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In celebration of the 60th birthday of Dr. Andrew K. Galwey

THE EFFECTS OF FAST NEUTRON, GAMMA-RAY AND COMBINED RADIATIONS ON THE THERMAL DECOMPOSITION OF AMMONIUM PERCHLORATE POWDER-ALUMINUM PARTICLE MIXTURES

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Abstract

The thermal decomposition kinetics of irradiated and unirradiated ammonium perchlorate and ammonium perchlorate powder - aluminum particle mixtures has been studied by determining decomposition gas pressure *vs.* heating time with samples at a controlled temperature. Qualitatively the radiation induced changes are similar to those obtained in previous studies on 'pure' ammonium perchlorate. The induction period is shortened and the acceleratory and decay period rate constants are increased. The data have been analyzed using Avrami-Erofeev kinetics. The results for pure unirradiated material are in accord with published results. The activation energies for the induction, acceleratory and decay periods for pure pellets were found to be 133.5±6.7, 131.8±6.7 and 127.2 ±6.7 kJ·mol, respectively. Samples were exposed to either a single gamma-ray irradiation, fission neutron irradiation followed by a gamma-ray irradiation, or to a proton irradiation. When compared on an equal energy deposited basis, the fast neutron induced changes are appreciably larger than the gamma-ray changes. However, the proton induced changes are comparable or slightly more than the gamma-ray effects. Some, or all, of the fast neutron effects can be attributable to the concentrated radiation damage 'spikes' along the path of lattice atom recoils. It is likely that these become thermal decomposition sites when the crystals are heated. Protons create fewer spikes than fast neutrons. Overall, the results indicate that any ammonium perchlorate - aluminum propellant mixtures that may be exposed to radiation environments, such as used in this study, should be subjected to a thorough radiation effects analysis if reliable performance is required.

Keywords: ammonium perchlorate, kinetics, radiation effects

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Introduction

The investigations on radiation effects in ammonium perchlorate have been extended to include powders, pellets, and powder-aluminum particle mixtures. The studies utilized radiation conditions which would apply to solid propellants containing ammonium perchlorate which might be encountered by space probes and similar applications involving radiation environments.

The early studies [1–9] were confined almost exclusively to measurements on single crystals with nominal dimensions 0.1 to 1.0 mm. Two complementary techniques have been employed in this study to provide qualitative and quantitative measurements of the radiation induced effects, i.e. the radiation damage. First, quantitative measurements of the radiation induced damage are obtained from thermal decomposition studies [1–4]. Specifically, decomposition gas pressure *vs.* time curves were obtained using an all glass system, containing a quartz spiral gauge for pressure measurements, and with the samples in an oven maintained at a constant temperature by an electronic controller. After inserting the sample into an unheated part of the system it is evacuated, usually overnight. The system is then pumped to approximately 10^{-6} torr for several hours and the sample inserted into the oven with a magnetic 'pusher'. The thermal inertia of the oven is sufficient to bring the samples to oven temperature (±0.1°C) in 3 minutes of less. Single crystals, and almost all powders, pellets and powder-aluminum particle mixtures of ammonium perchlorate were decomposed at temperatures well below the ammonium perchlorate phase change at 240°C. The pressure *vs.* time curves are sigmoid and contain an induction, acceleratory and decay period. The acceleratory and decay periods are best described by the well-known Avrami-Erofeev kinetics [10]. As the radiation dose increases, the acceleratory period rate constant increases markedly; also the decay period rate constant usually increases.

The induction period (I) is related to the total dose by the relation [4]

$$I = (\text{Const.})_1 - (\text{Const.})_2 \lg(\text{dose}). \quad (1)$$

In fact, this relation appears to be an accurate indicator of the observed radiation effects and provides a useful internal measure of the absorbed dose. Activation energies for irradiated materials are the same, or very nearly so, as those for unirradiated materials. This observation, together with the Avrami-Erofeev analysis indicates that the radiation-induced effects in ammonium perchlorate can be attributed to an increase in decomposition sites [2, 3]. Subsequent studies showed that the sites were, almost certainly, dislocations [8, 9]. Furthermore, it has been demonstrated that dislocations are generated in ammonium perchlorate by gamma-ray irradiation [9].

Optical microscope and both transmission and scanning electron microscope studies have been employed to obtain information on the radiation related decomposition sites [5–9]. It has been shown that, as a function of increasing gamma-ray dose or X-ray dose, radiation-induced decomposition sites can be observed after doses as low as 10^4 rad. As the dose increases these sites enlarge into voids. At doses of approximately 10^7 rad the crystals are strained sufficiently to fracture along cleavage planes [5].

Studies on color-center formation in single crystal ammonium perchlorate indicate that radiation-induced ionization causes electrons and/or holes to be trapped in the lattice [10]. Radiation-induced absorption curves from large, clear, ammonium perchlorate crystals contain four obvious color centers attributable to trapped charges. The color center concentration *vs.* irradiation time, or dose, curves contain a small saturating exponential part superimposed on a larger linear component. Usually the saturating exponential part is attributed to charge trapping on defects existing prior to irradiation and the linear part to charge trapping on defects created by irradiation. Thus, ammonium perchlorate responds to radiation in a manner usually observed in most transparent nonmetals. It appears, at least at the present, that the radiation-induced changes in the ammonium perchlorate decomposition kinetics can be adequately explained without invoking a mechanism directly including the observed trapped charge. However, it is not difficult to 'invent' trapped charge related mechanisms, especially those including electron-hole recombination ionization damage which occurs as the sample is heated. Such mechanisms can provide 'explanations' for the empirical observations, especially Eq. (1).

To provide information that would be particularly applicable to an ammonium perchlorate propellant aboard a deep space probe, some powder-aluminum particle mixtures were exposed to single gamma-ray irradiation and others to fission spectrum neutron irradiations. Additional samples were exposed to either a proton or neutron irradiation followed by a gamma-ray irradiation.

Experimental materials and procedures

The ammonium perchlorate and ammonium perchlorate-aluminum powder and/or pellets used in these measurements were prepared at the Jet Propulsion Laboratory. The mixtures contained approximately 93% ammonium perchlorate and 7% aluminum by mass. The aluminum particles were approximately 18 μm across. The mixtures were prepared by precipitating the ammonium perchlorate on the aluminum particles. Pellets were prepared in the usual manner and contained approximately the same proportions. After pelleting, the material was placed in evacuated sealed glass ampoules. It remained in

these ampoules during all irradiations etc. and was removed and placed in desiccators just prior to decomposition. Approximately one year elapsed between the irradiations and the thermal analysis studies.

The samples were irradiated with Co^{60} gamma rays at a dose rate of 300 rad per hour. Although not determined directly, the maximum sample temperature during all irradiations was 30°C. The gamma-ray dose rate is known to about 12 percent.

Fast neutron irradiations were made in the Shield Test and Irradiation Reactor (STIR) Facility of Atomics International in Santa Susana, California. The neutron spectrum and flux data was provided by Dr. R. Pashall of Atomics International. The fast neutron spectrum can be characterized as a slightly degraded ^{235}U fission neutron spectrum. However, for the radiation dose calculations described below, a fission spectrum was assumed. The slow neutron component in this facility is negligible. The gamma-ray component is also small, for the largest neutron irradiation the gamma-ray dose was less than 1000 rad. When samples were exposed to both fast neutrons and gamma rays, the fast neutron irradiation always preceded the gamma-ray irradiation.

Proton irradiations were made at the NASA Langley Field Irradiation Facility. The neutron and gamma ray component present during the 144 MeV proton irradiation was measured and included in the dose computations. The fast neutron, gamma ray and proton irradiations were adjusted to five and twenty five times the dose expected to be imparted to a typical solid propellant on a deep space probe, i.e. from natural sources, cosmic rays, onboard nuclear powder devices, etc.

All thermal decomposition measurements were made in the apparatus used previously. A trap, at melting toluene temperature, located between the decomposition chamber and the gauge was put in operation prior to decomposition. This ensures that only those gases which would not be condensed at –95°C are monitored. The trap was in operation for all the measurements reported here. Each sample weighed approximately 50 mg. Two separate $\alpha(t)$ curves were obtained for each of the various irradiations. The reproducibility was excellent. Consequently, only a single data set is shown in the figures.

The sigmoid pressure *vs.* time curves, which were observed in all cases, were analyzed as follows. The induction period, during which little or no gas was detected, was determined from the point of departure from the linear induction period to the acceleratory period. The acceleratory and decay periods were analyzed using Avrami-Erofeev kinetics [10]. Using the notation in Ref. [2], the acceleratory period data were fitted to the equation

$$[-\lg (1-\alpha)]^{1/4} = k_6 t$$

and for the decay period

$$[-\lg(1-\alpha)]^{1/3} = k_7 t$$

where k_6 and k_7 are the Avrami-Erofeev rate constants for the acceleratory and decay periods respectively. The extents of fit for the acceleratory periods were $0.05 \leq \alpha \leq 0.40$ and for the decay periods $0.40 \leq \alpha \leq 0.95$.

To determine how these rate constants vary with imparted dose, it is necessary to specify a procedure for determining the dose to be attributed to neutron irradiations. The neutron doses were computed, as was done previously [14], by calculating the total number of elastic collisions between fission spectrum neutrons and lattice atoms and assuming that all of the energy transferred contributed to the dose. A second methods is based on the observation given by Eq. (1), namely (Induction Period) = $(\text{Const.})_1 - (\text{Const.})_2 \lg(\text{Dose})$. From a plot of induction period *vs.* dose, determined with samples exposed only to gamma rays, one finds the equivalent gamma-ray dose associated with an observed induction period. This method was also used to obtain an equivalent gamma-ray dose from the induction period of the proton irradiated samples. The proton dose was calculated in two ways. First, by using an effective $Z = 11.90$ for ammonium perchlorate and the energy deposited per proton, as determined from the range-energy relations [16]. For 144 MeV protons, a value of 4.942 MeV cm^2/g was obtained. Alternatively, using the Z of each atom the energy deposited per atom was calculated and then summed over each molecule. This method produced a value of 6.990 MeVcm^2/g, the latter value is the more accurate of the two values. The irradiation used and the doses attributable

Table 1 "Dose" attributed to neutron and gamma-ray irradiated ammonium perchlorate aluminum mixtures determined in three different ways

Measured irradiations	Equivalent dose from induction Period data / rad	Total dose from calculated Neutron dose / rad
5×10^4 rad γ-ray	5×10^4	–
5×10^{12} neutrons / cm^2	9.0×10^4	0.78×10^4
5×10^{12} neutrons / cm^2 5×10^4 rad γ-ray	14.0×10^4	5.8×10^4
25×10^4 rad γ-ray	25×10^4	–
25×10^{12} neutrons / cm^2	19×10^4	3.91×10^4
25×10^{12} neutrons / cm^2 25×10^4 rad γ-ray	44×10^4	28.9×10^4

to neutron and proton irradiations, as determined by both methods, are summarized in Table 1.

Results

Unirradiated compressed pellets

The total pressure *vs.* time plots for the decomposition of compressed pellets not containing any aluminum admixtures closely resembled those of the powdered and single crystal material reported previously [2–4]. The curves are sigmoid and, at a given decomposition temperature, the observed induction period lies between the induction period for powdered material and single crystal material. Scanning electron microscope studies of pellets revealed that both the external surfaces and internal (fractured) surfaces closely resemble the final product obtained by decomposing single crystals. The individual grains of decomposed crystals contain numerous pits and voids typical of the open network structure previously observed [6].

Table 2 Thermal decomposition induction period and reaction rate constants for accerelatory and decay periods of unirradiated ammonium perchlorate pellets

Decomposition temperature /°C	Induction period length / min	Acceleratory period / k_6 (all k values in units of 10^{-2} min^{-1})	Decay period / k_7
228	55	3.06	3.37
224	62	2.67	2.54
220	75	2.08	2.20
215	105	1.48	1.50
211	130	1.14	1.19
207	190	0.76	0.92
203	260	0.57	0.74

The induction period was linear and described the extent of decomposition up to $\alpha = 0.05$. The length of the induction period, the acceleratory period rate constant, k_6, and the decay period rate constant, k_7, are tabulated, as a function of temperature, in Table 2. Plots of lg[1/(length of the induction period in minutes)], lg k_6 and lg k_7 *vs.* $1/T(K)$, where T is the isothermal decomposition temperature, were used to compute the corresponding activation energies. These were 133.5±6.7 for the induction period, 131.8±6.7 for the acceleratory period and 127.2±6.7 kJ/mol for the decay period. These values are in agreement with those found by Galwey and Jacobs [12] for pelleted material. They obtained,

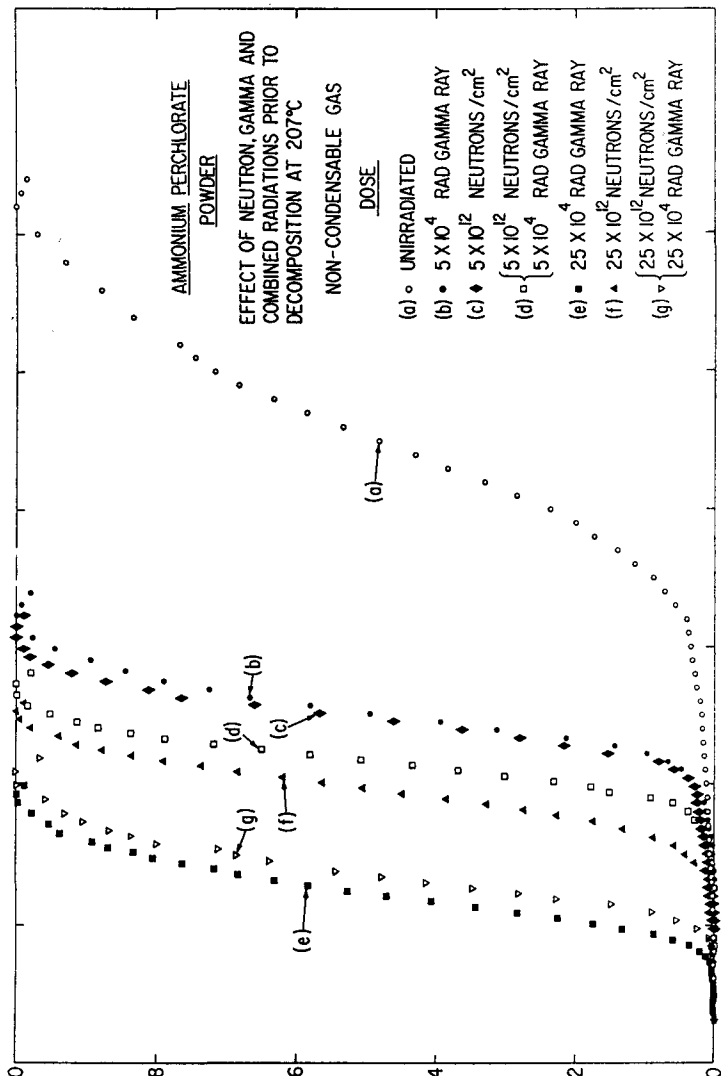

Fig. 1 The effects of gamma-ray, ^{235}U fission spectrum neutron and combined neutron and gamma-ray irradiation on powdered aluminum-ammonium perchlorate mixtures thermally decomposed at 227°C. In the combined irradiation the neutron irradiation always preceded the gamma-ray irradiation

using the Avrami-Erofeev equation with $n = 3$ to fit their data between $\alpha = 0.05$ to 0.75, an activation energy of 125.9 kJ/mol. Later, a redetermination was made by Jacobs *et al.* [13], using $n = 2$ between $0.03<\alpha<0.85$, and $n = 3$ between $0.03<\alpha<0.87$. The results obtained, using the appropriate Avrami-Erofeev equation for both regions, was a single activation energy of 111.3±3.6 kJ/mol. The activation energy of the induction period was determined to be 125.9±8.2 kJ/mol. An overall average of all their published data fitted to the Avrami-Erofeev equations yielded a value of 141.9±6.9 kJ/mol for pelleted material.

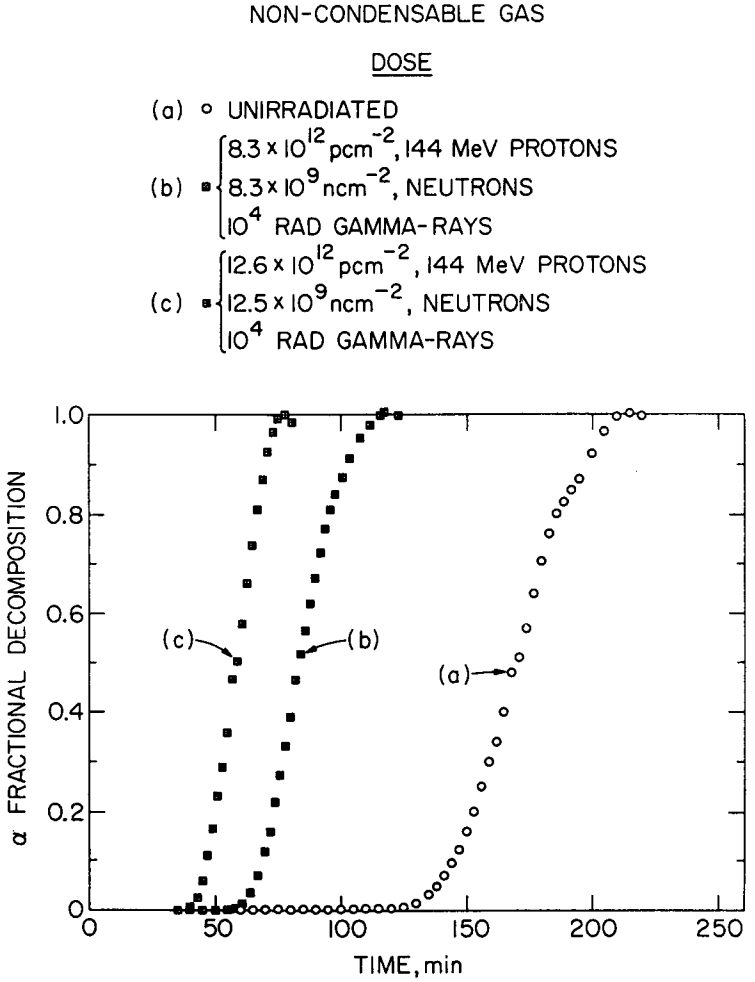

Fig. 2 The effects of combined proton and gamma-ray irradiations on ammonium perchlorate pellets thermally decomposed at 211°C

Irradiated powdered aluminum-ammonium perchlorate mixtures

Neutron and gamma-ray irradiated samples, both irradiated and unirradiated, were decomposed at 207°C (Fig. 1). The decomposition curves are similar to those obtained for single crystals, powder and pristine compressed pellets, i.e. they are clearly divided into an induction, acceleratory and decay period. As observed with single crystals and pristine powder [2], irradiations decrease the induction period and greatly increase the rate constants of the acceleratory and decay periods of the decomposed mixtures.

The Avrami-Erofeev kinetic analysis ($n = 4$ for the acceleratory, $n = 3$ for the decay period) was found to give a very good fit to all the data for the powder mixtures and alternative analyses were not attempted. Also, although the data are sparse, the induction period for these samples appears to follow the lg(dose) relation (Eq. 1) mentioned above. This data is summarized in Table 3.

Proton irradiated ammonium perchlorate pellets

Pelleted powdered ammonium perchlorate was subjected to a proton irradiation followed by a gamma-ray irradiation. During the proton irradiation the samples were subjected to small doses of fast neutrons and gamma-rays which have been included in the total dose calculations. Subsequently the samples were decomposed at 211°C with a trap at –95°C in the system. The resulting

Table 3 Thermal decomposition parameters for unirradiated and gamma-ray and neutron irradiated ammonium perchlorate aluminum mixtures

Measured irradiations	Induction period / min	Avrami-Erofeev constants	
		Acceleratory period $\times 10^{-2}$	Decay period $\times 10^{-2}$
Unirradiated	144	0.549	0.608
	146	0.557	0.583
5×10^4 rad γ-ray	72	1.667	1.871
5×10^{12} neutrons /cm^2	56	1.777	2.157
5×10^{12} neutrons /cm^2 25×10^4 rad γ-ray	56	2.105	2.546
25×10^4 rad γ-ray	25	1.907	1.982
25×10^{12} neutrons/cm^2	40	1.739	2.254
25×10^{12} neutrons /cm^2 25×10^4 rad γ-ray	36	1.904	2.037

$\alpha(t)$ curves are shown in Fig. 2. A decomposition curve for an unirradiated pellet is also shown. By applying the Avrami-Erofeev analysis the acceleratory (k_6) and the decay period (k_7) rate constants were obtained. These constants and the induction period data are tabulated in Table 4.

Table 4 Thermal decomposition parameters for unirradiated and proton irradiated ammonium perchlorate pellets at 211°C

Measured irradiations	Induction period / min	Avrami-Erofeev constants	
		Acceleratory period $\times 10^{-2}$	Decay period $\times 10^{-2}$
Unirradiated	130	1.14	1.19
8.3×10^{12} p cm^{-2}, 144 MeV proton 8.3×10^{9} n cm^{-2}, neutrons 1.0×10^{4} rad, gamma-ray	55, 55	2.14, 2.06	1.79, 1.73
12.6×10^{12} p cm^{-2}, 144 MeV proton 12.5×10^{9} p cm^{-2}, neutrons 1.0×10^{4} rad, gamma-ray	40, 40	3.84, 3.75	2.42, 2.48

The total energy deposited in this material may be calculated or may be expressed as a gamma-ray equivalent dose. The fluence of 10^9 neutrons cm^{-2} concomitant with the incident 144 MeV protons corresponds to a gamma-ray dose of approximately 20 rad and can be neglected. However, the energy deposited in ammonium perchlorate from the proton irradiation is significant. Using an effective $Z = 11.6$, for fluences of 8.3 and 12.6×10^{12} protons/cm^2, the imparted dose is 6.6×10^5 rad/g and 1.0×10^6 rad/g respectively. Using the alternative energy per atom method the imparted doses of 6.48×10^5 rad/g and 9.83×10^5 rad/g were obtained. In principle, the latter values should be the more reliable. To determine an equivalent gamma-ray dose from the (Induction period = $(\text{Const.})_1 - (\text{Const.})_2 \lg(\text{dose})$ relation, two procedures may be used. First, well established data must be available for gamma-ray irradiated samples decomposed at the temperature used for the measurements. Or, second, the measured induction periods, obtained at one temperature, must be convertible to temperatures for which an established curve is available. Unfortunately, only the latter alternative was possible. The only well established induction period data were determined at 227°C (Fig. 6 in Ref [4] and Fig. 6 in Ref. [15]). It is reasonably well established that the induction period temperature dependence is given by

the usual ln(–*E/RT*) dependence [11]. Using this relation and the measured activation energy for pellets, 133.5 kJ/mol, the 55 and 40 min induction periods determined at 207°C convert to 19.0 and 13.8 min periods at 227°C. The corresponding gamma-ray equivalent doses for these induction periods are roughly 3.0×10^5 and 1.0×10^6 rad.

These values are roughly equal or somewhat higher than the calculated proton dose. This is contrary to previous results. Past studies on fission neutron irradiated ammonium perchlorate have always led to gamma-ray equivalent doses which were two to five times larger than the calculated doses [15]. However, the proton flux measurements may not be sufficiently accurate to make this result significant. Also, this result should not be considered surprising. The fast proton energy loss rate is closer to the electron loss rate than that of the heavier, higher *Z*, charged lattice atom recoils.

Discussion and summary

From the results given above, several conclusions can drawn. For unirradiated pelleted ammonium perchlorate the activation energies obtained are consistent with previously reported single crystal [2, 3] and pelleted powders [13, 14]. Unlike previously reported results, the Avrami-Erofeev analysis was found to fit the data with $n = 4$ over the acceleratory period and the extent of fit was larger than previously reported. This might result from the grain size being different from that used in other studies. A smaller grain size would tend to increase the surface sites available for nucleation. Scanning electron microscopy showed that surface deterioration did not increase during prolonged storage. In addition, the surfaces of the decomposed pellets closely resembled those from single crystal decomposition.

The pellet radiation effects are, in general, the same as those found previously for both neutron and gamma-ray irradiated single crystals and powder. The irradiation shortens the induction period and produces a two to threefold increase in both the acceleratory period and decay period rate constants. Furthermore, these effects, as observed in single crystals, are consistently reproducible and independent of the time elapsed between irradiation and decomposition.

In addition, the proton results indicate that the 144 MeV protons do not change the decomposition kinetics as much as fission spectrum neutrons. In terms of the radiation damage mechanisms discussed in Refs [2] and [3], the 144 MeV protons are less effective than fission spectrum neutrons in creating decomposition sites. The calculated proton dose is equivalent to, or at most two times larger, than that given by the empirical induction period relation Eq. (1).

In contrast, the fission neutron results correspond to a dose 4 or 5 times higher than that determined from Eq. (1) i.e. induced by the heavier charged lattice atom recoils. The proton energy loss is more like that of electrons. Thus it was expected that the proton results would be more like the gamma-ray results. Stated alternatively, fission spectrum neutrons transfer a large fraction of their energy to the crystal by creating lattice atom recoils which are, compared to protons, heavy charged particles. Protons also produce lattice atom recoils but only a relatively small fraction of the incident energy is lost in this fashion.

The presence of aluminum particles in the aluminum-ammonium perchlorate powder mixtures might be expected to influence both the thermal decomposition mechanism and the neutron irradiation effects. In both cases studied here, this does not occur, at least in any obvious way. However, the aluminum powder content was only 7% and this may have been insufficient to give rise to an observable difference. More specifically, the inclusion of aluminum in powdered ammonium perchlorate did not markedly affect the thermal decomposition, at 207°C, observed in this study. Previous decomposition studies on pure powdered material (without aluminum inclusion) produced $\alpha(t)$ data which had shorter induction periods and higher Avrami-Erofeev acceleratory and decay rate constants than obtained with aluminum powder admixtures. This previously observed effect could result from:

(1) A deceleration of the reaction due to the presence of the aluminum inclusion i.e. a negative catalytic effect.

(2) It could be due to a difference in the particle size of the specimens. Smaller and more finely ground pure powder will decompose faster than aluminum mixtures containing larger ammonium perchlorate particles.

(3) Also there is the possibility that the presence of the metallic aluminum, which does not undergo the radiation damage observed in nonmetals, simply neutralizes a part of the absorbed dose proportional to the aluminum content. In fact, the aluminum particles are very efficient electron-hole recombination centers and, because of this, their influence may extend into the ammonium perchlorate surrounding each particle. In this case they could reduce the dose to the ammonium perchlorate crystals by a factor larger than that estimated from the aluminum content.

In summary, the effects of neutron irradiation, gamma-ray and combined gamma-ray and proton radiation on ammonium perchlorate and ammonium perchlorate-aluminum pellets are similar to the effect observed on single crystal material [15]. The induction periods are shorter and the acceleratory and decay periods rate constants are increased. The neutron effect is three to nine times larger, and the proton effect is roughly equivalent, to that expected from the calculated dose. Also the energy losses in the aluminum appear to have little

or no effect on the overall radiation damage. This is not surprising considering that $Z = 13$ in aluminum and the effective Z is 11.9 in ammonium perchlorate. The aluminum would receive approximately the same dose per unit mass as is imparted to the ammonium perchlorate. In other words the aluminum does not appreciably alter the dose, on a unit mass basis, received by the ammonium perchlorate. Thus, the presence of aluminum particles apparently does not alter in a detectable way, the large radiation effects that occur in the adjacent ammonium perchlorate crystals during irradiation and thermal decomposition.

In conclusion, the observed radiation effects (radiation damage) in admixtures of ammonium perchlorate and aluminum are large enough to indicate that any ammonium perchlorate propellants or aluminum ammonium-perchlorate mixtures used in radiation environments, similar to those described above, must be subjected to a thorough radiation damage study if reliable operation is to be assured.

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Zusammenfassung — Mit Hilfe der Bestimmung des Zersetzungs-Gasdruckes in Abhängigkeit von der Erhitzungsdauer und Proben bei kontrollierten Temperaturen wurde die Kinetik der

thermischen Zersetzung von bestrahltem und unbestrahltem Ammoniumperchlorat und eines Gemisches aus Ammoniumperchloratpulver und Aluminiumpartikel untersucht. Qualitativ ähneln die strahlungsinduzierten Änderungen denen, die in einer vorangehenden Untersuchung für 'reines' Ammoniumperchlorat gefunden wurden. Die Induktionsdauer wurde verkürzt und die Geschwindigkeitskonstante für Beschleunigungs- und Auslaufperiode erhöht. Die Daten wurden mit Hilfe der Avrami-Erofeev-Kinetik analysiert. Die Ergebnisse für reines unbestrahltes Material stimmen mit bisherigen Veröffentlichungen überein. Für die Aktivierungsenergie von Induktions-, Beschleunigungs- und Auslaufperiode wurden für reine Pellets Werte von 133.56.7, 131.86.7 und 127.26.7 $kJ \cdot mol^{-1}$ ermittelt. Die Proben wurden entweder einer einfachen Gammastrahlung, einer Spaltungsneutronenstrahlung gefolgt von einer Gammastrahlung oder einer Protonenstrahlung ausgesetzt. Verglichen auf der Grundlage gleicher Energieeinstrahlung induzieren schnelle Neutronen beträchtlich größere Veränderungen als Gammastrahlung. Protoneninduzierte Änderungen sind vergleichbar oder etwas größer als Effekte, die durch Gammastrahlung induziert wurden. Einige oder alle der durch schnelle Neutronen ausgelösten Effekte kann den konzentrierten Strahlungsschädigungs-Spitzen entlang des Weges der Gitteratomrückstöße zugeschrieben werden. Es ist wahrscheinlich, daß diese bei der Erhitzung der Kristalle zu Orten thermischer Zersetzung werden. Protonen verursachen weniger Spitzen als schnelle Neutronen. Die Ergebnisse zeigen, daß alle Ammoniumperchlorat – Aluminium Treibmittelgemische, die – wie in vorliegender Untersuchung – einer Strahlung ausgesetzt werden, einer Durchstrahlungseffektananalyse unterzogen werden sollten, wenn eine zuverlässige Funktion gefordert wird.