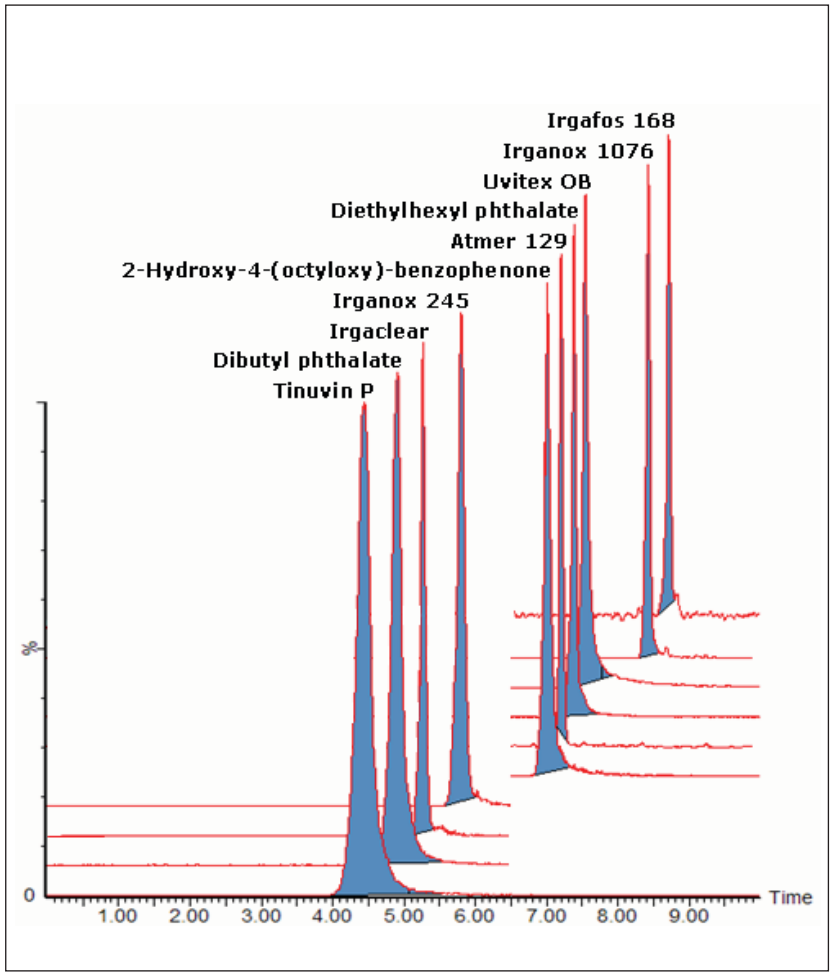

Figure 1. MRM chromatograms for 10 polymer additives acquired using Xevo TQD fitted with an APPI source, coupled to an ACQUITY UPLC System.

SUMMARY

Xevo TQD MS fitted with an APPI source, coupled to an ACQUITY UPLC System, were successfully used to analyze a diverse range of widely used polymer additives. The MRM data acquired were processed using TargetLynx Application Manager.

All the analytes of interest were readily ionized by APPI with acetone acting as the dopant. Good responses were observed for solutions with a concentration of 1 µg/mL (1 ppm), which suggest that the technique could be used to detect low levels of these types of compounds.

The source diversity offered with the Xevo TQD MS equips today's analytical laboratories with powerful tools to meet ongoing challenges.

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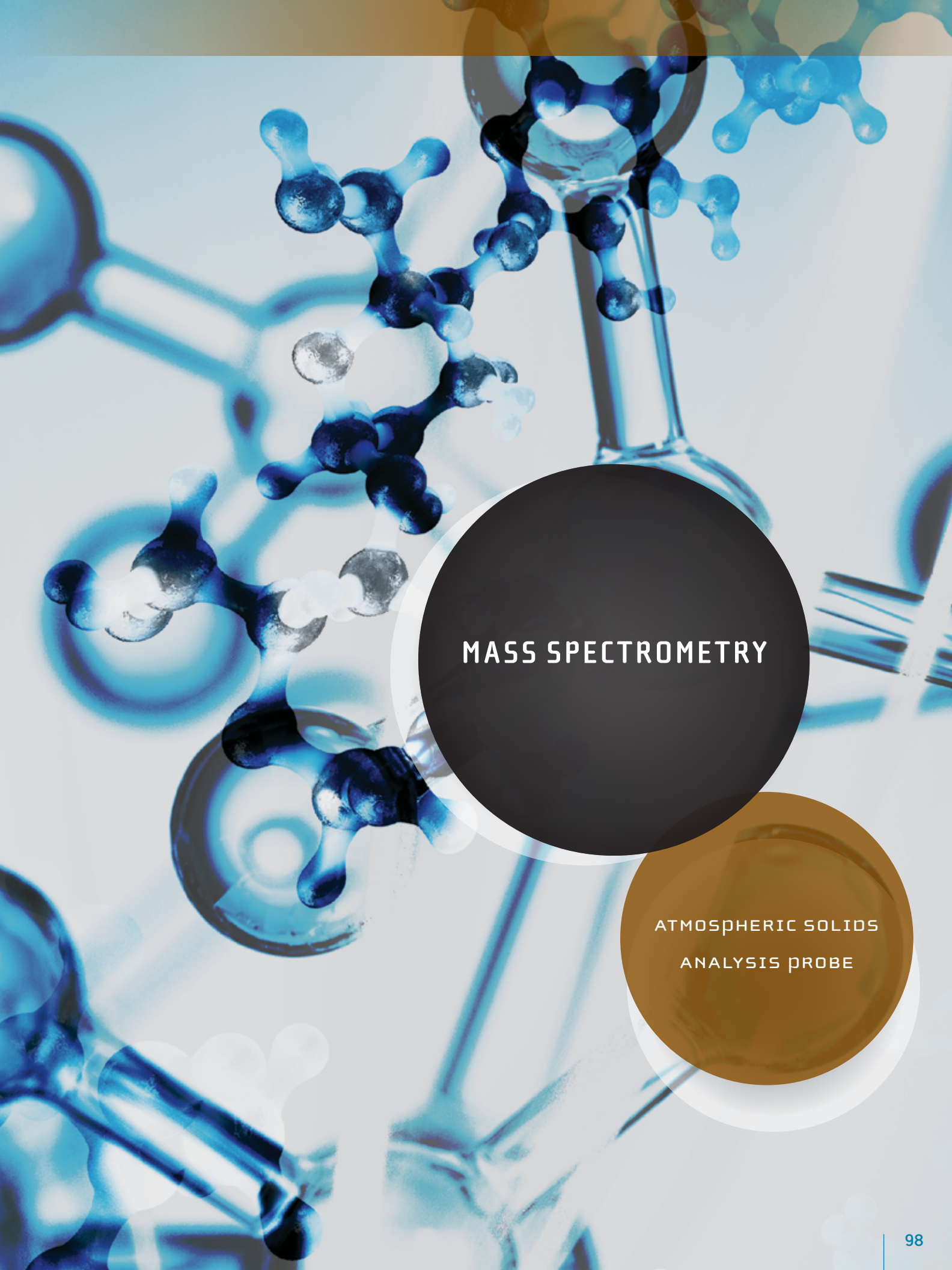


MASS SPECTROMETRY

ATMOSPHERIC SOLIDS ANALYSIS PROBE

Rapid Polymer Analysis with Atmospheric Solids Analysis Probe/ Mass Spectrometer (ASAP/MS)

GOAL

To successfully and rapidly analyze short chain natural and synthetic specialty polymer, surfactant, and oligomeric materials in order to provide absolute molecular weight profiles, data, and valuable material architecture in five minutes or less using desorption mass spectrometry with Waters® ASAP sample inlet and ACQUITY® SQ Detector (SQD).

BACKGROUND

Analysis of specialty polymers and surfactants is often limited to size-based analysis, such as Size Exclusion Chromatography (SEC) with an appropriate detection method. Inherent in this technique is the requirement for a suitable calibration protocol that takes into account detector bias and chromatographic stability. Further, as product space expands to include multi-functional materials, the SEC approach is limited when addressing compositional variation in the material.

The goal of matching the SEC analysis with mass spectrometry can provide necessary compositional analysis, but it is fraught with significant challenges. Typical SEC solvents, such as THF, DMF, and toluene, do not allow for a suitable environment for mass spectral analysis. Infusion of polymeric material for mass spectral analysis has been explored, but this approach is limited due to ionization suppression effects caused by the competing ionization of many infusion solvents. Use of ASAP as a sample inlet

ASAP/MS provides data including absolute molecular weight profiles for polymer materials in less than five minutes.

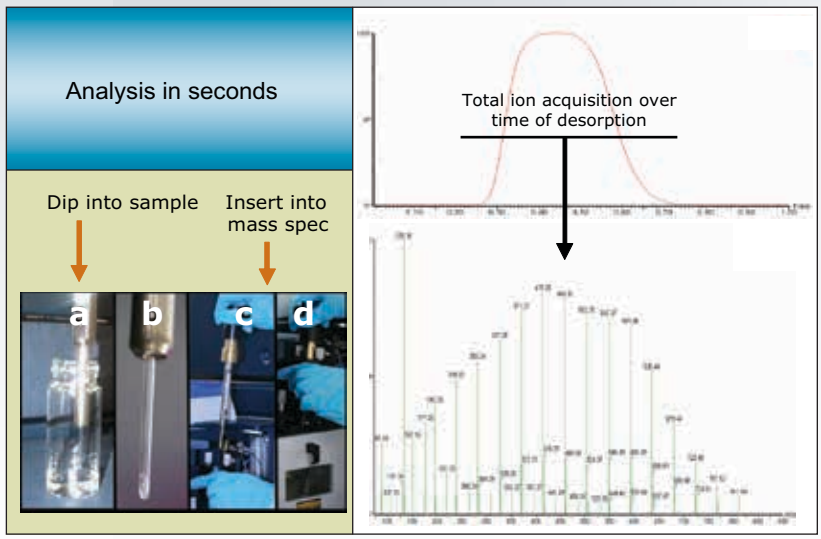


Figure 1. Using ASAP as a sample inlet, a sample is loaded directly onto the capillary tip of the probe, vaporized using heated gas, and then ionized using a corona discharge.

provides for direct mass spectral analysis. ASAP eliminates the solvent impact since the sample is loaded directly onto the capillary tip of the probe, vaporized using heated gas, and then ionized using a corona discharge.

THE SOLUTION

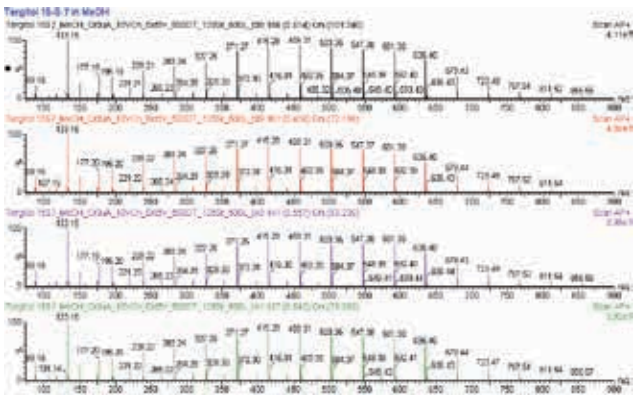
ASAP coupled to ACQUITY SQD has proven to be a powerful laboratory tool for polymeric analysis. The utility of the solids probe provides a simple, direct, and rapid mode of sample introduction. Due to sample desorption from the probe tip, the analyte is introduced without interference from solvents, allowing consistent ionization of the analyte. The resulting thermally desorbed molecular chains are ionized across their molecular weight distribution.

The analysis is completed in a few steps:

- The sample is dissolved in solvent and applied to the tip of a melting point capillary tube. The solvent is flashed off of the tip in the first seconds of the analysis due to the controlled desolvation gas flow and temperature. The analyte is left on the capillary tip free of background solvent and related ionization and suppression effects.
- The polymeric material thermally desorbs or volatilize from the tip under controlled desolvation gas temperature and flow.
- As the analyte molecules volatilize they are ionized.
- The ionized molecules are detected using the ACQUITY SQD.

The resulting thermal desorption data is tabulated based on the *m/z* (equal to mass for singly charged molecules) and abundance of each polymer chain length. The mass is adjusted for proton inclusion and the adjusted mass and abundance data is combined and summed over the weight distribution.

Sample: $CH_3(CH_2)_mO(CH_2CH_2O)_nOH$ Where m = 10-14 and n = 1-14



$M_n = \Sigma (m_i^* C_i) / \Sigma (C_i)$
$M = \Sigma (m_i^{2*} C_i) / \Sigma (m_i^* C_i)$
$M_Z = \Sigma (m_i^{3*} C_i) / \Sigma (m_i^{2*} C_i)$
$M_{Z+1} = \Sigma (m_i^{4*} C_i) / \Sigma (m_i^{3*} C_i)$

Where m_i is the molecular weight (m/z) for the i-th ion detected and C_i is the concentration or abundance of the i-th ion detected.

	Replicate Test 1	Replicate Test 2	Replicate Test 3	Replicate Test 4
Mn	408	394	401	400
Mw	487	478	485	484
Mz	537	533	540	540
Mz+1	572	571	577	578

Figure 2. The summed data is computed as the number average, weight average, Z average, and Z+1 average molecular weights (Mn, Mw, Mz, and Mz+1).

SUMMARY

The versatility and advantages of Waters ASAP/SQD approach has shown that a broad array of samples can be evaluated in one or two minutes, depending on the sample type and its volatility. Reproducible data can be easily obtained without sample specific method development. Further, the unique mass spectral signature of the sample allows for the analysis of compositional 'fingerprint' variations not seen with conventional size exclusion separation analysis. The approach offers a reduction in the time required for analysis and operator training, as well as elimination of costs associated with solvent consumption and waste treatment.

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Applying ASAP to the Analysis of Synthetic Polymers

GOAL

To provide a direct analysis tool for mass spectrometric analysis of synthetic polymers and blends with limited method development or sample preparation.

BACKGROUND

Analysis of specialty polymers and surfactants is often limited to size-based analysis, such as Size Exclusion Chromatography (SEC) with an appropriate detection mode. When employing this technique, a proper test method must be established, including a calibration set that takes into account detector bias and chromatographic stability. Further, as product space expands to include multi-functional materials, this analytical approach has been found to be limited when addressing compositional variations in the material.

ASAP (Atmospheric Solids Analysis Probe) developed by McEwen *et. al*[1] has been shown to be a useful tool for the rapid direct analysis of volatile and semi-volatile solid and liquid samples, such as synthetic polymers and oligomers[2]. The ability of Ion Mobility Spectrometry (IMS) to separate ions based on their collision cross sectional area and charge state provides a powerful orthogonal separation technique, when coupled with mass spectrometry for the analysis of complex mixtures.

ASAP IMS-MS shows excellent potential for the rapid fingerprinting of complex polymeric samples.

Figure 1. The sample is loaded directly onto the tip of a glass capillary. The sample is then directly inserted into the ionization source chamber. Bulk MS data are collected in seconds.

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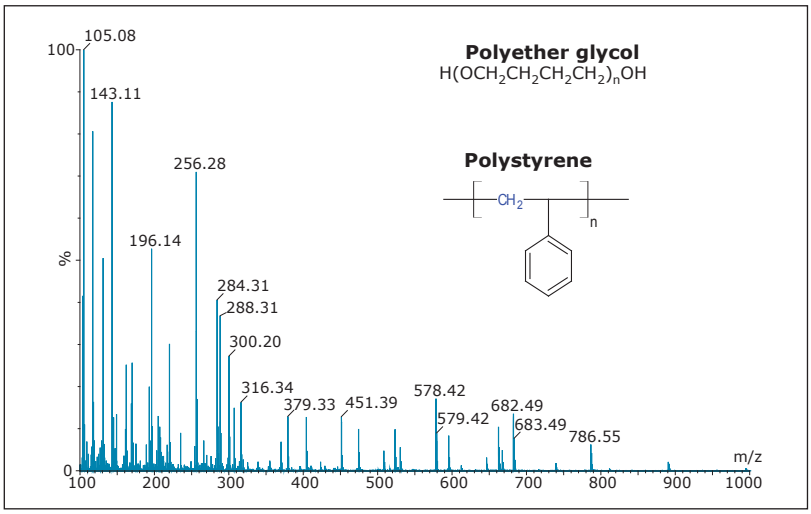

Figure 2. ASAP analysis of polystyrene 1000 and polyether glycol 1000 mix.

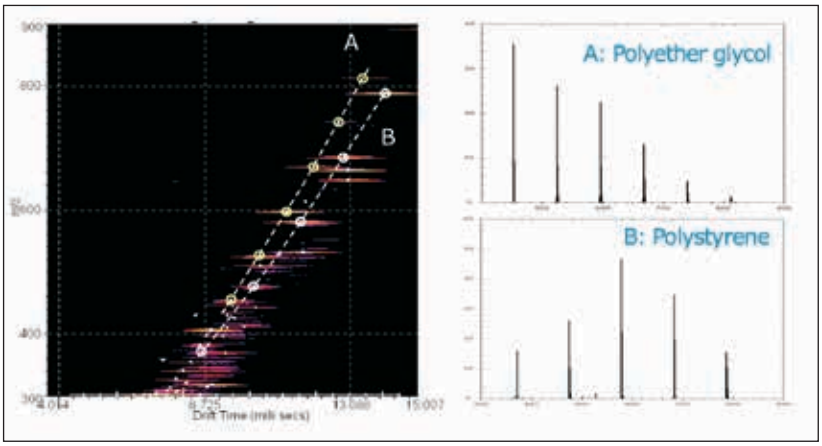

Figure 3. m/z versus DT plot for ASAP IMS-MS of polystyrene 1000 and polyether glycol 1000 mix and extracted spectra.

THE SOLUTON

All analyses were performed using a Waters® SYNAPT® G2 HDMS™ System. An ASAP device was used in place of the instrument's Electrospray probe, as shown in Figure 1. The source was operated in ESCi® mode to facilitate the use of the Electrospray desolvation heater in conjunction with a corona discharge. This configuration also allowed the LockSpray™ interface to be used for exact mass measurements. Samples were introduced on a sealed glass melting point tube and vaporized in a stream of heated nitrogen. The temperature of the nitrogen was ramped to control the vaporization of components in the complex mixtures. The sample in the gas phase was ionized by proximity to a corona discharge needle. Ions then passed from the atmospheric pressure region into the mass spectrometer.

The polymer mixture was analyzed by ASAP on a SYNAPT G2 HDMS System, shown in Figure 2, and the IMS-MS data were post-processed using a 3-dimensional peak detection algorithm 'APEX 3D' to determine *m/z*, drift time (DT), and intensity, as shown in Figure 3. Ion mobility separated spectra of the polyether glycol and polystyrene were readily extracted using this software. This approach has potential for wider application in the rapid characterization of polymeric mixtures. ASAP IMS-MS shows excellent potential for the rapid fingerprinting of complex polymeric samples.

SUMMARY

- ASAP provides a rapid method for the direct analysis of complex mixtures such as blended polymers without any sample preparation.
- Non-polar compounds which are not amenable to analysis by ESI or APCI were readily detected with good sensitivity.
- ASAP IMS-MS shows excellent potential for the rapid fingerprinting of complex polymeric samples.

References

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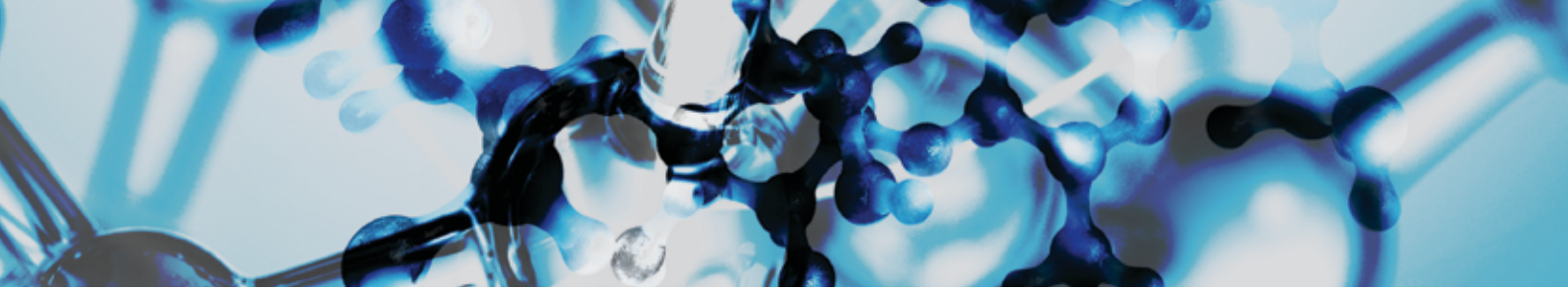

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