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PITFALLS IN HIGH STAKES ENVIRONMENTAL CHAMBER TESTING FOR TRANSPARENT ARMOR

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ABSTRACT

Transparent armor, also known as ballistic glass, is a primary sustainment cost for tactical wheeled vehicle programs, accounting for 10's of millions of dollars annually. The "Accelerated Life Test" is required in first article testing, and is an effective predictor of part life. However, the test takes 4-6 months and is expensive. Passing the test is a major hurdle, contributing to backlogs for critical Marine Corps and Army tactical vehicles. The test is also a very 'high stakes' test because it is only required once per design and is a primary factor in determining selection of the winning company bid. While the test requirements appear simple, multiple seemingly minor test errors have had dramatic effects on the test results. It is critical for both manufacturers and government program offices to understand how to properly run the test, analyze results, and report the results in a way that can be confidently accepted as a technically sound measure of part quality. This work highlights key pitfalls using a thermal model to show their potential effect. Recommendations are provided for correctly running and reporting the test.

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1. INTRODUCTION

Environmental tests are very common in procurement decisions. They are used to predict the future performance of parts. For example, lithium ion batteries are extensively tested to identify the number of times they can be cycled before their capacity fades [1]. Even though two batteries may look identical and have identical voltage and power at purchase, some will last longer than others, and those have higher value for procurement.

In the military, environmental exposure testing is particularly important because of the widely varied environments in which items are used and the criticality of part performance. Many environmental tests are described in MIL-STD-810H [2]. The standards describe a set of conditions (temperature, humidity, moisture, chemical exposure, irradiation, etc.) to which samples must be exposed. Following the test, samples must be inspected, and the resulting changes measured and reported.

The purpose of these tests is to provide a metric to quantify the degree to which a part will survive a given environment. For this to be acceptable,

1. The test must be run in a fair and consistent way.
2. There must be data to verify that the test was run correctly.
3. The test results, typically part inspections, must be carried out consistently.
4. There must be data to verify the test inspection results, either pass or fail.

Transparent armor (TA, also known as ballistic glass) is a crucial part in all manned tactical vehicles such as HMMWV, JLTV, MTVR, and others. In the past 15 years, TA has become one of the costliest items of sustainment due primarily to premature delamination, which reduces visibility. One study reported costs of $10-$30M annually just for the Marine Corps [3]. The Army has approximately an order of magnitude more vehicles, putting estimated costs well over $100M annually.

TA consists of multiple layers of glass with an inner spall liner of polycarbonate. These are bonded together in an autoclave with a thermoplastic polyurethane (TPU) interlayer. This laminate is then placed in a frame using either a chemical potting or mechanical gasket. A schematic of a notional TA is shown in Figure 1. Delamination typically occurs between the polycarbonate spall liner and the TPU adhesive. This delamination can happen in as little as 2-4 years and has even been reported to happen in the crates prior to installation on the vehicle.

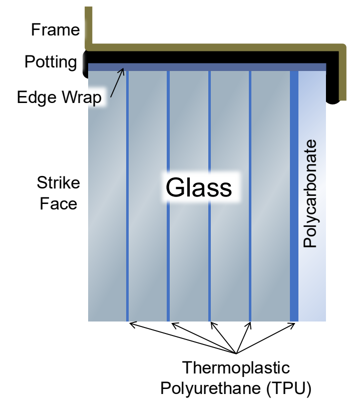

Figure 1. Schematic of TA

To address delamination, in 2019, a new transparent armor purchase description, known as ATPD 2352U,[4] was released with a few major updates from the previous version. These included: 1) Strict requirements to declare all materials and processing techniques and to maintain those during manufacturing, 2) clarification that tests needed to be done on full parts in frame, 3) a new accelerated life test (ALT). The ALT is a harsh environmental chamber test that includes both hot humid/cold cycles and long hot humid holds. The ALT test has been shown to cause field-relevant delamination in a range of manufactured parts and is the best predictor of delamination.

Prior work supported by the Defense Logistics Agency (DLA) showed that most production parts prior to ~2020 would survive fewer than 4 cycles of the ALT test. The target in the ATPD 2352U is 12 cycles, though several programs are currently operating with waivers for parts that have passed 6 cycles. These parts still represent a significant advance in quality compared to older parts. While very effective, the ALT is expensive ($20k-$40k per test depending on a variety of factors) and requires more than 4 months to test a full 12 cycles.

The ALT is a high value test for the government by allowing the selection and qualification of durable TA parts, but it is also a high-risk test. Because of the test length and cost, it is only required during first article testing, not during production control testing. Furthermore, if a given part passes the ALT, that test result can be applied to any similar part, regardless of shape (windshield vs side window or two different platforms with similar ballistic requirements). This means that a single test can be used to qualify a very large number of parts over several years.

The ALT is also a high-risk test because small differences in test procedures have been shown to produce large variations in measured performances, as documented in prior chamber to chamber comparisons [5]. In that study, nominally identical parts survived only 1-2 cycles in one chamber but reached 10 cycles in another running a conceptually similar cycle with minor differences in max temperatures and hold times. This creates a significant risk for manufacturers during competition to ensure that competing designs are compared on an even basis.

1.1. ALT Procedure and Pitfalls

The ALT procedure is relatively simple. A part is required to experience a given environment (temperature/humidity) for a given amount of time. It then ramps to a new setpoint in a certain time and is held at the new setpoint for an amount of time. Thus, all parts, regardless of thickness, experience the same test environment. Parts are evaluated by a technician examining the part to find any delamination, cracking, crazing, clouding, etc. This style of testing is very common. However, multiple years of government-led testing has shown that the very large thermally insulating parts and the aggressive cycling have led to a variety of pitfalls which have been shown to produce test results which could mislead TA manufacturers and should not be accepted by the government as they would lead to unfair evaluations between different products.

Test pitfalls that have been observed to skew test results include:

1. Insufficient temperature data to validate that the parts experienced the stated cycle. Often temperature is measured or tracked only at a single point (the chamber heating/cooling vent).
2. Overpacking chambers to save cost. When this happens, parts don’t experience the required temperature extremes because they are thermally insulating each other.
3. Chambers often do not have adequate cooling capability to perform the required ramp rates.
4. Tracking temperatures for the full test to validate chamber performance. In a 4-month test, unavoidable equipment malfunctions will happen, so the environment must be tracked.
5. Delamination or other damage is missed during inspections. Some delamination appears to ‘disappear’ or ‘heal’ when the two materials come back in contact (kissing bonds).

This paper analyzes the potential impact of these test pitfalls on the validity of the test. The evaluations are carried out using a 1-dimensional thermal transport model that has been validated against production TA parts in environmental chamber testing. A new metric, internal environmental intensity, is introduced to summarize the internal part history in a single number based on the external environment. The paper provides test guidance and suggestions to avoid these pitfalls.

2. Methods & Materials

2.1. Transparent Armor

For this publication, a fictitious piece of TA configuration that is not designed for any ballistic level is simulated. It is a generic stack of glass, TPU, and polycarbonate with a total thickness of 100 mm. The materials used in each layer and their thicknesses are similar to typical TA designs. The layup, starting from the strike face, consisted of 9 layers of mixed 8mm or 9mm glass, each separated by 1.27 mm of TPU. Then a 6mm layer of glass, 1.9 mm of TPU, and a 6 mm PC spall liner. This is shown in Figure 2 with a few key node numbers noted. The thermal properties used for the materials are in Table 1. These properties are approximate properties typical of the classes of materials.

Table 1. Thermal Properties Used

Material	k (W/m/K)	Density, ρ (kg/m^3)	Specific Heat Capacity, c_p (J/kg/K)
Glass	1	2510	858
PC	0.2	1125	1319
TPU	0.43	1080	1200

Because the thermal model is one dimensional, the frame, potting, etc. are ignored for this model. While these would undoubtedly change the thermal profile at the rim of the part, the simplified model provides sufficient insight to demonstrate the importance of the test controls that are the focus of this study.

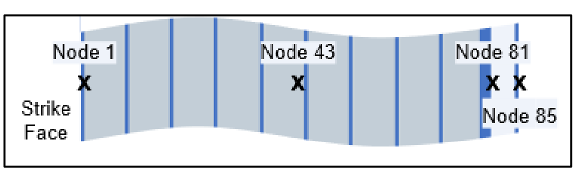

Figure 2. Schematic of the modeled laminate.

2.2. Environmental Intensity Metric

A Best Value Model for TA procurement was developed by the authors to correlate ALT results with field life. A key component of that model, which is still being refined, is the concept of environmental intensity. This is explained in detail in [5], but essentially uses a combination of time and temperature. In a chamber with no solar loads, the formulation would be:

$$I_n = \frac{\int \begin{Bmatrix} T - T_{ref} & T > T_{ref} \\ 0 & T \leq T\_ref \end{Bmatrix} dt}{t_{total}} \quad (1)$$

Where T is the relevant temperature, $T_{ref} = 20°\text{C}$ is the reference temperature below which no damage is assumed to accumulate, and t_{total} is the total exposure time. The cold phase contribution is excluded in the intensity calculation because previous testing and qualitative reports from parts stored in cold weather environments have shown almost no delamination. By contrast, in chamber testing, hot-to-cold cycles have been found to be necessary to produce field-relevant delamination in that accelerated environment. Further work needs to be done to understand the reason, but one hypothesis is that the hot temperatures degrade the bond and cold temperatures provide a driving force to open the interface.

The simplified intensity metric has been successfully used to correlate environmental chamber testing to real-world life. And it provides a simple way to summarize temperatures, solar exposure, and time into a single number.

The thermal model used in this study explicitly captures through-thickness temperatures during both hot and cold segments, so the computational model accounts for the full thermal history.

2.3. Computational Model

A one-dimensional transient heat transfer model was developed in MATLAB to quantify how chamber test deviations alter the internal thermal environment of TA. The model solves multilayer conduction using an explicit finite difference formulation following the standard approach in *Fundamentals of Heat and Mass Transfer* [6]. This time marching scheme allows rapid modification of boundary conditions to represent chamber anomalies such as altered ramp rates, overshoot, or non-uniform cycling.

The model automatically generates a spatial mesh from a user defined list of materials and layer thicknesses. Each region is discretized with sufficient resolution to maintain numerical stability. Node spacing varies from layer to layer depending on layer thickness, with a minimum of 4 nodes per layer. Material-specific thermal properties (k, ρ, cp) are assigned to each node. Nodes which are located at the boundary between two different materials use material properties calculated by a rule of mixtures scaled by the node spacing in the two materials. Subscripts indicate the location, with "-1" indicating the node to the left and "+1" the node to the right.

$$k_m = \frac{x_{m+1} - x_{m-1}}{\frac{x_m - x_{m-1}}{k_{m-1}} + \frac{x_{m+1} - x_m}{k_{m+1}}} \quad (2)$$

$$\rho_m = \frac{(x_m - x_{m-1})\rho_{m-1} + (x_{m+1} - x_m)\rho_{m+1}}{x_{m+1} - x_{m-1}} \quad (3)$$

$$c_{p,m} = \frac{(x_m - x_{m-1})c_{p,m-1} + (x_{m+1} - x_m)c_{p,m+1}}{x_{m+1} - x_{m-1}} \quad (4)$$

Chamber air temperature is supplied as a time history input, enabling arbitrary thermal cycles including holds, ramps, and multi-segment profiles. Convection at both external surfaces is modeled using a user-specified heat transfer coefficient.

At each timestep, the model computes temperature at all nodes and evaluates the environmental intensity metric for both the ambient air and the internal laminate.

Model verification was performed using analytical solutions for 1D conduction, and validation was completed using previously collected chamber test data. A prior Excel based implementation using the same explicit formulation was also cross checked for consistency.

The model directly supports the findings and recommendations in this paper by demonstrating how small chamber procedure variations can produce large differences in internal intensity, explaining the chamber to chamber variability observed in prior testing.

3. Results

The purpose of the ALT is to provide an external environment that leads to internal delamination. Therefore, in the results, the focus is primarily on the internal part temperatures. The most important location is the PC-TPU interface where delamination typically happens. In our model, this is at node 81 (see Figure 2).

To summarize the results of a test over a full 10-day cycle with both high and low temperature extremes the environmental intensity formula was used applied to the internal nodes of interest instead of to the external temperature. We call this the internal intensity.

As explained, small variations in ALT conditions can produce large variations in predicted life. The required temperature resolution in the ALT corresponds, for the modeled part, to roughly a 5.5% change in internal intensity. This could be considered a metric for the absolute limit of allowed deviations in these simulations.

3.1. Pitfall 1-2: Chamber Temperature and Overpacking

The ATPD 2352U specifies the environment which a part should experience. However, one of the most common pitfalls is when a test is performed without evidence that the parts themselves, not the chamber, experienced the required temperature profile.

This is particularly at risk when chambers are overpacked.

The primary risk is that often environmental chambers use only a single thermocouple, placed in the 'free stream' or vent where the heated/cooled air enters the chamber. The vent temperature measures the well mixed air near the chamber vent, where air flow is the highest, and thermal gradients are minimal. In contrast, thermocouples near parts measure the true temperature experienced by the part. That temperature is influenced by local airflow and the adjacent part temperatures. As a result, the free stream thermocouple over-reports both the heating and the cooling rates relative to the actual chamber environment on the TA parts.

Figure 4 uses real data from a prior test to emphasize the difference between vent temperature and actual part temperature. This was an ideal test with well-spaced parts in a chamber with carefully designed airflow to ensure good circulation. The temperature was controlled using a thermocouple located near the TA parts. As can be seen, the vent temperature had to overshoot the setpoints to achieve the needed chamber temperatures. Further, the vent temperature was consistently 1-2C higher than the chamber temperature.

By evaluating the thermal lag between the vent temperature and the chamber air temperature near the parts, it is possible to estimate how the chamber would behave if the vent thermocouple had been used as the control point. Under vent-based control, the vent temperature would rise directly to the programmed setpoint without overshoot, because the controller would see no need to drive the system harder. However, the air surrounding the parts warms more slowly than the vent location. Without the overshoot that normally compensates for the lag, the chamber air near the parts would remain below the intended temperature for a significant portion of the cycle, resulting in

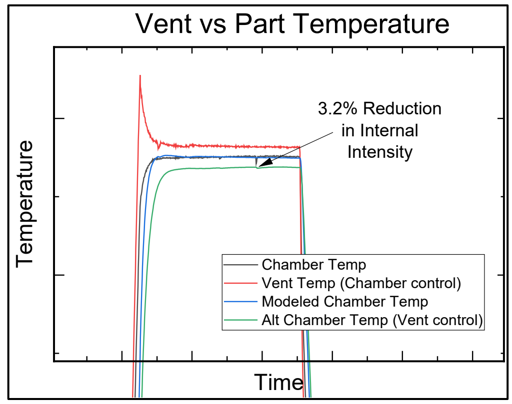

Figure 3. Temperature data from a lightly loaded environmental chamber. The chamber temperature is from thermocouples near the TA parts. The green is a prediction of chamber temperature if the vent temperature was used as

lower part temperatures throughout the ramp and hold. When this effect is applied across an entire 10-day cycle, the internal intensity of the modified test would have dropped by at least 3.4% at the PC-TPU interface.

If this drop happened in an ideal test, the difference would be even more in a less efficient chamber or in one with less ideal air mixing.

Overpacking chambers amplifies the above effect. Because of the length and expense of the test, it is natural to load the chamber as heavily as possible. While operationally efficient, this practice introduces significant thermal non-uniformity inside the chamber. Overpacking restricts airflow between adjacent parts, reduces the effective convective heat-transfer coefficient, and slows both heating and cooling rates. The result is a thermal environment that no longer matches the ATPD 2352U requirement that *each part experiences the full temperature extremes of the cycle*.

To quantify this effect, the model was run across a range of convection coefficients representing progressively more restricted airflow (h = 2-70 W/m^2*K). A perfect temperature profile was input. Lower convection coefficients correspond to heavily overpacked conditions, while higher values

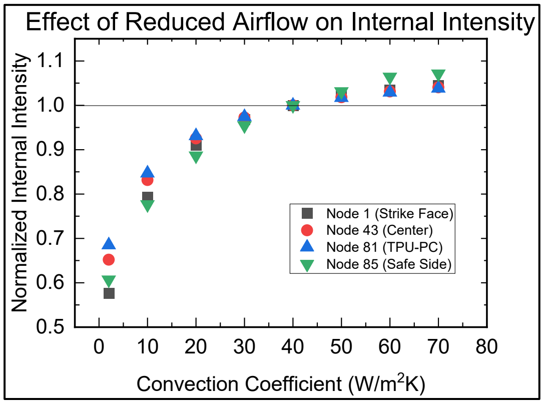

Figure 4. Effect of reduced convection (overpacking) on the internal intensity of parts. Lower heat-transfer coefficients, representative of restricted airflow between parts, significantly reduce the test intensity for the transparent armor.

represent unobstructed flows. Figure 3 shows the resulting internal intensity metric at four representative nodes: The strike face (Node 1), the mid thickness of the laminate at 50 mm (Node 43), the PC-TPU interface where delamination happens (Node 81) and the back face (Node 85).

Based on the results, below roughly 30 W/m^2*K, the internal intensity drops off rapidly. Static air – even at ideal temperatures – reduces part intensity by over 30% compared to a part exposed to a good airflow. As a rough approximation for TA parts, an airspeed of 5-10 mph would correspond to a 30-40 W/m^2K convection coefficient and would be reasonable.

These results demonstrate that overpacking does not simply slow the chamber's response; it fundamentally alters the thermal environment experienced by the laminate. A chamber may appear to meet its programmed temperature profile at the vent thermocouple while the parts never reach the required extremes or experience greatly reduced ramp rates and shorter thermal holds. This leads to under-testing, reduced environmental intensity, and non-representative behavior.

Test Recommendations: Place thermocouples throughout the chamber to ensure uniform flow. At a minimum, thermocouples should be centered between each part and between parts and walls at the part centerline. Ramp rates and hold times are determined by 'worst case' thermocouple readings. Space parts such that they all experience the chamber airflow. Photograph the loaded chamber and indicate thermocouple locations.

3.2. Pitfall 3: Slow Ramps and Short Holds

Environmental chamber specifications from ATPD 2352U require that the chamber achieve a prescribed temperature change within a fixed ramp duration (such as one hour). In practice, many chambers struggle to meet these ramp rates, particularly during cooling transitions where refrigeration capacity is limited. Many chambers operate from a fixed set of cycle instructions (e.g., ramp for 1 hour, hold for 6 hours…). Depending on chamber age and electronic sophistication, the controller may have very limited feedback logic. And as shown above the vent temperature control may not be representative of the parts. This means that if the ramp is slow, the hold time experienced by parts is reduced.

A common concern raised by both government and industry is whether slower than specified ramp rates meaningfully alter the thermal exposure of TA parts and therefore compromise the validity of the ALT.

To quantify the effect of ramp duration on internal thermal exposure, the model was run using a series of modified chamber cycles. A simple cycle with a 1 hour ramp (hot to cold) followed by a 6 hour hot hold was altered to include 1-, 2-, 3-, and 4-hour ramps. Two cases were then run. In the first case, the hold time (6 hours) was kept fixed. In the second case, the total cycle time (7 hours) was fixed – meaning that a longer ramp time reduced

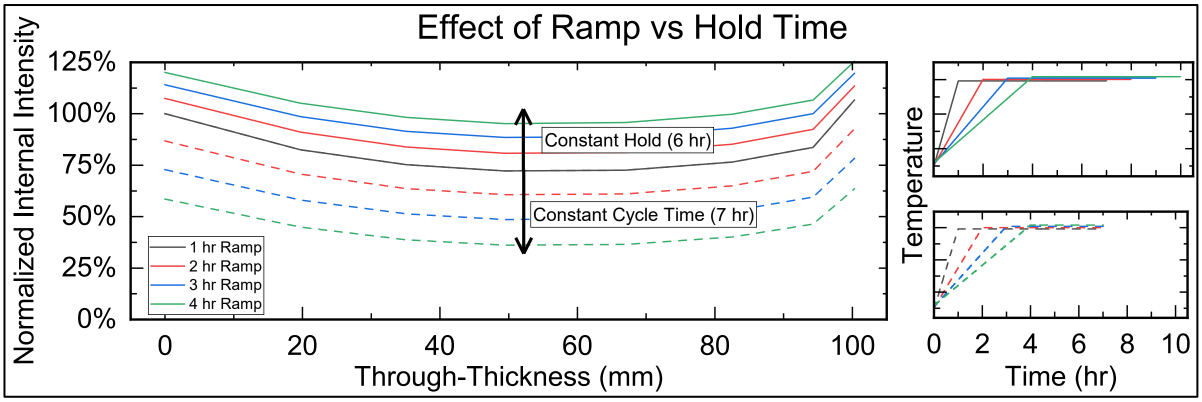

Figure 5. Environmental-intensity metric across the laminate thickness for chamber cycles with varying ramp rates but either fixed hold (6 hours, solid line) or fixed cycle time (7 hours, dashed). Fixed hold time maintains intensity regardless of ramp time. Plots on the right show the applied thermal cycles.

the hold time (e.g., a two-hour ramp reduced the hold to 5 hours).

For each scenario, the model computed the internal environmental intensity at representative nodes throughout the laminate thickness.

The results are summarized in Figure 5, and the difference is very stark. When the hold time is fixed at six hours, then slower ramp rates result in moderate increases to the test intensity. By comparison, when hold times are reduced to keep cycle time constant, internal test intensities drop rapidly with increasing ramp rate. For example, a 2 hr ramp followed by a 6 hr hold increased intensity by about 7%. A 2 hr ramp followed by a 5 hr hold reduced intensity by 14%.

Test Recommendation: Test controls should focus on maintaining the hold time regardless of ramp rate. A very easy metric at the end of a test is to report the total time at the hot and cold temperatures. These two metrics correlate closely to the test intensity and prove parts experienced the require range of temperatures for the required length of time.

3.3. Pitfall 4 – Tracking Test Anomalies

Environmental chambers occasionally experience short, unintended temperature excursions during the long duration of ALT cycles. These events are often caused by machine malfunctions, and their impact on the laminate can be disproportionately large, particularly for temperatures over the max test temperature. Some TPU and polycarbonate materials melt or can be damaged only a few degrees higher than the top ALT temperature. Even relatively brief excursions can cause damage.

Figure 6 shows a simulation where a chamber malfunctioned and ramped to 150C. Internal temperatures were simulated for 2.5 hours. A temperature of 85C was placed as the damage threshold. In 1-2 hours, parts

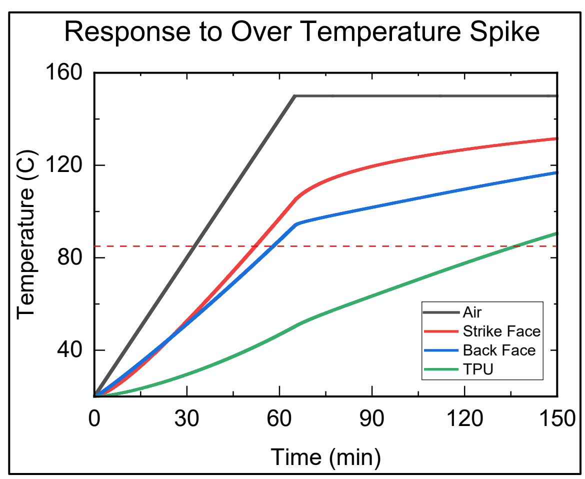

Figure 6. Temperature lag between vent temperature and chamber temperature. Less than 10 minutes after the vent temperature crossed 85C, the parts were experiencing damaging

were being exposed to potentially damaging temperatures.

This emphasizes that short excursions matter. Even a brief, unintended spike can push internal TPU temperatures above critical limits.

While an overtemperature event is relatively rare, it is very common for chambers to lose power in storms, humidifier systems to fail, compressors to burn out, etc. Most 4 month tests include some aberrations which must be tracked, reported, and evaluated.

Test Recommendation: Temperatures (near parts) should be logged for the entire test. Datalogging rates should be at least every 5 minutes. The full data should be provided with the test report in a machine-readable format.

3.4. Pitfall 5 – Inadequate inspection and reporting

Because of the high stakes inherent to the ALT test, program managers within the government often request to see ALT test results. However, reports often lack the key results and data. Test reports must verify that the test was carried out correctly, the results of the test inspections (pass, fail), and sufficient supporting evidence to allow the program office to make significant purchase decisions.

Technicians must be trained to recognize delamination and other flaws listed in the ATPD 2352U. Depending on the temperature of the part, humidity, etc., some delaminations are very difficult to see. Best practices include a flashlight to provide angled light or even a laser pointer at an angle which can highlight each layer. One strongly encouraged approach is in Figure 7 where cross polarized films are used. Fogging is sometimes present and measurable, but identifying delamination is often much more obvious when using cross-polarized films. Cross-polarization has enabled identification of delamination fronts even when fogging was not present and delamination was not visible even to trained technicians.

Figure 7. Photograph of a part with delamination. The cross polarized sheet covered only part of the TA. While fogging is visible in this case without the cross polarized films, the cross polarization makes the delamination far more clear for measurement and photography.

Test Recommendation: Final inspections should include both a sketch of the part with all anomalies noted by a skilled technician who has carefully examined the part, typically with a flashlight to provide angled light. Photographs with cross-polarized films are also encouraged. In addition, a brief inspection and sketch of the parts after each major cycle is recommended. Damage and delamination are sometimes caught early that may be hard to see later.

3.5. Practical test and chamber considerations

While not in the category of ‘common pitfalls’ there are some test requirements and best practices that are sometimes realized late. The ALT is a challenging test for TA – and for the chambers themselves. Some preparation before testing can be helpful.

Frames: The ATPD 2352U requires that tests be carried out on parts that are fully assembled with all frame, potting, etc. Most vehicular TA comes as a framed part that is then bolted to a truck. In this case, the test is carried out on a framed part. If the part is typically installed unframed, such as by bonding it to a cab in a manner similar to typical automotive windshields, then a surrogate frame should be built for the test with the windshield bonded to this frame using the same materials and procedures.

Racks: TA parts are quite heavy and large. They should be tested upright, so racks are built to hold them in place. Racks must not block the airflow. Additionally, it is often convenient if racks can be built to allow TA to be easily pulled from the chamber for inspections.

Problems have been observed when racks are constructed using pressure-treated lumber. The ALT results in significant condensation and water absorption by the wood. Additionally, the harsh freeze-heat cycles may release some of the chemicals used in the treated lumber. No direct evidence has been observed indicating that these chemicals have damaged TA samples or contributed to delamination; however, their use still presents a potential risk.

4. Conclusions

The analysis presented in this paper demonstrates that seemingly small deviations in environmental chamber operation can meaningfully alter the internal thermal environment of transparent armor. Those deviations in turn directly affect the severity by which a part is tested, how quickly a part fails, and how parts are compared to each other.

Thermocouple placement, airflow restriction from overpacking, short holds caused by long ramps, and chamber malfunctions all produced measurable changes in the through thickness temperature history of the part and the resulting environmental intensity metric. Across all scenarios, the internal environmental intensity provided a clear, quantitative measure of how chamber deviations, packing, etc. translate into altered thermal histories within the laminate.

Recommendations for valid, consistent testing were provided. These are further summarized in the Appendix. These recommendations are based on years of researching TA delamination and testing of TA. There are many other best practices and pitfalls that are not included in this paper.

Implementing these recommendations will improve the reliability, repeatability, and interpretability of ALT results, strengthening the connection between chamber testing and real-world delamination behavior. In doing so, they support more accurate lifecycle prediction, more defensible procurement decisions, and ultimately more durable transparent armor components across the tactical vehicle fleet.

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8. ACRONYMS

ALT	Accelerated Life Test
ATPD	Army Technical Purchase Description
DLA	Defense Logistics Agency
FAT	First Article Test
HMMWV	High Mobility Multipurpose Wheeled Vehicle
MTVR	Medium Tactical Vehicle Replacement
PC	Polycarbonate
TA	Transparent Armor
TPU	Thermoplastic Polyurethane

Appendix: Sample ALT Test Requirements

We provide a series of guidelines to improve test consistency as well as recommendations for reporting requirements for test laboratories. Continued involvement of technical SME's is recommended. These recommendations do not include all possible scenarios and should be used as a starting point for TA manufacturers and test laboratories.

Part Spacing, Chamber Layout, and Data Acquisition

- Part placement depends on the chamber cooling power and on airflow uniformity for all parts.
- Parts must be placed such that they all experience the chamber environment. Racks must not obstruct the airflow.
    - Aluminum or fiberglass racks are suggested rather than wood or steel.
- Place thermocouples throughout the chamber to validate temperature. At a minimum, thermocouples should be centered between each part and between parts and walls at the part centerline.
- If a chamber is heavily loaded or there is reason to doubt uniform airflow, additional thermocouples should be used.
- Log thermocouple and humidity readings in a computer-accessible format (*.csv, *.txt, etc.) with readings at least every 5 minutes (1 minute preferred).
    - Redundant datalogging is recommended. For example, recording the chamber thermocouple separately from the part thermocouples.

First Cycle Verification

- The test shall be paused after the first 10-day cycle and the thermocouple data quantitatively analyzed to demonstrate that the temperatures are within specification. If there are deviations, adjustments should be made and reported.
- Ramp rates and hold times are determined by 'worst case' thermocouple readings.

Test Operation

- Both hot and cold temperatures are an important part of the test.
- Hold time is more important than ramp rate. The required hold period should be maintained. This might mean a programmed cycle that has a slightly longer hold to accommodate slower ramp rates.

Over the 122 day test, it is not uncommon to have test anomalies occur.

- Logging of all thermocouples and humidity sensor must be continued throughout the test and provided in a computer-accessible format as proof of the process.
- All anomalies must be reported.
- A high temperature 'spike' over 85C could potentially cause melting and should be immediately reported.
- Cold spikes should also be reported but are not typically a problem unless visible damage is seen (cracking, etc.).

- Cycles which didn't reach required temperature, humidity, etc. could be evaluated on a case-by-case basis. The rule of thumb would be to repeat the inadequate cycles or holds.

Part Inspection

- Technicians must be competent and experienced with a strong understanding of the requirements of ATPD 2352U and experience recognizing TA failures, particularly delamination.
- Parts should be inspected following every cycle (so roughly every 10 days) with sketched reports showing the approximate location of anomalies and exact measurements of the size of anomalies and distance from the frame (see the ATPD 2352U for Areas A, B, and C).
    - Flaws extending into Area C are typically what constitutes failure, therefore, careful measurements from the frame are critical.
- More detailed inspections, including cross-polarized photographs clearly showing delamination or anomalies should be included as needed, particularly if parts are near failure.

Identification of the final 'passing' cycle

Data, sketches, and photographs should be used to support how many cycles a part has passed. A photograph of a failed part at cycle 10 does not necessarily prove that cycle 9 passed.

- Taking photographs after cycle 6, 9, and 12 is recommended.
- Following all 12 cycles and/or when parts are believed to have failed, a formal inspection shall be carried out. In addition to the ATPD 2352U recommendations:
    - Detailed sketches of every part with anomalies marked and size scales listed.
    - Photographs of the parts using best practices. These include a zebra board or cross polarized light to best highlight any flaws.

Reporting

The report should include:

- Photograph(s) of loaded chamber prior to test start and after any changes. Thermocouple locations should be marked.
- Plots / analysis to verify that the environment near the parts met the ALT requirements
- Final inspection sketches and photographs of the final passing cycle.
- Test lab recommendation for number of cycles passed.
- As separate files:
    - All thermocouple and humidity data in a computer-readable format
    - All inspection logs
    - High resolution photographs, do not simply embed all photographs in a pdf.

Examples

The elements listed above are demonstrated here. This is not intended to be a sample report format, but rather to show the type of evidence that could be used.

<u>Chamber validation is shown including a photograph of the loaded chamber.</u>

The photograph below shows a chamber test. Note the parts are well spaced and the airflow would be expected to be good between the parts with air coming from the top and racks lifted up off the floor. In this case, the chamber uses a control thermocouple that was placed between two parts. The ‘209’ is the vent thermocouple. 210 was the humidity sensor.

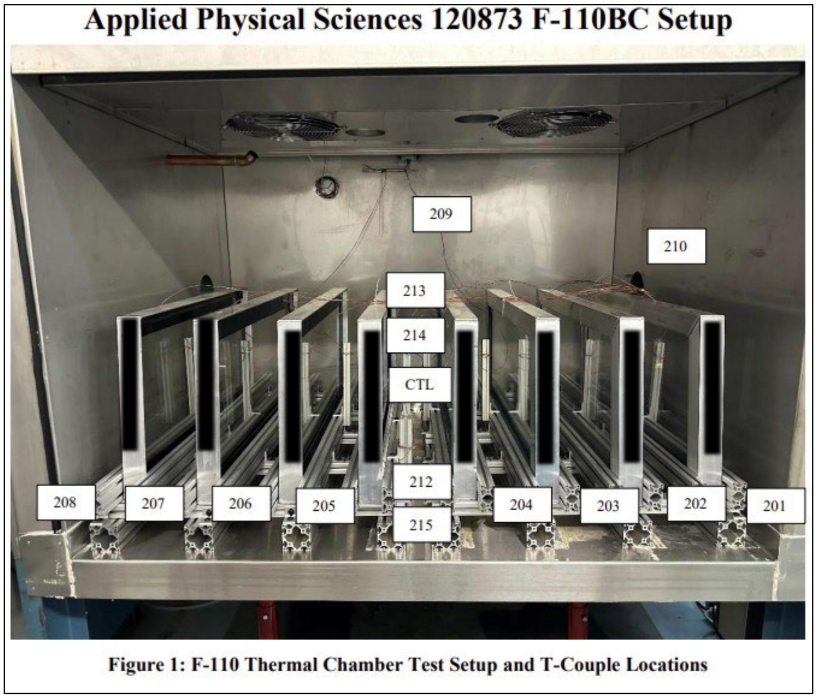

Figure A1. Photograph of a loaded chamber showing well-spaced parts with thermocouple locations.

<u>ALT profile validation</u>

We show a few typical cycles, a table summarizing the full test, and a trace of the temperature across the entire test with anomalies noted. The typical cycle (Figure A2) shows the spread of temperatures for the part thermocouples. The hold and ramp times should not be accepted to represent all holds and ramps for the full test, as those typically vary somewhat throughout the test. Instead, validation of overall performance comes from the table. The metrics in the table are easy to calculate in an automated way within Excel. Time at which the average part thermocouple was within a set range of the hot or cold extreme was summed and then compared with the ideal from the ALT. While the data is fictitious, the listed errors are from an actual test. The -6% for the time at hot/humid was further addressed in the report and was eventually accepted.

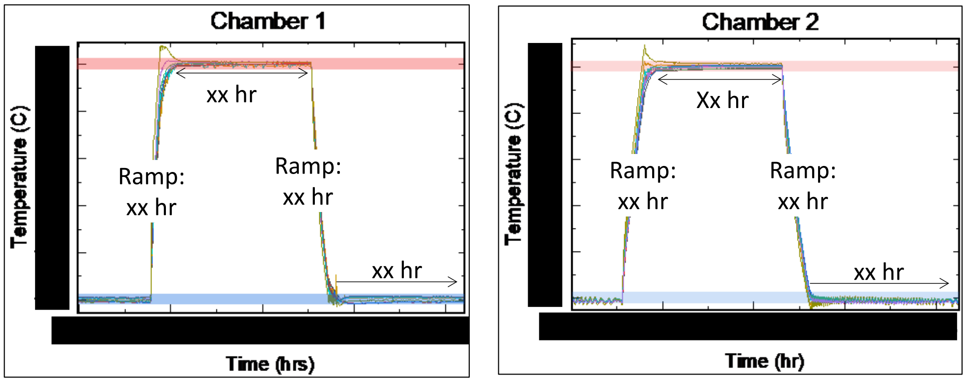

Figure A2. Typical cycle (data redacted) showing the spread of thermal measurements across all part and chamber thermocouples. Note that the chamber thermocouple (placed in the chamber vent) must overshoot the cycle to maintain the required cycle. Exact hold and ramp times vary from cycle to cycle.

Table A1. Sample ALT Chamber Summary (Fictitious Data)

	Ideal	**Experimental**	**% Error**
Time at hot extreme (hr)	1000	1030	+3%
Time at hot + humid extreme (hr)	1000	940	-6%
Average hot temperature (C)	100	101	+1%
Time at cold extreme (hr)	750	840	+12%
Average cold temperature	0	1	+1%
Number of cold cycles (hot to cold, hold, back to hot)	100	97	-3%
Number of hot cycles (cold to hot, hold, back to cold)	100	100	0%

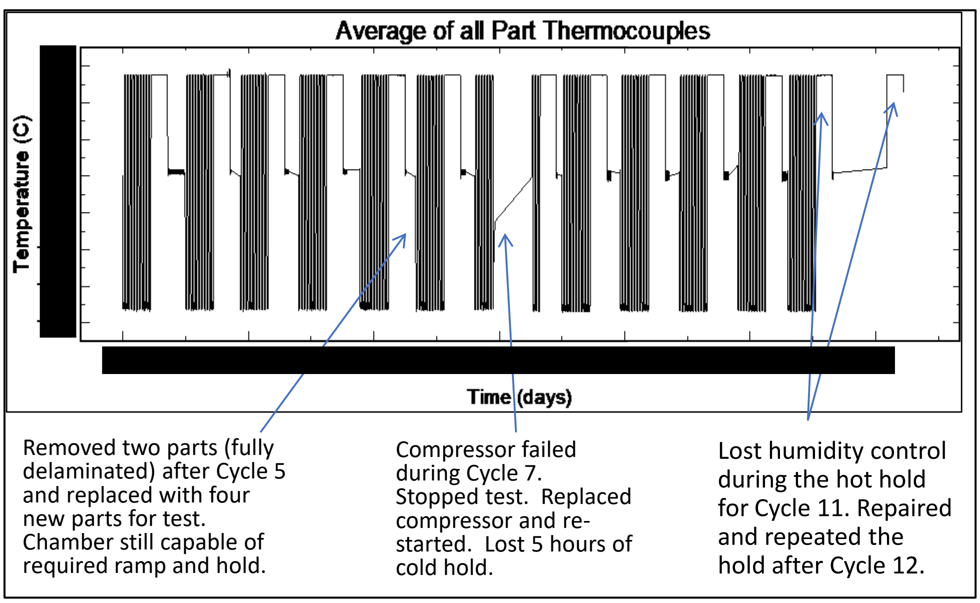

Figure A3. Full test profile with comments on all anomalies. Data redacted.

Part Inspection

Cycle part inspections typically include basic data, such as the cycle on which damage was first noted as well as the cycle at which a part was considered failed. Final photographs (cross polarized) were used to validate the final results with a scale present. This is shown in Figure A4.

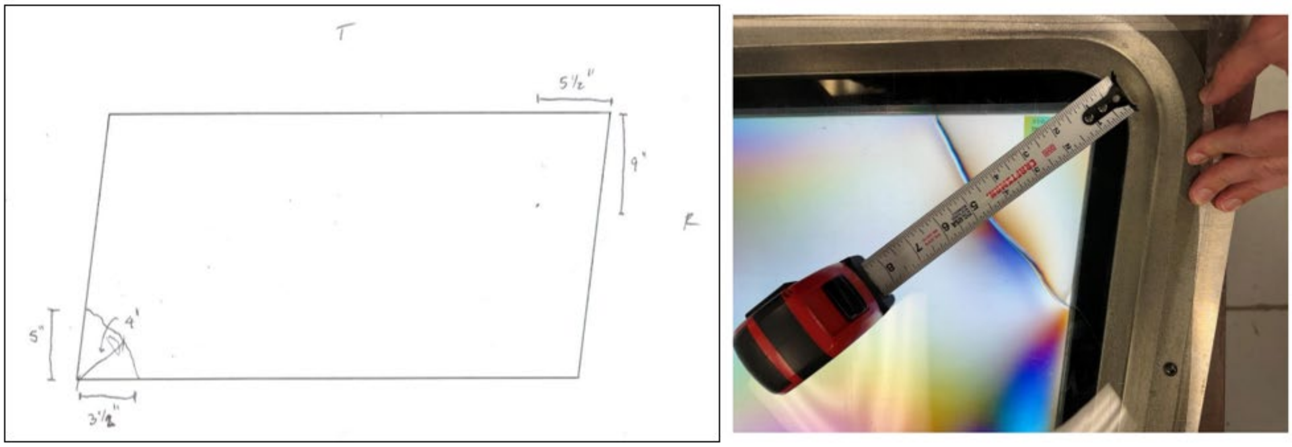

Figure A4. Showing a typical report with both a sketch of the part and clear photography of the damage.