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THE EFFECT OF VARIATIONS IN THERMAL PROPERTIES ON TRANSIENT THERMOVISCO-ELASTIC RESPONSE OF PROPELLANT GRAINS

Donald L. Martin, Jr.

Army Missile Command
Redstone Arsenal, Alabama

January 1973

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The sensitivity of the transient thermoviscoelastic behavior of a case-bonded propellant grain to variations in thermal properties was investigated. The results indicate that a 10-percent increase in the propellant conductivity resulted in a 4.4-percent reduction of the temperature differential across the propellant grain, a 2.4-percent reduction in the cumulative damage at the inside surface of the propellant grain, and a 22-percent increase in the cumulative damage at the case-grain interface. A 10-percent increase in the convection coefficient outside the motor case resulted in a 2.2-percent increase in the temperature differential across the propellant grain, a 2-percent increase in the cumulative damage at the inside surface of the propellant gr[illegible]n, and a 1-percent reduction in the cumulative damage at the case-grain interfac[illegible] The variation in the thermal conductivity and convection coefficient is shown [illegible] additive with respect to their effect on the temperature differential across the [illegible]nt grain and the cumulative damage fraction.

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CONTENTS

1. Introduction

The ability to predict numerically the structural integrity of propellant grains subjected to various complex thermal and mechanical loading conditions requires as a prerequisite the characterization or mathematical description of the mechanical and thermal response of each of the materials in the system. The mathematical description of the materials response to thermal and mechanical loading together with the knowledge of applied surface loads and displacements and the appropriate field equation of engineering mechanics and thermodynamics comprise a system of equations whose solution yields the temperature, stress, and strain at the various points within the grain. The success or failure of a structural reliability prediction can only be as good as the material properties or constitutive equations defining the material's response. The structural reliability of a propellant grain design requires a comparison of calculated stresses and strains within the body with some established failure criterion. Therefore a failure analysis will be of little consequence if the predicted stresses and strains are in error.

It has long been recognized that the constitutive equation, loads definition, structural analysis, and failure criterion are interrelated and the motor performance predictions are equally dependent on the accuracy of each of these elements. The purpose of this report is to discuss the effect of variations in certain thermal properties on the temperature distribution and the viscoelastic response of a propellant grain when subjected to transient thermal loads.

A knowledge of the propellant's density, specific heat, thermal conductivity or thermal diffusivity, and coefficient of thermal expansion is required for the ballistic design and structural analysis of solid propellant rocket motors. Density determinations are normally made using the bouyancy technique, an air pycnometer, or similar methods. Specific heat determinations normally utilize calorimetry techniques. The garded hot plate [1, 2] is apparently the most accurate of several methods used in determining the thermal conductivity. The direct measurement of the thermal diffusivity is very difficult and is normally calculated from the density, specific heat, and thermal conductivity. The thermal expansion coefficient is routinely determined from linear measurements of change in sample length with temperature utilizing a quartz tube or similar dilatometer. An important question arises concerning the accuracy of the determination of these thermal properties and the effect errors in their determination will have on failure predictions utilizing state-of-the-art linear thermoviscoelastic analysis.

Several significant studies have been reported in the literature [3 - 6] which indicate favorable comparison between the heat transfer theory and experimental results. San Miguel [7] conducted a sensitivity analysis to determine the effect of thermal properties uncertainties on the temperature gradients in propellant grains. San Miguel concluded that specific heat could be determined with 10 percent, thermal conductivity within 50 percent, and that the heat convection coefficient could be estimated within 100 percent of the actual value. However, other authors [1, 2, 8] present data in support of their conclusion that thermal conductivity can be determined within ±5 percent. Probably the most uncertainity in a thermal analysis is associated with the coefficient of convective heat transfer which determines the amount of heat flow allowed to cross the boundary as a function of time and temperature. Most of the time this coefficient must be estimated or experimentally determined for the particular problem at hand [4]. Most investigators tend to agree that with sufficient care and instrumentation the thermal properties can be determined experimentally within 10 percent. However, it is not the intent in this investigation to determine the amount of absolute uncertainity associated with the measurement of each thermal property, but rather to determine what effect the variations in thermal properties will have on the structural integrity analysis of propellant grains under transient loading conditions.

2. Method of Analysis

A closed form solution to the transient thermoviscoelastic response does not exist because of the complexity associated with the problem. Several computer programs are available to the propellant industry that utilize combined heat conduction and stress analysis codes based on the finite element approach [9 - 13]. These programs may be used to predict the thermoviscoelastic response of propellant grains when subjected to transient or steady state boundary conditions. Three computer codes are currently in operation in the Propulsion Directorate that will handle the transient thermoviscoelastic problem. These are the thermoviscoelastic stress analysis program from the University of California, Berkley [11]; the computer code for the transient heat conduction/thermoviscoelastic stress analysis of infinite cylinders from Aerojet General Corporation, Sacramento, California [10]; and the code for the dynamic one-dimensional transient thermoviscoelastic analysis (DIDTTV) from the Propulsion Directorate, US Army Missile Research, Development and Engineering Laboratory, US Army Missile Command (MICOM), Redstone Arsenal, Alabama [12]. The DIDTTV program of the MICOM Propulsion Directorate was selected to study the effect of variations in the propellant thermal conductivity and the film convection heat transfer coefficient on the outside of the motor case. It is of interest to determine how the output from DIDTTV compares with that of Aerojet's and Berkley's. The transient thermoviscoelastic behavior of a case-bonded propellant grain when subjected to a complex thermal environmental history was analyzed by the three programs.

The motor propellant grain had an inside radius of 0.375 inch and an outside radius of 1.31 inches. The grain stress free temperature was considered to be 110°F. The motor was analyzed for the environmental history presented in Figure 1. The environmental temperature was considered to be initially at the stress free temperature of 110°F. The

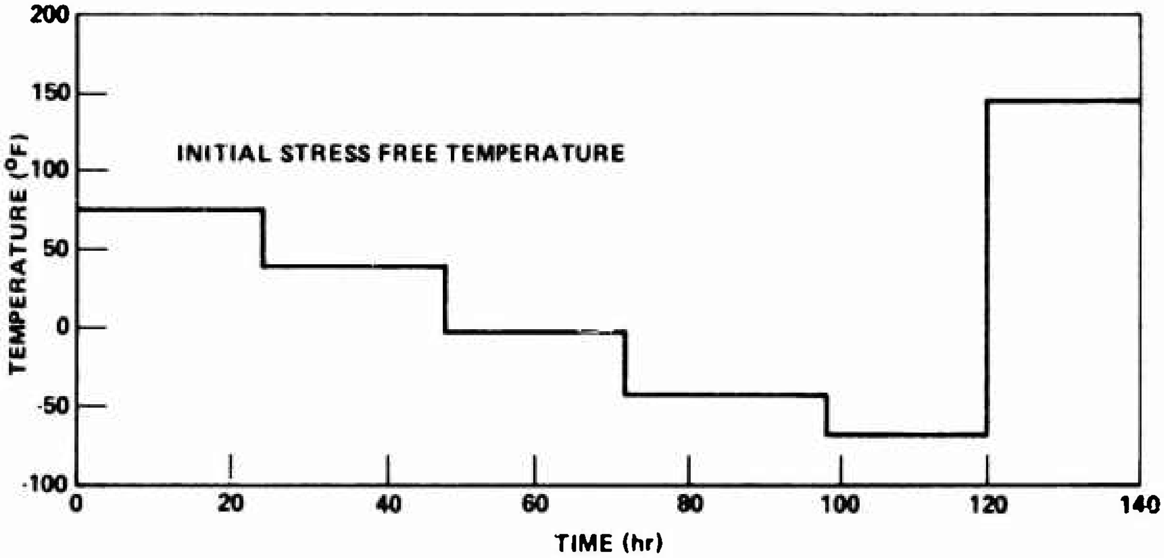

Figure 1. Environment Temperature Versus Time

environmental temperature was changed instantaneously to 75°F at 0 hour, 40°F at 24 hours, 0°F at 48 hours, -40°F at 72 hours, -65°F at 96 hours, and 150°F at 120 hours. The environmental temperature was maintained constant for 24 hours after each change. The solution time points for each 24-hour interval were chosen to be 10 at 0.01 hour each, 9 at 0.1 hour each, 20 at 0.25 hour each, and 9 at 2.0 hours each. The temperatures, stresses, and strains were determined for each solution time point for the plane strain configuration. Each computer program utilizes the same grid network for the heat conduction and stress analysis. Plots of the hoop stress in the element nearest the inside surface of the propellant grain versus elapsed time from the start of the cycle as obtained from Aerojet's, MICOM's, and Berkley's programs are presented in Figure 2. The program of the University of California at Berkley predicted a slightly higher stress than either Aerojet's or MICOM's programs for the first three 24-hour portions of the cycle but appeared to loose much of its sensitivity to temperature changes for times longer than 72 hours. Aerojet's and MICOM's programs appeared to retain the same degree of sensitivity to temperature changes throughout the cycle. Aerojet's program predicted values of stress slightly larger than MICOM's program throughout the cycle. Based on the results presented in Figure 2 and easier data input procedure, MICOM's DIDTTV program was chosen for the study of the effects of variations in propellant conductivity and convection coefficient. The cumulative damage calculation based on the maximum principal stress in the element, as used by Aerojet [10], was incorporated in MICOM's DIDTTV program.

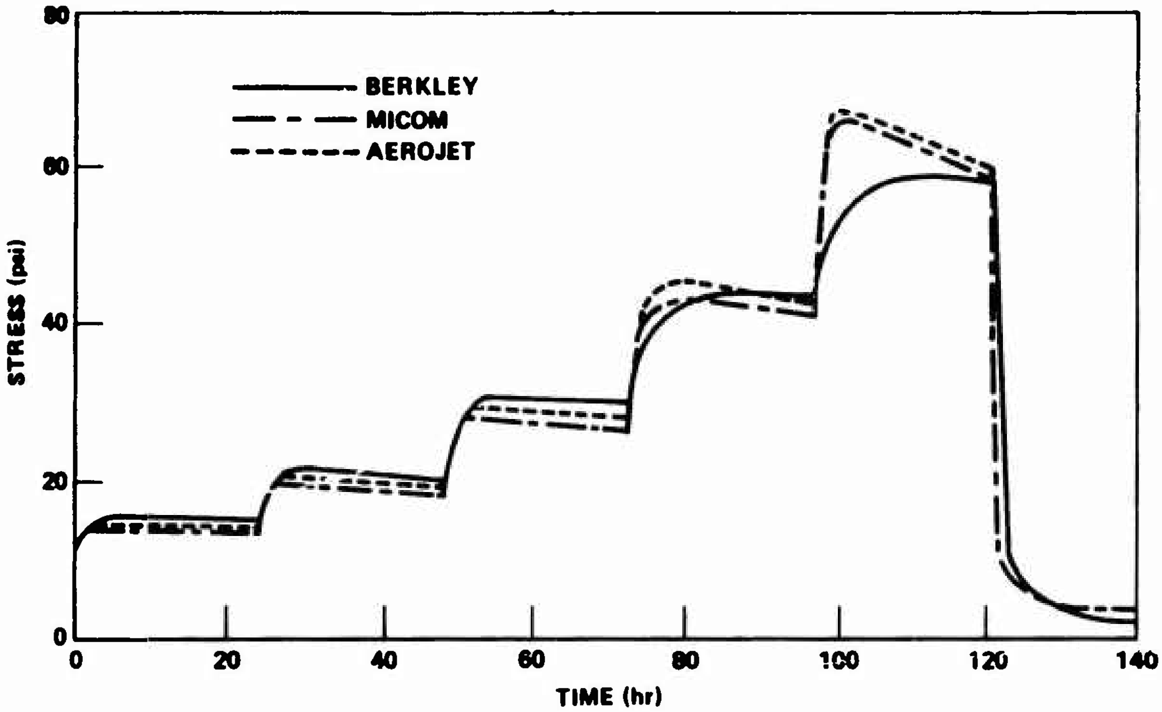

Figure 2. Hoop Stress at Inside Grain Surface Versus Time

3. Results

The effect of changes in propellant conductivity and the convection coefficient on the transient thermal stress in propellant grains were investigated. A case-bonded propellant grain was analyzed in a plane configuration. The grain dimensions were 5.75 inches inside diameter and 8.0 inches outside diameter. The environmental temperature was instantaneously changed from a stress free temperature of 110°F to -100°F and held at -100°F for 48 hours. The material properties presented in Table I were assumed to be temperature independent. Only the propellant and liner shear modulus was assumed to be dependent on time and temperature. The Prony series representation of the propellant and liner shear modulus is presented in Table II. The time-temperature shift factor, Log a_T, was determined from the predicted temperature for each element at each time step according to the relationship [4]

$$\text{Log } a_T = \left\{ \frac{-8.86 \left(T_m - T_s\right) \frac{5}{9}}{101.6 + \left(T_m - T_s\right) \frac{5}{9}} + 3.26 \right\} \left(1 + V_e\right) \qquad (1)$$

where

T_m = element temperature, °F

T_s = reference temperature, °F

V_e = volume fraction or extractable binder which was equal to 0.20 for the material used.

Table I. Material Properties

Property	Propellant	Liner	Case
Conductivity, K (Btu/in., hr, °F)	0.0209	0.0103	1.2167
Specific Heat, C_p (Btu/lb, °F)	0.262	0.229	0.086
Density, ρ (lb/in.^{3})	0.064	0.064	0.289
Thermal Expansion Coefficient, α (in./in., °F)	5.51×10^{-5}	5.51×10^{-5}	5.9×10^{-6}
Shear Modulus (psi)	*	*	1.15×10^{7}
Bulk Modulus (psi)	5.46×10^{5}	5.46×10^{5}	2.68×10^{7}

*The propellant and liner shear modulus is represented by the Prony series given in Table II.

Table II. Series Representation of Propellant and Liner Shear Modulus

Modulus Component	Relaxation Time
4285.6	2.0×10^{-10}
1010.7	2.0×10^{-8}
372.27	2.0×10^{-6}
83.270	2.0×10^{-4}
48.225	2.0×10^{-2}
25.055	2.0×10^{0}
4.5228	2.0×10^{2}
10.469	2.0×10^{4}
20.000	2.0×10^{10}

a. Time Dependency of the Analysis

Thus with the elapsed time and temperature of each element known, the appropriate temperature shift factor and hence the reduced time and appropriate shear modulus were determined. The property values given in Tables I and II were used as the reference conditions. Figure 3 presents a plot of temperature versus radius for the reference properties.

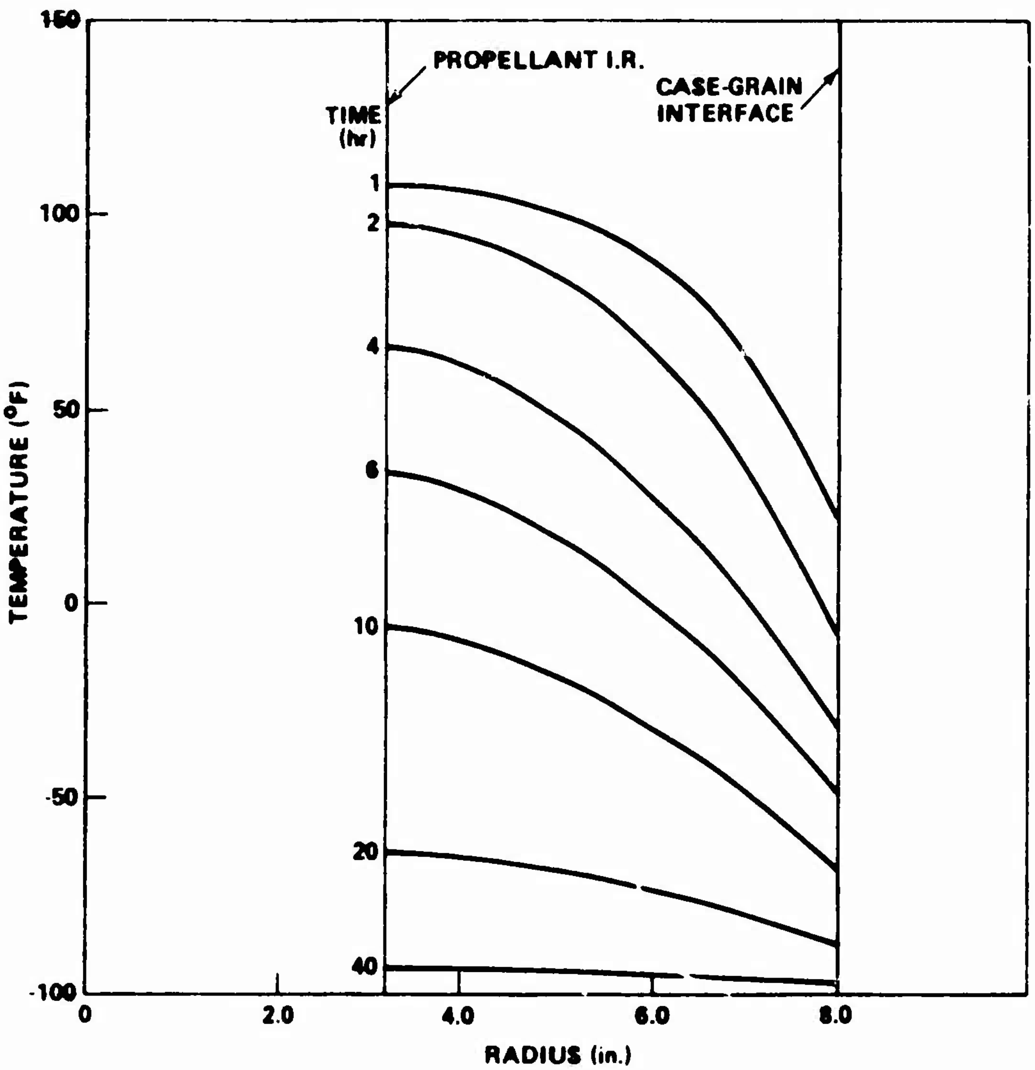

Figure 3. Temperature Distribution Versus Radius

The calculated temperature differential across the propellant grain varied from a maximum of approximately 108°F at 2 hours to approximately [illegible]°F at the end of 48 hours. Figure 4 presents a plot of the calculated hoop strain versus radius at the specified times. The hoop strain varied from near zero at the case-grain interface to a maximum at the inside

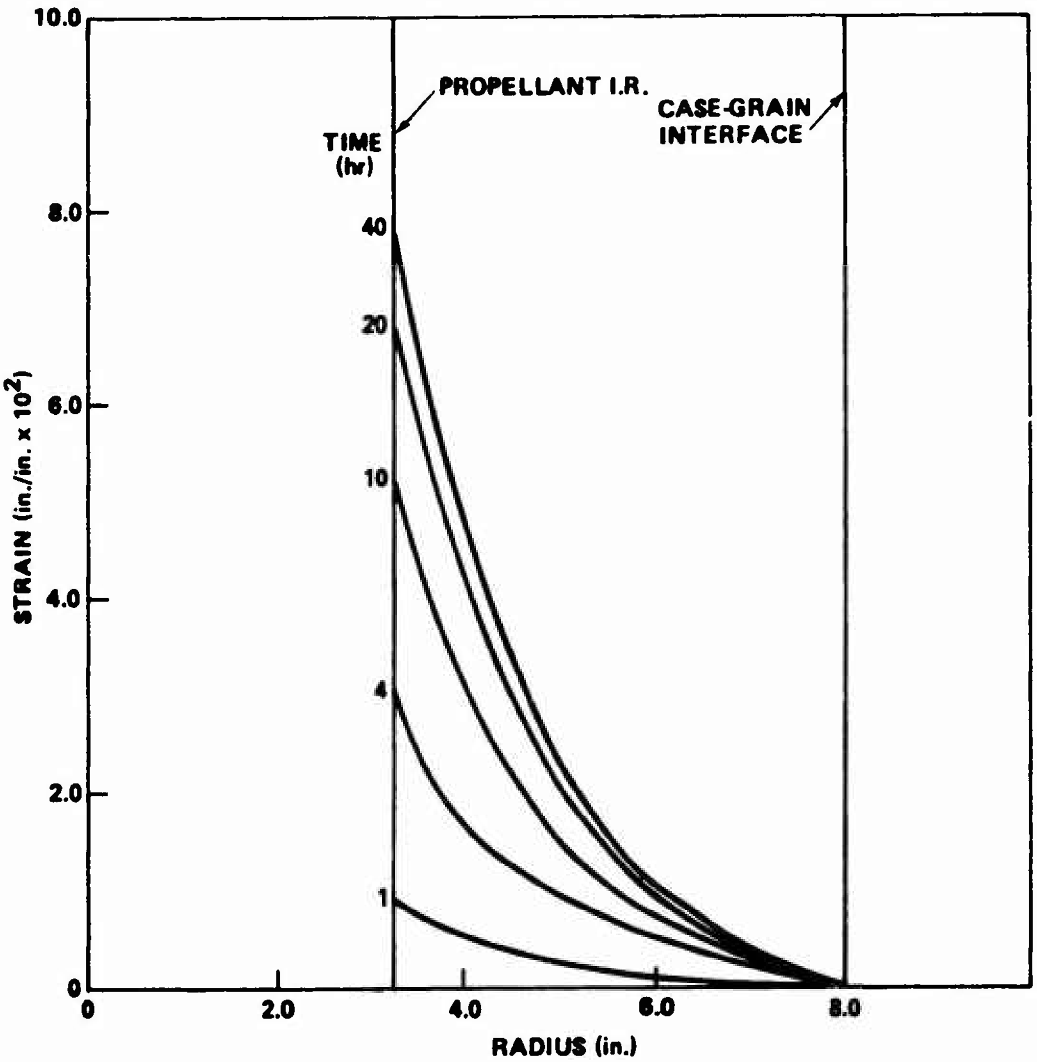

Figure 4. Hoop Strain Versus Radius

surface of the propellant grain. The hoop strain in the element closest to the inside surface continually increased with time to approximately 8 percent at the end of 48 hours. The hoop stress versus radius at the specified times is presented in Figure 5. At times up to approximately 10 hours, the maximum hoop stress in the propellant grain was at the case-grain interface. The maximum hoop stress then shifted to the inside surface of the propellant grain at longer times. A comparison of Figures 3 and 5 indicates that when the temperature differential across the propellant grain is approximately 60°F the hoop stress at the case-grain interface is approximately equal to that at the inside surface of the propellant grain. At temperature differentials larger than 60°F (times $<$ 10 hours), the thermal gradients are such that the maximum hoop stress occurs at the case-grain interface. At temperature differentials across the

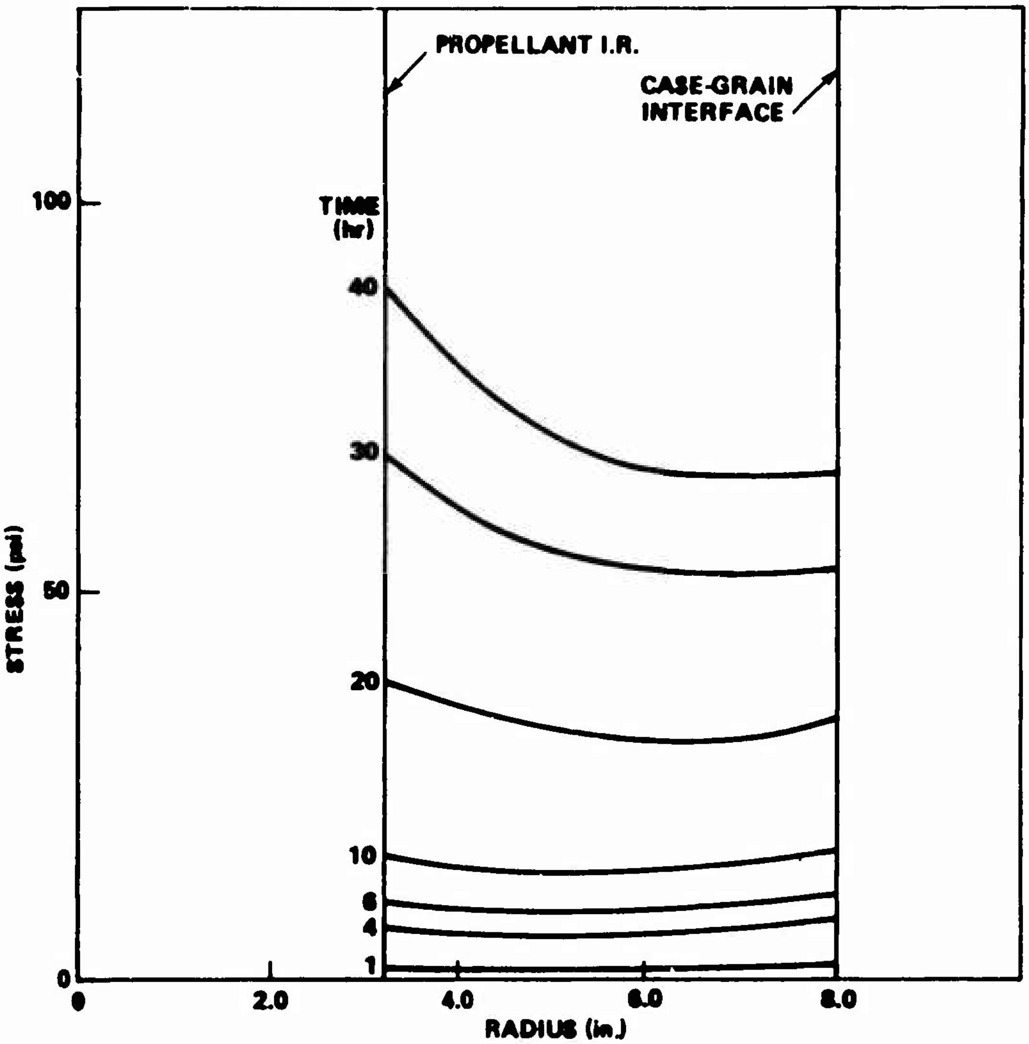

Figure 5. Hoop Stress Versus Radius

grain less than 60°F (times > 10 hours), the thermal gradient through the grain is approximately the same and therefore the maximum hoop stress occurs at the inside grain surface. The radial stress versus radius at the specified times is presented in Figure 6. The radial stress is a maximum at the case-grain interface at all times and approaches zero at the inside surface of the grain. It is interesting to note that the hoop stress near the case-grain interface is always larger than the radial stress for the problem investigated. This condition is expected to change during the heating portion of a thermal cycling environment. Figure 7 presents the log of the cumulative damage versus radius at the end of 48 hours. The cumulative damage calculations are based on the maximum principal stress in the element and is calculated according to Bills' Method [10]. The log of the cumulative damage varies from approximately -6.6 at the case-grain interface to -3.65 at the inside surface of the propellant grain.

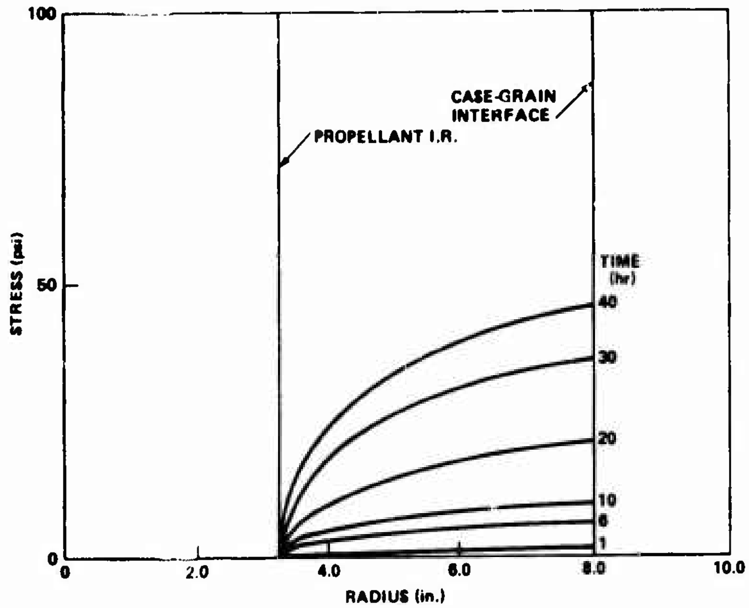

Figure 6. Radial Stress Versus Radius

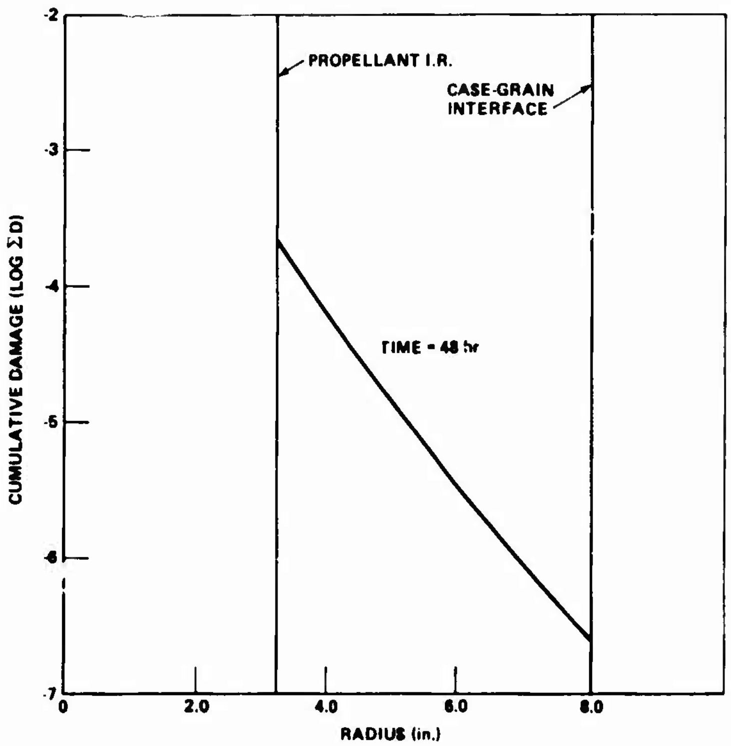

Figure 7. Cumulative Damage Versus Radius

b. Temperature Gradients

The temperature gradient and the differential temperature across the propellant grain were shown in the previous section to influence the place of maximum stress within the propellant grain. The next phase of this investigation is to determine the effect of changes in the propellant conductivity and convection coefficient on the temperature differential across the propellant grain and the thermal gradients within the grain. From Figure 3 it is noted that at times larger than 2 hours as the temperature differential across the propellant grain decreases, the maximum thermal gradient within the grain also decreases. Therefore, we will examine the temperature differential across the propellant grain and see how this quantity changes with variation in the thermal properties. The ΔT across the propellant grain versus the propellant conductivity is presented in Figure 8. The temperature differential across the propellant grain continually decreases with increases in the propellant conductivity. From Figure 8 it is noted that increasing the propellant conductivity from 0.020 to 0.030 Btu/in., hr, °F, decreases the temperature differential across the propellant grain by approximately 22°F.

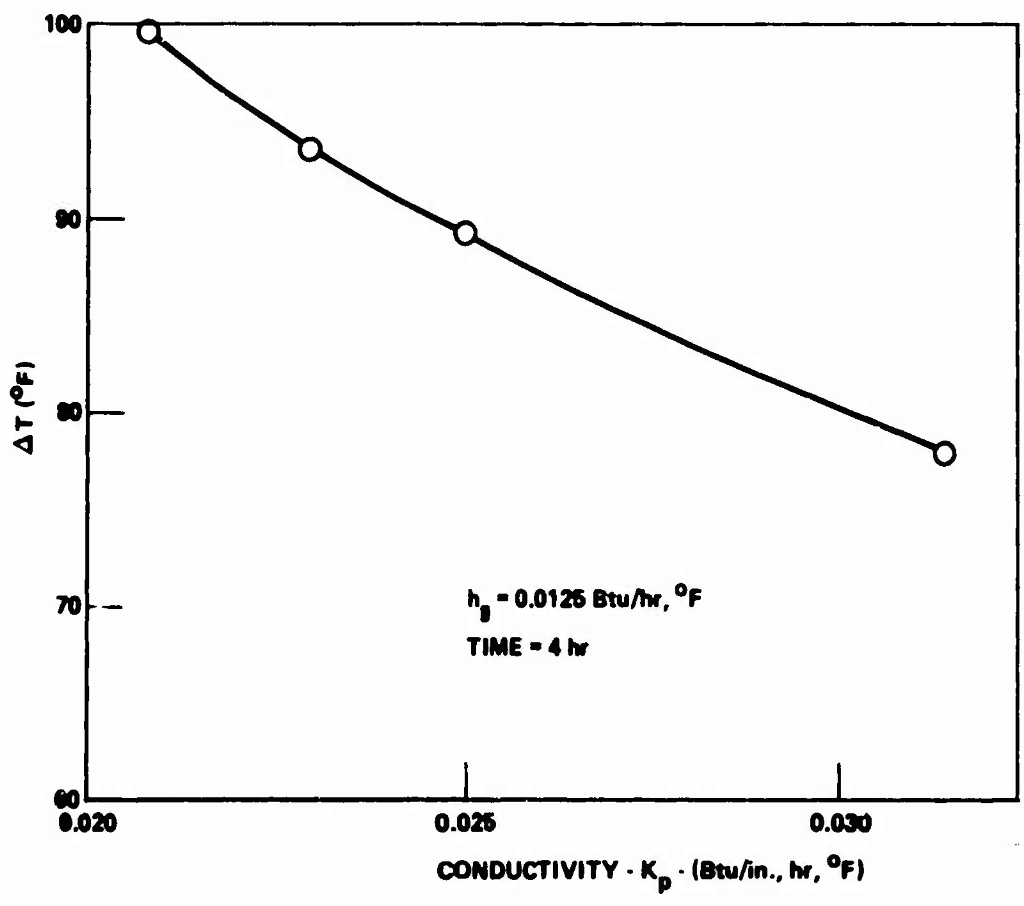

Figure 8. ΔT Across the Grain Versus the Propellant Conductivity

Therefore, as a general rule, one can conclude that a 10 percent increase in the propellant conductivity will result in approximately 4.4 percent decrease in the temperature differential across the grain.

Figure 9 presents a plot of ΔT across the propellant grain versus the convection coefficient outside the motor case. Increasing the convection coefficient increases the temperature differential across the grain. Increasing the convection coefficient by 50 percent increased the ΔT across the motor by approximately 8°F. Therefore these data indicate that the temperature differential across the motor is less sensitive to the errors in the convection coefficient than in the propellant conductivity for cooling problems. As a general rule a 10-percent increase in the convection coefficient results in approximately a 2.2-percent increase in the temperature differential across the propellant grain.

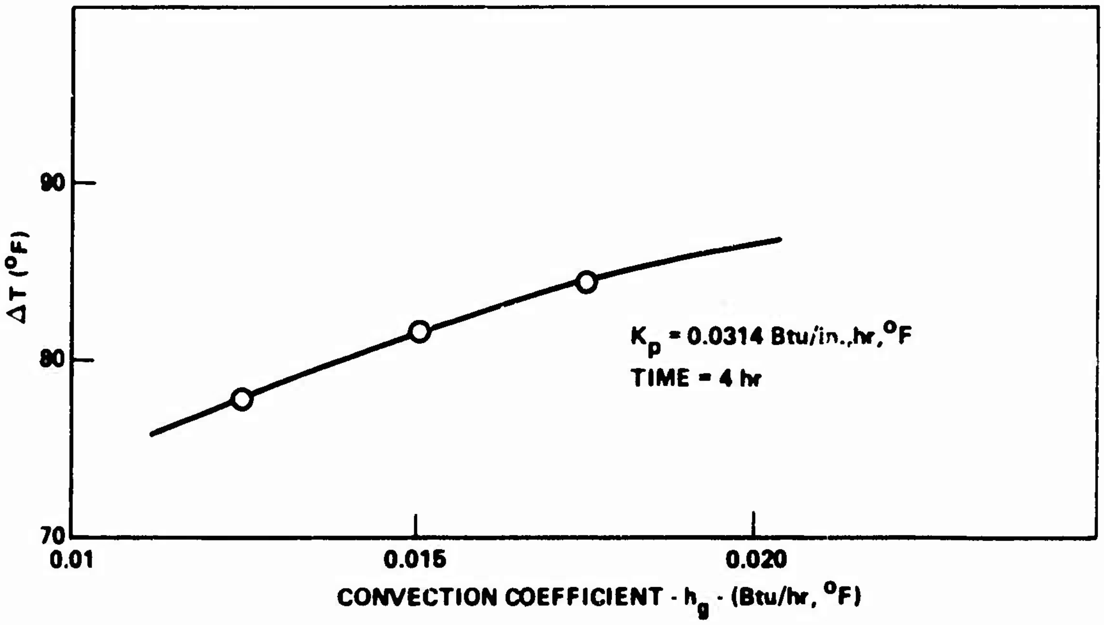

Figure 9. ΔT Across the Grain Versus the Convection Coefficient

Additional computer analyses were conducted in which the propellant conductivity and the convection coefficient were increased simultaneously by 20 percent and then 50 percent from the reference properties to determine if the resultant of changes in the individual properties were additive. Figure 10 presents ΔT across the propellant grain versus the change factor for the propellant conductivity and convection coefficient. Increasing the propellant conductivity and the convection coefficient simultaneously by 50 percent decreased the temperature differential across the propellant grain by approximately 14°F. This is the same conclusion one would reach by adding the effects of changes in the individual properties presented in Figures 8 and 9.

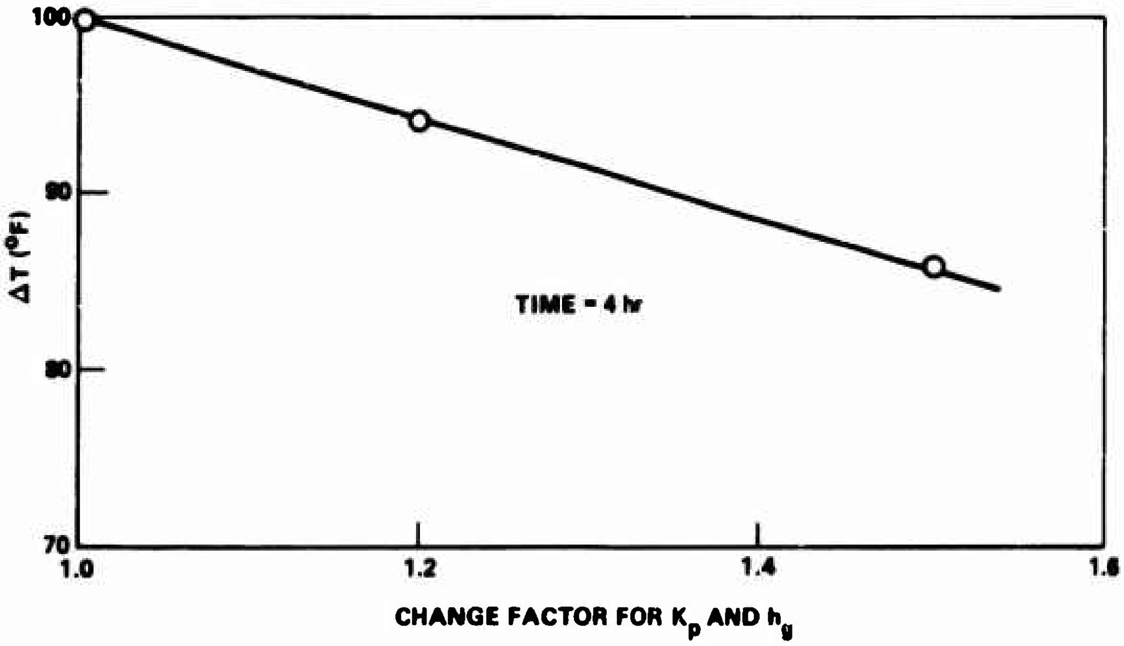

Figure 10. ΔT Across the Grain Versus Simultaneous Change in K_p and h_g

c. Cumulative Damage

The changes in the propellant conductivity or convection coefficient affect the temperature distribution within the propellant grain as indicated in the previous section. The maximum temperature differential and the associated transient thermoviscoelastic response do not necessarily occur at the same time step because of the different rates of heat transfer produced by changes in the thermal properties. It was therefore desirable to select a quantity that would reflect the effect of variations in the thermal properties over the total time frame. The quantity selected for this correlation was a cumulative damage calculation based on the maximum principal stress in the element and a stress-time failure relationship established from laboratory experimental data [10]. In Figure 7, which was discussed previously, the cumulative damage for this cooling study indicated that the log of the cumulative damage for the reference properties varies approximately linearly across the radius. The points of most interest in cooling problems of the type considered are usually the hoop stress at the inside surface of the propellant grain and the bond stress at the case-grain interface. Figure 11 presents changes in cumulative damage versus changes in the propellant conductivity. The cumulative damage at the propellant grain inside diameter is shown to decrease with increases in the propellant conductivity. A 50-percent increase in the propellant conductivity reduces the cumulative damage at the inside surface of the propellant grain by approximately 12 percent. Therefore a 10-percent increase in the propellant conductivity

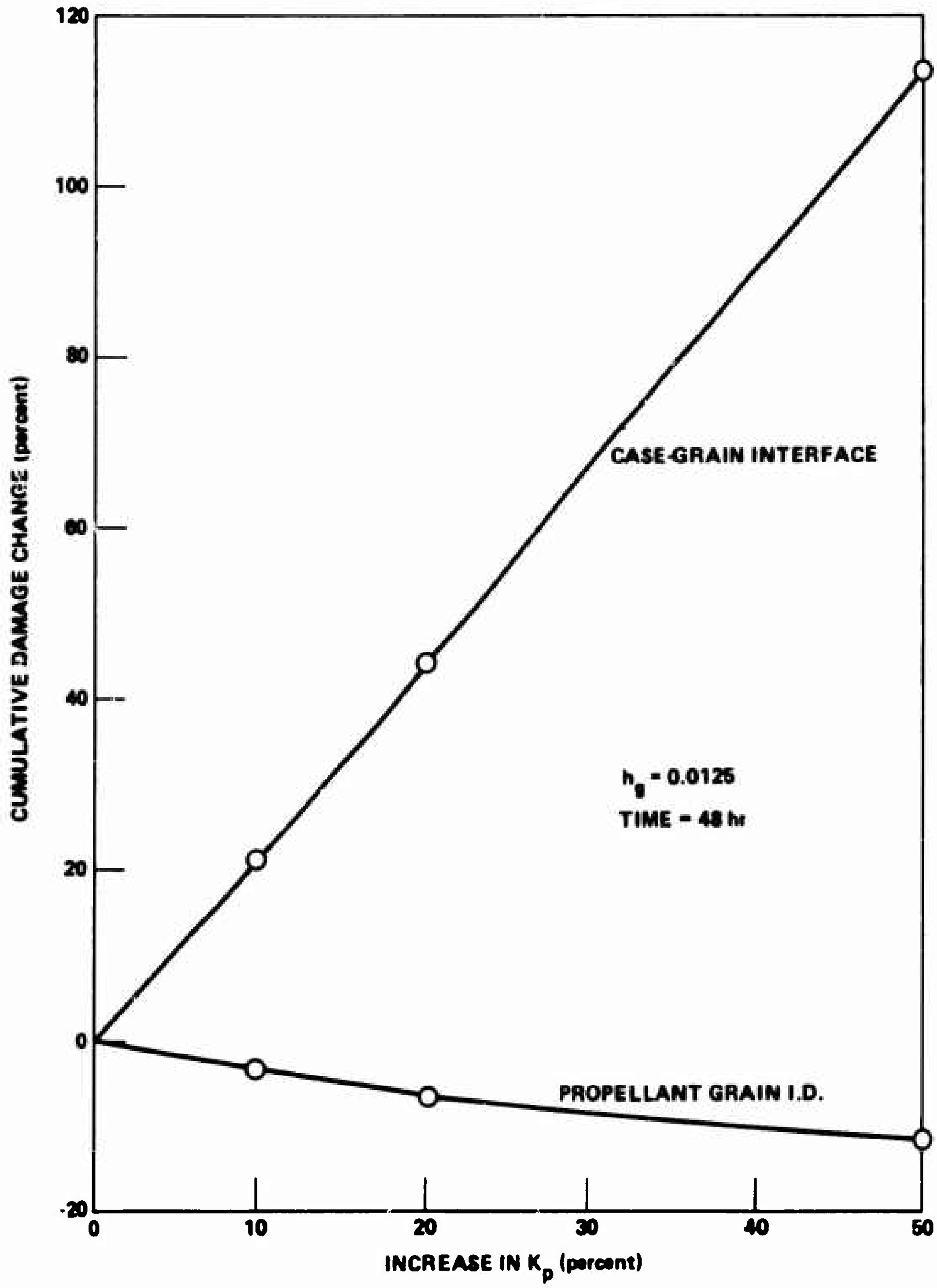

Figure 11. Cumulative Damage Change Versus Propellant Conductivity Change

decreases the cumulative damage at the inside surface by approximately 2.4 percent. The cumulative damage at case-grain interface is shown to increase by approximately 114 percent for a 50-percent increase in the propellant conductivity. These data indicate that a 10-percent change in the propellant conductivity would result in approximately a 22-percent increase in the cumulative damage at the case-grain interface. No other webb fractions were analyzed but the relationships would be expected to hold for different webb fractions of propellant.

Figure 12 presents the cumulative damage change versus changes in the convection coefficient. Increasing the convection coefficient is shown to increase the cumulative damage at the inside surface of the propellant grain and decrease the cumulative damage at the case-grain interface. A 10 percent change in the convection coefficient increases the cumulative damage at the inside surface of the propellant grain by approximately 3 percent while the cumulative damage at the case-grain interface is decreased by approximately 1 percent.

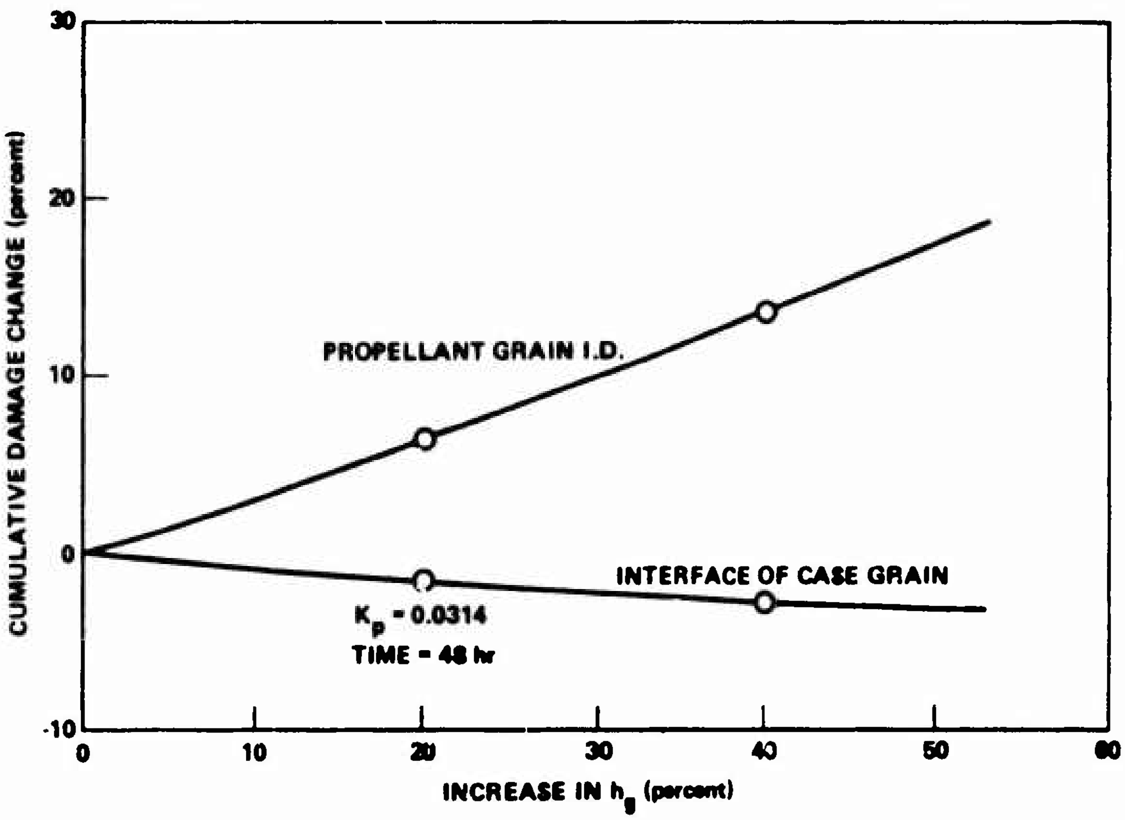

Figure 12. Cumulative Damage Change Versus Convection Coefficient Change

Figure 13 presents plots of the cumulative damage versus simultaneous increases in the propellant conductivity and convection coefficient. A 10-percent increase in both properties simultaneously produced approximately a 1-percent decrease in the cumulative damage at the inside surface of the propellant grain and approximately a 20-percent increase in the cumulative damage at the case-grain interface. These data indicate that the effect of individual changes in K_p and h_g properties on the cumulative damage is also additive.

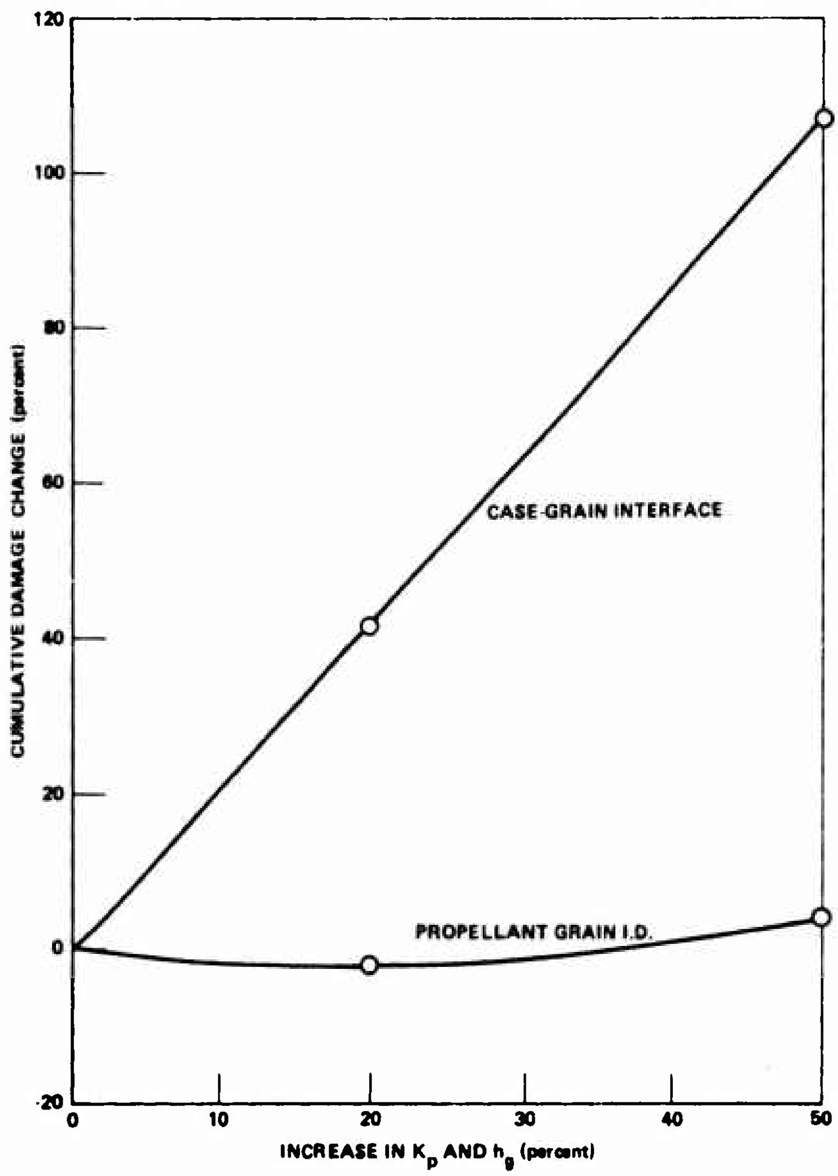

Figure 13. Changes in Cumulative Damage with Simultaneous Changes in K_p and h_g

4. Conclusions

The effects of variations in the propellant conductivity and the convection coefficient on the transient thermoviscoelastic response of a case-bonded propellant grain were investigated. The initial environmental temperature was instantaneously changed from the stress-free temperature of 110°F to -100°F and maintained at -100°F for 48 hours. The results presented indicate that, as a general rule for cooling problems, a 10-percent increase in the propellant conductivity resulted in approximately a 4.4-percent reduction in the temperature differential across the propellant grain, a 2.4-percent reduction in the cumulative damage at the inside surface of the propellant grain, and a 22-percent increase in the cumulative damage at the case-grain interface. A 10-percent change in the convection coefficient outside the motor case results in approximately a 2.2-percent increase in the temperature differential across the propellant grain, a 3-percent increase in the cumulative damage at the inside surface of the propellant grain, and a 1-percent decrease in the cumulative damage at the case-grain interface. The propellant conductivity and the convection coefficient are shown to be additive with respect to their effect on the temperature differential and the cumulative damage.

While no thermal cycling problems or different motor geometries were analyzed in this investigation, it is anticipated that qualitatively the same general relationships will be approximately true for these situations. Future work should be directed toward an investigation of these situations.

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