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PREDICTIVE MODELLING OF ADHESIVE JOINT DETERIORATION AND NITROESTER MIGRATION IN THE M829 APFSDS KINETIC ENERGY ROUND

15 December, 1993

Prepared for

U. S. Army Armament Research,
Development and Engineering Center
Predictive Technology and
Quality Evaluation Division
Picatinny Arsenal, New Jersey 07806-5000

by

R. W. Counts, C. K. Bayne, and W. H. Griest

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

This work was sponsored by the U.S. Army Armament Research, Development and Engineering Center, under Interagency Agreement No. 1892-A078-A1 under U.S. Department of Energy contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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EXECUTIVE SUMMARY

Field reports of the deterioration of combustible cartridge case wall material and adhesive joint ("skive joint") strength in the M829 APFSDS kinetic energy round, although infrequent, indicate the need for predictive surveillance of this munitions component.

This study reviews three accelerated exposure studies conducted on full-up M829 rounds to determine the effects of external and internal factors on the lifetime of joint strength. Two of the studies were conducted by the U.S. Army Armament Research, Development and Engineering Center (ARDEC) Predictive Technology Branch. An additional study was conducted by the Oak Ridge National Laboratory (ORNL) for the ARDEC.

The main objective of this report was to review all three accelerated studies to compare and contrast the results. These results from these studies should allow prediction of useful field service lifetimes of the M829 rounds under storage and field conditions.

The ARDEC accelerated exposure study was initiated by Predictive Technology (PT) in 1986 to examine the ammunition storage life due to the aging of the American adhesive (cellulose nitrate conforming to MIL-A-82484, Type I) used in the skive joint of the M829 round. Unloaded rounds and rounds loaded with the JA-2 propellant were exposed in a time, temperature matrix. Tensile tests for the ARDEC accelerated exposure study were conducted on coupons cut from the case and adapter wall to include the skive joint. Motivated by the results from this study, PT initiated another accelerated exposure study with ORNL. The ORNL study used full-up M829 rounds manufactured in December, 1989, to military specifications at the Milan Army Ammunition Plant (MAAP) at Milan, Tennessee. The full-up rounds were exposed to a time, temperature, relative humidity matrix and tensile tests were made on the full-up rounds. The ARDEC Operation Desert Storm high temperature/solar radiation (HT/SR) study was initiated by PT to evaluate critical item safety and reliability under previously untested conditions characteristic of a worst-case thermal scenario in the Southwest Asia theater. The study was designed to expose rounds to a worst-case Southwest Asia diurnal temperature, humidity, and solar radiation cycling for up to 90 days. Tensile tests were made on full-up rounds that had been exposed to the diurnal cycling.

From these three accelerated exposure studies, we can conclude that:

1. The external factors of time, temperature, and relative humidity are important environmental factors for skive joint lifetimes. These factors also affect the migration of propellant components diethyleneglycol dinitrate (DEGDN), and nitroglycerin (NG). These propellant components interact with the adhesive to accelerate skive joint failures.

2. The logistic model is applicable for predicting joint strength as a function of time, temperature, and relative humidity. The logistic model indicates that skive joint disbonding at high-temperatures are activated by failure modes due to more complicated chemical reactions than those described by the Arrhenius model. It is also concluded that either NG, DEGDN, or total nitroesters serve equally well as a predictor of joint strength.

3. The main factor limiting the accuracy of prediction models was round-to-round variability (Std. Dev. = 838 lbs.) of the tensile strength measurements. The uncertainty in the predicted tensile strength at the time that disbonding would occur using the logistic model was about 1051 pounds. This underlines the need for an engineering study to improve the design and production of the adhesive joint.

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1. INTRODUCTION

The 120 mm M829 APFSDS kinetic energy round in Figure 1 is a unique munition fired in the main gun of the M1A1 Abrams main battle tank. This round features a combustible cartridge case which is consumed upon firing, and only the metal base remains for disposal. This considerably reduces the crew compartment clutter normally resulting from a full steel cased round.

One critical feature of this round is the adhesive joint (called the skive joint in the M829) between the combustible cartridge case and the cellulose adapter cone which holds the penetrator assembly in place. Reports from the field have indicated that disbonding of the adhesive joint can cause the loss of the penetrator assembly. This problem indicated the need for predictive surveillance of this munitions feature. Studies at the U. S. Army Armament Research, Development and Engineering Center (ARDEC) [*1,2*] and Honeywell [*3*] identified the external variable of temperature and the secondary internal effect of propellant nitroester migration as important contributors to skive joint deterioration and failure. Studies of accelerated environmental exposures with measurements of nitroester migration rate and skive joint deterioration predicted field service lifetimes of 4.8 to 8.6 years [*2,3*] under mild (about 21°C) conditions. These studies suggested the feasibility of constructing a mathematical model for field service lifetime prediction.

The ARDEC study suggested that temperature had a more important effect on adhesive joint strength than time. On the basis of this pioneering work, a more detailed study was designed. Oak Ridge National Laboratory (ORNL) designed an accelerated environmental exposure experiment to test the effects of temperature, time, and relative humidity on the tensile strength of the skive joints. The accelerated environmental experiment was performed by Milan Army Ammunition Plant (MAAP) with 70 full-up M829 rounds. The results from the ORNL study were used to develop a statistical model called a logistic model that predicted M829 skive joint strength. The logistic model could predict useful field service lifetimes of the M829 under any given set of exposure conditions and used to define limits for storage conditions.

The Predictive Technology Operation Desert Storm high temperature/solar radiation study (HT/SR) subjected 27 full-up M829 rounds to cyclic temperatures to simulate Southwest Asia "worst case" conditions. Tensile strengths were measured on 12 of these full-up M829 rounds at Aberdeen Proving Grounds and MAAP and propellant components on coupons were measured at ORNL.

Additional laboratory experiments have exposed M829 coupons to different environments at Honeywell [*3*] and ORNL [*4*]. These laboratory experiments are not included in this analysis because of the difficulty of comparing experimental results using full-up M829 rounds with those using M829 coupons. The ARDEC experiments are included because full-up M829 were used for the exposure experiments even though the tensile strengths were measured on M829 coupons. Table 1 summarizes the exposure experiments used for this comparison study.

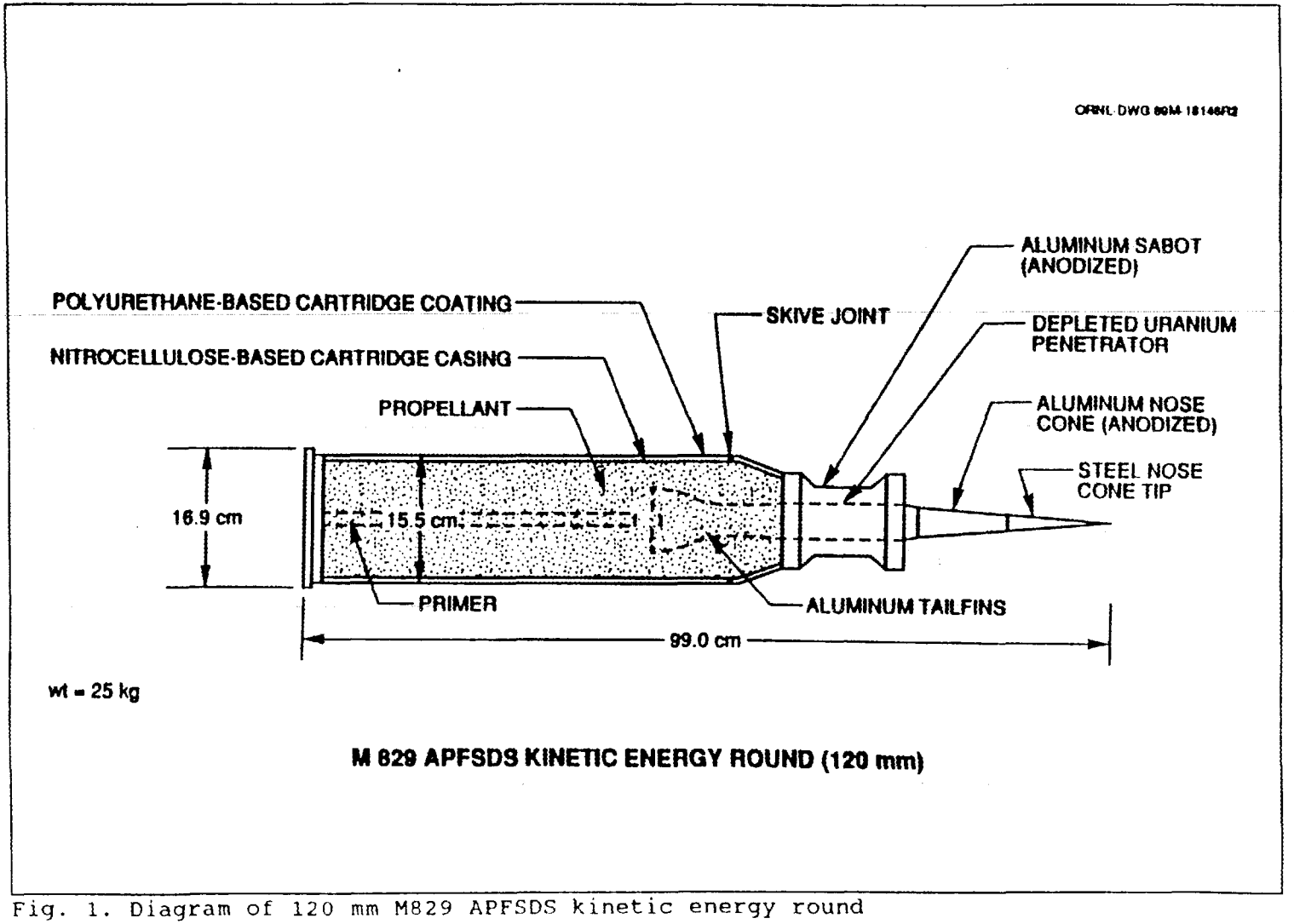

Fig. 1. Diagram of 120 mm M829 APFSDS kinetic energy round

A secondary objective of the three exposure studies was to investigate the effect of two nitroester components nitroglycerin (NG) and diethyleneglycol dinitrate (DEGDN). Laboratory studies using coupons cut from the M829 case walls have shown that time, temperature, and relative humidity are important environmental factors for propellant chemical degradation and/or migration. The nitroester components interact with the adhesive to accelerate skive joint failures.

Table 1. Accelerated exposure studies using full-up M829 rounds.

Exposure Study	Number of Rounds	Round Type	Exposure Parameters	Response Measurement[a]
ARDEC Accelerated	16 16	Full-up with JA-2 Full-up without JA-2	5-30 Days 21-85°C	TS on Coupons NG on Coupons DEGDN on Coupons
ORNL Accelerated	70	Full-up with JA-2	1-49 Weeks 9-85°C 40-80% RH	TS on Full-up NG on Coupons DEGDN on Coupons
ARDEC HT/SR	12	Full-up with JA-2	0-90 Days Cyclic °C	TS on Full-up NG on Coupons DEGDN on Coupons

[a]TS = tensile strength, NG = nitroglycerin, DEGDN = diethyleneglycol dinitrate

2. ARDEC ACCELERATED EXPOSURE STUDY

The ARDEC initiated an exposure study in 1986 to examine the ammunition storage life due to the aging of the American adhesive (cellulose nitrate conforming to MIL-A-82484, Type I) used for the skive joint of the M829 round. The objective was to predict adhesive joint storage life based on nitroester migration kinetics at various temperatures. ARDEC investigators concluded that nitroester migration affects storage life, but these effects could not be isolated and quantified because of the significantly high degradation of tensile strengths by elevated temperatures [1].

2.1 ARDEC Experimental Design

Charles Y. Manning [2] reported the following description on the ARDEC exposure study. "Sixteen M829 (120-mm tank KE round) case/adapter assemblies, bonded at Iowa AAP on 24 September 1986, were fitted with cloth bags (p/n 12525642) and loaded with JA-2 propellant lot RAD85-J-001S204 (17 lb 9.6 oz per charge). The bags were knotted and the tops of the cases plugged with tapered wooden discs (4 5/8 in. to 4 13/16 in. diameter) to simulate actual

storage conditions where the top of the case is closed by the attached projectile. Since these cases were shipped from Iowa with metal bases, insertion of spent primer heads into the metal cases provided an appropriate seal for the base.

These 16 loaded and 16 empty cases were individually packaged in standard fiber packing tubes (p/n 9354465) and wooden boxes, then stored in constant temperature chambers (or air-conditioned bunkers) as follows:

4 empty cases and 4 loaded charges at 85°C (185°F)
4 empty cases and 4 loaded charges at 70°C (158°F)
4 empty cases and 4 loaded charges at 50°C (122°F)
4 empty cases and 4 loaded charges at ambient (21°C, 70°F)

After 5, 12, 21, and 30 days storage, one empty case and one loaded charge were removed from each temperature chamber and allowed to cool."

After removing the propellant from the loaded M829 rounds, samples were taken from the bottom of the cases under the baseplate for high pressure liquid chromatography (HPLC) analysis (NG, DEGDN), then marked and sealed in polyethylene bags to minimize evaporative loss of the two nitroesters. Tensile strengths were also measured on each full-up M829 round by cutting four 1 in. X 8 in. coupons longitudinally from the top of each case so as to include a section of the skive joint. These coupons were tested on an Instron machine (6.5 in. grip separation, 500 FSL, 0.1 in./min crosshead speed) at room temperature to the breaking point. The experimental data from this ARDEC exposure study are tabulated in Table A.1 in Appendix A.

2.2 ARDEC Logistic Model

Originally, the tensile strength data from the ARDEC exposure study were analyzed for each individual temperature. This statistical analysis lead to some general conclusions about the rapid degradation of the skive joint at elevated temperature. This review of the data shows that additional analysis of the data can be made by fitting a model that represents a tensile strength response surface as a function of both time and temperature.

Polynomial models were initially used to predict skive joint tensile strengths. This standard approach assumed that the true underlying theoretical function can be approximated by a truncated Taylor's series expansion. First-order and second-order terms of the experimental factors (i.e., time and temperature) were candidates to be included in the approximating polynomial. Approximating polynomial models accounted for the variability of tensile strength values reasonably well in the experimental region defined by the data. However, extrapolating tensile strength values outside the experimental region was found to be completely misleading. For example, predicted values from polynomial models indicated that tensile strength would increase with times beyond 30 days. For skive joint disbonding (zero tensile strength values), predicted values were negative. Alternative tensile strength models were investigated to overcome the prediction deficiencies of the approximating polynomial model.

Several models (including Arrhenius and kinetics models) based on nonlinear growth [5,6] were investigated that would predict positive near-zero values for conditions resulting in skive-joint failure (zero tensile strengths). In addition, predicted tensile strength should start at a limiting value at ambient conditions. The logistic model has these two properties and gives consistent extrapolation results. The form of the logistic model used for the ARDEC coupon data is:

$$TS = \frac{A}{[1 + \exp(B + C_1 t + C_2 T + C_3 t \times T + C_4 t^2 + C_5 T^2)]} + \epsilon.$$

where TS = tensile strength (lbs/in), t = time (weeks), and T = temperature (°C). The coefficients (i.e., A, B, C_1, C_2, C_3, C_4 and C_5) were estimated from the data in Table A.1. The ϵ represents the measurement error. The logistic model has an S-shape curve for any one of the independent variables.

As the independent variables increase [e.g., $(t,T) \rightarrow \infty$], the tensile strength approaches zero. As the independent variables decrease [e.g., $(t,T) \rightarrow -\infty$], the tensile strength approaches the limiting value of TS = A. This logistic model represents the change in tensile strength with respect to any one of the three independent variables (i.e., dTS/dX_j, where X_1 = t, and X_2 = T) to be proportional to the product of the present tensile strength (TS) and the future tensile strength (A - TS):

$$\frac{dTS}{dX_j} = \frac{-C_j\ TS\ (A - TS)}{A} \qquad j = 1, 2, 3.$$

The coefficients in the logistic model were estimated by nonlinear regression [6,7] using Marquardt's procedure [8]. The logistic model for the unloaded M829 rounds accounted for 91% of the total variation of measured tensile strengths from the average. For the loaded M829 rounds, the logistic model accounted for 92% of the total variation of measured tensile strengths from the average. In addition, no significant lack of fit could be detected at the 5% significance level for either case when the variance estimated by the logistic model was compared with the variance estimated from replicate measurements. The estimated coefficients with 95% confidence intervals are given in Table 2.

Figures 2 and 3 show the tensile strength response surface for the coupons from unloaded and loaded M829 rounds, respectively. Both response surfaces show tensile strength starting at about 250 lb/in and slightly decrease until temperature reaches about 50°C. Tensile strengths at temperatures above 50°C will quickly degenerate with time. Tensile strengths for loaded M829 rounds decrease much more rapidly with time and temperature than those for unloaded M829 rounds. This difference in the rate of tensile strength decrease is due to nitroester migration. Figure 4 shows a comparison of unloaded and loaded M829 rounds for selected time periods (10, 20, and 30 days). These plots show tensile strength for both unloaded and loaded M829 rounds decreasing with time and temperature and the rate of decrease is accelerated by nitroester migration.

Table 2. Logistic model coefficients estimated by non-linear least squares.

Logistic Variable	Unloaded M829 Round		Loaded M829 Round	
	Coefficient	95% Confidence Interval	Coefficient	95% Confidence Interval
A	240.4	(229.0, 251.8)	254.8	(242.2, 267.4)
B	-18.4	(-32.7, -4.1)	-37.7	(-106.5, 31.2)
time (t, days)	0.67	(0.26, 1.07)	1.98	(0.33, 3.64)
Temperature (T, °C)	0.18	(-0.11, 0.46)	0.15	(-1.43, 1.73)
t x T	-0.0037	(-0.0075, 0.0002)	-0.0100	(-0.0281, 0.0081)
t^2	-0.0077	(-0.0114, -0.0039)	-0.0279	(-0.0402, -0.0155)
T^2	0.00016	(-0.00142, 0.00173)	0.00274	(-0.00675, 0.01224)
Statistics[a]	$\%R^2 = 91\%$	St.Dev. = 24.9	$\%R^2 = 92\%$	St. Dev. = 30.7

[a] $\%R^2$ = Percent of the total variation accounted for by the logistic model.
St. Dev. = Standard deviation (lb/in) of an individual tensile strength measurement.

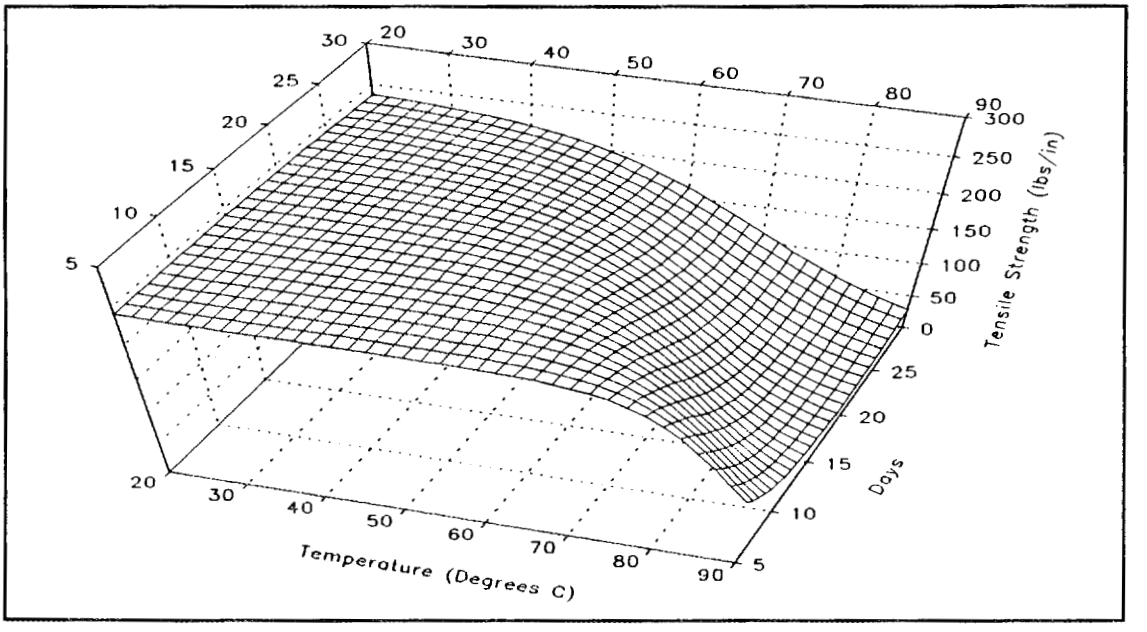

Fig. 2. Response surface of coupon tensile strengths for unloaded M829 rounds.

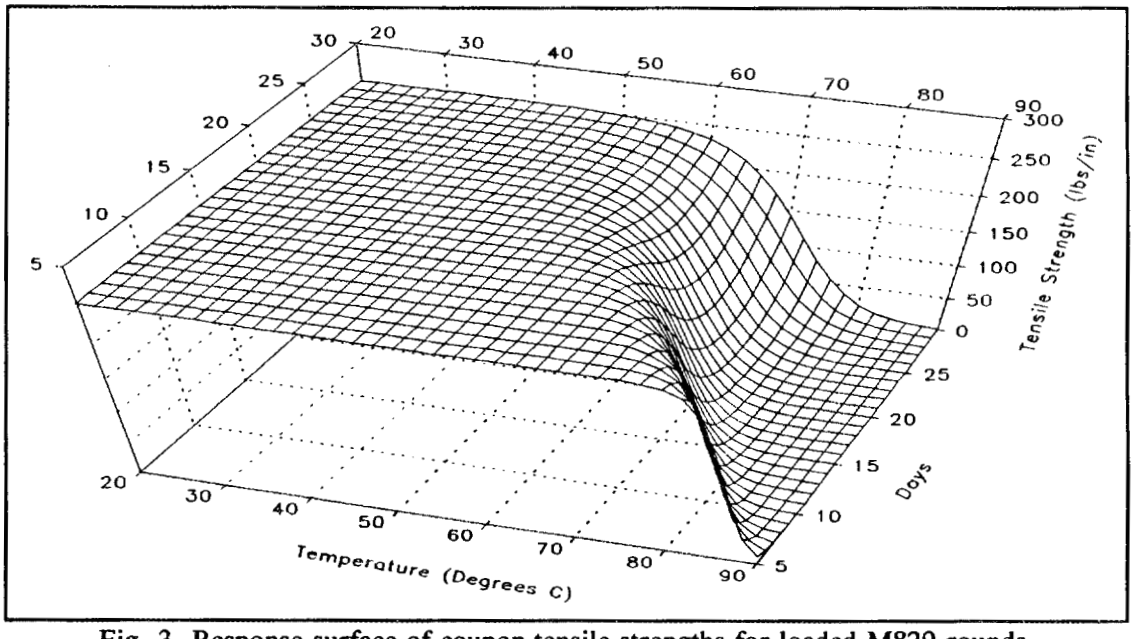

Fig. 3. Response surface of coupon tensile strengths for loaded M829 rounds.

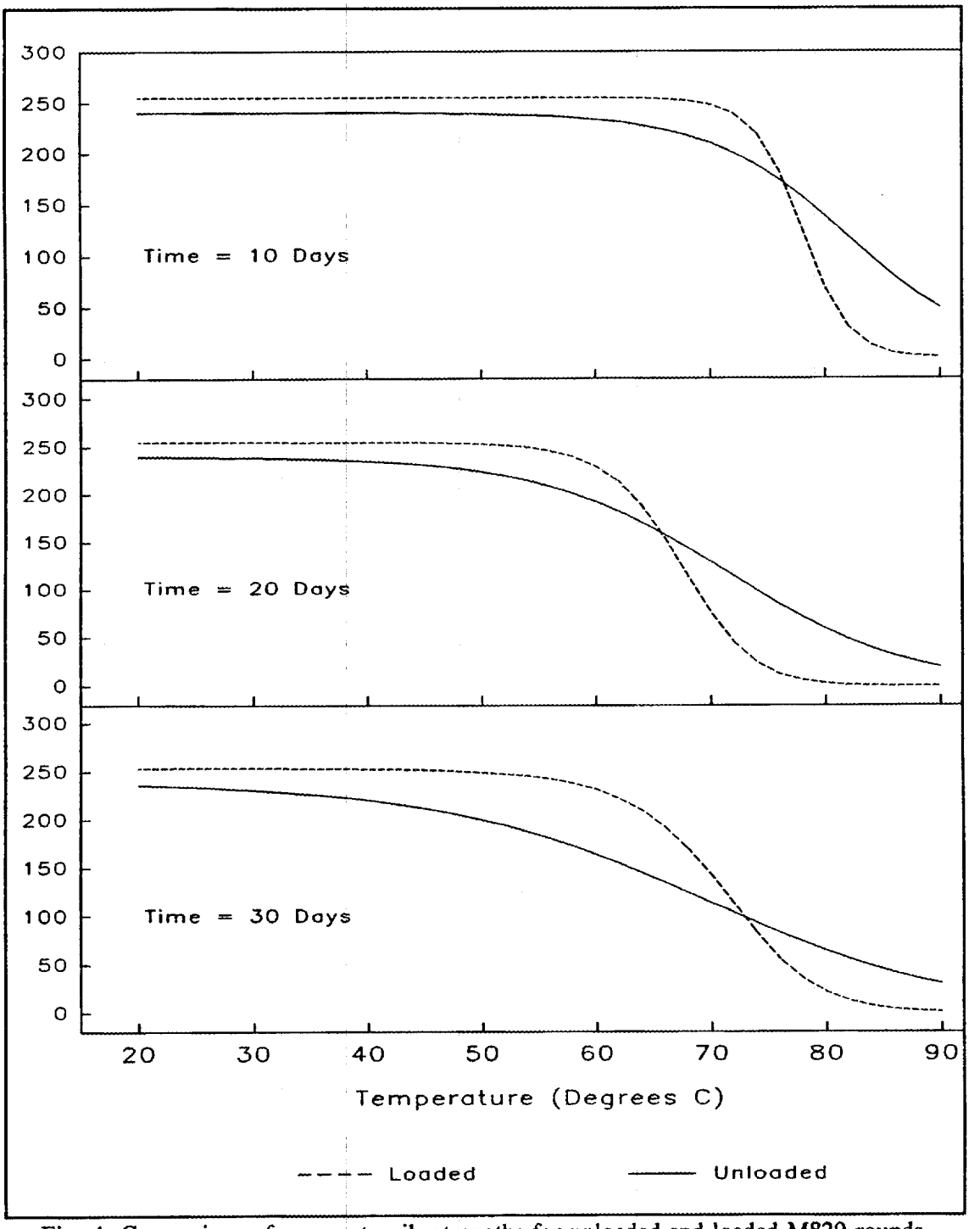

Fig. 4. Comparison of coupon tensile strengths for unloaded and loaded M829 rounds.

2.3 ARDEC Nitroester Migration

The full-up M829 round contains about 17 lbs of JA-2 propellant, which has the following specification:

59.5 ± 2%	Nitrocellulose (13.1 ± 0.1% N)
24.8 ± 1.5%	Diethyleneglycol dinitrate
14.9 ± 1%	Nitroglycerin
0.7 ± 0.2%	Methyldiphenyl urea (Akardite II)
1.03 - 0.05%	Graphite
1.03 - 0.05%	Magnesium oxide
≤0.25%	Graphite glaze

ARDEC's tensile strength data show an effect on skive joint disbonding due to the presence of nitroesters (NG and DEGDN). The internal nitroester factors have a synergistic effect with the external time and temperature factors on the skive joint tensile strengths. Both NG and DEGDN were measured on the coupons from the loaded M829 rounds. These two measurements are highly correlated with a correlation coefficient of r = 0.99. Figure 5 shows a least-squares line fitted to the NG vs DEGDN data that indicates these two nitroesters seem to have similar migration kinetics. Because NG and DEGDN have such a strong linear relationship, only the total nitroester (NG+DEGDN) values were used to develop prediction models.

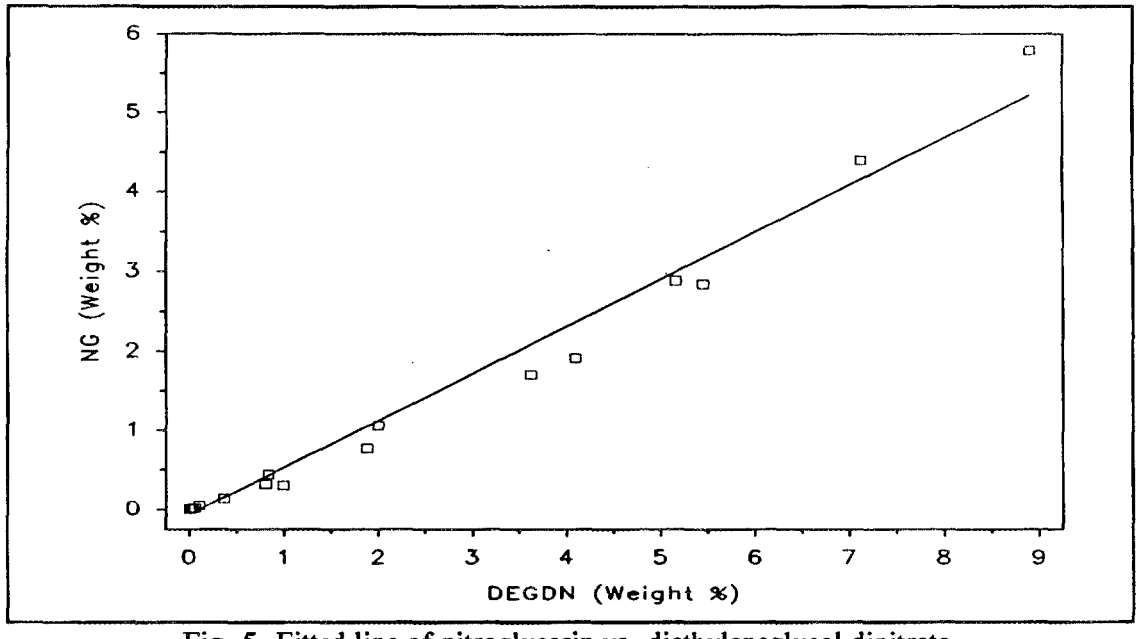

Fig. 5. Fitted line of nitroglycerin vs. diethyleneglycol dinitrate.

Nitroester migration depends on time and temperature and also affects the strength of the skive joint. If the function for nitroester migration is represent by g(t,T), then tensile strength would be a function represented by f[t, T, g(t,T)]. These functional relationships show the difficulty of separating the effects due to time and temperature and those due to nitroester migration. The function g(t,T) for nitroester migration can be approximated by an Arrhenius relationship that accounts for 91% of the variation of the total nitroester measurements on coupons.

$$g(t,T) = Kte^{(-\frac{E_A}{RT})} \quad .$$

where t = time (days), T = temperature (Kelvin = °C + 273.15), R = gas constant (1.9872 cal/°K-mole). The pre-exponential constant with its 95% confidence interval is estimated as $K = 66.976 \times 10^6 \pm 441.284 \times 10^6$. The estimated activation energy of the reaction with its 95% confidence interval is estimated as:

$$E_A = 13.26 \pm 4.65 \ Kcal/mole \quad .$$

The response surface for total nitroesters is given in Fig. 6.

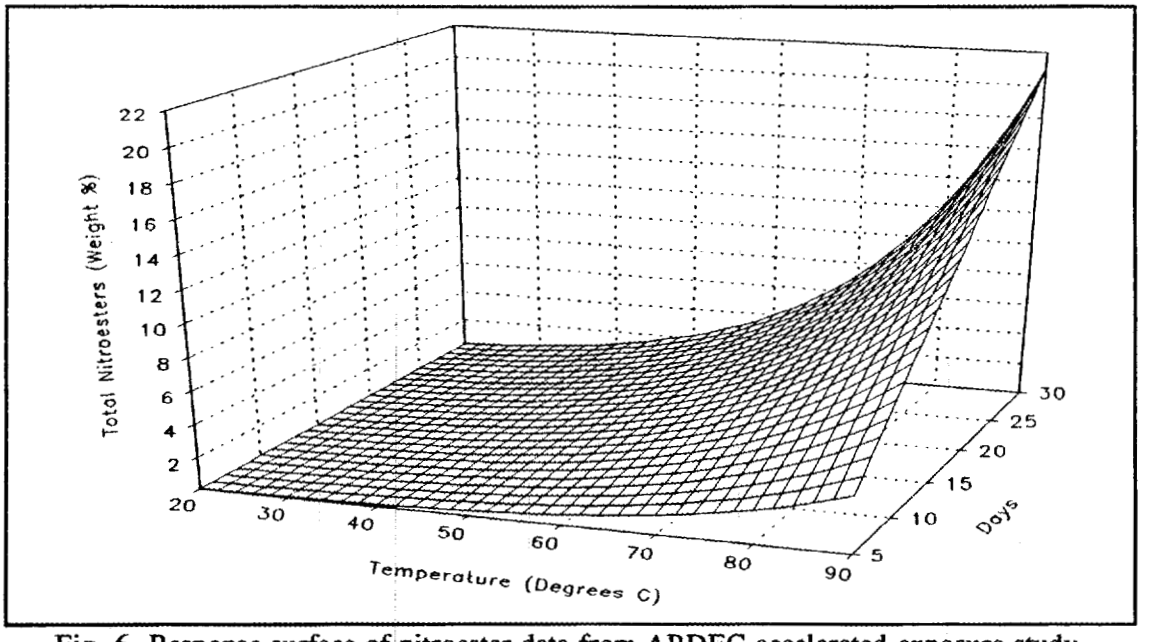

Fig. 6. Response surface of nitroester data from ARDEC accelerated exposure study.

This response surface shows that nitroester concentrations start to increase rapidly at about

50°C. This temperature effect corresponds to the rapid decrease in tensile strength illustrated in Fig. 3. Storage time also increases the nitroester concentration in the coupons and has a greater influence at elevated temperatures. Figure 7 shows the increase in nitroesters vs time for selected temperatures (lines are from the fitted response surface).

Discussions with Dr. George Guiochon (Distinguished Scientist with ORNL/University of Tennessee) indicated that the estimated activation energy of 13.26 Kcal/mole is larger than expected for a simple diffusion process. Rather, this value suggests that a molecular interaction is occurring between the nitroesters and the case wall material. The energy associated with a hydrogen bond is about 5 Kcal/mole. The estimated activation energy of nitroester migration into the case wall is between two and three times this value. It is interesting to note that DEGDN has two nitro groups which could hydrogen bond to hydroxyl groups on cellulose, and NG has three. The estimated activation energy suggests that some interaction of this type is occurring in the migration process. These results call for further studies of nitroester migration.

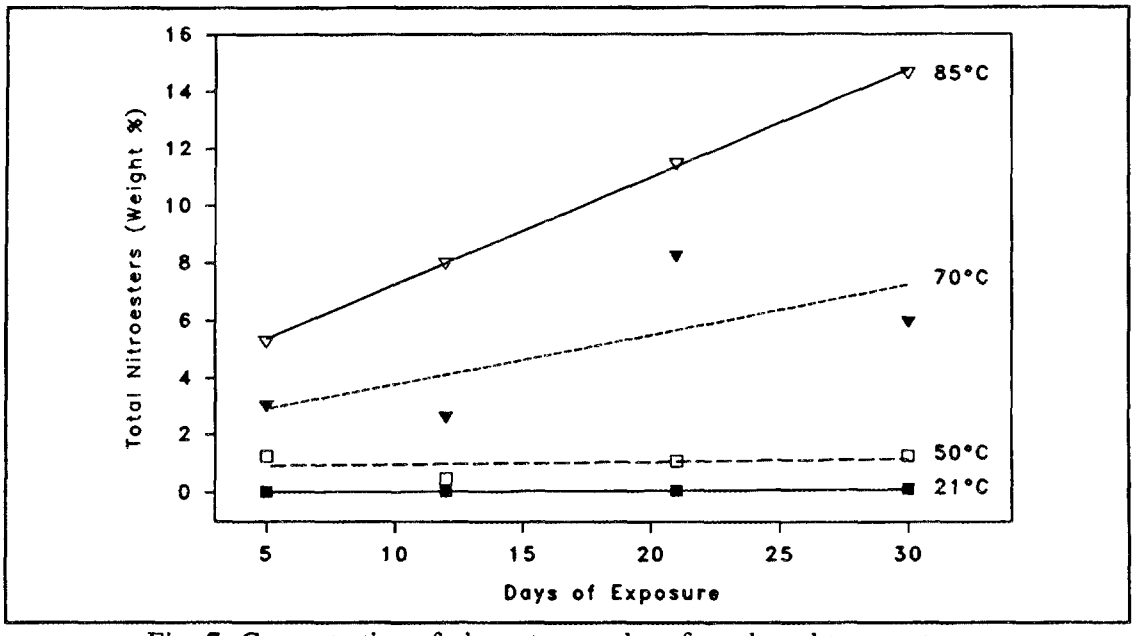

Fig. 7. Concentration of nitroesters vs days for selected temperatures.

3. ORNL ACCELERATED EXPOSURE STUDY

Motivated by coupon results from full-up M829 rounds, ARDEC initiated another accelerated exposure study with Oak Ridge National Laboratory (ORNL). The ORNL accelerated exposure study [*4*] used full-up M829 rounds manufactured in December 1989, to military specifications at the Milan Army Ammunition Plant (MAAP) at Milan, Tennessee.

The statistical analysis of data from the ORNL accelerated exposure study made the following

conclusions: (1) a logistic prediction model can approximate tensile strengths for the full-up M829 rounds but will have a large confidence interval ($0 \leq TS \leq 1051$ lbs) for long storage times, (2) any prediction model will have large confidence intervals because of the large round-to-round variation (St. Dev. = 838 lbs), and (3) disbonding of adhesive skive joints can occur rapidly for critical time, temperature, and relative humidity conditions.

3.1 ORNL Experimental Design

Full-up M829 rounds for this study were manufactured in December 1989, to military specifications on the Milan Army Ammunition Plant (MAAP) M829 production line, using calibration hardware provided by the Iowa Army Ammunition Plant. The sequentially numbered M829 rounds were kept in standard metal protective cases (PA116) and stored in a bunker until use. The accelerated environmental exposures were conducted in temperature and humidity-controlled chambers housed in a remote area of MAAP. After each exposure experiment, the M829 rounds received a battery of tests: a visual inspection of the case wall and coating condition, chambering test on the production line chamber gauge, diameter measurement at the skive joint to test for swelling, measurement of the case wall indentation hardness (D-scale durometer) at several points located around the circumference of the round at the skive joint and midway down the round as well as at intermediate points down the side of the case, and determination of the tensile strength of the skive joint using a Slota apparatus. Indentation hardness measurements around the adapter base were added after the start of the study.

Time, temperature, and relative humidity are three external environmental factors most likely to affect the deterioration of skive joints. Tensile strengths were measured on skive joints for full-up M829 rounds subjected to different combinations of these environmental factors. From these experiments, a mathematical model was developed to predict the tensile strength of the skive joint as a function of the environmental factors. A central-composite experimental design [*5*] was employed to estimate coefficients for second-order effects. Table 3 gives the levels of the three environmental factors in the central composite design. Figure 8 illustrates the three components of the central composite design: eight factorial or cube points $(\pm 1, \pm 1, \pm 1)$; six axial points $[(\pm a,0,0),(0,\pm a,0,),(0,0,\pm a)]$; and four center points (0,0,0).

The exposure ranges selected for this experiment included those temperatures used in previous ARDEC and Honeywell studies [*1-3*]. Also, the temperatures and relative humidities overlapped those measured in the M1A1 Tank hull and bustle ammunition compartments [*9*] in the continental U.S. and European deployment, as well as those reported for shipboard prepositioned storage and Southwest Asia storage areas [*10*]. The highest temperatures actually extended beyond those found in the field to shorten the time required for observation of exposure effects.

Table 3. Levels of the environmental factors for the central composite design.

Factors	Levels				
	-a	-1	0	+1	+a
Time (weeks)	2	6	12	18	22
Temperature (°C)	40	50	60	70	80
Humidity (% relative)	25	40	60	80	95

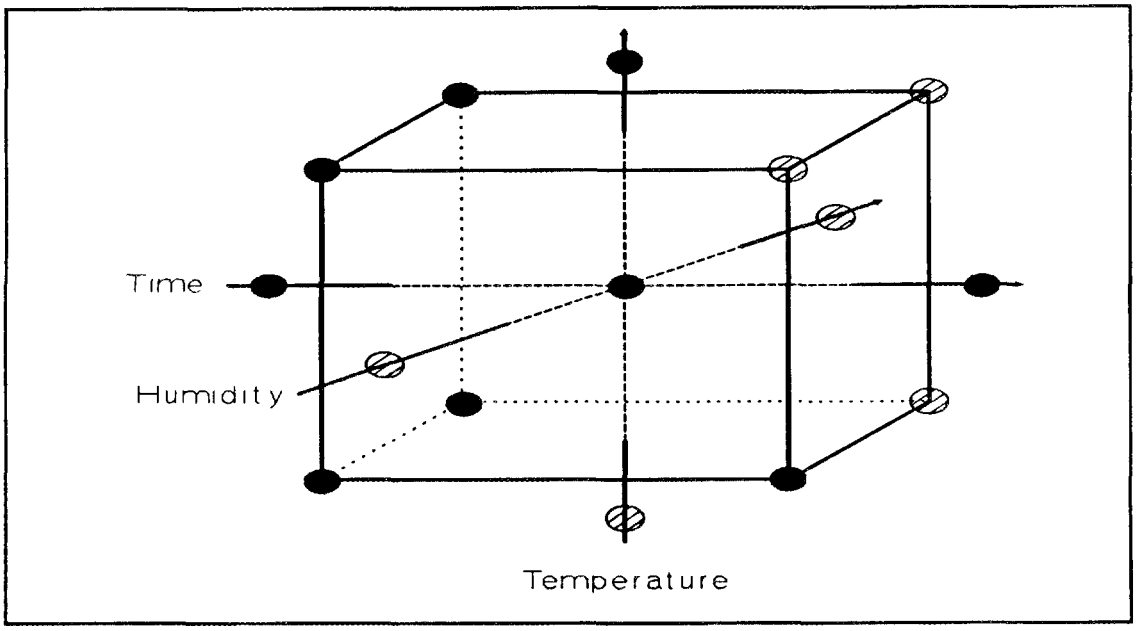

Fig. 8. Central composite design for the ORNL accelerated exposures study of M829 rounds. (Solid circles are completed experiments. Shaded circles are uncompleted experiments.)

Simultaneous with the accelerated environmental exposure experiment, M829 rounds were removed from bunker storage and subjected to the same battery of tests as those in the central composite design. These M829 rounds served as controls. The control M829 rounds also should show effects of storage under conditions similar to parts of Western Europe. At each experimental run in the accelerated environmental exposure experiment, 4 replicate M829 rounds were exposed to prescribed time, temperature, and relative humidity conditions except for four ambient tests of 1, 8, 43 and 49 weeks durations. These 4 ambient tests had 7, 3, 4, and 4 replicates, respectively.

3.2 ORNL Logistic Model

The appearance of the M829 case wall changed considerably during some of the severe exposures. Engineers inspected sections of the combustible case wall taken from just below the skive joint after the tensile strength testing was conducted. For the 85°C exposures, the case wall coating turned a golden brown after 2 weeks of exposure, and to a reddish brown after 3 weeks. The nitrocellulose also turned to an orange-brown color. This discoloration is probably from the accumulation of nitrated diphenylamines derived from the Akardite II stabilizer. Considerable case wall softening accompanied the color changes. The importance of relative humidity to case wall deterioration also is evident from the appearance of specimens that were exposed to 70°C at 40% and 80% RH.

Disbonding was observed at 85 °C as a "clean" adhesive failure. A cohesive mode of failure in the nitrocellulose immediately below the adhesive was observed in all tensile strength tests where a finite strength was determined.

Table A.2 in Appendix A lists tensile strength data from the truncated (i.e., experiment terminated in June 1991) accelerated environmental exposure experiment. These data were used to develop the tensile strength prediction model for the M829 skive joint tensile strength.

Replicate tensile strengths measured on 6 of the 17 experimental design points were zero (i.e., the joints disbonded in the test chamber). From the non-zero values, an estimate of tensile strength variation was obtained by pooling the standard deviations (S_{rep}) of the replicate measurements. This estimated pooled standard deviation had 35 degrees of freedom:

$$S_{rep} = 838 \ lbs.$$

This estimate of tensile strength variation is independent of any mathematical model used to predict tensile strengths. The variation due to replicate measurements also implies an upper bound on the amount of total variation from the average that can be explained by any prediction model.

Figure 9 shows the data plotted as increasing average tensile strength versus the experimental conditions. This plot shows the tensile strength (TS) data is either at a low level (e.g., TS = 0 lbs) or at a high level (e.g., TS $\geq$ 2500 lbs). Only two experimental conditions show average tensile strength between these two values (e.g., 1351 lbs and 1972 lbs). Figure 9 also shows the large variability in skive joint strength that was observed for each of the exposures.

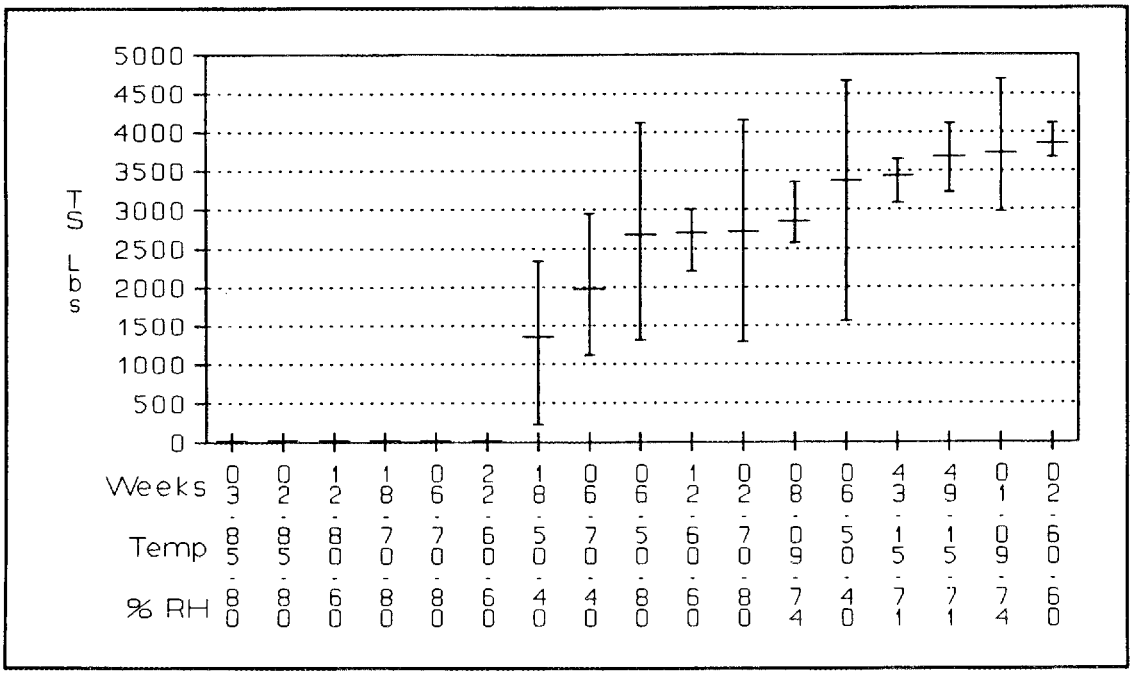

Fig. 9. ORNL tensile strength data ordered by increasing average values.

Several models (including Arrhenius and kinetics models) based on nonlinear growth [*4*] were investigated that would predict positive near-zero values for conditions resulting in skive joint failure (zero tensile strengths). In addition, predicted tensile strength should start at a limiting value at ambient conditions. The form of the logistic model developed for the ORNL data is:

$$TS = \frac{A}{[1 + \exp(B + C_1 t + C_2 T + C_3 H + C_4 T \times H)]} + \epsilon.$$

where TS = tensile strength (lbs), t = time (weeks), T = temperature (°C), and H = relative humidity (%RH). The coefficients (i.e., A, B, C_1, C_2, C_3, and C_4) were estimated from the data in Table A.2 in Appendix A. The ϵ represents the experimental measurement error.

The coefficients in the logistic model were estimated by nonlinear regression using Marquardt's procedure. Four outlier values were identified by the initial fitting of the data. These unusual tensile strength values were more than 2.5 standard deviations from the predicted values (i.e., 1286 lbs, and 4154 lbs in Run 3-1; 1556 lbs in Run 6-2; and 1315 lbs in Run 7-1). We set aside these outlier values to develop the logistic model. The refitted logistic model accounted for 91% of the total variation of measured tensile strengths from the average. In addition, no significant lack of fit could be detected at the 5% significance level when the variance estimated by the logistic model was compared with the variance estimated from replicate measurements. The estimated coefficients with 95% confidence intervals are given in Table 4. An example of the logistic model response surface is given in Figure 10.

Table 4. Coefficients for the logistic model to predict tensile strengths on full-up M829 rounds.

Logistic Variable	Coefficient	Standard Deviation	Lower 95% Confidence Interval	Upper 95% Confidence Interval
A	3566.479	99.362	3367.793	3765.164
B	-42.081	-[a]	-[a]	-[a]
time (weeks)	2.439	0.319	1.802	3.076
Temperature (°C)	0.267	0.051	0.166	0.368
% RH	-1.818	0.370	-2.559	-1.077
T x %RH	0.029	0.006	0.017	0.041

[a]The variance of B could not be estimated from the truncated accelerated environmental exposure experiment.

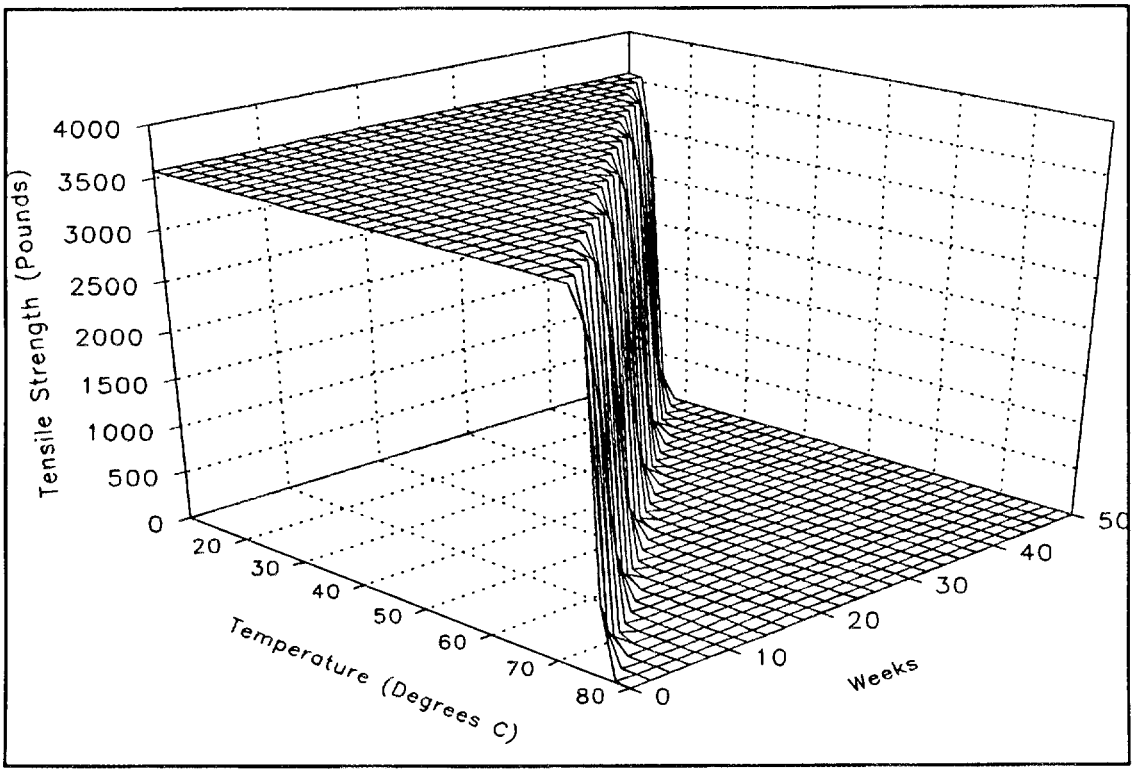

Fig. 10. Response surface at 60% relative humidity of tensile strengths on full-up M829 rounds.

Figures 11, 12, and 13 give prediction values and the two sided 95% confidence intervals for three conditions (21°C, 80% RH), (35°C, 50% RH), and (66°C, 90% RH), which include worst case conditions for Operation Desert Storm. Logistic predictions of lifetime for these cases are all less than 55 weeks. These prediction values seem unusually short in view of anecdotal reports of field experience. The upper 95% confidence interval reached an asymptotic limit of 1051 lbs at the time point the average tensile strength was predicted to be zero. Therefore, the short time predicted for skive joint deterioration and failure is the time beyond which a round could have any tensile strength in the interval $0 \leq TS \leq 1051$ lbs. This wide interval again reflects the large variability in round-to-round strength. It is interesting to note that the upper confidence interval of 1051 pounds is similar to the average strength of 1530 pounds (n=2) determined on unexposed control rounds in the ARDEC HT/SR study. These rounds were from the same lot of ammunition as the ORNL study (see section 4). These rounds were sightly over three years old at the time of the ARDEC HT/SR study.

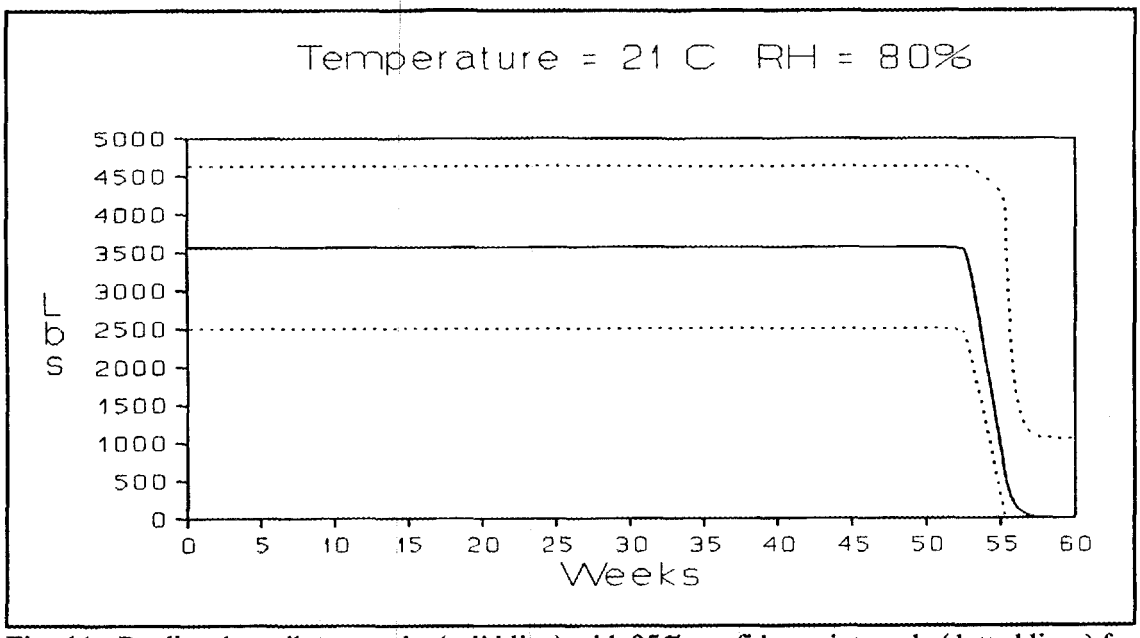

Fig. 11. Predicted tensile strengths (solid line) with 95% confidence intervals (dotted lines) for exposures at 21°C and 80% RH.

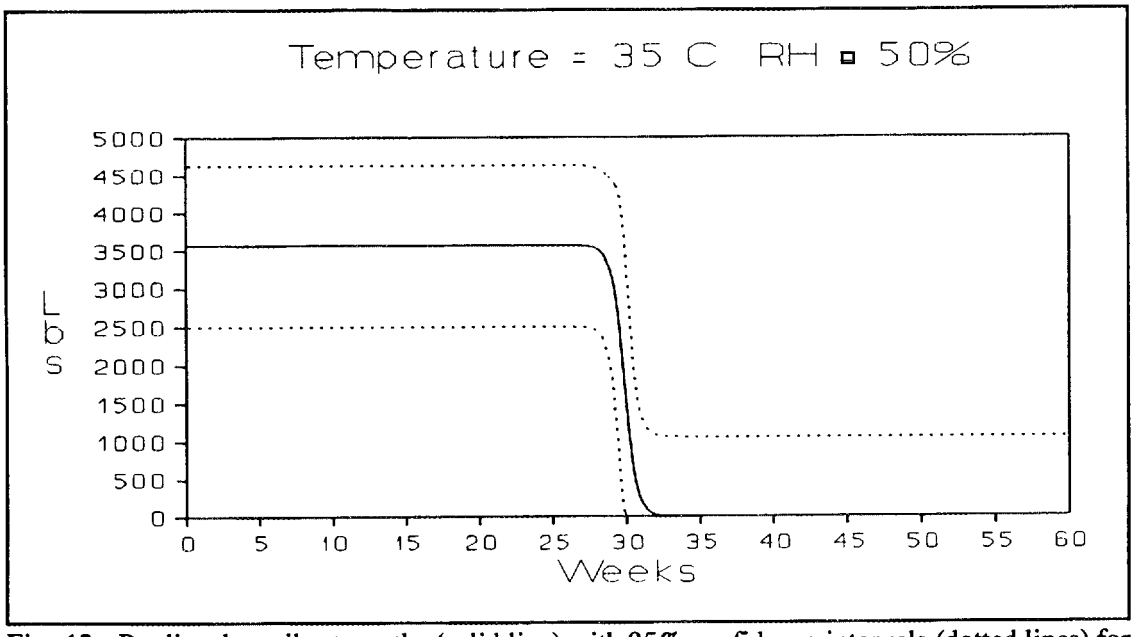

Fig. 12. Predicted tensile strengths (solid line) with 95% confidence intervals (dotted lines) for exposure at 35°C and 50% RH.

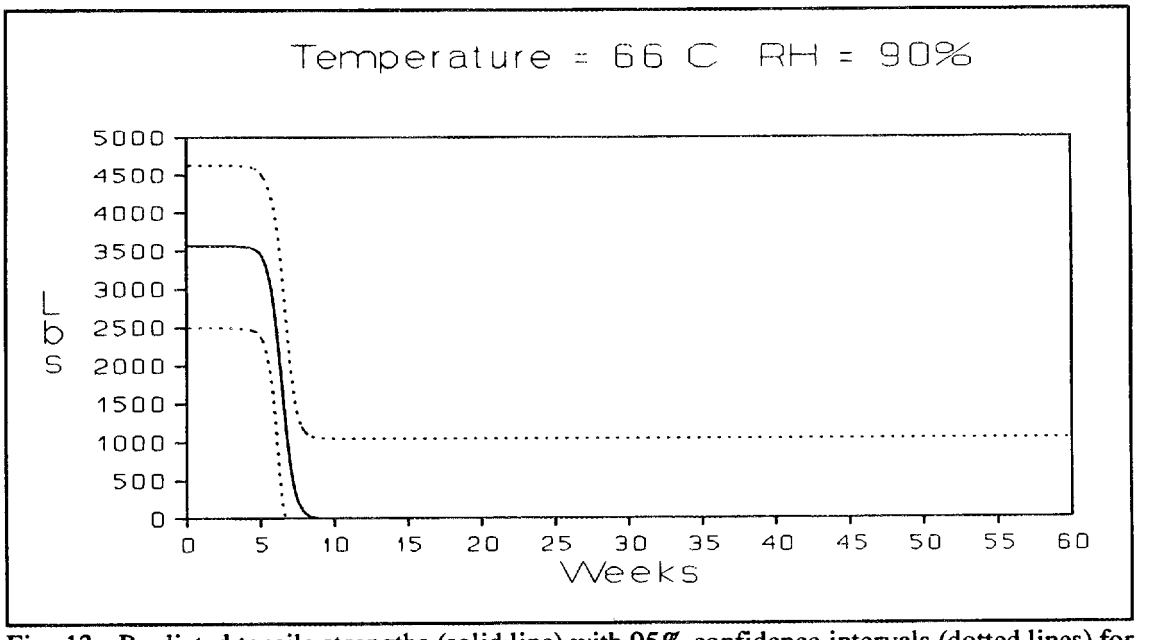

Fig. 13. Predicted tensile strengths (solid line) with 95% confidence intervals (dotted lines) for exposure at 66°C and 90% RH.

3.3 ORNL Nitroester Migration

M829 rounds selected from the ORNL accelerated environmental exposure study to represent a wide range of skive joint strengths were characterized for nitroester content to test for a relationship between nitroester migration and skive joint strength. About 1 g samples of the M829 nitrocellulose case wall immediately below the skive joint were analyzed for DEGDN, NG, and Akardite II (methyldiphenyl urea) by the same procedure as used by Dr. Chen of ARDEC. Briefly, about 1 g samples from selected rounds were ultrasonically extracted in methanol, allowed to soak 48 hrs, were re-sonicated, and then the supernatant was diluted and analyzed using high performance liquid chromatography with ultraviolet absorbance detection. Reanalysis of some extracts after an additional 48 hr soaking and resonication did not reveal significantly more nitroesters, suggesting that extraction was complete.

Samples from two M829 rounds were analyzed to establish the uniformity of the nitroester and stabilizer distribution around the circumference of the case wall. Four case wall specimens from each M829 round were taken 90° apart around the nitrocellulose side of the rim of the skive joint and analyzed. The results are listed in Table A.3 in Appendix A. The estimated precisions suggest that all three constituents varied only from 4%-9% relative standard deviation (RSD) around the M829 skive joint circumference, and that only a single specimen needs to be analyzed. There was a concern that the horizontal position of the rounds during the accelerated environmental exposures would lead to a clumping of the propellant more toward the bottom side of the round, and would result in an uneven nitroester migration.

Case wall samples from selected M829 rounds were then subjected to the analytical method, and the results are presented in Table A.4 in Appendix A. The data showed a high correlation ($r = 0.99$) between the NG and DEGDN measurements which is a similar result for the ARDEC accelerated exposure study. This high correlation again indicates that total nitroester concentration (NG + DEGDN) can be used for prediction. A prediction model for nitroester migration is limited because only selected M829 rounds were analyzed for nitroesters. Figure 14 shows the location in a temperature vs time plot of nitroesters weight percents for the six time/temperature combinations tested. This plot shows it would be difficult to separate the effects due to temperature and to time because most nitroester measurements lie on a diagonal line.

As in previous work [*1-3*], there is a rough relationship between nitroester concentration and skive joint strength. A least squares linear regression of the tensile strength versus nitroester data yielded a correlation coefficient of -0.76. The nitroester concentration corresponding to 0 lbs tensile strength was 15.3% (weight percent), which is considerably higher than the 6.0% suggested in previous work [2]. The differences between the two studies may reflect the different lots of ammunition, round-to-round variability, and the basic differences in how the exposures were conducted in the two studies. Also, the nitroester measurements were conducted on specimens taken from different parts of the case wall.

Clearly, the studies conducted both by ARDEC and ORNL indicate that the higher the nitroester concentration the weaker the skive joint will become. Somewhere in the low weight percent

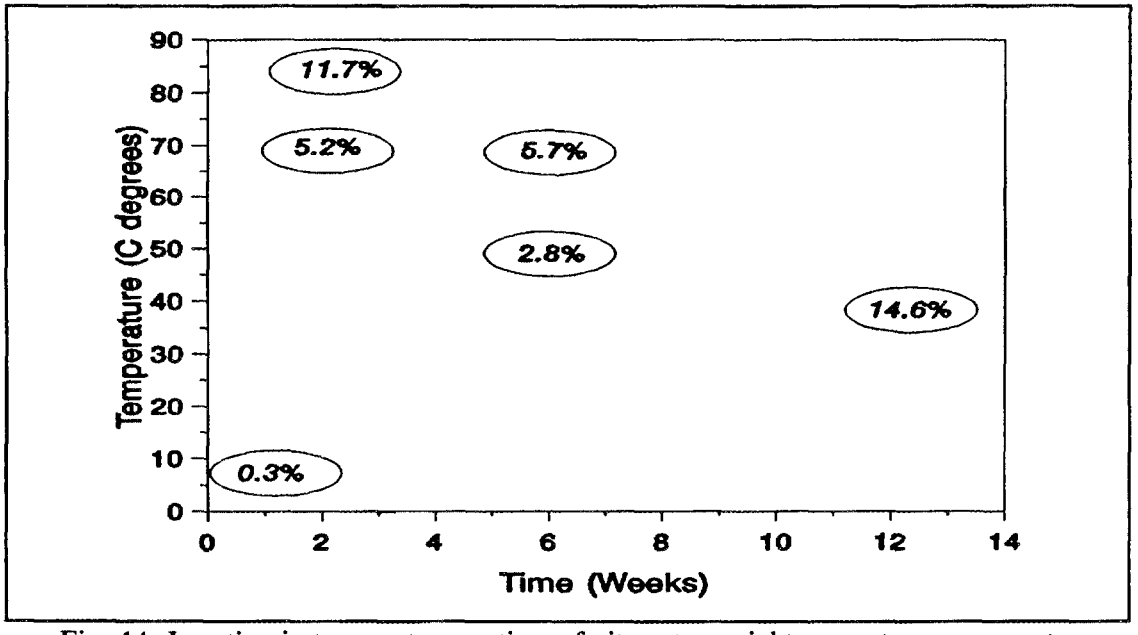

Fig. 14. Location in temperature vs time of nitroester weight percent measurements.

concentrations, the joint will disbond. This suggests that a means of visually indicating the nitroester content of the case wall at the skive joint could allow in-field surveillance of M829 rounds (and other munitions with such adhesive joints) and identification of those liable to failure. Accordingly, a study was made of chemical systems for a color change strip which could visually indicate the presence of nitroesters in the M829 case wall. The results of that study are reported elsewhere [*11*].

3.4 Comparison of ORNL and ARDEC Accelerated Exposure Studies

Accelerated exposure studies conducted by ORNL and ARDEC have several differences but arrive at similar conclusions about the disbonding of the M829 skive joint. The 1986 ARDEC accelerated exposure study measured tensile strengths on coupons from full-up M829 rounds while the ORNL accelerated exposure study measured tensile strengths directly on full-up M829 rounds. ARDEC did not control relative humidity while ORNL included this external factor in their experimental plan. The two accelerated exposure studies also used different ranges for their time and temperature factors. Figure 15 illustrates the time and temperature conditions for each experiment.

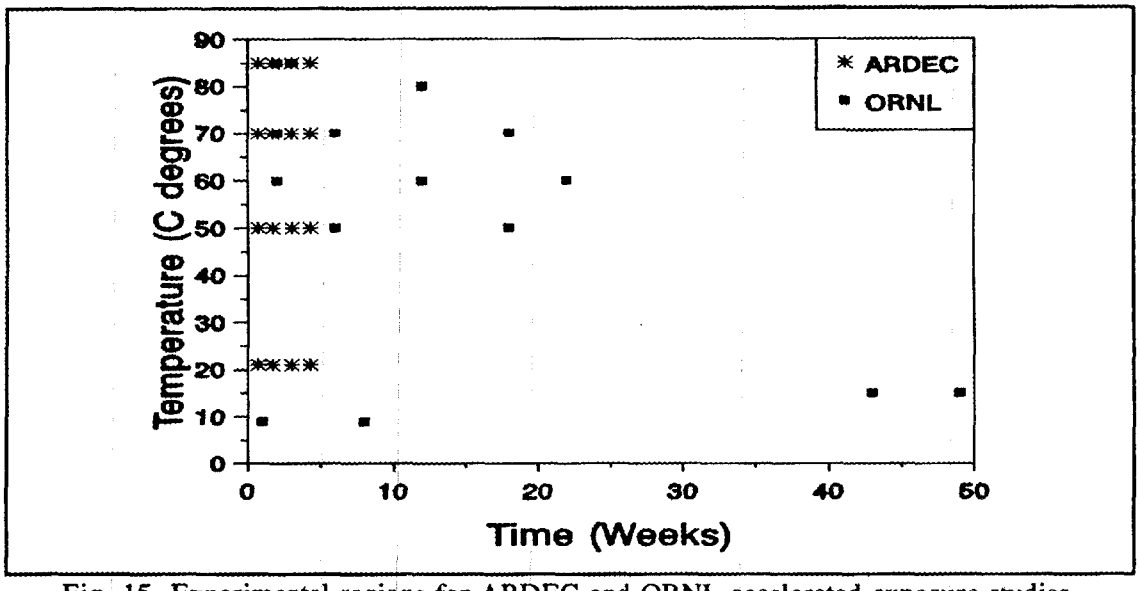

Fig. 15. Experimental regions for ARDEC and ORNL accelerated exposure studies.

In spite of the differences between the two accelerated exposure studies, we can conclude that:

1. The tensile strength data supports a logistic prediction model as a good approximating model using the external factors of time, temperature, and relative humidity . This logistic prediction model represents an autocatalytic failure mechanics that is quite different from mechanics assumed by an Arrhenius approximating model.

2. The logistic model indicates that skive joint disbonding at high temperatures are activated by failure modes due to more complicated chemical reactions than those described by the Arrhenius model.

3. Large round-to-round variation for the tensile strength of the skive joint causes large confidence intervals of predicted tensile strength.

4. Nitroester migration has a synergistic effect with the external time and temperature

factors on the skive joint strength. Nitroester migration into the skive joint accelerates the disbonding process.

4. ARDEC HT/SR STUDY

An experiment to study skive joint life under simulated Southwest Asia ("worst case") conditions was conducted by the Combat Systems Test Activity at the Aberdeen Proving Ground. Experimental data [*12*] from this study were provided by ARDEC.

4.1 ARDEC HT/SR Experimental Design

The twenty seven full-up M829 rounds for this study were from the same lot of rounds used in the ORNL accelerated exposure study discussed in Section 3. Twenty four of the rounds were exposed at Aberdeen Proving Ground to a "worst case" Southwest Asia diurnal cycle and the remaining eight rounds served as controls. The cycle was designed by Predictive Technology staff from Southwest Asia regional temperature data compiled by the U.S. Air Force and Army. The rounds were exposed in their protective metal cases to a controlled temperature and solar radiation cycle. Humidity was introduced once a day (0400 hours) until the chamber achieved 23% RH and then was allowed to dissipate naturally throughout the daily cycle. The temperature of each round was monitored by thermocouples placed in the fourteen different locations shown in Fig. 16. Figure 17 presents a representative temperature exposure cycle for one 24 hour period. Three of the 24 rounds were removed after 30 days of conditioning, eight were removed after 60 days, and the remaining eight were removed after 90 days.

After conditioning, 10 of the exposed rounds and five of the control rounds were subjected to ballistic testing. The remaining 12 rounds were subjected to full-up tensile testing. Rounds that received 30 days of conditioning were tested at Aberdeen and the remaining rounds were transported to MAAP for testing. Tensile strengths were measured on the full-up rounds. After tensile testing, two coupons were cut from the combustible case wall and two from the adapter wall. Each of the four coupons was analyzed for nitroesters at ORNL. Sample locations for the nitroester measurements are shown in Fig. 18.

4.2 Results of ARDEC HT/SR Study

Table A.5 in Appendix A summarizes the data from the ARDEC HT/SR study. The nitroester data were used to develop a nitroester migration prediction model. The tensile strength data was compared to the ORNL full-up study data.

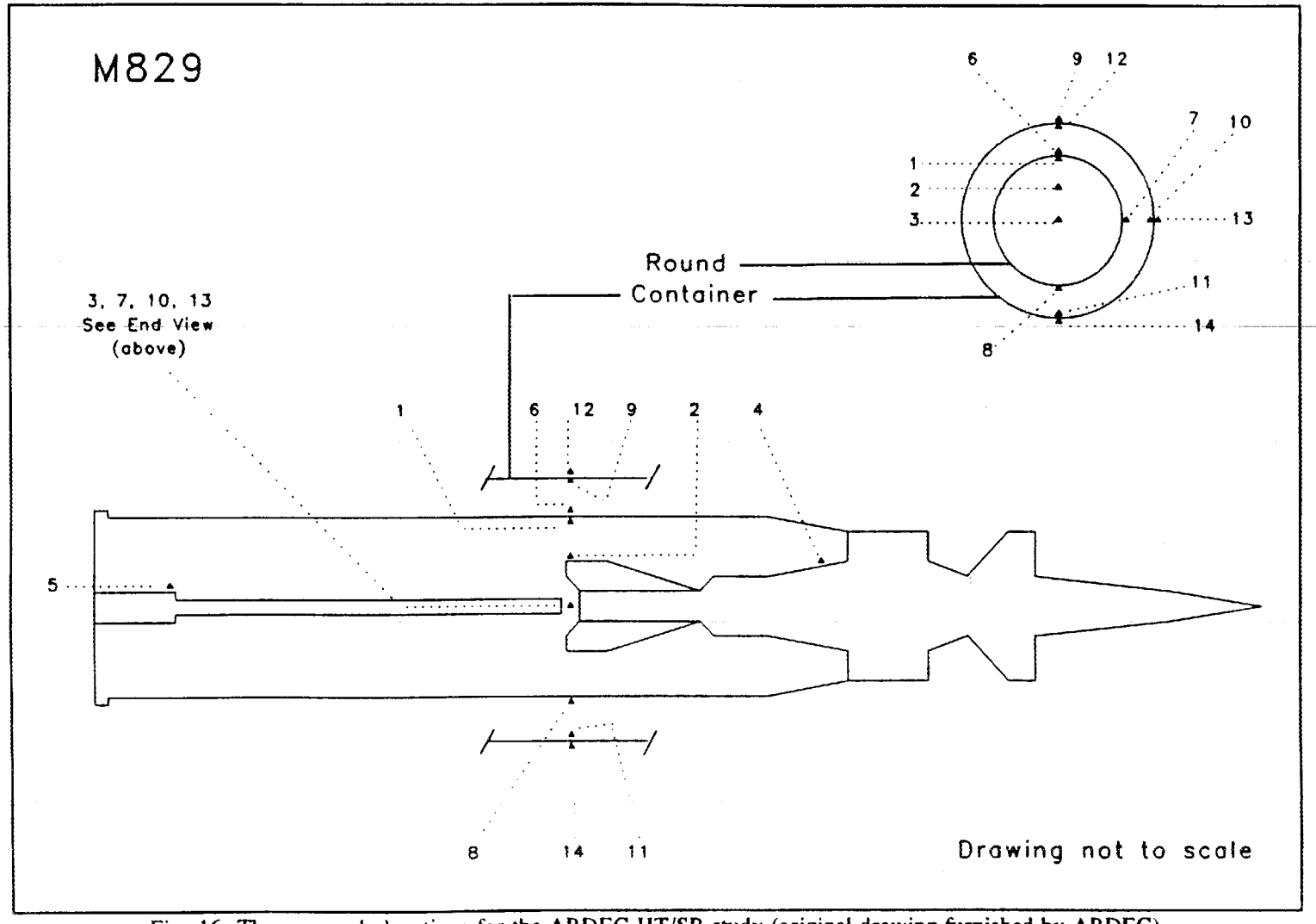

Fig. 16. Thermocouple locations for the ARDEC HT/SR study (original drawing furnished by ARDEC).

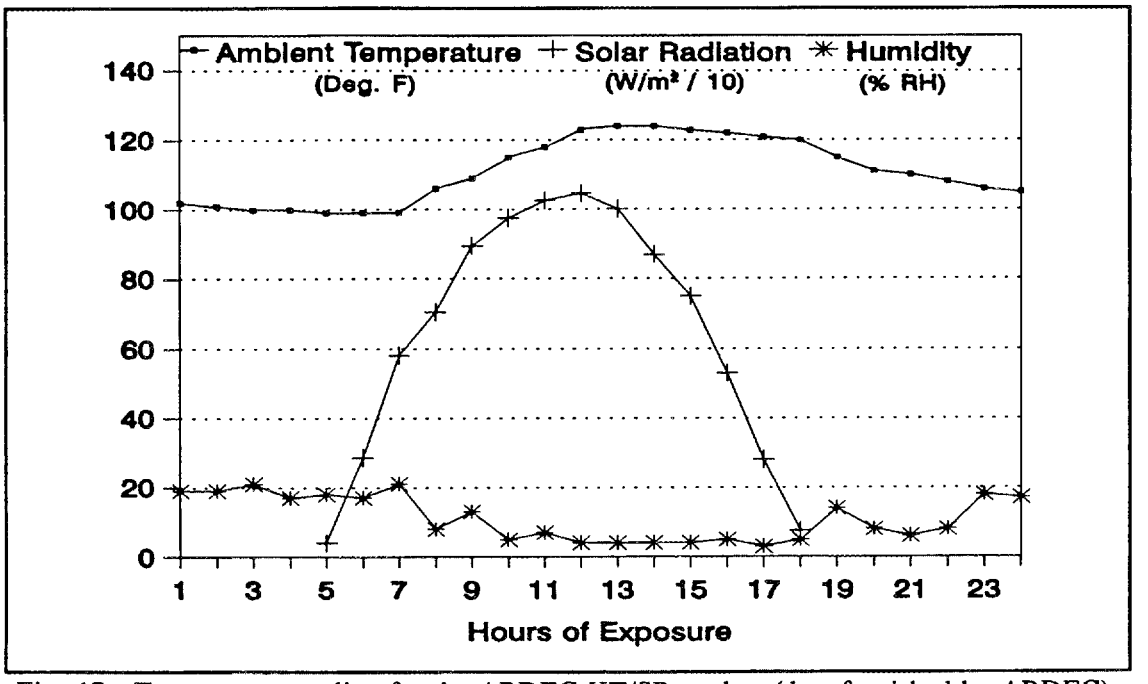

Fig. 17. Temperature cycling for the ARDEC HT/SR study. (data furnished by ARDEC).

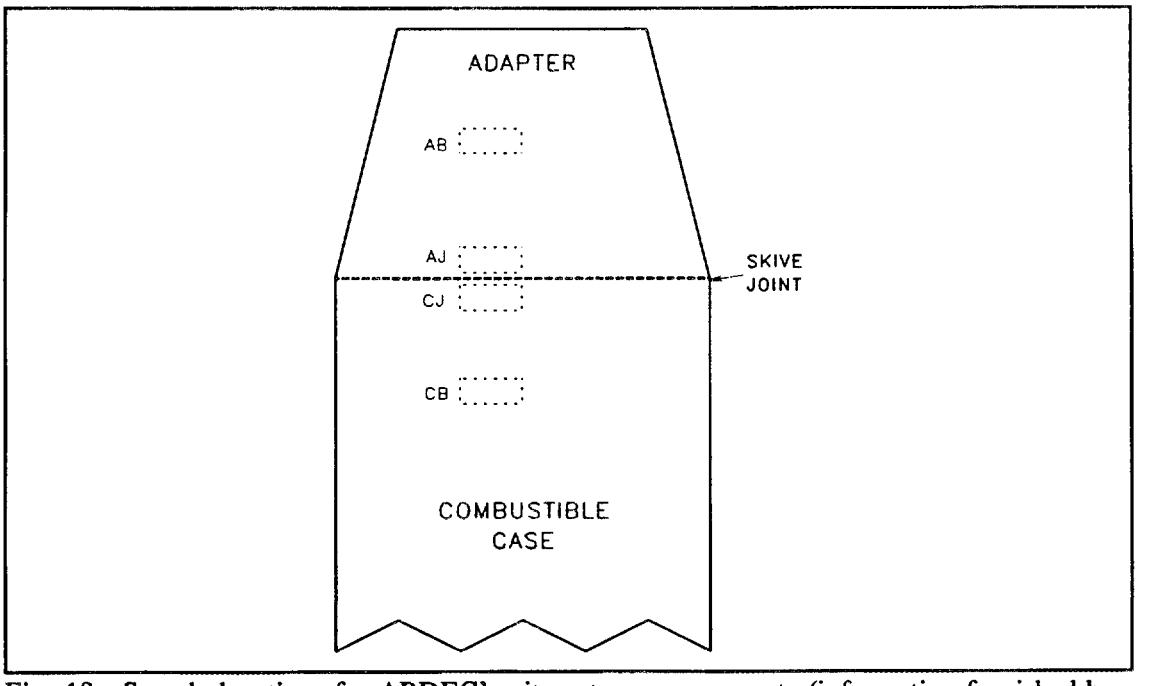

Fig. 18. Sample locations for ARDEC's nitroester measurements (information furnished by ARDEC).

4.3 ARDEC HT/SR Nitroester Migration

Both the ARDEC and the ORNL accelerated exposure data demonstrated a strong correlation between the two nitroester components (see Sections 2 and 3). The correlation between NG and DEGDN measurements from the ARDEC HT/SR study was also investigated. Figure 19 shows the NG concentration versus DEGDN concentration for the HT/SR data. The correlation coefficient for this linear relationship is r = 0.95. Again, this strong linear relationship between the two nitroester components demonstrates that either NG, DEGDN, or total nitroesters would serve equally well as a predictor of joint strength.

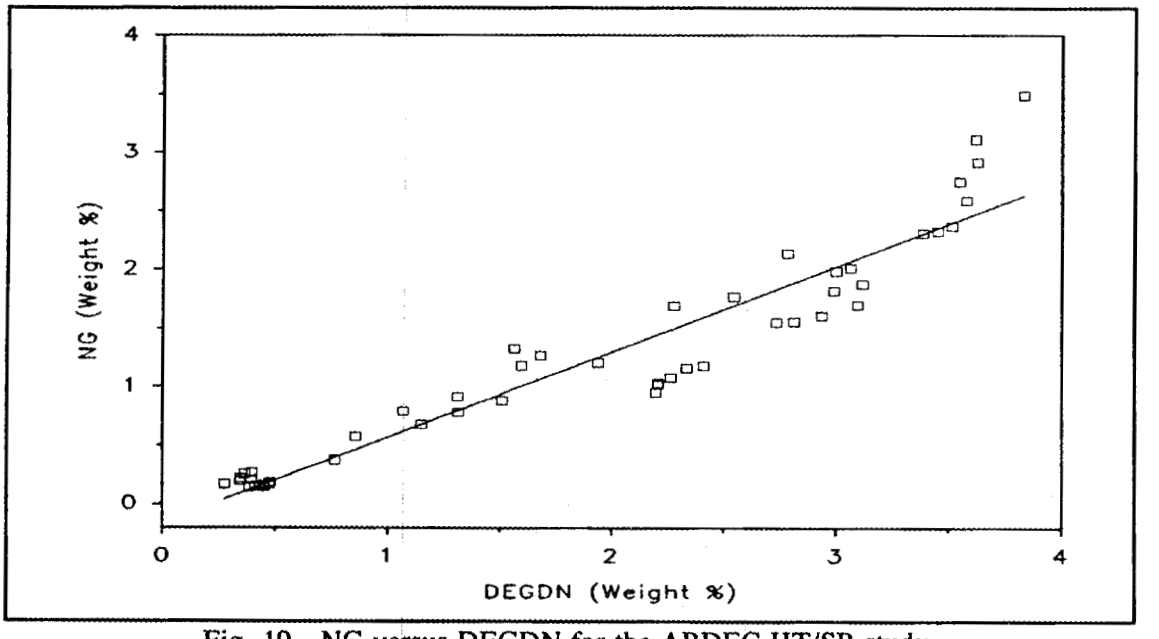

Fig. 19. NG versus DEGDN for the ARDEC HT/SR study.

Figure 20 shows a plot of average total nitroesters versus days of exposure by sample location (i.e. AB, AJ, CJ, CB). All locations showed a significant increase in nitroesters over time. The plot shows that the combustible case samples contained a higher nitroester concentration than the adapter samples. The highest concentration was in the samples taken from the combustible case closest to the skive joint. This seems reasonable because the adapter is at the top of the propellant bag and consequently does not have as large a surface area or as direct a contact with the propellant and nitroester diffusion would be hindered. The similarity of results for the two positions along the length of the case plus the observation of uniformity in results for samples taken around the circumference of the round (see section 3.3) suggest that nitroester migration from the propellant into the case wall is reasonably uniform within a given round.

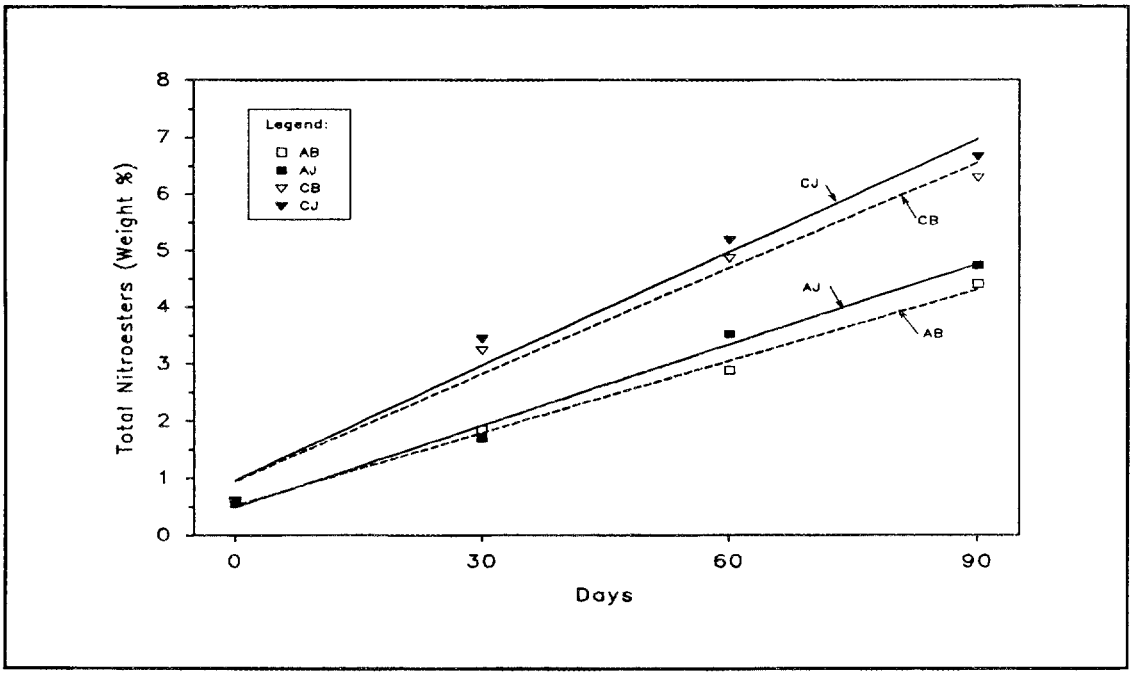

Fig. 20.Total nitroesters versus days of exposure for the ARDEC HT/SR study (sample locations are indicated by AB, AJ, CB, and CJ).

4.4 Comparison of ARDEC HT/SR and ORNL Studies

A predictive model for tensile strength versus nitroester concentration was obtained for the high temperature data and compared to the ORNL full-up data. Figure 21 shows both sets of data along with the best-fit regression lines.

The least-squares lines with standard deviations of the coefficients in parentheses is given by:

ARDEC HT/SR Study:

$$\textit{Tensile Strength} = \underset{(671.5)}{2072.2} - \underset{(148.6)}{303.5}\ \textit{Total Nitroesters}$$

ORNL Study:

$$\textit{Tensile Strength} = \underset{(393.3)}{3794.9} - \underset{(36.3)}{252.5}\ \textit{Total Nitroesters}$$

Although there is a significant difference (5% significance level) between the intercepts, there is no significant difference between the slopes. The similar slopes suggest the same mechanism

for adhesive joint deterioration by nitroesters for the two studies (i.e., softening of joint adhesive from nitroester diffusion through a hydrogen-bonding case wall matrix). The difference between the two intercepts along with the 95% confidence limits on the difference is 1723 ± 313. The implication is that the average tensile strength decreased by approximately 1700 pounds during the time between the ORNL full-up study and the ARDEC HT/SR study.

The "Total Nitroesters" variable in the ORNL tensile strength model was replaced with the predicted values from the Arrhenius nitroester migration model for ARDEC coupons developed in Sect. 2.3. The relative error [100%*|Avg. TS - Predicted|/Avg. TS] ranged from 2% to 37% for environmental conditions where disbonding didn't occur. These predictions suggest that similar migration mechanisms were operating in both the ARDEC and ORNL accelerated exposure studies.

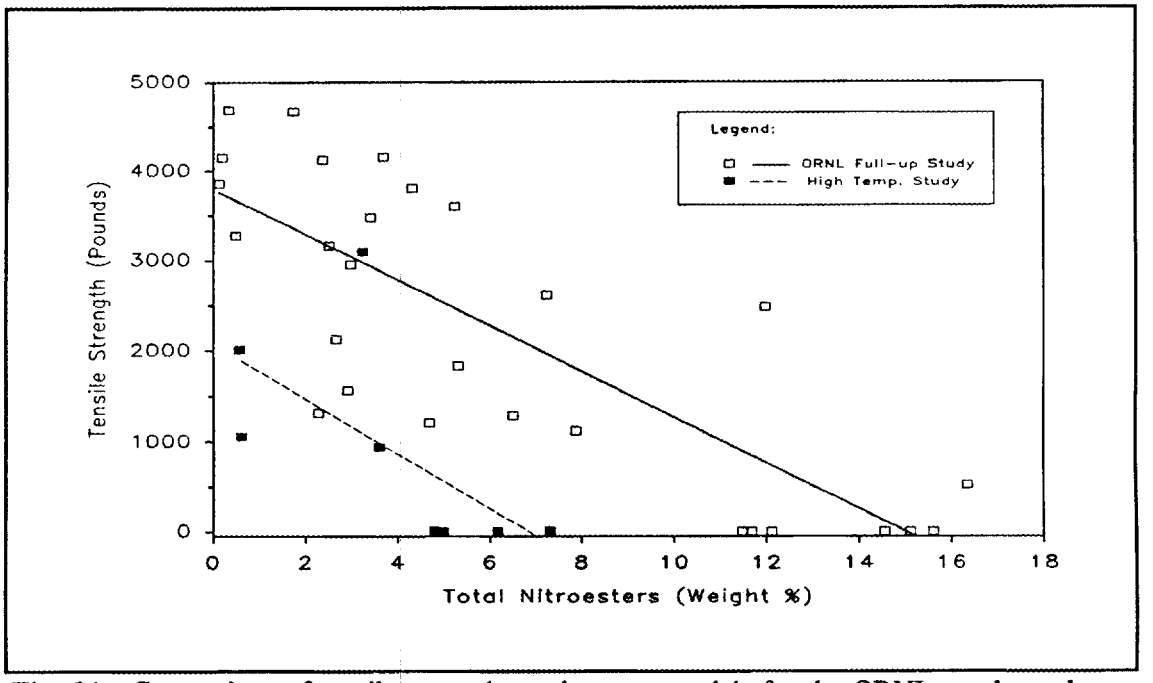

Fig. 21. Comparison of tensile strength vs nitroester models for the ORNL accelerated exposure study and the ARDEC HT/SR study.

5. CONCLUSIONS AND RECOMMENDATIONS

The statistical analysis of tensile strength data from the accelerated environmental exposure of full-up M829 rounds leads to the following conclusions:

1. Prediction models for tensile strength data based on accelerated testing conditions will have large confidence intervals on predicted values because of the large round-to-round variation (S_{rep} = 838 lbs). This result is independent of the model used for prediction.

2. The logistic prediction model is a good approximation of the observed data from the accelerated environmental exposure study. The shorter failure times than observed in field conditions indicates the time beyond which there is large uncertainty $0 \leq TS \leq 1051$ lbs.

3. The accelerated environmental exposure study suggests that disbonding of adhesive joints can occur rapidly if the right conditions for time, temperature, and relative humidity are reached. These results suggest the kinetics of adhesive joint behavior are not well understood. First-order, second-order, Arrhenius kinetic, etc. models may not provide improved tensile strength prediction until more information on the chemical properties of the adhesive joint bonding and the adhesive is known.

4. The increase in tensile strength variation from adaptor/case assemblies to full-up M829 rounds may indicate that the additional fabrications steps required for full-up M829 rounds introduce a significant amount of variability into the final skive joint strength.

5. A greater than expected estimated activation energy suggests that a molecular interaction and not a simple diffusion process is occurring between the nitroesters and the case wall material. These results call for further studies of nitroester migration.

6. The strong linear relationship between the two nitroester components NG and DEGDN, demonstrates that either NG, DEGDN or total nitroesters would serve equally well as a predictor of joint strength.

7. Because nitroester migration depends on time and temperature and also affects tensile strength, the effects of time and temperature on joint deterioration cannot be separated from the effect of nitroesters.

8. Nitroester migration appears to involve diffusion with a significant interaction with the case wall material (such as hydrogen bonding).

The results of this study suggest that future work should focus on achieving a better understanding of the properties of the joint adhesive and on improving the engineering and production of the skive joint. It is also recommended that existing M829 storage lifetime data based on actual field experience be made available so that the accuracy of the predictive model can be better determined.

Time-to-failure lifetime studies appear to be the main alternative to response surface modelling. This approach to predictive modelling of the M829 may meet with the same round-to-round variability as observed in this study, with the variability being exhibited as a wide distribution of the times required for failure (skive joint disbonding). It is suggested that if such a study is attempted, that the rounds be apportioned among the exposures according to the severity of the temperature or relative humidity stress [*13*]. A greater number of rounds should be used in the less severe exposures where times to failure are likely to be long and differences among rounds magnified.

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APPENDIX A

Experimental Data from Accelerated Exposure Studies

Table A.1. Experimental data from the ARDEC accelerated exposure study.

Temp. (Deg. C)	Days	Loaded Cases						Unloaded Cases		
		Nitroester Conc. (Wt. %)			Replicate Tensile Strengths (lbs/in)	Average	Standard Deviation	Replicate Tensile Strengths (lbs/in)	Average	Standard Deviation
		DEGDN	NG	Total						
85	5	3.62	1.70	5.32	152, 100, 133, 142	131.8	22.54	182,134,186,142	161.0	26.81
85	12	5.16	2.88	8.04	0, 0, 0, 0	0.0	0.00	87,49,66,88	72.5	18.66
85	21	7.12	4.39	11.51	0, 0, 0, 0	0.0	0.00	33,9,7,11	15.0	12.11
85	30	8.90	5.79	14.69	0, 0, 0, 0	0.0	0.00	27,34,38,42	35.2	6.40
70	5	2.00	1.05	3.05	174, 177, 189, 203	185.8	13.20	235,231,226,228	230.0	3.92
70	12	1.88	0.76	2.64	205, 261, 223, 235	231.0	23.49	190,192,165,178	181.3	12.47
70	21	5.45	2.84	8.29	49, 86, 85, 54	68.5	19.74	127,150,139,142	139.5	9.54
70	30	4.10	1.91	6.01	180, 141, 130, 122	143.3	25.71	93,160,116,138	126.7	28.79
50	5	0.83	0.43	1.26	343, 236, 300, 246	281.3	49.85	186,233,242,222	220.8	24.57
50	12	0.36	0.13	0.49	288, 276, 300, 308	293.0	14.00	234,262,314,251	265.3	34.48
50	21	0.80	0.31	1.11	242, 270, 238, 266	254.0	16.33	207,211,203,216	209.3	5.56
50	30	0.99	0.30	1.29	257, 202, 238, 267	241.0	28.65	177,191,187,159	178.5	14.27
21	5	0.02	0.00	0.02	246, 244, 210, 239	234.8	16.76	263,201,194,249	226.8	34.37
21	12	0.03	0.01	0.04	293, 290, 266, 270	279.8	13.72	258,233,236,240	241.8	11.21
21	21	0.05	0.01	0.06	252, 260, 243, 262	254.3	8.66	215,273,242,240	242.5	23.76
21	30	0.10	0.04	0.14	281, 255, 272, 226,	258.5	24.20	268,242,274,281	266.3	17.02

Table A.2. Tensile strength data from the ORNL accelerated environmental exposure study.

Run[a]	Weeks	Temperature (°C)	Relative Humidity (% RH)	Tensile Strength (lbs)	Average (lbs)	Standard Deviation (lbs)	Design Type
1-3	1	9	74	2972,3082,3269,3851, 4110,4146,4683	3730	639	Ambient
2-2	2	60	60	3675,3775,3851,4115	3854	188	Axial
3-1	2	70	80	1286,1828,3601,4154	2717	1377	Test
4-2	2	85	80	0,0,0,0	0	0	Test
5-2	3	85	80	0,0,0,0	0	0	Test
6-2	6	50	40	1556,3473,3802,4665	3374	1312	Cube
7-1	6	50	80	1315,2118,3156,4123	2678	1223	Cube
8-1	6	70	40	1120,1207,2612,2947	1972	944	Cube
9-2	6	70	80	0,0,0,0	0	0	Cube
10-3	8	9	74	2574,2624,3352	2850	436	Ambient
11-2	12	60	60	2199,2767,2837,3001	2701	349	Center
12-2	12	80	60	0,0,0,0	0	0	Axial
13-1	18	50	40	227,944,1895,2336	1351	948	Cube
14[b]	18	70	80	0,0,0,0	0	0	Cube
15-2	22	60	60	0,0,0,0	0	0	Axial
16-3	43	15	71	3082,3435,3563,3646	3432	249	Ambient
17-3	49	15	71	3226,3604,3779,4112	3680	369	Ambient

[a] Second number denotes test chamber (i.e., chamber 1, chamber 2, and storage bunker 3).
[b] Results based on tensile strength values of run 9-2.

Table A.3. Uniformity of nitroester and stabilizer distribution in nitrocellulose wall at the skive joint from selected M829 rounds in the ORNL accelerated exposure study.

Round No.	Replicate	Concentration in Case Wall, mg/g		
		Akardite II	DEGDN	NG
108	1	2.72	90.2	60.9
	2	2.59	91.4	63.5
	3	2.57	87.9	59.4
	4	2.45	78.2	54.1
	Avg. ± Std. Dev. (%RSD)	2.58 ± 0.11 (4.3%)	86.9 ± 6.0 (6.9%)	59.5 ± 4.0 (6.7%)
54	1	3.75	97.0	66.4
	2	3.89	102.0	72.4
	3	3.41	94.2	64.4
	4	3.20	86.4	59.6
	Avg. ± Std. Dev. (%RSD)	3.56 ± 0.32 (8.8%)	94.9 ± 6.5 (6.9%)	65.7 ± 5.3 (8.1%)

Table A.4. **Results for nitroester and Akardite II measurements in M829 nitrocellulose case wall at the skive joint for the ORNL accelerated environmental exposures.**

Test	Round No.	Temperature °C	Relative Humidity	Time Weeks	Concentration in Case Wall, mg/g			Tensile Strength lbs
					Akardite II	DEGDN	NG	
Control	100	9	74	1	8.16	1.81	1.49	4,683
	129				6.54	1.97	ND	3,851
	153				27.5	0.66	0.54	3,269
	63				9.44	2.47	2.26	1,259[a]
	78				21.0	2.45	2.35	4,145
2-1	5	85	80	2	13.4	55.6	60.6	0
	47				2.78	68.3	46.6	0
	65				1.72	73.0	48.2	0
	162				1.66	69.3	47.3	0
1-3	108	40	60	12	2.58	86.9	59.5	0
	148				2.69	91.9	64.2	0
	54				3.56	94.9	65.7	517
	105				3.60	73.7	46.1	2,480
1-2	151	70	40	6	<0.01	19.3	10.5	2,947
	30				1.13	28.8	18.1	1,207
	138				5.79	51.6	27.2	1,120
	37				11.9	48.2	24.2	2,612
1-1	4	50	80	6	3.33	16.2	7.50	4,123
	160				25.0	18.0	8.55	2,118
	161				6.05	16.0	6.75	1,315
	68				4.96	16.2	8.89	3,156
1-5	118	70	80	2	6.35	41.7	23.3	1,286
	39				5.84	34.0	19.0	1,828
	52				2.71	33.2	19.3	3,601
	114				4.70	28.0	8.89	4,154
2-8	67	50	40	6	7.54	24.9	9.22	3,473
	156				16.8	27.6	15.6	3,802
	16				0.01	19.9	9.16	1,556
	115				0.28	13.5	3.92	4,665

[a]Skive joint and case damaged in Slota apparatus fixture. Tensile strength is artificially low.

Table A.5. Nitroester and tensile strength data from the ARDEC HT/SR study.

Days	Sample Location[a]	Round	Concentration in Case Wall (Weight %)				Tensile Strength (Pounds)
			Akardite II	DEGDN	NG	Total Nitroesters	
0 (Control)	AB	1	0.006	0.275	0.169	0.444	
		2	0.005	0.365	0.254	0.619	
		3	0.004	0.393	0.207	0.600	
		Average	0.005	0.344	0.210	0.554	
	AJ	1	0.055	0.396	0.265	0.661	
		2	0.016	0.347	0.216	0.563	
		3	0.028	0.343	0.196	0.539	
		Average	0.033	0.362	0.226	0.588	
	CJ	1	1.193	0.412	0.151	0.563	2010
		2	0.638	0.448	0.160	0.608	1050
		3	1.035	0.449	0.144	0.593	
		Average	0.955	0.436	0.152	0.588	Avg.= 1530
	CB	1	1.167	0.386	0.146	0.532	Std. Dev.= 679
		2	0.687	0.478	0.184	0.662	
		3	1.009	0.474	0.170	0.644	
		Average	0.954	0.446	0.167	0.613	
30	AB	1	0.004	1.313	0.911	2.224	
		2	0.003	0.856	0.570	1.426	
		3	0.004	1.071	0.786	1.857	
		Average	0.004	1.080	0.756	1.836	
	AJ	1	0.007	1.315	0.775	2.090	
		2	0.029	0.766	0.371	1.137	
		3	0.015	1.150	0.674	1.824	
		Average	0.017	1.077	0.607	1.684	
	CJ	1	0.205	2.411	1.179	3.590	930
		2	0.044	2.207	1.027	3.234	3090
		3	0.398	2.336	1.159	3.495	
		Average	0.216	2.318	1.122	3.440	Avg. = 2010
	CB	1	0.109	2.264	1.078	3.342	Std. Dev. = 1527
		2	0.496	2.198	0.946	3.144	
		3	0.455	2.209	1.018	3.227	
		Average	0.380	2.224	1.014	3.238	

[a] AB = Adapter Body, AJ = Adapter Joint, CJ = Combustible Case Joint, CB = Combustible Case Body

Table A.5 (continued). Nitroester and tensile strength data from the ARDEC HT/SR study.

Days	Sample Location[a]	Round Number	Concentration in Case Wall (Weight %)				Tensile Strength (Pounds)
			Akardite II	DEGDN	NG	Total Nitroesters	
60	AB	1	0.006	1.566	1.327	2.893	
		2	0.006	1.598	1.178	2.776	
		3	0.008	1.683	1.267	2.950	
		Average	0.007	1.616	1.257	2.8731	
	AJ	1	0.026	1.941	1.206	3.147	
		2	0.013	1.512	0.876	2.388	
		3	0.785	3.000	1.982	4.982	
		Average	0.275	2.151	1.355	3.506	
	CJ	1	1.102	3.117	1.874	4.991	0
		2	0.587	3.095	1.695	4.790	4
		3	1.349	3.450	2.321	5.771	
		Average	1.013	3.221	1.963	5.184	Avg. = 2
	CB	1	1.080	2.813	1.554	4.367	Std. Dev. = 2.8
		2	0.560	2.936	1.606	4.542	
		3	1.339	3.385	2.303	5.688	
		Average	0.993	3.045	1.821	4.866	
90	AB	1	0.008	2.546	1.766	4.312	
		2	0.005	2.785	2.131	4.916	
		3	0.006	2.278	1.691	3.969	
		Average	0.006	2.536	1.862	4.399	
	AJ	1	0.042	2.990	1.814	4.804	
		2	0.028	2.735	1.551	4.286	
		3	0.103	3.065	2.009	5.074	
		Average	0.058	2.930	1.179	4.721	
	CJ	1	0.649	3.832	3.477	7.309	10
		2	0.536	3.578	2.587	6.165	0
		3	0.308	3.626	2.916	6.542	
		Average	0.498	3.679	2.993	6.672	Avg. = 5
	CB	1	0.838	3.619	3.105	6.724	Std. Dev. = 7
		2	0.714	3.514	2.364	5.878	
		3	0.303	3.548	2.748	6.296	
		Average	0.618	3.560	2.739	6.299	

[a] AB = Adapter Body, AJ = Adapter Joint, CJ = Combustible Case Joint, CB = Combustible Case Body

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