NCPTT

Molecular Characterization and Technical Study of Historic Aircraft Windows and Head Gear using Portable Raman Spectroscopy | 2013-01

Smithsonian Institute National Air and Space Museum

National Park Service
U.S. Department of the Interior

National Center for Preservation Technology and Training

NATIONAL PARK SERVICE

FINAL REPORT

MOLECULAR CHARACTERIZATION AND TECHNICAL STUDY OF HISTORIC AIRCRAFT WINDOWS AND HEAD GEAR USING PORTABLE RAMAN SPECTROSCOPY

(NCPPTT GRANT MT-2210-10-NC-10)


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Smithsonian Institution

TABLE OF CONTENTS

I. Executive Summary

This report summarizes work completed under the National Center for Preservation Technology and Training (NCPTT) grant MT-2210-10-NC-10, "Molecular characterization and technical study of historic aircraft windows and head gear using portable Raman spectroscopy." The grant impetus was to evaluate a portable Raman spectrometer as a potential survey tool for rapid characterization of plastics in museum collections. This was explored through an applied case study of window materials used in aviation beginning in World War I. The Smithsonian's National Air and Space Museum (NASM) and Museum Conservation Institute (MCI) collaborated in this endeavor.

Initially, a historic collection of aircraft windows was sought to test the portable Raman spectrometer with the assumption that transparent, colorless plastic sheets would be a relatively simple analytical problem. Plastics that were colored, opaque, and of varying thickness could be studied once the usefulness of Raman was established. As it turned out, the grant award coincided with NASMs collection move to its new Steven F. Udvar Hazy Center, and many aircraft of interest have not been accessible. NASM provided a collection of >80 aviator goggles and helmets for study in the interim. It was assumed that the lenses would meet the requirements of transparency and color. The headgear was examined for construction and condition, and lenses and other plastic elements were analyzed by Raman and X-ray fluorescence (XRF) spectroscopies to identify the materials.

The research goals of the grant have been met. Portable Raman spectroscopy has proven a useful tool for identification of synthetic polymers, plasticizers, and other compounds in plastic. It now is used routinely for sorting transparent and colorless plastics at MCI and often can identify major components of intentionally colored or degraded plastics too. We modified the spectrometer probe for analysis of laminated glass structures, a category of materials we had not anticipated when the grant was written. Using these tools, plus more sophisticated research Raman and XRF spectrometers at MCI, we have constructed a timeline for the development of historic window materials and aviator eyewear through the present day. The technological evolution of protective eyewear is much more rich and complex than anticipated. We are ready to continue our investigation of aircraft windows when access to aircraft from those periods becomes available. From archival research we have a good idea of how these materials evolved industrially and look forward to improving that with examples of aircraft in the NASM collection.

II. Introduction

It is no understatement that the advent of automobiles and manned flight in the early 20th century completely changed the way people move. Going faster, in all kinds of weather, on rutted unpaved roads, and at higher and higher altitudes, brought the need to enclose automobiles and aircraft while at the same time see out of them. An evolution in transparent window materials occurred as a result, and innovations adopted for driving and flying developed in subsequent decades into much more sophisticated versions, solved critical safety issues that we now take for granted, and now are being adapted for use in a wide range of fields including transportation and aviation, architecture, energy efficiency, electronic displays, and even fashion. The intersecting and synergistic histories of polymer technology, aeronautics, and automobiles are interesting from the perspectives of technological history, preservation of the early examples of these technologies, and their contributions to intriguing descendant technologies. For museums, this is particularly important in that the materials represented in goggles and windows pose preservation challenges that can be expected to appear more often in the future.

One challenge in researching technological histories is determining what products were projected versus those that were realized. Patent and trade literature are valuable sources of information about innovation but do not necessarily coincide with the innovative technologies went into production. Similarly, manufacturing records may describe numbers of objects produced or how they were distributed but may not describe what technology went into making them. Study of artifacts as evidence of their own manufacture can help complete the picture. Visual examination combined with scientific analysis can "reverse engineer" the materials and fabrication methods by which an object was made. The fact that the artifact exists (and the number of instances) can give an idea of manufacturing success.

Our ability to characterize polymeric materials has improved dramatically in recent years. Of particular interest to this study, Raman spectroscopy can identify many constituent molecules of natural and synthetic polymeric materials that are present in concentrations down to the low percent range. The technique involves excitation of a sample by a laser beam and collection of the light scattered inelastically by the sample, meaning the light bounces back to the detector at a slightly different wavelength from that of the laser. The plot of the energy distribution of the scattered light is a molecular fingerprint of the sample, from which the compounds that make up the sample can be identified. In theory the technique is non-destructive and does not require removal of samples. In reality, there is potential for the laser to alter the sample, though this risk is reduced by an experienced and cautious operator. Because Raman analysis requires that the sample be placed in the path of the excitation laser, there are limits to the size and geometry of artifacts that can be analyzed directly; analyses of objects outside that range require removal of a sample.

Portable Raman spectrometers have the potential to circumvent limitations imposed by the size and geometry of an artifact. A portable instrument can be brought to artifacts, such as airplanes, that are too large to move to a laboratory. Handheld versions of the portable instruments, as opposed to those that are designed to be moved on a wheeled cart, can be positioned at any angle, which can improve access to many artifact surfaces. Instruments that use fiber optic probes have the potential to access more tight places on an artifact, such as recesses.

At MCI, the potential o of Raman to characterize natural and synthetic polymeric materials has been studied since 2006. MCIs instrumentation includes two research grade instruments (one dispersive and one Fourier-transform (FT)) and two portable instruments (one handheld unit without fiber optic probe, and one lightweight instrument that can be suspended from the operator with a strap and utilizes a fiber optic probe). The portable instrument with fiber optic probe was purchased in 2009 with funds from a private donor, and the NCPTT grant was intended to evaluate the effectiveness of that instrument for analyzing plastics in the field.

Plastics that are transparent, colorless, and flat present the simplest analytical scenario for Raman analysis, and aircraft windows in the Smithsonian's National Air & Space Museum (NASM) were identified as a set of artifacts that met the analytical criteria for the initial study. NASM is the world's largest collection of historic aircraft with examples spanning from the Wright flyer, through World Wars I and II, to the Space Shuttle Discovery. However, the grant award coincided with NASMs collection move to their new Steven F. Udvar Hazy Center in Chantilly, Virginia, and most of the collection's largest artifacts became inaccessible. NASM provided a collection of >80 aviator goggles and helmets for study in the interim. It was assumed that the lenses would meet the requirements of transparency and color, but the technological evolution of protective eyewear turned out to be much more rich and complex than anticipated. The goggles and headgear made for a more diverse range of materials for study, including glass lenses, glass laminates, and colored plastic lenses. The headgear was examined for construction and condition, and lenses and other plastic elements were analyzed by Raman and X-ray fluorescence (XRF) spectroscopies to identify the materials. Other parts of the goggles, including frames, face pads, and fasteners, were very interesting, so the opportunity was taken to study these elements as well.

One benefit of the switch from aircraft to goggles was the opportunity to compare the analytical results of MCIs portable Raman spectrometer to data collected with MCIs two more sophisticated, non-portable research Raman spectrometers. The elemental composition of the goggle lenses was determined by XRF, and in the laboratory setting it was possible to look at light elements that would not have been possible working directly on aircraft. This analytical data is compiled in a project specific database, also designed as part of the grant, that also includes curatorial information, archival research, condition assessment, and images of each object. The database will be available as a research aid in the future.

III. Materials and Methods

The project research methodology was in three parts: technical study of artifacts, and analysis of artifacts by Raman and X-ray fluorescence spectroscopies, and organization of data in a project specific database.

A. Technical study of artifacts

Eighty-three sets of goggles, many of which include multiple lenses, were examined. Each artifact was weighed, measured, photographed, examined for evidence of the methods by which it was fabricated, and assessed for current condition (Figure 1). This information was collected directly into the project database and recorded visually with drawings and photographs (Figures 2 and 3). The goggles were compared and categorized by type of lens and frame style.

B. Analysis of artifacts by Raman and X-ray fluorescence spectroscopies

The lenses of each pair of goggles were analyzed by portable Raman and XRF spectroscopies. The portable Raman spectrometer is a BW Tek MiniRam II dispersive instrument equipped with a 785 nm excitation laser delivered through a fiber optic cable (Figures 4 and 5). The Raman signal is collected through a fiber optic cable to a CCD detector with 10 cm^{-1} spectral resolution**.** A common challenge of Raman spectroscopy is interference from sample fluorescence, and this was a problem with many of the colored or deteriorated goggle lenses. Fluorescent lenses were analyzed by Fourier-transform Raman spectroscopy using a benchtop, research grade Thermo Scientific NXR module attached to a 6500 Fourier transform infrared spectrometer. The Raman module features 1064 nm excitation using a YVO_4 laser. Spectral resolution was adjusted from 2-8 cm^{-1}.

The elemental composition of the goggle lenses was measured by XRF. Two instruments were used. An ElvaX ED-XRF, which features an enclosed sample compartment was used for most measurements (Figure 6). Goggles that were too large to fit in the ElvaX sample compartment were analyzed with an ARTAX micro-XRF manufactured by Bruker Corporation (Figure 7). Light and heavy element data was collected for most goggles.

C. Organization of data in a project specific database

Information collected during the technical survey was collected in a database designed specifically for the project (Figure 1). The database is built in FileMaker Pro software and incorporates curatorial information provided by NASM registrars, measured dimensions, fabrication information gleaned from archival research and observation of the artifacts, an assessment of each artifact's current condition, analytical data (spectra and interpretation of results), and drawn and photographic images. The data fields can be exported into Excel format which in turn can be incorporated into the NASM collections management database (The Museum System (TMS)).

Figure 1. Kim Cullen Cobb arranging printed images of goggles based on similar materials and fabrication.

Figure 2. Screen shots of the survey database.

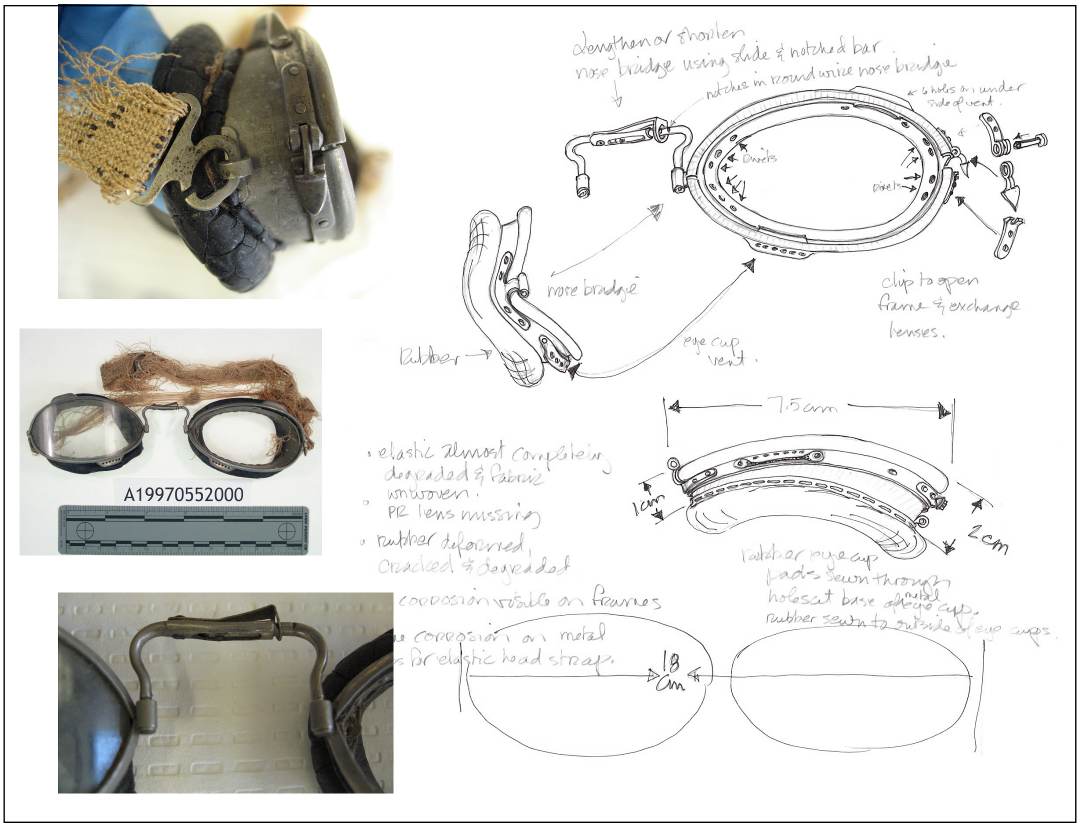


Figure 3. Drawn and photographed documentation created as part of the technical study.

Figure 4. BW Tek MiniRam II portable Raman spectrometer.

Figure 5. Analysis of safety glass interlayer of a goggle lens by portable Raman spectroscopy.

Figure 6. ElvaX ED-XRF spectrometer by ElvaTech.

Figure 7. ARTAX micro-XRF spectrometer by Bruker.

IV. Results and Discussion

A. Goggle and aircraft windows

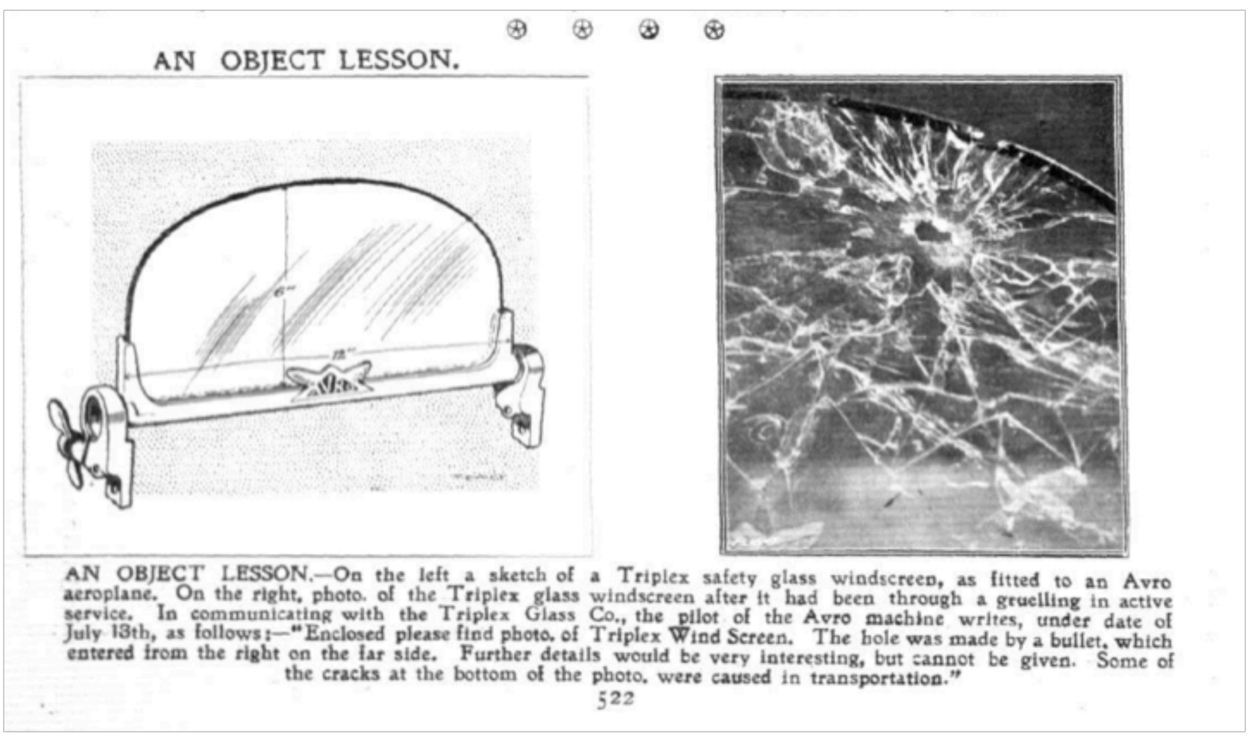
The examination of goggles and aircraft windows revealed that the evolution of these technologies is more complex than anticipated. To put the survey data in context, extensive archival research was conducted of published histories of aviation headgear and aircraft construction, trade journals such as *Modern Plastics* and *Flying*, and the advertisements contained therein (Figure 8). The Raman and XRF data was correlated with observations from the visual examinations and archival research to develop a history of goggle and window technologies.

To give one broad research thread as an example, we found that in the time of open cockpit aircraft, goggles were the first line of eye protection for a pilot. Laminated safety glass with cellulose nitrate interlayers, often referred to by the trade name Triplex, was the material of choice for goggles through World War I and were specified by the United States Army by 1917 (Figures 8 and 9) (United States War Department 1917, Flight 1918).   Cellulose nitrate was also the interlayer material for the small windshields of open cockpit aircraft (Figure 10) (Flight

1915, Flight 1919). News accounts and trade articles reported then that this interlayer material did not have good aging properties and tended to turn brown and opaque during service (Watkins 1933). This is supported by several pairs of deteriorated goggles in the NASM collection (Figure 9).

Figure 8. The first commercially successful laminated glass was manufactured first by the Frenchman Edouard Benedictus as Triplex safety glass, and the brand name Triplex was used as a synonym for laminated glass in general (Flight 1918).

Figure 9. World War I era aviator goggles with laminated safety glass lenses. Deterioration of the cellulose nitrate interlayer is visible as discoloration, cracking, and delamination of the glass and polymer layers (NASM Accession Numbers A19500122000 (top) A19620048000 (middle) and A19790846000 (bottom)).



AN OBJECT LESSON.

AN OBJECT LESSON.—On the left a sketch of a Triplex safety glass windscreen, as fitted to an Avro aeroplane. On the right, photo. of the Triplex glass windscreen after it had been through a gruelling in active service. In communicating with the Triplex Glass Co., the pilot of the Avro machine writes, under date of July 13th, as follows:—"Enclosed please find photo. of Triplex Wind Screen. The hole was made by a bullet, which entered from the right on the far side. Further details would be very interesting, but cannot be given. Some of the cracks at the bottom of the photo. were caused in transportation."

522

Figure 10. Triplex laminated safety glass windscreen from an Avro airplane after "a gruelling in active service," (left) Drawing of the windscreen, (right) photograph of window pierced and shattered by a bullet hole (F*light* July 16, 1915, p. 522).

Despite these aging problems, laminated glass became standard for windshields in automobiles in the 1920s, and we see from the NASM collection that it continued to be used in airplane windowpanes that required good optical clarity (for gunning, dropping bombs, or aerial surveillance) (Figure 11).

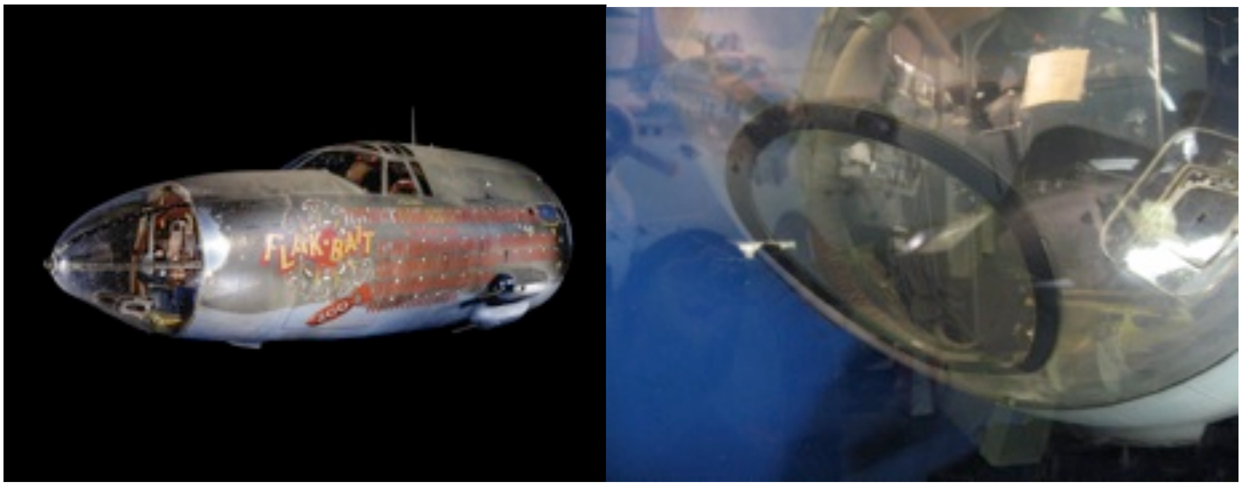


Figure 11. Martin B-26B Marauder "Flak Bait," an American, twin engine bomber built by Martin Aircraft Co., in 1943. The transparent nose cone is made of panes of curved plastic sheet and a single piece of laminated glass on the underside (detail on right) (NASM A19600297000)

We know from our archival research that cellulose acetate replaced cellulose nitrate as a safety glass interlayer because it had better aging properties (Watkins 1933). This probably happened in the later 1920s through mid-1930s. The change also may have been motivated by a general shift from flammable cellulose nitrate to the acetate version in other applications. Then in 1939, a multi-corporate research program developed polyvinyl butyral (PVB) as an ideal interlayer (Time 1939). It had good aging properties, and performed well over the extreme range of temperatures that an automobile can experience without becoming brittle or too soft. PVB remains the industry standard for laminated automobile windshields today. However, we did not see this evolution in goggle lenses. It seems that the enclosure of airplane cockpits in the 1920s and 1930s reduced the need for shatterproof goggle lenses. We did not find any examples of cellulose acetate or PVB laminated lenses in the NASM collection. Instead goggle technology of this time shifts toward interchangeable, optically clear, not laminated, glass lenses (Figure 12) and interchangeable cellulose acetate plastic sheet lenses as used in the rubber framed B-8 goggle that was introduced in the United States by Polaroid in the early part of World War II (Figures 13-15). The first would have allowed for better vision. The cellulose acetate lenses would have provided a more distorted view but were shatterproof, lightweight, and probably could have been mass produced cheaply and quickly, which would have been a benefit during World War II. Both the glass and cellulose acetate goggles had interchangeable lenses that were offered in several colors to suit different lighting conditions. The coloring technology differed according to whether the lens was glass or plastic. For example, glass lenses could incorporate cerium as a ultraviolet absorber that transmitted visible light well. Cellulose acetate lenses were colored with organic compounds and could be polarized to reduce glare. Our research found Edwin Land's patents for incorporating oriented needlelike herapathite (iodoquinine sulfate) crystals into sheets of cellulose nitrate as a polarizer (Land 1933). We found what we believe to be herapathite crystals in one pair of cellulose acetate lenses in the NASM collection (Figure 15). These also caught our attention because they happen to be among the most degraded goggles in the collection. Working with pre-doctoral fellow Molly McGath, who simultaneously was studying degradation in certain cellulose acetate formulations, we have hypothesized that the crystals act as nucleation sites for recrystallization of a solid plasticizer, which clouds and breaks up the sheet (McGath 2012).

Figure 12. World War II era AN-6530 goggles were consisted of metal frames, interchangeable polished glass lenses , rubber face pad lined with leather chamois and a woven elastic head strap. A range of colored lenses were produced for various lighting conditions. Of particular interest are the light green lenses which incorporate cerium to filter out ultraviolet radiation without drastically reducing visible light transmission. (NASM A20010216000 and A20050338000)

Figure 13. One set of B-8 goggles manufactured by Polaroid and issued by the United States Air Force. The set includes a molded rubber frame, interchangeable cellulose acetate lenses packaged in paper, and a cloth pouch for spare lenses, and a cardboard box. (NASM A19970586000)

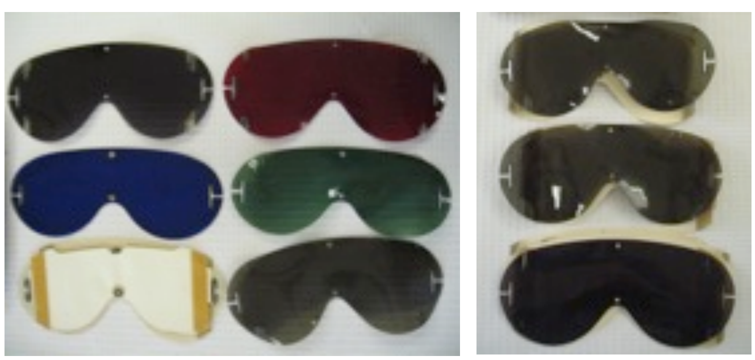


Figure 14. Tinted lenses for the B-8 goggle. The different colored lenses were suited to various lighting conditions, and included polarizing versions that incorporated needle-like crystals into the plastic to block scattered light. (NASM T2005103100)

Figure 15. M-1944 goggles were a simplified version of the B-8 and were general issue goggles by the United States military. This pair is fitted with a polarizing lens and supplemental shades of the same material. The plastic lens was shown by FT-Raman spectroscopy to include cellulose acetate polymer and triphenyl phosphate, and the latter is crystallizing out of the plastic. XRF spectroscopy confirmed the presence of iodine, which suggests that the polarizing substance is herapathite. (NASM A19910412000)

This research thread is one of many that we discovered during this research. Rather than incorporate all the research into a single historical paper, our challenge will be to tease these threads into several publications and other didactic materials. We anticipate that there is several dissertations worth of information here.

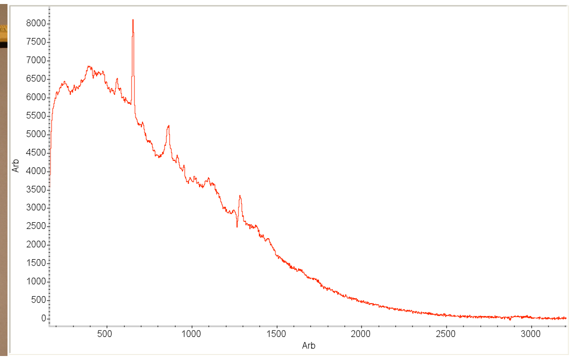
B. Portable Raman spectroscopy

The BW Tek MiniRam II portable Raman spectrometer (Figures 4 and 5) has proven to be a very useful sorting tool for plastics, particularly those that are transparent and uncolored. We can quickly distinguish glass from plastic and identify many polymers, including cellulose nitrate, cellulose acetate, polyvinyl chloride, and polymethyl methacrylate (Figure 16). One benefit of the MiniRam II is that many collection parameters can be adjusted, including laser power, integration time, and the number of averaged scans. This increases the operator's possibilities for collecting a good spectrum, which is important when dealing with the wide variety of materials and condition states that one encounters in collections of museum artifacts. Not all portable Raman spectrometers on the market are as flexible.

The spectrometer produced many "good" spectra from which the plastic materials could be identified (Figure 16, Appendix A). Drawbacks of this instrument, which was purchased for approximately $20,000 and less than ⅕ the cost of a research grade instrument, and handheld Raman spectrometers in general include a maximum spectral resolution of 10 cm^{-1}, which is sufficient to distinguish classes of polymers and additives but not sufficient for detecting subtle differences or changes in materials; a poorer signal-to-noise ratio than research grade instruments; and a powerful laser that can burn many polymeric materials. In addition, the operation of the instrument is less smooth in general than a benchtop instrument; this is true of both the hardware and software interface.

We experienced problems with the computer and battery life of our instrument, which delayed the project considerably. The small integrated tablet computer died early on and could not be replaced because the manufacturer from which BW Tek sourced the tablet had gone out of business. We attached a 32-bit laptop to the spectrometer with a USB cable instead. The laptop has the benefit of a larger keyboard, but it is one more item to carry up a ladder during analysis. The laptop makes the instrument less portable. The instrument batteries also failed early in the project. We used very long power cords for a while, and eventually replaced the batteries, which are expensive and customized to this instrument. This is a problem when working with small manufacturers whose instruments can be more like a prototype than the well-tested products of larger manufacturers.

Even with the laptop computer, the instrument is quite easily portable. The spectrometer weighs approximately 6 lbs and fits in a carry-on size rolling suitcase. Some assembly is required to attach the fiber optics and power cables, and this process requires approximately 5 minutes. The spectrometer can be worn by the operator with a neck strap, but it is easier to work as a team of two people, one to position the probe and the other to operate the spectrometer.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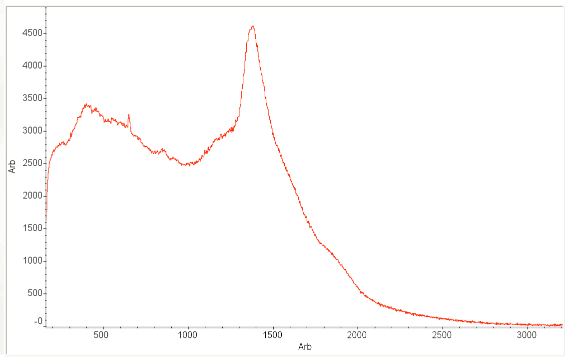
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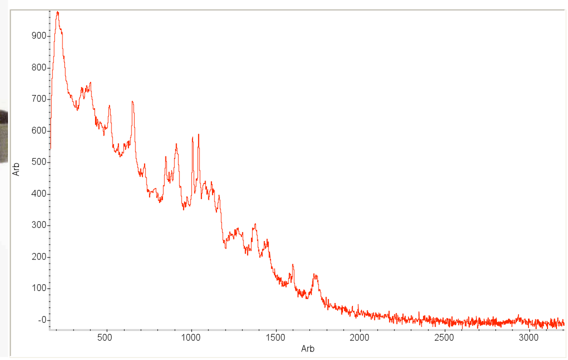
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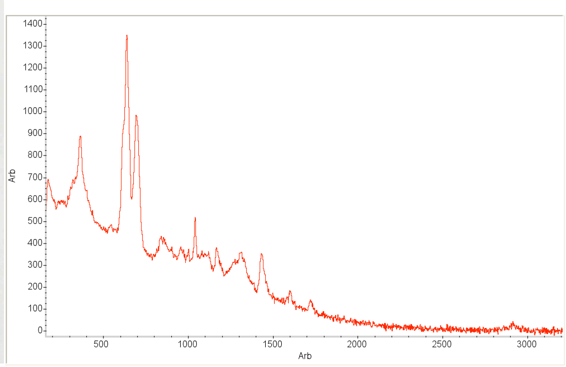
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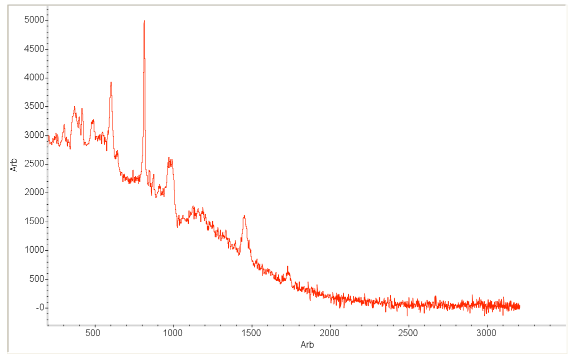


Figure 16. Images of goggles and visors from NASM collection and spectra of the visors collected with the BW Tek MiniRam II portable Raman spectrometer. These spectra reveal the composition of each plastic artifact by comparison to reference spectra of known compounds as presented in Attachment A.

As expected, fluorescence interference is a challenge for many artifacts. This was particularly true of plastics that are colored. Better spectra were obtained for many of these with a FT-Raman spectrometer, which uses a longer excitation wavelength (1064 nm) that electronically excites fewer chemical species (Figure 17). However, the FT-Raman spectrometer is set up with a fixed sample compartment rather than a flexible fiber optic probe, which limits the range of artifacts and positions that can be analyzed.

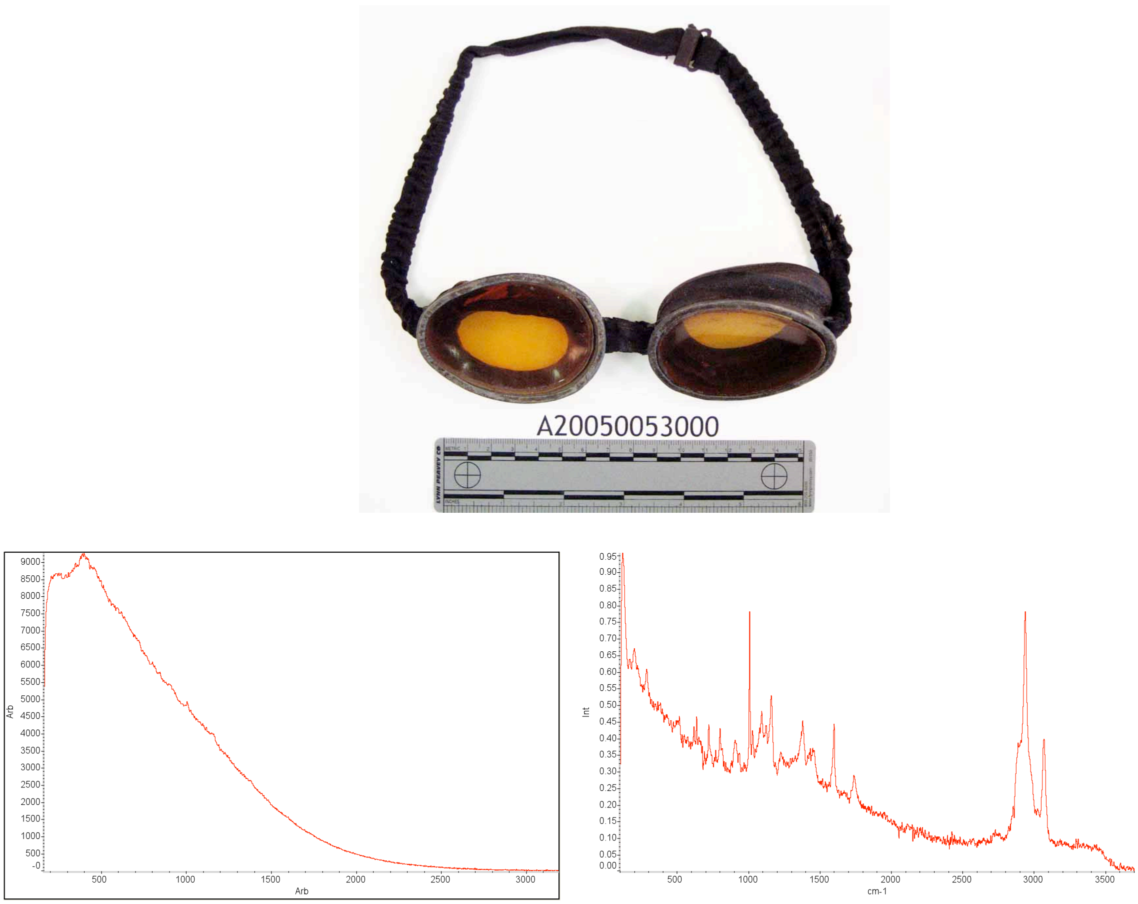


Figure 17. A pair of World War I era German goggles with plastic lenses (top), and two Raman spectra of one lens collected with the BW Tek MiniRam II portable Raman spectrometer (bottom left) and a research grade FT-Raman spectrometer from Thermo Electron Corporation (bottom right).

1. Adjustable focal length adaptor

One unexpected product of the grant is the development of an adjustable focal length adaptor for the fiber optic probe of the BW Tek MiniRam II portable Raman spectrometer. The adaptor is a two-part sleeve that fits over the end of the probe (Figures 18-21). One metal tube fits over the existing probe tube and is threaded on the exterior (Figure 20). A second sleeve, that is threaded on the interior, screws onto the first and the distance of its tip from the end of the fiber optic probe can be adjusted (Figure 20). By screwing the outer sleeve further back toward the inner sleeve, the focal point of the laser is positioned beyond the tip, which allows for analysis of the interlayers of laminated safety glass (Figure 21). The attachment is the subject of a scholarly article that will be published in the spectroscopy literature.

Figure 18. Diagram of existing fiber optic probe for BW Tek MiniRam II portable Raman spectrometer. Laser light from the spectrometer travels through the fiber optic from left to right and exits the probe through a lens (blue) at the tip. The lens focuses the laser beam (red lines) at a point beyond the probe tip. This focal point is the optimal position for the sample during analysis.

Figure 19. Existing fiber optic probe covered with a fixed focal length adaptor that is provided with the instrument. The adaptor is a metal tube that slides part way over the fiber optic probe, such that the opening of the sheath is positioned exactly at the focal point of the laser.

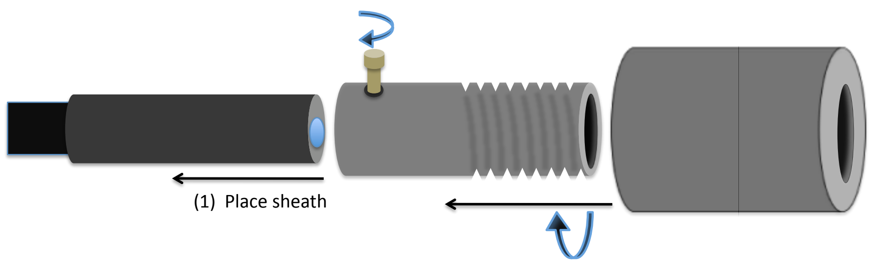


Figure 20. Design for first iteration of adjustable focal length adaptor.

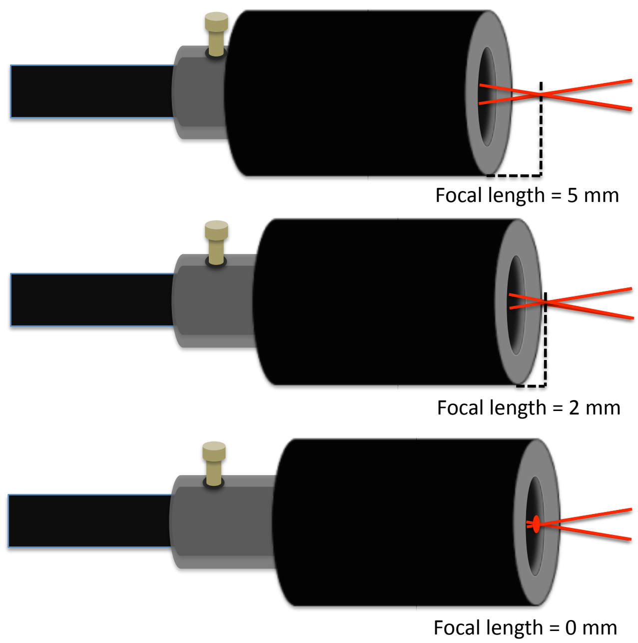


Figure 21. Schematic of focal length adjustment.

V. Conclusions

The research supported by this grant has shown that portable Raman spectroscopy is a valuable tool for identifying synthetic plastics in the field. The value of Raman data is augmented with elemental data gained by XRF, which also are available as portable instruments.

VI. Acknowledgments

This study involved many Smithsonian staff, contractors, fellows, and interns. In particular, the investigators are grateful for the contributions and support of Kim Cullen Cobb, Paula DePriest, and Robert Koestler (MCI); Dawn Planas, Jennifer Stringfellow, Chris Moore, Lisa Young, Samantha Snell, Ellen Folkama, Erik Satrum, Liz Garcia, and Peter Jakab (NASM); and Molly McGath (Freer Sackler Gallery).

VII. References

[Flight 1918] “Triplex Safety Glass A Vital Necessity,” advertisement in *Flight*, January 3, 1918, xxvii.

[Flight 1919] “Side winds,” *Flight*, February 20, 1919, 1069.

Land, E. H. and J. S. Friedman “Polarizing refracting bodies,” United States Patent 1,918,848, Patented July 18, 1933, (Application Serial No. 358,288 April 26, 1929).

McGath, M. *Investigations of Deterioration Mechanisms in Cellulose Acetate Compounded with Triphenyl Phosphate*, PhD dissertation, University of Arizona, 2012.

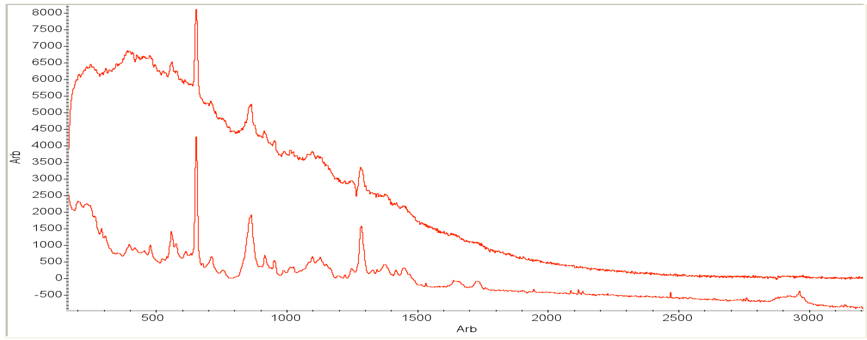
[Time] “Science: Softness for Safety” *Time*ˆ, April 10, 1939 (accessed online on 2/16/2010 at http://www.time.com/time/magazine/article/0,9171,761001,00.html.)

United States War Department Specifications for the Uniform of the United States Army. *Special Regulations No. 42*, U. S. War Department, Washington, DC, 1917.

Watkins, G.B. & Harkins, W. 1933, "Laminated Safety Glass," *Industrial & Engineering Chemistry,* vol. 25, no. 11, pp. 1187-1192.

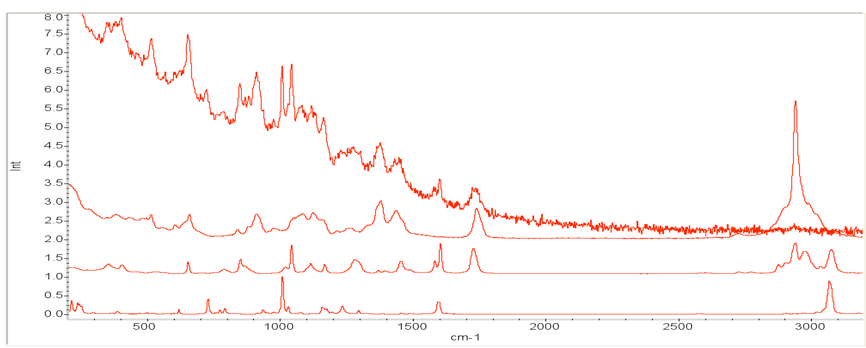
VIII. Supplemental Material

Attachment A: Raman spectra from Figure X reveal the composition of each plastic artifact through comparison to reference spectra of known compounds.

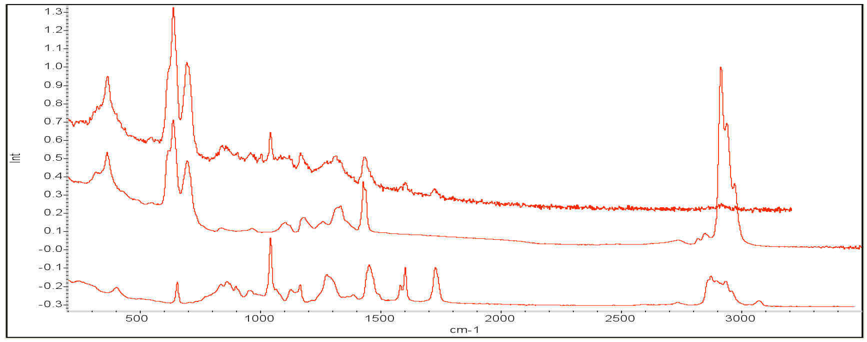


Top: Spectrum collected from window from Douglas World Cruiser
Bottom: Reference spectrum of cellulose nitrate and camphor

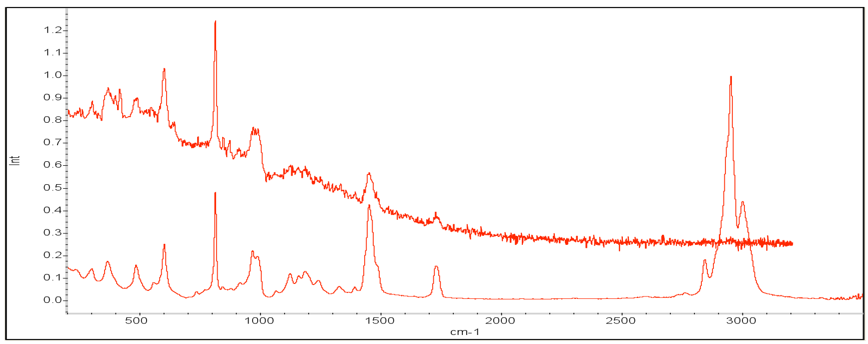
Top: Truncated spectrum collected from untinted interlayer of laminated glass lens
Middle: Reference spectrum of cellulose nitrate
Bottom: Reference spectrum of camphor



Top: Spectrum collected from lens of B-8 goggle
Second: Reference spectrum of cellulose acetate
Third: Reference spectrum of diethyl phthalate
Bottom: Reference spectrum of triphenyl phosphate



Top: Spectrum collected from goggle lens
Middle: Reference spectrum of polyvinyl chloride
Bottom: Reference spectrum of diethyl hexyl phthalate (DEHP)



Top: Spectrum collected from helmet visor
Bottom: Reference spectrum of polymethyl methacrylate