

# Ballistic Body Armor

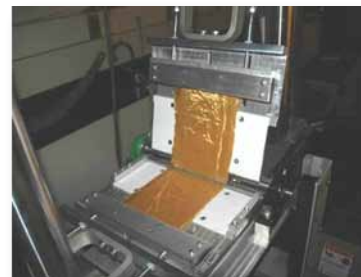
## Objective

Our goal is to prevent the catastrophic failure of ballistic body armor by developing measurements and predictive models to test and determine the long-term reliability of polymers used in ballistic resistant armor. Our approach, which utilizes conventional analytical techniques in addition to newly developed minimally invasive test methods, seeks to identify the chemical and mechanical mechanisms underlying reductions in ballistic performance and to link these mechanisms to chemical structure and deformation mechanics.



## Impact and Customers

- Ballistic resistant armor is credited with saving more than 3,000 lives; but in 2003, the failure of a first responder vest identified the need for long-term stability and durability tests.
- NIST developed a tool to assess the impact of folding during normal wear on ballistic body armor and demonstrated that repeated folding can reduce ballistic resistance of the armor by up to 40%.
- As a result of NIST's fold tests, the NIST Office of Law Enforcement Standards (OLES) and the Department of Justice's National Institute of Justice (NIJ) are incorporating folding as one of the critical durability specifications for the new revision of the ballistic fiber standard.



**NIJ**



## Approach

To quantify the impact of mechanical degradation on ballistic fibers, NIST developed a novel device for controlled folding of yarns and woven fabrics. In addition, we developed test protocols that employ single fibers to assess the effect of folding using a recently developed modified single fiber test and a newly acquired commercial, rapid, automated fiber testing apparatus. Morphological changes in the folded fibers are being quantified by small angle X-ray scattering (SAXS).

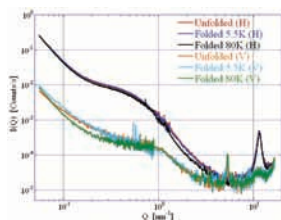


Systematic and controlled extraction procedures designed around the molecular architecture of the ballistic fibers are also being developed to elucidate the factors that cause their hydrolytic degradation. The extracted material is being evaluated by X-ray fluorescence spectroscopy, matrix assisted laser desorption ionization (MALDI), mass spectrometry (MS), and a newly acquired gas chromatography (GC)/MS system. These techniques are augmented by the use of novel derivatization methods to facilitate the detection of compounds suspected of causing hydrolytic degradation.

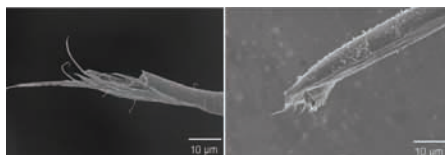
# Accomplishments

## Mechanical Degradation

Recently, our folding research has shifted to the analysis of polyaramid (Kevlar) fibers, the most widely used ballistic fiber in soft body armor. Results indicate that these fibers may not be as susceptible to folding damage as poly(benzoxazole) (PBO) fibers. Prior data obtained on PBO ballistic fibers with NIST's automated fold tester showed that repeated folding decreases the mechanical properties that govern ballistic performance. Tests designed to simulate six months and 10 years of wear indicated performance reductions of 15% and 40%, respectively. Furthermore, small angle X-ray scattering (SAXS) data from the PBO damaged fibers (shown below) indicated that the transition from fibrillar failure to brittle failure (also below) that accompanies repeated folding is associated with the formation of micro-cracks perpendicular to the fiber axis.



SAXS data from unfolded and folded fibers



Fibrillation (l) and brittle (r) failure

To show the potential impact of the folding degradation mechanism on first responders, fibers from a new vest, a hydrolytically aged vest, and a field return vest were analyzed along

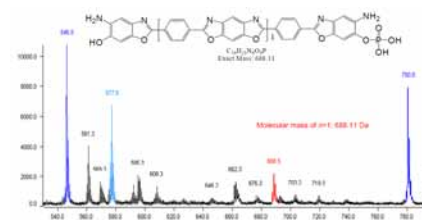
with the back panel from the compromised vest. Data from the new vest showed that there is minimal damage to the PBO fibers during the manufacturing process, while hydrolytic ageing can result in a significant reduction in ballistic performance. More importantly, data from the field return vest showed that the folding mechanism works in addition to the hydrolytic damage mechanism to create localized weak spots in the vest that have even lower ballistic performance. Also, these results indicate that the back panel of the compromised vest is not a good indicator of the ballistic performance of the front panel, because of the additional folding that occurs to the front panel.

The success of the above research has led to a proposal being submitted to NIST-OLES to link the results from the single fiber tests to those of the Kolsky bar, where single fibers are deformed at a much higher strain rate.

## Chemical Degradation

It is now known from GC/MS data that the readily extracted residual phosphorus from PBO fibers is mostly an n-octadecyl phosphate, a processing aid that is added during manufacturing, and a much smaller amount of phosphoric acid. Analysis of three sets of fibers also indicates that the manufacturer of the PBO fibers may have developed a more efficient washing process to remove nearly all of the readily extractable phosphoric acid, leaving mostly non-extractable phosphorus.

Our research indicates that the non-extractable phosphorus is phosphoric acid that is chemically attached to the hydroxyl groups on the DADHB (i.e., 1,3-diamino-4,6-dihydroxy benzene) molecules, forming aryl-phosphate esters. The DADHB preferentially end-caps the PBO polymer chains (see below). Furthermore, it is now known that these aryl-phosphate esters are stable to the caustic wash solutions that are used in the manufacturing process to neutralize the



MALDI-TOF MS of PBO model oligomers showing aromatic phosphate ester

phosphorus pentoxide (drying agent) enriched PPA (i.e., poly(phosphoric acid) reaction medium.

By exposing PBO fibers that have been extracted multiple times, to remove all readily extractable phosphorus to a pH 4 HCl solution under sealed conditions for several days, additional phosphorus in the form of phosphoric acid was removed from the fibers. These results support the supposition that the non-extractable phosphorus that remains in the PBO fibers is in the form of an aryl-phosphate ester that is stable in neutral to basic aqueous washes. More importantly, these results indicate that the residual phosphoric acid, if not removed, can accelerate the deterioration of the PBO fiber architecture through the destruction of the benzoxazole ring structure that seems to provide it with its initial increase in mechanical properties relative to Kevlar. Because of the transformational nature of the PBO technology with respect to the development of ultra light-weight soft body armor, the above findings should aid researchers in discovering ways to manage the weakness of the PBO fibers, so that they can be safely used in ballistic applications.

The Polymers Division research team has been asked by NIST/OLES to develop collaborations with the Natick research institute and other government agencies interested in soft body armor, by leveraging our knowledge and expertise to find workable solutions to the PBO problem.

## Learn More

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## Publications

Holmes GA, Rice K and Snyder CR *Ballistic Fibers: A Review of the Thermal, Ultraviolet and Hydrolytic Stability of the Benzoxazole Ring Structure* Journal of Materials Science, 41: 4105 (2006)

Kim JH, Brandenburg N, McDonough WG, Blair W and Holmes GA *An Apparatus for Mechanically Folding Yarns and Woven Fabrics of Ballistic Fibers* Journal of Applied Mechanics, 75(1): 015001 (2008)

Holmes GA, Kim JH, McDonough WG, Riley MA and Rice KD *A Detailed Investigation of the Mechanical Properties of Polybenzoxazole Fibers within Soft Body Armor* Journal of Materials Science, DOI: 10.1007/s10853-009-3338-6 (In Press, 2009)