Transparent Armor for the New Standard in Transparent Battle Performance

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ABSTRACT

Armor Transparent Purchase Description (ATPD) 2352 revision P[1] was issued in July 2008 to create a new standard for transparent armor aimed at improving battlefield performance, maintenance costs, equipment survivability, and general durability based on data collected from performance of transparent armor in the battlefield. A transparent armor specifically focused on satisfying all of the ATPD 2352 requirements was invented, developed, and commercialized. A Cooperative Research and Development Agreement with TARDEC resulted in evaluating armor to all the metrics of ATPD 2352.

This paper reports on this initial and subsequent work and;

a) explains the requirements of ATPD 2352 and the challenges they present from a materials properties, armor performance, lifetime testing, transparency, durability, and environmental perspective;
b) presents data, analysis, and preliminary modeling showing the materials and performance properties of a variety of materials to highlight how and why a discontinuously nano-reinforced glass system was able to pass all the requirements;
c) describes the tests and presents test data on the key tests performed for ATPD 2352, including ballistic, environmental, and optical, many never successfully mastered in transparent armor before.

BACKGROUND

The requirements of the new specification for transparent armor, Armor Transparent Purchase Description (ATPD) 2352,[1] were defined over a period of time with an abundance of feedback from the theater in Iraq and other places.[2-6] While the first vehicles put into service in Iraq were frequently unarmored, those armored windows that followed were often found wanting in terms of threat resistance, visibility, and life cycle.

Figure 1: Attack by a small IED shows multiple impacts on the window indicating close proximity and high impact velocity.

The U.S. Army's Tank and Automotive Command (TACOM) conducted a cost benefit study on transparent armor[2] and identified that from a sample of 266 transparent armor damage incidents 68.2% were a result of combat damage. Battlefield reports, for example including news articles and pictures,[3,4] showed that close range rifle and machine gun fire and multiple roof top snipers were an early threat in urban areas where it was learned that in many cases if a window stopped a first round it did not stop subsequent shots. Detonation from improvised explosive devises (IEDs) of various size

Report Documentation Page

Form Approved OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
04 JAN 2011	**Technical Document**	**06-03-2010 to 27-11-2010**

4. TITLE AND SUBTITLE
Transparent Armor for the New Standard in Transparent Battle Performance

5a. CONTRACT NUMBER
CRADA #08-18

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Kathie Leighton; John Carberry; Wiktor Serafin; Terrance Avery; Douglas Templeton

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
; #21439

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000

10. SPONSOR/MONITOR’S ACRONYM(S)
TARDEC

11. SPONSOR/MONITOR’S REPORT NUMBER(S)
#21439

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Submitted to American Ceramics Meeting

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Public Release**	**12**	

were ubiquitous and found to impact windows with high velocity spray of fragments,[5,6] for example as shown in Figure 1.

In addition to battle field threats, the harsh environment imposes strong thermo-mechanical challenges to transparent armor degrading the polymer layers resulting in delamination, bubbles, loss of adhesion, clouding and discoloring. Extreme thermal excursions and shocks caused cracking in the glass and also contributed to delamination. Sand abrading against the armor windows produces surface defects and surface defects are known to reduce the strength of glass and lead to cracking.[7,8]

Thermal extremes in Afghanistan have been reported from as low as -46^{o}C (-51^{o}F) and as high as 51 ^{o}C (124 ^{o}F), and in Iraq extreme highs in the summer can reach 46 ^{o}C (115 ^{o}F) to 52 ^{o}C (125 ^{o}F) in the desert areas and have even been reported to 49 ^{o}C (120 ^{o}F) in the mountain valleys.[9] Thermal extremes of the natural environment combine with thermal shocks and contamination associated with operation and logistics including moving from storage to use, air drops, chemical spray downs, water exposure in fording, and vehicle road dynamics and vibrations.

This severe thermo-mechanical and contamination prone environment is made even worse by the degrading power of the sun. NASA Goddard reports data collected by the Solar Radiation and Climate Experiment[10,11] satellites show that the electromagnetic energy of the sun that hits Earth's atmosphere varies with solar conditions and is about 1368 W/m^2. The insolation, the amount of electromagnetic energy that impinges the surface of the Earth, is less due to cloud cover and surface obliquity and varies with elevation, latitude, time of day and season being greatest at high elevations, tropical latitudes, noon, and in the northern hemisphere summer. The spectrum of insolation also varies with location on the Earth, and due to the fact the direct irradiance from the sun varies more in spectrum than in total energy. NASA's Total Ozone Mapping Spectrometer results indicate the majority of the recent battlefield conflicts take place in regions of the World exposed to the most damaging high energy waves, UV-B in the 290 to 320 nm range.

Replacement and operation needs for transparent armor was running at a cost of $3-$12 million a month during Fiscal Years 2006 - 2008, with a significant percentage related to replacements due to the problems above.

In the same time frame, windows that could offer the necessary higher level of protection were too heavy and too thick. Armor weight strains the mechanical components of a vehicle increasing wear and fuel consumption; in one study 16% of fuel consumption was directly related to road weight of a vehicle.[12] Reducing the weight of a 4.8 liter V8 diesel engine truck can save 0.3-0.9% in fuel costs per 100 lbs of weight savings.[13] Since windows are mounted high up in a vehicle, transparent armor weight was also contributing to the problem of mine resistant vehicles rolling over. Armor weight can slow down transportation to theater and mobility once there.

While life cycle costs are critical and long term budgets require low maintenance costs, the equipment's role in mission effectiveness is the primary and first priority and it is unacceptable for the equipment to fail and compromise a mission. The materials used in many of the first transparent armors delivered to the field absorbed light in the infrared spectrum (IR) making the use of night vision goggles, which function in the near infrared, impossible or impractical requiring such high power levels that glare impaired vision to the point of being useless. The armored window is first a window, so thick windows with distortion, poor visibility, and lost visibility after impact were a problem in many cases.

THE ATPD 2352 REQUIREMENTS

The ATPD 2352 specification addressed all these challenges with well defined requirements related to visible and optical properties in the visible and IR, requiring rifle and fragment penetration resistance at various levels, and providing requirements to maintain necessary visible and optical capabilities after exposure to thermal shock, humidity, solar loads, cycles of high temperature, low temperatures relevant to storage, abrasion on strike face and safe side, and chemical exposures on both sides.

Visible and Optical Requirements

First and foremost a window must offer visibility for situational awareness both in daylight and at night. In this military setting, night vision is critical to maintain situational awareness in the dark and the use of night vision goggles (NVG) is not optional. The ATPD 2352 provides requirements and test protocols for six optical tests.

The first is a visual inspection with defect limitations where, in the most recent version, Paragraph 4.1.1 Allowable Defects in ATPD 2352 Revision R, the inspection is required to be performed looking from the inside through the window, a procedural detail that illustrates that most importantly these are windows to see through and secondly armor.

The next two tests are to measure the transmission of the window in the visible range, luminous transmission, and then in the near IR for NVG compatibility.

ATPD 2352 paragraph 4.4.1 defines how to measure luminous transmittance, "Luminous (photopic) transmittance shall be determined in accordance with the photopic transmission measurement procedure given in MIL-DTL-62420. Transmittance shall be determined before and after the exposure of the Sun Exposure Weathering test, 4.3.5. Spectral transmittance shall be measured at wavelength intervals of 10 nm or less over the 400 to 930 nm band at normal incidence. Luminous visible light transmittance corresponding to daylight vision is determined by integration of individual photopic transmission values in the 400 to 700 nm range, as discussed in MIL-DTL-62420."

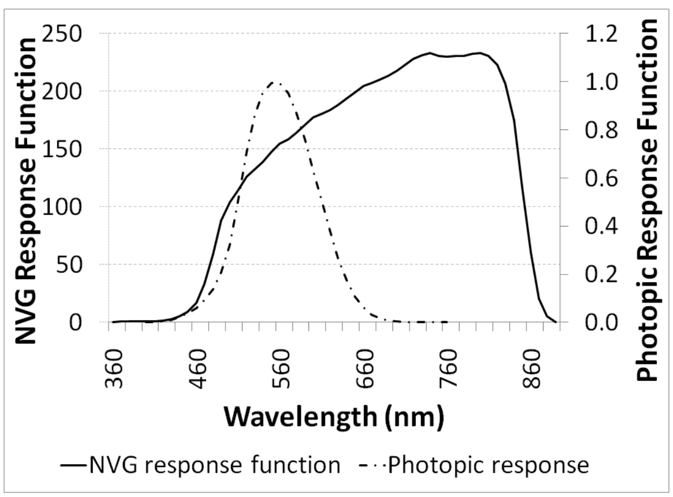


Figure 2: Response functions for photopic and NVG transmittance.

In the ATPD 2352, NVG compatibility was quantified and defined as part of the critical performance of a good window. ATPD 2352 Paragraph 4.4.1.1 states, "The NVG-weighted integrated spectral transmission is determined using the same procedure for determining the luminous transmission, except that the photopic visibility response function is replaced by the NVG-response function and the integration is over the 400-930 nm bandwidths."

Both requirements include calculating integrated transmissions based on response functions, presented in Figure 2. As the response functions show, the photopic transmittance is most heavily weighted by transmission near 555nm, where as visibility through night vision goggles is increasingly weighted approaching the NIR and most heavily from 770nm to 850nm.

The last three required optical properties to measure are haze, deviation, and distortion. Haze is the diffuse transmittance as a percentage of the total transmittance as measured by ASTM D1003[14] (CIE Illuminant A; Method: Procedure B, Diffuse Illumination/Unidirectional Viewing). Deviation is measured by ASTM F801-96[15] or ASTM F2469-05.[16]

The distortion requirement is intended to address the problem that some of the thick windows were distorting the far field images such that telephone poles or edges of buildings would appear curved or wiggly. It is measured in accordance with ASTM F2156[17] where a grid pattern viewed with and without the window is compared and the difference in the straightness of the lines is quantified as a grid line slope (GLS).

Ballistic Requirements

Ballistic protection required stopping kinetic energy rounds in a tight 4-shot “T” pattern, as shown in Figure 3, over temperature range of -43°C up to 63°C.

During 2000/2001 the TARDEC AIL (TARDEC Armor Integration Laboratory) the predecessor of the current TARDEC SABL (Survivability Armor Ballistic Laboratory) performed tests to determine the expected shot spacing of urban attacks on vehicles. This was done by preparing a computer generated generic type SUV vehicle target shown at an angle so that it could contain four identical passengers. The targets were printed full size and presented to groups of shooters of various skill levels. The shooters were NATO troops from several countries and US civilians at our test site.

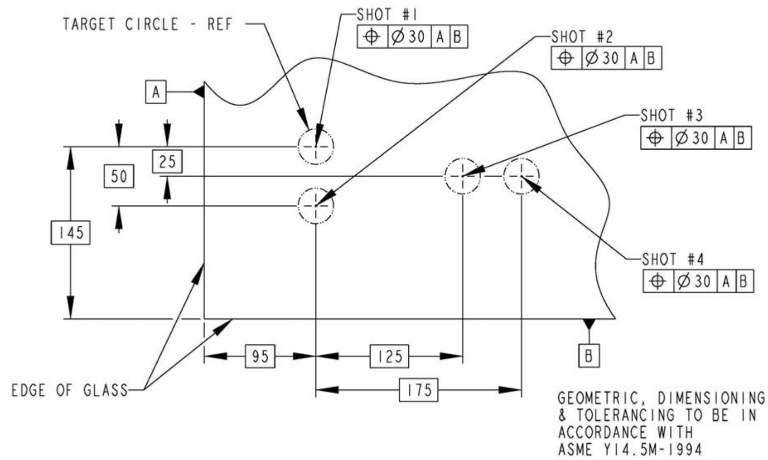


Figure 3: Four-Shot “T” pattern from ATPD 2352 Rev P.

Although the purpose of the test was to determine multi-hit shot spacing the shooters were only told to kill the people in the vehicle during an 18 second time limit at 20 meters. The military shooters used their service weapons while the civilian shooters were allowed to select which military weapons to shoot. The shooters were free to select which method of fire they used, i.e. single shots, burst fire, or fully automatic fire.

The four figures were identical thus allowing the targets to be separated into four "attacks" of 4.5 seconds where the shooters were aiming at the figure seen through the vehicle window. Hundreds of targets were analyzed by measuring the spacing between shots and determining the minimum size triangles that were formed. This data was plotted for three typical threat weapons, the Soviet AK-47, the US M-16, and the German G-3 representing a heavier .30 caliber cartridge. Graphs were made showing minimum shot spacing distance vs. probability of that spacing appearing in this data set. Graphs were also prepared showing the minimum triangle perimeter vs. probability. Thus for example, a shot spacing of 25 mm with the M-16 rifle represents the 10th percentile of that data set. Therefore only 10% or less of the shooters had shot spacing of 25 mm.

This data was used to formulate the NATO AEP-55[18] specification entitled, “Procedures for Evaluating the Protection Level of Logistic and Light Armored Vehicles.” The protection level desired, i.e. probability of non-penetration, in this NATO specification is 90% so the shot spacing occurring 10% of the time was selected as the multi-hit requirement. This shot spacing when tested as required by the NATO specification to "exploit the Localized Weak Areas" of the transparent armor (shooting at the edges with a minimum spacing of 25 mm) causes the glass to be made very thick.

When the TACOM ATPD 2352 specification was written the multi-hit shot spacing for rifle/machine gun threats was increased. This was done based on the realization that testing is done at worst case condition for window orientation (zero obliquity) and temperatures. Therefore, the shot spacing selected represents approximately the 40th shooter percentile for the various projectiles used. A four shot "T" shaped pattern was selected with the spaces made of two pairs of shots at the 40th percentile spacing and the spacing between the pairs equaling the long side of the 40th percentile triangle. The requirements of ATPD 2352 were not selected to be equivalent to any particular TACOM vehicle system, but rather it was selected to be the standardized criteria for lot acceptance of transparent armor. It is important to remember that "passing" the ATPD 2352 ballistic requirements do not assure that the product will pass the protection requirements of a particular vehicle system.

Environmental Requirements

Environmental specifications and tests in the ATPD 2352 derive, with some modifications, from the United States Military Standard referred to as MIL-STD-810, "Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests" which establish chamber test methods to replicate the effects the environment has on materials and structures rather than on direct simulation of the environment.[19] Two different versions of MIL-STD-810, F and G, are referenced in the ATPD 2352 presumably because both standards were being modified during the same time period. Five different tests are required; Low Temperature, High Temperature, Humidity, Temperature Shock, and Sun exposure weathering. De-icing requirements and tests also test response to thermal stresses. After each test the part is returned to room temperature and ambient conditions and inspected to the six optical, including visual, requirements discussed above, and held to the standards of the original optical requirements.

The low temperature cycle includes a 24 hour hold at -54^{o}C in accordance with MIL-STD-810F Method 502.4 Procedure I. This method was developed to replicate material failures that can occur during low temperature storage of military equipment, Specific failures identified by MIL-STD-810 that are relevant to transparent armor are; hardening and embrittling of polymers leading to cracking and crazing, reduced impact strength, static failure of restrained glass, and condensation and freezing of water. This procedure is intended to test materials in storage conditions and prepare them for additional testing to ensure they meet operating requirements after storage, which in the case of the ATPD 2352 includes the visual inspection and optical tests above.

The high temperature test is in accordance with MIL-STD-810G Method 501.5, Procedure I, A2, Induced. It includes a 24 hour heating and cooling cycle where the chamber varies between 30 and 63^{o}C. The relative humidity is varied from 44% to 5% with the lowest levels at the highest temperatures. Three cycles are required. Failures listed by MIL-STD-810 that can occur under high temperature and relevant to transparent armor include discoloration, cracking or crazing of organic materials, out gassing, and binding due to differential expansion of material with dissimilar coefficients of thermal expansion (CTE). This test is limited to use to evaluate the effects of short term, even distributions of heat without synergistic effects. Procedure I is applicable to storage conditions where the parts are protected from the added heat, +19^{o}C (35 ^{o}F),[19,20] and synergistic radiation damage that can be generated by the sun. Its effect on window operation is evaluated by post test visual and optical measurements.

Conformance to optical properties after exposure to warm humid environs is evaluated by exposing windows to five modified cycles of the aggravated humidity profile shown in MIL-STD-810G, Figure 507.5-7. The modified cycle is 48 hours duration at 95% relative humidity and each cycle includes a 30 hr hold at 60^{o}C, and an 8 hr hold at 30^{o}C. After the test, the sample is conditioned at 23°C ± 10°C and 50% maximum relative humidity for 48 hours then inspected to ensure no indication of moisture buildup, bond separation, or any other forms of image degradation per the allowable defects specification. The sample returns to normal ambient conditions and is inspected to the visual and optical specifications.

Temperature shock effects on the transparent armor are evaluated using Method 503.5, Procedure I-C of MIL-STD-810 adapted to include an 18 hour period at -30°C followed by an 18 hour period at +60°C with a transfer time of not more than five minutes. At the conclusion of the thermal shock test the sample is required to conform to the visual and optical requirements. MIL-STD-810 suggests the use of this test when material is likely to experience sudden changes in temperature such as during transfer from climate controlled storage or enclosure to hotter or colder outside temperatures, or when ascending to high altitudes from a high temperature ground environment, or vice a versus such as in an air drop. It is not intended to test for conditions such as water hitting a hot surface or rapid localized heating of a cold surface. Transparent armor exposed to this test may experience shattering of glass, differential contraction or expansion rates or induced strain rates from dissimilar materials, deformation or fracture of components, cracking of surface coatings.

De-icing specifications in the ATPD 2352 require de-icing at -25°C in 60 minutes. A window is cooled to -25°C and held for 12 hours then sprayed with water from a 345kPa pressure gun. The water is allowed to form into ice for 25 minutes before the de-icer is turned on. This ATPD 2352 specified test imposes a combination of thermal stresses and the window is required to be inspected for visual and optical requirements after the test.

Sun exposure weathering tests require the use of Procedure II in MIL-STD-810 Method 505. This procedure was developed to include both the temperature and actinic effects of solar loads. The specified cycle is 20 out of 24 hours at 1120W/m^2 at a constant temperature of 49°C. For four hours each cycle the lights are turned off to induce alternating thermal stressing and allow “dark” processes to occur. The most intense naturally occurring total irradiance on the earth at sea level is represented by the irradiance cycles of Procedure I, which only reach 1120W/m^2 for 2 hours out of each 24 hours. Procedure II accelerates the amount of total irradiance impinging the sample by 2.5 times requiring the 1120W/m2 for 20 of the 24 hours. In addition, Procedure II requires the use of full sun spectrum lamps with 68.3% of the spectrum comprising the high energy UV wavelengths below 400nm so are more active in evaluating actinic material responses which show up in yellowing, discoloration, cracking, or, in extreme cases, mechanical degradation. The acceleration of these actinic processes may be much more than 2.5 times due to the added UV content and require correlation with natural processes and conditions to quantify.

GLASS-CERAMICS TO MEET ATPD 2352

The emerging requirements of APTD 2352 dictate new and critical properties the components and window systems should have:

i) Opaqueness in the ultra-violet (UV), below 370 nanometers to protect the polymer constituents from solar radiation;
ii) Good transparency between 400 and 1200 nanometers for human and night vision visibility;
iii) Very low or no coefficient of thermal expansion (CTE) to promote resistance to thermal shock and cycling;
iv) Unique failure mechanisms to promote multi-shot performance at low weight;
v) Superior ballistic performance to promote low weight against IED fragments.

Glasses used in armor are primarily soda-lime-silicate, which can be improved for infra-red (IR) transmission if made with very low iron and borosilicate glass which has a low density and low CTE. Both offer good transparency in the visible range, but are transparent in the UV (see Table I).

Table I: Properties of soda-lime-silicate and borosilicate glass compared to glass-ceramics.

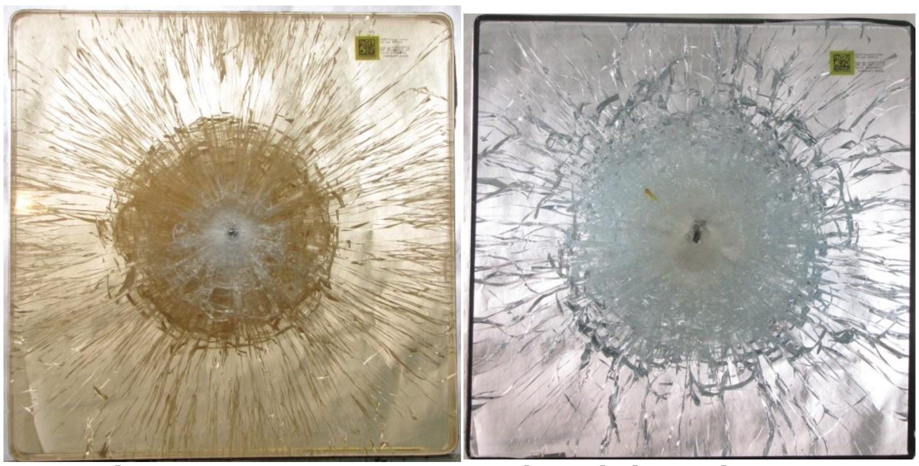
Material	Density (g/cc)	CTE (ppm)	Transmission at 370 nm	Young’s Modulus (GPa)
Soda-Lime	2.49[20]	9.03[21]	>50%[21]	73.1[20]
Borosilicate	2.22[20]	3.25[22]	>85%[23]	63.1[20]
LAS Glass-Ceramic	2.56[25]	0 +/- 0.3[24]	0 [24, 27]	92[25]

Evaluation of commercially available glass-ceramics, focusing on large production of glass-ceramics available in the lithium alumino silicate, Li_2-Al_2O_3-SiO_2 (LAS) family, often used in fire places and cook tops and other appliances, reveals several advantages of this material.[24, 25, 26]

The CTE is 0.3 parts per million but is balanced between the LAS crystal having a negative CTE and the glass a positive CTE.

The glass-ceramic is filled about 65% by volume with nano-crystals of about 70 nanometers and smaller size. This offers the unique advantage that it blocks all wave lengths less than four times this size, but allows the higher wavelength visible light to pass. Properties are listed in Table I.

Its unique microstructure offers advantages in armor as its failure mechanism isolates damage and sets up superior multi-shot performance. For instance Figure 4 compares the damage pattern in a glass-ceramic target to one in a soda lime target, both impacted with an armor piercing round at muzzle velocity. The diameter of the opaque zone which is comprised of a network of radial and circumferential cracks, is 203 mm diameter in the LAS glass-ceramic and 241 mm diameter the soda-lime-silicate glass target, which is 1.41 times larger area with no visibility.



4a: Glass-ceramic target 4b: Soda-lime-silicate target

Figure 4: Damage pattern in comparable glass-ceramic and soda lime targets.
Each target is 400 x 400 mm square.

Two disadvantages with production available glass-ceramic were the “orange peel” surface found on both sides due to the nature of the rolling process that pulls it off the melting tank, and transmission in the visible caused by additives and contaminates in the melt.

The glass-ceramic was made clearer by eliminating colorants used in appliance grade LAS glass-ceramic by reducing impurities. The resulting typical transmission as shown in Figure 5 is opaque below 370 nm and transparent from 370 to 1100 nanometers.

The representative orange peel, surface shown in Figure 6, was solved by using an interlayer with an index of refraction suitably but not perfectly matched to the glass-ceramic, taking into account the angles imposed by the geometries of the orange peel. Without the suitable matched interlayer and surface geometries, images viewed through the laminate were fuzzy and blurred. With appropriate interlayer and surface geometry match, images are clear and windows pass all optical requirements of the ATPD 2352.

TESTING LAS GLASS-CERMIC CONTAINING LAMINATED ARMOR TO ATPD 2352

Complex assemblies of plastic and LAS glass-ceramic which offered superior transparency, IR functionality for NVG, and still block UV and survive solar radiation, thermal shock, thermal cycling and all ballistic requirements of ATPD 2352 have been developed. Optical Measurements and Results

Transmission is measured to the requirements of the ATPD 2352 using a UV/VIS/NIR spectrometer with dual beam, dual monochromatic optics having a range from 185 nm to 3300 nm attached to a PC with full spectrum software. Because of the lateral size constraints of this system, specimens are limited to 50 x 50mm up to 100 x 100mm size. Larger samples and full size windows are measured on a custom setup using diffuse illumination and a portable fiber optic spectrometer that is calibrated by correlating with the calibrated spectrometer.

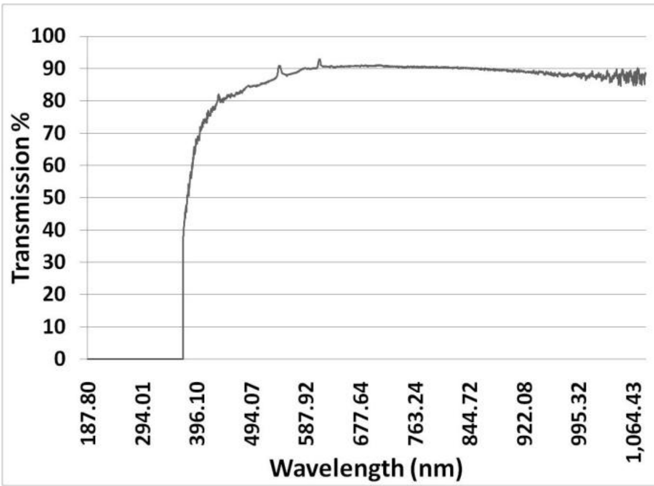


Figure 5: Transmission of LAS Glass-ceramic, 8 mm thick.

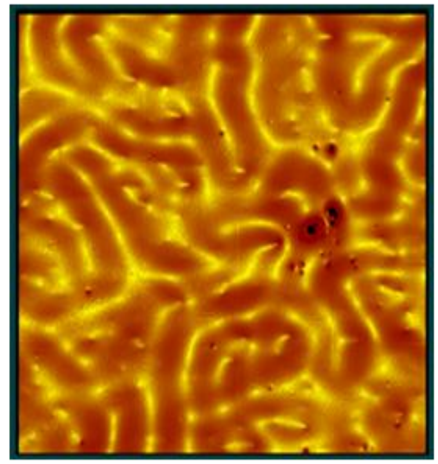


Figure 6: Characteristic orange peel on the surface of rolled glass-ceramic. The image, 15 mm wide, was created with a 3D optical surface profiler.

The transmission characteristics of four different sample constructions are presented in Table II. The cut-on wavelength is the value at which the sample begins to show positive transmittance. Below this wavelength the samples block 100% of the electromagnetic radiation. All the lay-ups meet the optical requirements, exceed the NVG transmittance, and provide UV blocking.

Table II: Transmittance for various laminates using glass-ceramic layers.

Sample ID	Thickness (mm)	Areal Density (kg/m^2)	Wavelength Cut-on (nm)	Photopic Transmittance (%)	NVG Weighted Transmittance (%)
daptms001	50	103	395	71	80
dap1772	90	161	400	73	74
daptms002	90	186	405	55	68
dap200081	109	215	399	62	77

Production grade processes controlling dust and debris in lay-up rooms and consistency with glass production increase the photopic transmission from an initial value ranging from 58.9% to 60.8% to an average production value of 66.5% with a minimum of 61%.

Environmental Tests and Results

Sun weathering tests are performed in a Xenon test chamber using B/B filters and Xenon Arc lamps to produce the required spectrum and energy. It is capable of controlling the ambient temperature to the required 49^{o}C and has on the fly calibration performed with dedicated radiometer and thermometer traceable to NIST standards. The first samples are transparent armor, comprised of glass-ceramic and polycarbonate laminated into a 171 kg/m^2 system, approximately 81mm thick. The sample is 300mm x 300mm, wrapped in silicone foam edging and gasket material, and framed in an aluminum casing. Temperature probes are attached to the front and back surface. The sample is placed with the “safe side” laying on an aluminum tray and the glass “strike face” facing the lights. It is exposed to 56 cycles; each cycle is 24 hours long comprised of 20 hours with the light on and 4 with the light off. The air temperature control was set at 49^{o}C. The surface temperature of the glass face reached a maximum of 73^{o}C during the light on phase and dropped back to the chamber air temperature during the lights off phase of each cycle. The surface of the safe side was only 6 mm away from the aluminum tray and the maximum surface temperature on the safe side was highest, 82^{o}C, when the sample was rotated to a position where the thermocouple was located with less than 30 mm of air space between the tray and bottom of the chamber. MIL-STD-810G part one c-2 states, with respect to hottest climates on earth, “except for a few specific places, outdoor ambient air temperatures will seldom be above 49°C (120°F). … The thermal effects of solar loading can be significant for material exposed to direct sunlight, but will vary significantly with the exposure situation. The ground surface can attain temperatures of 17 to 33°C (30 to 60°F) higher than that of the free air, depending on the type/color of the ground surface,” So the surface temperatures measured for the sample are on the upper limit of what might be seen in the field. Post test, the sample passes the allowable defect specification of the ATPD 2352 having grown only one small bubble, <1.6mm diameter, which is less than half the minimum size allowed.

A second series of experiments compare glass-polycarbonate laminates with various amounts of glass-ceramic, from none (dap004446), one layer just under the strike face (dap004435, and all except the strike face (dap004440). All specimens are 100 x 100 mm and have edges finished with a two part polyurethane sealant. Samples are inspected every week. Post test, all samples show delamination lines related to contamination by the sealant. Results summarized in Table III, show that the addition of one layer of glass-ceramic nearly doubles the life time of resistance to delaminating even in an environment of contamination.

Table III: Effect of glass-ceramic layers on solar loading test results.

Sample ID	Sample	Thick (mm)	Delam Day	Pre-Photopic (%)	Post-Photopic (%)	Pre-NVG (%)	Post-NVG (%)
dap004446	Soda-lime	125	21	74	57	54	42
dap004435	One layer glass-ceramic	128	56	49	49	35	34
dap004440	Multiple glass-ceramic	101	56	56	55	71	69

Evaluation against the remaining environment tests, high temperature, low temperature, thermal shock, and humidity is performed on two types of full size window samples; one (dap-GC) made of mostly glass-ceramic weighs 201 kg/m^2 (41.1 psf), the other (dap-SL) uses one layer of glass-ceramic just under the strike face and weighs 244 kg/m^2 (49.8 psf). Both systems, post test, meet the allowable defect specification, and retain the required levels of photopic and NVG transmittance (see Table IV).

Table IV: Optical properties of two different transparent armor systems after exposure to environmental tests.

TA Type	Sample ID#	Post Test Luminous Transmittance (%) Min: 55%	Post Test NVG (%) Min: 30%	Post Test Allowable Defects	Environmental Test
dap-GC	4575	56.3	70.0	pass	High Temp
dap-GC	4578	56.7	71.1	pass	High Temp
dap-GC	4563	56.3	70.1	pass	Humidity
dap-GC	4566	57.6	69.3	pass	Humidity
dap-GC	4576	56.1	70.2	pass	Low Temp
dap-GC	4562	56.1	70.0	pass	Low Temp
dap-GC	4569	57.0	70.0	pass	Temp Shock
dap-SL	4611	67.5	54.9	pass	Low Temp

dap-SL	4615	67.0	54.4	pass	Low Temp
dap-SL	4616	65.8	56.3	pass	Temp Shock
dap-SL	4617	67.2	55.0	pass	Temp Shock
dap-SL	4618	67.9	55.8	pass	Humidity
dap-SL	4622	66.8	55.8	pass	Humidity
dap-SL	4628	66.7	54.4	pass	High Temp
dap-SL	4625	68.7	56.6	pass	High Temp

BALLISTIC PERFORMANCE

Ballistic weight efficiencies of the developed LAS glass-ceramic containing transparent armor recipes are typically 20% - 50% lighter than incumbent soda-lime based transparent armor depending on the specific threats of interest. Examples are listed in Table V.

Table V. Ballistic performance of various LAS glass-ceramic based armor recipes

Sample #	Areal Density (kg/m^2 (psf))	Thickness (mm)	Projectile	Impact Velocity Range (m/s)		Multi-hit	Test Temp
1829	255 (52)	168	7.62 x 51 AP M993	968	981	4-shot T	65 ^{o}C
8092B	255 (52)	114	7.62 x 51 AP M993	966	977	4-shot T	-43 ^{o}C
8068L	254 (52)	114	7.62 x 51 AP M993	962	973	4-shot T	Ambient
ddm1226	231 (47)	107	20mm FSP	1509	1522	3-shot 160 mm Triangle	Ambient
ddm1827	202 (41)	142	0.30 Cal AP-M2	877	882	4-ahot T	65 ^{o}C
ddm1031	188 (38)	89	0.30 Cal AP-M2	875	889	4-shot T	Ambient
ddm0983	169 (35)	82	20mm FSP	1054	1080	3 shots 150 mm triangle	Ambient
ddm0971	168 (34)	79	7.62 x 54R API	884	895	3 shots 120mm triangle	Ambient
ddm0947	173 (35)	83	7.62 x 54R LPS Ball	871	878	4-shot T	Ambient
ddm0923	103 (21)	51	7.62 x 51 M80 Ball	831	853	5-shot NIJ 0108.01 III	Ambient
ddm0944	103 (21)	48	7.62 x 39 PS Ball	724	729	4-shot T	Ambient
ddm0925	103 (21)	51	0.50 Cal FSP	1226		1-shot	Ambient
ddm0926	103 (21)	55	0.30 Cal AP-M2	844		1-shot	Ambient
ddm0927	103 (21)	48	7.62 x 51 M61 AP	836		1-shot	Ambient
ddm1012	95 (19)	43	0.30 Cal AP-M2	872		1-shot	Ambient
ddm1470	84 (17)	42	7.62 x 51 M61 AP	781	794	2-shot in 12"	Ambient
ddm1472	66 (14)	35	7.62 x 51 M80 Ball	826	837	3-shot 120mm triangle	Ambient
p39	60 (12)	34	0.50 FSP	V50 = 1089			Ambient
ddm696	60 (12)	33	7.62 x 51 M80 Ball	888		1-shot, UL 752 level 5	Ambient
ddm693	60 (12)	33	7.62 x 51 M80 Ball	859		1-shot, UL 752 level 5	Ambient
ddm752	60 (12)	33	5.56 x 45 M855	908	919	3 shots in 8" dia. circle, SD-	Ambient

						STD-01.01	
hat-4D	54 (11)	27	12.7 mm AP @ 60^o	496		1-shot	Ambient
hat-5c	39 (8)	21	7.62 AP @ 60^o	773		1-shot	Ambient

CONCLUSIONS

An LAS glass-ceramic based transparent armor was developed which is the lightest weight transparent armor recipe to date that is ballistically qualified to the 3a all temperature level of the ATDP 2352. In addition, it is capable of passing all other requirements of ATPD 2352 Rev R weighing 201 kg/m^2 (41.1 psf).

ACKNOWLEDGEMENTS

The authors appreciate the support of TARDEC under CRADA #08-18, the funding from the Technical Support Working Group through EMRTC that supported the environmental test on the full size windows, and the extensive funding and contributions of materials and the transparent armor inventions from DiamondView Armor Products (DAP) and then SCHOTT DiamondView Armor Products which acquired DAP. We acknowledge and appreciate the numerous discussions with TARDEC staff working to develop the ATPD 2352 purchase description including David Hanson, David Sass, Steve Hoffman and Robert Goedert who also provided luminous and NVG transmittance calculation templates. The authors recognize and appreciate that the optical measuring equipment and techniques were developed and exercised by optical experts at SCHOTT's R&D facility in Duryea PA, Carsten Weinhold, David Badack, Joe Granko, and Beth Gober-Mangan. The authors are indebted to Edgar Aleshire who made numerous contributions to the designs and fabrication of the many test coupons and to developing production grade processes for improved quality. The authors are grateful to Rebecca Neill for overseeing tests performed at Dayton T. Brown and for helpful suggestions in editing the manuscript. Authors acknowledge Zygo Corporation for making the surface profile measurements shown in Figure 6 free of charge and Tim Talladay for photographs in Figure 4.

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