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Changes in the Mechanical Properties of Energetic Materials With Aging

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The mechanical properties of energetic materials were studied as a function of actual age and accelerated aging produced by heat treatment at elevated temperatures for several months. All measurements were made in uniaxial compression at one or more of three temperatures——45, 25, and 65° C—at strain rates between 1 and 10/sec. For TNT that was in the stockpile for up to 40 years, no change in the compressive properties were found. Single-base nitrocellulose propellants that were subjected to 65° C for 18 months also gave no change in the compressive strength. In addition, the compressive strength of a plastic-bonded explosive, PAX 2A, was not changed after 6 months at 60° C and 12 months at 50° C. In contrast, after 6 months at 70° C the compressive strength and modulus of octol were reduced by up to about 40%. The compressive strengths of double- and triple-base nitrocellulose propellants were also decreased by 50–70% by the same heat treatment given to the single-base propellants. These changes for octol and the propellants are a function of measurement temperature. Other changes in most of these material were observed and are discussed. Probable reasons for the changes in mechanical properties are presented.

Introduction

Changes in performance and safety characteristics of explosive and propellant formulations with aging are a continuous concern. For example, the degradation of nitrocellulose with time is well known,

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and there are very active surveillance programs to monitor the properties of nitrocellulose-base propellants with aging. In addition, there have been programs to determine if the properties of explosive fills have changed with time in the field [1]. Changes with aging of plastic-bonded explosives (PBXs) and TNT-based explosives properties are also of considerable interest. The effect of thermal conditioning at elevated temperatures to simulate aging on the properties of PBX 9501 have been and continue to be the object of studies, and changes with this type of treatment have been found [2, 3]. Similar studies have been made for LX-14 [4–6]. The stability of the properties of one of the newest PBXs, PAX 2A, developed recently by the Army is also of interest [7]. The composition of PAX 2A is similar to that of PBX 9501 since it has the same explosive and plastizer but a different polymer [2, 7]. The stability of TNT and the TNT-based explosive octol are also of interest.

Therefore, the aging of both PAX 2A and octol were studied experimentally. Because TNT has been in the stockpile for many years, it was possible to obtain data as a function of actual age. The work reported here on mechanical property aging is part of more general studies to determine if several properties of PAX 2A, TNT, and octol change with aging [1, 8]. However, rather than wait many years before initiating the study of aging, the work with PAX 2A and octol was done by accelerating the aging processes by conditioning samples at elevated temperatures but for shorter periods.

Some gun propellants have compositions similar to those of plastic-bonded explosives [9]. Therefore, it is appropriate to present results on the effect of the same type of accelerated aging on the mechanical properties of some of these materials [9, 10].

Experimental

Stress-strain data for PAX 2A, octol, and TNT in uniaxial compression were obtained using an MTS servo-hydraulic system operated at a constant strain rate of 1.0/sec. The strain rate for the propellant samples was approximately 10/sec. All samples were in the form of cylinders. The samples of PAX 2A and octol were 1.90 cm in length and diameter, and the samples of TNT were 1.27 cm in length and diameter. The propellant samples had length-to-diameter ratios between one and two. The end faces of all samples and the loading platens were lubricated to minimize frictional effects between the samples and the platens. Samples were conditioned at temperatures between −45

and 65°C for at least 2 hrs before mechanical measurements and were then compressed along the cylinder axis to obtain engineering stress and engineering strain. In most cases three samples of PAX 2A and TNT were measured at each condition, four or in most cases five samples of octol were measured at each condition, and between three and nine propellant samples were measure for each condition.

Samples of PAX 2A were prepared by pressing at 71°C to the approximate size and then machining to final dimensions. Samples of octol were prepared by casting into molds 15.2 cm in length and 2.54 cm in diameter, and then cutting and machining to the final dimensions. Samples of TNT were obtained by sectioning shells that were brought in from the stockpile, by cutting and then machining to the final dimensions. Precautions were taken to ensure that the cylinder end faces of all these samples were flat and parallel. In contrast, the propellant samples were cut from propellant grains containing perforations. The densities of all PAX 2A and octol samples were measured and were in a narrow range close to the maximum theoretical (zero porosity) density. A range of densities was obtained for the TNT samples. The densities of the propellant samples were not determined. The densities of PAX 2A and octol before and after thermal conditioning but before deformation were determined by weighing in air and measuring the dimensions. The densities after deformation of PAX 2A were determined by weighing in air and in water. The water density was corrected to the measurement temperature.

The results for samples subjected to accelerated aging by conditioning at elevated temperatures—the aged samples—are compared to control samples from the same lot and measured under the same conditions. The aged samples of PAX 2A were held in air at 60°C for 6 months or at 50°C for 12 months while the aged samples of octol were held in air at 70°C and relative humidity of 30% for 6 months. Control samples were held at ambient temperature in air for 6 or more months. Because the results for the two groups of aged samples of PAX 2A are very similar, only the samples held at 60°C for six months are discussed here. There were also two groups of aged and control samples of octol produced by difference manufacturers. These two groups of samples also gave similar results, and so only one group is discussed here. The propellant samples were held at 65°C for varying time periods between 1 and 18 months.

Aged samples of PAX 2A and octol and the same number of control samples were compressed at each of three temperatures: −45, 25, and 65 C. In addition, a few samples of the aged and control groups of

Table 1
Principal components of energetic materials studied

Materials main components	
PAX 2A	HMX—85%, BDNPA/F—9%, CAB—6%
Octol	HMX—75%, TNT—25%
NACO	NC—93.61%, ethyl centralite—1.15%
M26	NC—66.1%, NG—25.8%, ethyl centralite—6.35%
M30	NC—27.61%, NG—22.67%, NQ—47.96%, ethyl centralite—1.49%

HMX: cyclotetramethylene tetranitramine; BDNPA/F: bis(2,2-dinitropropl)acetal/formal; CAB: cellulose acetate butyrate; TNT: trinitrotoluene; NC: nitrocellulose; NG: nitroglycerine; NQ: nitroguanadine.

each explosive formulation were measured at intermediate temperatures. Although most measurements were at a strain rate of 1.0/sec, a few aged and control samples were compressed at a strain rate of 0.001/sec. All of the TNT samples were compressed at 25°C, and the propellant samples were compressed at −45 and 23°C. The main components of the energetic materials considered here are given in Table 1.

Results

The stress-strain curves in uniaxial compression for all of the energetic materials considered here are as follows. With increasing strain from zero, the stress initially increases linearly with strain, and Young's modulus is obtained from the slope of this linear portion of the curve. With further increases in the strain the stress curves over and passes through a maximum. The maximum stress, the compressive strength, is taken as a measure of the failure stress, and the strain at the maximum is taken as a measure of the failure strain. For further increases in strain the stress decreases continuously. In most cases the stress decreases gradually in this region of the stress-strain curve because of work or strain softening. However, in some cases the stress decreases abruptly because of cracking and fracture. This abrupt decrease of the stress occurs primarily at lower temperatures.

Changes in the initial part of the stress-strain curve with aging, that is, changes in the compressive strength, Young's modulus, and the failure strain, are the primarily focus of this paper. In addition, changes in the work softening region are discussed for PAX 2A and octol. Changes in the brittleness are also discussed.

PAX 2A and Octol

In Table 2 the average percentage changes in the compressive strength, Young's modulus and the failure strain are given as a function of the temperature of compression for PAX 2A and octol for the accelerated aging conditions given above. The results of this table indicate significant difference in the effect of aging on the given properties

Table 2
Percentage change of PAX 2A and octol mechanical properties after accelerated aging

	Measurement temperature		
Parameter	−45°C	25°C	65°C
PAX-2A data			
Compressive strength	Unchanged*	Unchanged	Unchanged
Young's modulus	−10%*	15%	14%
Strain at maximum stress	16*	−5	−17
Octol data			
Compressive strength	−38	−36	−8
Young's modulus	−44	−18	−26
Strain at maximum stress	13	Unchanged	16
Damage modulus	−38	−63	−70

*Below the ductile to brittle transition temperature, which is about −30°C for PAX 2A for a strain rate of 1.0/sec, the mechanical properties of interest here are extremely variable from sample to sample. Therefore, the values given at −45°C are very tentative because of this variability and because the number of samples available for measurements at each temperature was limited.

of PAX 2A and octol. There is no change in the compressive strength of PAX 2A at all three temperatures within experimental uncertainty, but a decrease in the compressive strength of octol at all temperatures. The results of Table 2 also indicate an increase in Young's modulus for PAX 2A at the two higher temperatures, but a decrease in the modulus at all three temperatures for octol.

In addition to the results given in Table 2 for accelerated aging, several other properties of PAX 2A and octol were monitored with and without aging. The results are summarized as follows:

- Very small decreases in average dimensions and weights $<0.5\%$
- No change in average density within 0.5%
- Change of color from white to pale yellow
- Decreased stress at 65°C in the work-softening strain range
- Increased cracking after deformation at 65°C in the work-softening strain range
- Greater decrease in density due to deformation at 65°C in the work-softening strain range
- Lower work/volume required for deformation at 65°C in the work-softening strain range
- No change in the ductile to brittle transition temperature
- Octol
- Small decrease in average weight, less than 0.6%
- Small increase in average volume $\sim 1\%$
- Small decrease in average density $\sim 1.5\%$
- Change of color from tan to brown
- Decrease of the damage modulus (see text).

Of particular interest are changes in the work-softening region. For PAX 2A at 65°C measuring temperature there is a significant decrease in the stress in the work-softening region. In addition, at this temperature there is an increase in cracking, a larger density decrease due to deformation, and a decrease in the work/volume to deform to a strain in the work-softening region. For octol at all temperatures of measurement, straight lines can be fitted to the stress-strain curves in most of the work-softening region. Since the decrease of stress with increasing strain is due to strain-induced damage, the slope of this line is taken as a damage modulus, D, and the percentage changes with aging are given in Table 2. Very significant decreases in D are observed. The stress-strain curves for PAX 2A have continuous curvature in the work-softening region so that a damage modulus as in the case of octol cannot be clearly defined. However, these results for

both PAX 2A and octol suggest greater strain-induced damage in the aged material.

The changes in density are also of interest. For PAX 2A there are small decreases in weight and dimension of less than or of the order of 0.5%. These changes are such that there is no change in average density within an experimental error of about 0.3%. In contrast, for octol small decreases in weight and small increases in dimensions were found, thus giving decreases in densities of the order of 1–1.5%. Also, changes in the color of both explosives indicate that chemical changes have taken place with accelerated aging. These color changes were observed on both external surfaces and fracture surfaces, thus indicating changes throughout the volume. However, the densities of chemical species that are required to produce these color changes are most probably much smaller than the other percentage changes observed here.

Propellants

In Table 3, the compressive strengths of a single-base, double-base and triple-base nitrocellulose propellant are given at measuring temperatures of −45 and 23°C as a function of accelerated aging time at

Table 3
Compressive strengths measured at −45 and 23°C

Aging period (months)	Single base NACO	Double base M26	Triple base M30
	−45°C		
0	217 ± 17	239 ± 41	234 ± 32
6	232 ± 0	154 ± 44	172 ± 47
12	201 ± 0	76 ± 21	177 ± 23
18	230 ± 32	70 ± 18	109 ± 44
	23°C		
0	117 ± 1	61 ± 10	82 ± 5
18	134 ± 14	70 ± 4	59 ± 6

Between four and nine samples were measured at each aging period for each propellant. The ± is the standard deviation of the measurements in each case.

65°C [9]. Within the spread of the data at −45°C there is no change in the compressive strength of the single-base propellant, but very significant decreases in the compressive strengths of the double- and triple-base propellants. One other single-base and two other triple-base propellants gave similar results to those of Table 3 at −45°C [9]. Although the compressive strengths of the single-base propellants did not change with aging, the nature of the failure did exhibit change.

With increasing strain before the accelerated aging the stress decreased gradually after the maximum stress and then abruptly fractured only at large strains. Failure was in the form of cracking but not fracture. In contrast, after 18 months of accelerated aging the stress decreased abruptly at or near the maximum stress and the samples fractured. The stress as a function of strain for the double- and triple-base propellants at −45°C decreased in a moderately abrupt fashion after the maximum stress before aging, but decreased more abruptly after 18 months aging. Thus, all three types of propellants became more brittle after 18 months of accelerated aging. The rather large experimental spread of some of the data of Table 3 at −45°C was found for propellants and plastic-bonded explosives as well when the failure is brittle (see note to Table 2).

The compressive strengths measured at 23°C as a function of aging time are also given in Table 3. The results suggest a small decrease in the compressive strength of the triple-base propellant, no change in the double-base propellant, and either no change or possibly a small increase in the strength of the single-base propellant. One other single-base propellant gave similar results at 23°C.

TNT

Measurements of the compressive mechanical properties of samples of TNT taken from shells that had been in the stockpile for 20, 30, and 40 years indicate no statistically significant change of the compressive strength with age. The same is true for Young's modulus and the failure strain. In addition, the mode of failure did not appear to change with age. Over 100 samples were measured, and these were taken from a number of shells of three different diameters. The average compressive strength of all samples measured is 13.6 ± 2.3 Mpa. This number can be compared with the average compressive strength of 12.8 ± 1.2 Mpa for a group of TNT samples prepared for laboratory studies. This latter group of samples was measured within one year of preparation.

Discussion

A brief discussion of each energetic material or group of materials is given in this section.

PAX 2A

The compressive strength of PAX 2A was found to be stable for the temperatures and time periods of accelerated aging and the conditions of measurement used in this study (see Table 2). However, Young's modulus was found to increase somewhat ($\sim$15%), and the failure strain was found to decrease somewhat for the two higher temperatures of Table 2. For no change in the compressive strength but an increase in Young's modulus, there must be a decrease in the failure strain as observed if there are no significant changes in the shape of the stress-strain curve in this region. The increase in the modulus can be due to a segregation of plasticizer with aging. A more complete discussion of the mechanical properties of PAX 2A with this accelerated aging is given elsewhere [12, 13].

The most significant change in the mechanical properties of PAX 2A due to this aging occurs in the work-softening region of the strain-strain curve at higher temperatures, for example, 65°C. There is a marked decrease of the stress at strains in this region and so a smaller work/volume to deform the material in this region. Thus, for a constant energy of deformation, for example, by impact, the final strain and so the degree of cracking (see below) will be greater in the aged material than in the nonaged material. There also is greater cracking due to deformation of the aged material than the nonaged material for equal amounts of strain into this region of the stress-strain curve. This increased cracking is accompanied by a larger decrease in density in the aged samples due to deformation. This increased cracking can be attributed to thermally activated crack growth in the aged material, which does not occur in the nonaged material [12, 13]. The crack growth in the nonaged or reference samples was found to be approximately independent of temperature, while the additional crack growth in the aged samples increases with temperature such that it is not observed at 25°C but is observed at 65°C. There are other differences in the properties of this additional crack growth at higher temperatures. This matter is discussed in greater detail elsewhere [12]. The increased cracking in the aged samples could be associated with clusters of defects, for example, clusters of plasticizer molecules, formed during the aging process.

Because there are two aging periods at two temperatures, it is possible to obtain an activation energy by assuming first-order kinetics. In this manner an activation energy of about 0.6 eV is obtained. This value is close to the value obtained using first-order kinetics for PBX 9501.3. Since both materials contain HMX and BDNPA/F, the similarity of activation energies suggest that it is associated with one or both of these components. This activation energy may then be associated with the diffusion of NO_2 molecules as proposed for PBX 9501.3.

Octol

In contrast to the results for PAX 2A, for octol both the compressive strength and Young's modulus are decreased, and the failure strain is either increased or not changed after accelerated aging (Table 2) for all three measurement temperatures. However, the octol samples were aged at 70°C, 10°C higher than the highest temperature for PAX 2A sample aging.

A decrease in both the compressive strength and the modulus is expected if the porosity is increased by the aging process [15]. However, if some or all of the porosity is in the form of micro-cracks, calculations indicate that the compressive strength could increase or decrease, but the modulus is still decreased [15]. For specific porosity not in the form of micro-cracks, calculations indicate that the relationships between the strength, the elastic modulus, and porosity are approximately of the form

$$E = E_1 \exp(-a\Delta P) \tag{1}$$

and

$$\sigma = \sigma_1 \exp(-b\Delta P), \tag{2}$$

where E_1 and σ_1 are Young's modulus and the compressive strength at a porosity P before aging, E and σ are the values for an increase in porosity ΔP, and a and b are constants. Here ΔP is taken here as the fractional decrease in density, and a is not equal to b because the averaging processes are different for the strength and the modulus. Assuming that all of the decreases of E and σ after aging are due to porosity, values of a in the range of 13–37 and values of b in the range of about 8–30 are obtained for a porosity change of 1.5%. Although

these values of a and b are large compared to the predictions of calculations, values of this magnitude have been reported for Composition B (39.5% TNT, 59.5 RDX, and 1% Wax) and other materials [15]. Thus, the changes of the modulus and the compressive strength at all three measuring temperatures after aging may be due to porosity introduced during the aging process. However, the small percentage decrease of the compressive strength at 65°C and so the small value of b suggest that the form of the porosity has changed somewhat at this temperature (Table 2).

TNT and HMX are not expected to have significant thermal decomposition after 70°C for 6 months. In addition, the measurements given here for TNT indicate that the compressive mechanical properties of TNT are not changed with age up to 40 years. However, chemical analysis indicates an increase in the percentage of HMX in octol after treatment at 70°C for 2 and 4 months [16]. Although the percentages of TNT and impurities were not measured, this increase in the percentage of HMX indicates that either the percentage of TNT and or the percentage of impurities has decreased. Therefore, the observed small weight loss could be due to the loss of TNT and or impurities. However, the effects of these loses on the observed volume expansion and density decrease are not known. Impurities could decompose and cause internal strain. Sublimation of TNT might also take place since the aging temperature of 70°C is close to the melting temperature of TNT at 81°C.

In summary, the decreases of the compressive strength and Young's modulus can be attributed to porosity increases during the accelerated aging. The observed volume expansion and density decrease support this interpretation. A decrease in the percentage of TNT and/or impurities and the observed weight decrease indicate that TNT and/or impurities were lost during the aging. The porosity increase may be associated with this loss.

Propellants

Before aging the compressive strengths at −45°C of the single-, double-, and triple-base propellants of Table 3 and other single- and triple-base propellants are the same within experimental uncertainty [9]. It is therefore concluded that the compressive strengths of these propellants at this temperature are determined primarily by the properties of nitrocellulose. In contrast, before aging at 23°C the double- and triple-base propellants of Table 3 and other triple-base propellants

have lower compressive strengths than the single-base propellant of Table 3 and other single-base propellants [9]. From these observations it is concluded that the properties of nitrocellulose primarily determine the strength of the single-base propellants, but the lower values of strength for the double- and triple-base propellants at 23°C are due to the plasticizing effect of nitroglycerine. It is also concluded that the addition of a relatively large percentage of solids in the form of nitroguanidine has little or no effect on the compressive strengths at 23 and −45°C.

For the interpretation of the effects of aging it is desirable to know if these propellants are primarily in glass or rubber states at −45 and 23°C as a function of aging time. Although measurements have not been made to determine this as a function of aging, some measurements have been made on relatively freshly prepared propellant. For this purpose it is assumed that brittle properties are evidence of the glass state and that ductile properties are evidence of the rubber state. A ductile-to-brittle transition was found to take place in the nonaged triple-base propellant (M30) between 0 and −15°C for a strain rate of 10/sec. the same strain rate as used here [17]. Therefore, it appears that this propellant is in a glass state at −45°C but in rubber state at 23°C before aging. While a glass transition temperature of −57°C was observed for this propellant, this was measured at a much lower strain rate [17]. The glass transition temperature increases with rate. Because of the type of failure and the composition, the double-base propellant is most likely also in the glass state at −45°C and in the rubber state at 23°C. For the single-base propellant before aging the situation is not clear. At −45°C the failure mode is partly ductile and partly brittle. Therefore, at this temperature it may be in a transition between the rubber and glass states. At 23°C it should be in the rubber state.

The decomposition of nitrocellulose is auto-catalytic, and all nitrocellulose-containing propellants have a stabilizer, in these cases, ethyl centralite, to hinder this auto-catalytic action [9]. The concentration of the stabilizer was found to be significantly decreased with this aging, thus indicating nitrocellulose decomposition. In addition, nitroglycerine decomposes, and the products of this decomposition are known also to cause nitrocellulose decomposition [9]. It is therefore concluded that although there was decomposition of nitrocellulose for the aging conditions used in this study, this decomposition was not sufficient to effect the compressive strength of the single-base propellants (see Table 3). However, because of the presence of nitroglycerine

in double- and triple-base propellants and the added nitrocellulose decomposition caused by the decomposition products of nitroglycerine, the compressive strengths at −45°C are significantly decreased (see Table 3).

The decrease of the compressive strengths of the double- and triple-base propellants at −45°C may be due to the formation of porosity during the aging treatment as discussed above for octol. This porosity may be "frozen in" during the transition to the glass state on cooling and may cause the generation of micro-cracks. Alternately pockets of molecules or regions of more general damage produced during the decomposition may be frozen in and cause the generation of micro-cracks. Micro-cracks can decrease the compressive strength and increase the brittleness as observed. However, at 23°C these same propellants are in a rubber state. In this state the micro-cracks may not exist, may be blunted, or may be otherwise changed so that they have little on no effect on the compressive strength. Most probably the mechanism of failure at 23°C is significantly different from the mechanism at −45°C. Thus, the compressive strength is either unchanged or only mildly decreased at 23°C although it is strongly decreased at −45°C.

By the same analysis it can be deduced that the single-base propellants are primarily in rubber states at −45°C before aging. Thus, the type of disorder produced by decomposition, the amount of decomposition, and the failure mechanisms must be such that the compressive strengths at −45°C are not reduced. The amount of nitrocellulose decomposition is less in the single-base propellant because of the absence of nitroglycerine. The same argument applies to single-base propellants at 23°C and thus there is no observed reduction of the compressive strength at this temperature either. Because the single-base propellants become brittle at −45°C after long-term aging, there must be sufficient decomposition to change their states from primarily rubber to primarily glass without a change in the compressive strength. The rational given for the changes in the mechanical properties of single-, double-, and triple-base propellants are very speculative, and more measurements are highly desirable.

TNT

It was demonstrated that the storage of TNT in shell in stockpiles for up to 40 years does not result in changes in the mechanical properties that were measured. Since the storage temperature and other

conditions are not known, these results cannot, however, be easily applied to other storage conditions without knowledge of the decomposition kinetics of TNT and its impurities.

Comparison of Energetic Materials

The temperatures of aging are different for each energetic material or group of materials: that is, the temperature is unknown but probably in the vicinity of ambient for TNT, and the temperatures are 50 and 60°C for PAX 2A, 65°C for the propellants, and 70°C for octol. In addition, the kinetics and associated parameters for changes in the mechanical properties during aging are unknown. Therefore, it is not possible to make direct comparisons of the stability of all of these materials, and it is not possible to reliably extrapolate the results of accelerated aging to specific storage conditions. It is highly desirable to make measurements at least at two or more temperatures and a few aging periods so that a measure of the kinetics and associated parameters can be obtained. With this information extrapolations to other conditions, especially long-term storage conditions, can be made reliably.

Summary

The compressive strength, Young's modulus, and failure strain of TNT were found to be unchanged for storage under stockpile conditions for up to 40 years. In addition, the compressive strengths of single-base propellants were found to be unchanged after accelerated aging at 65°C for up to 18 months. The compressive strength of PAX 2A was also found to be unchanged for a 12 month accelerated aging period at 50°C and a 6 month accelerated aging period at 60°C. However, Young's modulus of PAX 2A was increased by about 15%, and the failure strain was decreased after these treatments. It is suggested that these later changes may be due to clustering of plasticizer.

The compressive strengths of double- and triple-base propellants at −45°C and octol at −45, 25, and 65°C were decreased after accelerated aging. However, the compressive strengths of the propellants at 23°C were either unchanged or decreased only slightly. Young's modulus of octol was decreased, and the failure strain was either increased or unchanged. The propellants were subjected to accelerated aging at 65°C for up to 18 months, and octol was subjected to

accelerated aging at 70°C for 6 months. The decrease of the compressive strength and Young's modulus of octol can be attributed to increased porosity after aging. This conclusion is supported by observations of small decreases in density and weight and increases in volume after the aging. The decreases in density and weight and the increases in volume are thought to be due to impurity processes since neither of the main components of octol, HMX and TNT, are expected to decompose significantly for the accelerated aging conditions of this work. Loss of TNT is also a probable cause of the weight decrease. The decreased compressive strength of the double- and triple-base propellants at −45°C may be due to increased porosity and/or regions of disorder produced by nitrocellulose and nitroglycerine decomposition that are effectively not load supporting and are frozen in the glass state at −45°C. Micro-cracks may also play a role in decreasing the compressive strength. The disorder that is frozen in the glass state and that causes a reduction of the compressive strength is not effective in reducing the compressive strength in the rubber state at 23°C.

The brittleness at −45°C of the single-, double-, and triple-base propellants is increased after accelerated aging. For PAX 2A increased cracking in aged samples was observed after compression, but only at the higher temperatures. This increased cracking is attributed to thermally activated crack growth in aged samples, which does not take place in nonaged samples.

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