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TEMPERATURE COMPENSATION TECHNIQUES AND TECHNOLOGIES - AN OVERVIEW

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Most current propulsion concepts are designed to operate below optimum performance levels solely because of the need to compensate for temperature sensitivity. Performance at ambient temperature is restricted such that firing under temperature extremes will not exceed system safety limits for pressure. This allows a propulsion concept to perform worldwide in environments ranging from desert to arctic.

If a system were available which had little or no temperature sensitivity in practical operating environments (-45 degrees C to 63 degrees C) propulsion concepts could be designed to operate at peak pressure levels through all temperatures. Such system optimization through temperature compensation could achieve significant performance gains.

Various concepts have been proposed, suggested, or in a few cases experimentally demonstrated which attempt to achieve temperature compensation. This paper surveys available literature on such concepts and assesses the practicality and performance benefits of each. Concepts addressed include chemical techniques (propellant formulation and use of additives), propellant surface area control, and relatively new volume compensation techniques.

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1. INTRODUCTION

Propulsion systems for conventional gun-based weapon systems are designed to operate safely over a variety of environmental conditions. Extremes of temperature are one of the more important conditions which the propulsion designer must consider when contemplating a new charge design. Global as well as widely varying local climatic conditions generally dictate that a propulsion concept must perform safely at temperature extremes of at least -45° C to +63° C.

Meeting these requirements with chemical based propulsion systems has entailed limiting the performance of the system at ambient conditions (21° C) so that when the system is fired at high temperatures safety constraints on chamber pressure are not exceeded. Since ambient, or close to ambient, conditions may represent a high percentage of the weapons exposure, it becomes obvious that weapon performance is rarely optimized. In addition, performance at lower temperatures generally degrades further, since the cold temperature pressures are usually lowest. Tables 1 and 2 detail velocity and pressure data for typical tank and howitzer propelling charges. Note that in general, higher pressure systems exhibit higher temperature coefficients.

Table 1. Typical Howitzer Charge Temperature Performance

155-MM 198 Howitzer Firing M203A1 Charge, System Pressure Limit 405 MPa

Parameter	Cold	Ambient	Hot
Chamber pressure (MPa)	311	363	394
Velocity (m/s)	782	833	860
Temperature coefficients			
Pressure (MPa/°C)	-0.72		0.74
Velocity (m/s/°C)	-0.71		0.64
Percent pressure change from ambient	- 14		9
Percent velocity change from ambient	- 6		3

Cold -51 ° C, Ambient 21° C, Hot 63° C

It is obvious that significant performance gains could be realized if the designer could control the changes in propulsion performance with temperature, usually termed velocity and pressure coefficients of temperature. Figure 1 demonstrates graphically the the result of flattening this coefficient.

Reducing temperature coefficients in gun based weapons will be referred to henceforth as temperature compensation techniques or simply temperature compensation. It is the intent of the authors to quickly review past research and then present results from recent inquiries.

Table 2. Typical Tank Charge Temperature Performance

120-MM M256 Cannon Firing M829 Cartridge, System Pressure Limit 670 MPa

Parameter	Cold	Ambient	Hot
Chamber pressure (MPa)	416	526	653
Velocity (m/s)	1535	1675	1768
Temperature Coefficients			
Pressure (MPa/° C)	-1.64		3.02
Velocity (m/s/° C)	-2.09		2.21
Percent pressure change from ambient	- 21		24
Percent velocity change from ambient	- 8		6

Cold -46 °C, Ambient 21 °C, Hot 63° C

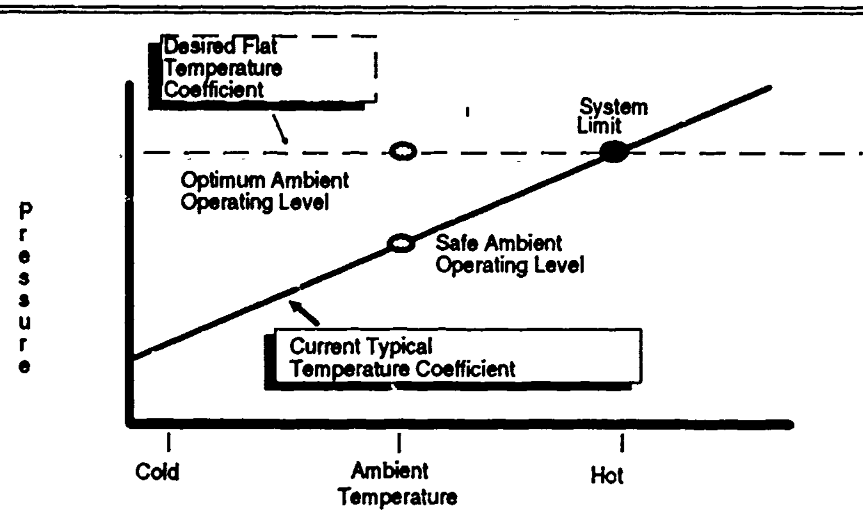

Figure 1. Real and Ideal Temperature Coefficients

Before addressing the details of past and present attempts to reduce temperature coefficients it is worthwhile to consider the idea of always firing the charge at the hot temperature limit.

Maintaining the ammunition storage areas in tanks and self-propelled artillery at hot temperatures has been discussed for several years. Using this method the charge could always operate at peak performance levels. Should the ammunition heating mechanism not work the charges could still safely be fired since they would perform at normal lower pressure and performance levels when cooled.

There are of course some readily foreseeable problems with this technique. First, the propellant might change performance levels after long periods of high temperature soaking or cycling due to the release of volatiles. Second, without the main power plant of the vehicle operating, a possible scenario for dug-in or concealed operations, there is not likely to be enough power to continue heating the propellant. Finally, many non-powered systems simply may not have the ability for propellant conditioning.

For certain applications, however, the idea seems to have significant merit and is worth further consideration.

2. THE GROUND RULES AND THEORY

The primary reason that temperature compensation techniques are difficult to achieve and promote is that by their very nature they are pushing a system to its "upper limits". By that it is meant that attempting to reduce the temperature coefficient of a propulsion system usually entails operation at top pressure levels for ambient conditions with temperature induced changes controlled or mitigated. Should these controls or techniques fail, the weapon system would likely be subjected to unacceptable and unsafe loads. Therefore the temperature compensation technique, whatever design it might take, must be absolutely fail-safe. This limitation is stated at the outset not to discourage examination of the feasibility of such concepts but as a common design constraint that is always present if not explicitly stated in the following discussions.

The variables available to the charge/weapon designer to control temperature related performance are controlled by basic physics starting with the equation of state:

$$P(V - mb) = nRT \, , \qquad (1)$$

where P = pressure, V = volume, n = moles of gas, R = universal gas constant, T = temperature, m = propellant gas mass, and b = covolume. Rearranging to $P = \frac{nRT}{(V - mb)}$ reveals the obvious dependency of pressure on available volume.

A projectile being fired from a weapon is somewhat analogous to piston movement in a cylinder in that the force driving the piston/projectile must be carefully controlled such that the cylinder/gun tube is not overloaded. This implies that the rate of pressure generation be balanced at some point (the tube pressure limit) by the generation of additional volume as the projectile moves downbore. The pressurization due to the burning propellant is dependent on the propellant gas mass generation rate as shown in Equation 2:

$$\dot{m} = \rho r S \, , \qquad (2)$$

where $\dot{m}$ = gas mass generation rate, ρ= propellant density, r = propellant burning rate and S = propellant surface area available. The propellant burning rate (r) is largely a function of chemical kinetics.

In summary, the controlling factors affecting ultimate pressure in a gun tube during firing are the volume available during the combustion cycle, the rate at which the propellant burns (largely controlled by its chemical make-up), and the amount of propellant surface area available at any point in the combustion process.

3. HISTORICAL AND RECENT WORK BY CONTROLLING MECHANISM

A literature study of temperature sensitivity related research was conducted (Copenhafer, McCarty, and Hughes 1980; Foster and Miller 1980; Graham and Martin 1975; Hamner, Hightower and Rector 1978; Jones, Foster, and Miller 1981; Corley and Kobbeman 1981; Palm 1983; Booth and Stokes 1986; Cohen and Flanigan 1983, 1984; Lyles, Flanigan and Askins 1971; Beardell and White 1982; Christian 1982; White et al. 1982; Stiefel 1983). The reported research generally address two generic modes by which temperature sensitivity is produced, or controlled.

3.1. Chemical

The first and the most extensively researched mode involves chemical make-up and propellant chemistry interactions. These studies, which focus primarily on solid fuel rocket motors, have had some success controlling temperature sensitivity through the use of additives such as aluminum, lead, copper, iron oxide, and others. These additives appear to lower temperature sensitivities at low pressures generally below 20 MPa. Attempts to control temperature sensitivity at higher pressures through the use of additives have generally met with little success. Since most gun systems operate in the 345 - 620 MPa range there has been no real success with this approach in guns and thus this option is not further addressed in this paper.

Deterrents have been used to retard excessively rapid burning or tailor performance of some propellant geometries. Their role in temperature coefficient reduction is unclear and undergoing continued study (Gonzalez and Worthington 1989; Anderson and Puhalla 1989). Deterrents may prove to be required to make use of propellant geometries which might otherwise be ballistically unacceptable, yet may have desirable temperature compensation properties through control of surface availability during combustion, such as ball propellant geometries.

3.2. Surface Area

Control of surface area available during the combustion process has been studied for many years as a solution to offset the natural tendency of any energetic material to change performance as a function of temperature. These studies generally center on control of surface generation as dictated by the mechanical properties of the grain or charge. The rationale for this approach follows:

- *At high temperatures the propellant may become pliable and during the pressurization process collapse inward to fill voids such as perfs. This occlusion process would in effect reduce the available surface area for combustion, thus reducing the rate of pressurization and most likely the peak pressure obtained.*

- *Under cold conditions the propellant may become brittle and break apart more readily during the combustion process producing additional surface area for burning and thus raising the pressure.*

- *For compacted charges the effect of cold temperatures is generally to produce quicker deconsolidation, additional grain surface area for burning, and a resultant increase in pressure. At hot temperatures the inverse occurs which reduces the grains exposed and lowers the pressure.*

Note that these control mechanisms may be counter-productive to each other. For instance, formulation changes to make a propellant more pliable at hot temperature are likely to make it less brittle at cold temperatures and vice versa. In addition care must be taken when working in the cold regime to not let the propellant become excessively brittle as this can lead to overly high increases in pressure should the available additional surface become too large.

Some specific examples of mechanical properties and surface control include recent low vulnerability propellants (LOVA) and compacted ball charges. These are further discussed below.

3.2.1. LOVA

During the development of High Energy LOVA Propellants reduced temperature coefficients relative to non-LOVA propellants were encountered. For instance for some LOVA formulations a hot temperature coefficient of 1.73 MPa per degree C was noted (Rocchio, personal communication 1989). Note that high energy non-LOVA propellants such as JA2 may have hot temperature coefficients as high as 3.11 MPa per degree C. It is believed that this reduced temperature coefficient is a result of surface area availablilty via one of the mechanisms noted above. LOVA temperature sensitivity is under continuing study.

3.2.2. Compacted Ball Propellant

Compacted ball propellant charges used in several medium caliber charges (20 and 30 mm) display favorable temperature compensation performance. Figure 2 demonstrates these results.

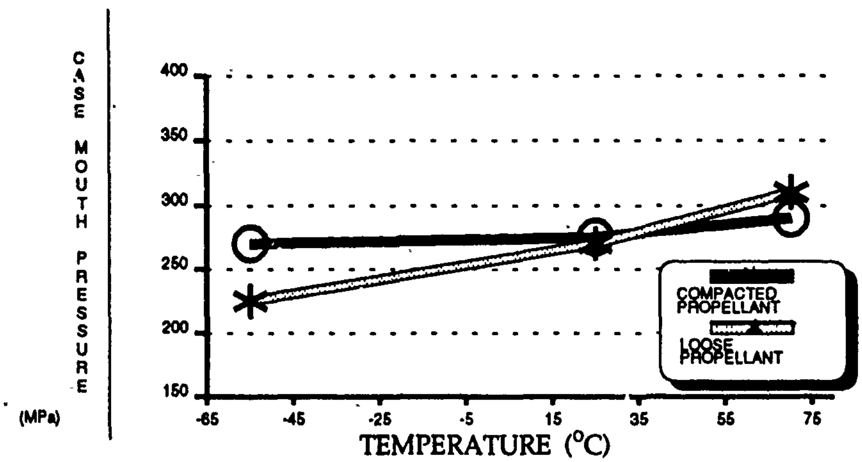

Figure 2. Compacted Ball Propellant Temperature Performance.

The mechanism involved in temperature compensation for compacted ball propellants is believed to be quite complex. This is due to the fact that the propellant balls are generally first coated with a deterrent coating of varying thickness depending upon application. Then they are rolled to change their geometry from that of a ball to that of an oblate sphere, which may induce fissures in the propellant surface. Finally they are compressed at high pressures to form a solid compacted block of propellant. The contributions of each process in reducing the temperature coefficient by surface control is not entirely clear and is undergoing extensive scrutiny. It does appear however that the compaction of the balls plays a key role in reducing the low temperature coefficient. For instance the compacted charge appears to deconsolidate at a much higher, but controlled, rate cold than ambient or hot (Gonzalez and Worthington 1989; Anderson and Puhalla 1989).

3.3. Volume Control

Recent temperature compensation research has centered around the third available mechanism to reduce temperature sensitivity, volume control, defined as the ability to control the initial free volume in a weapon chamber as a function of the propelling charge temperature. As detailed earlier the available volume during the combustion process directly effects the achieved peak pressure. Two such studies are detailed below.

3.3.1. Control Tube Device

A control tube device has the ability to adjust the position of the projectile prior to igniting the main charge. This allows it to increase the effective chamber volume for a hot

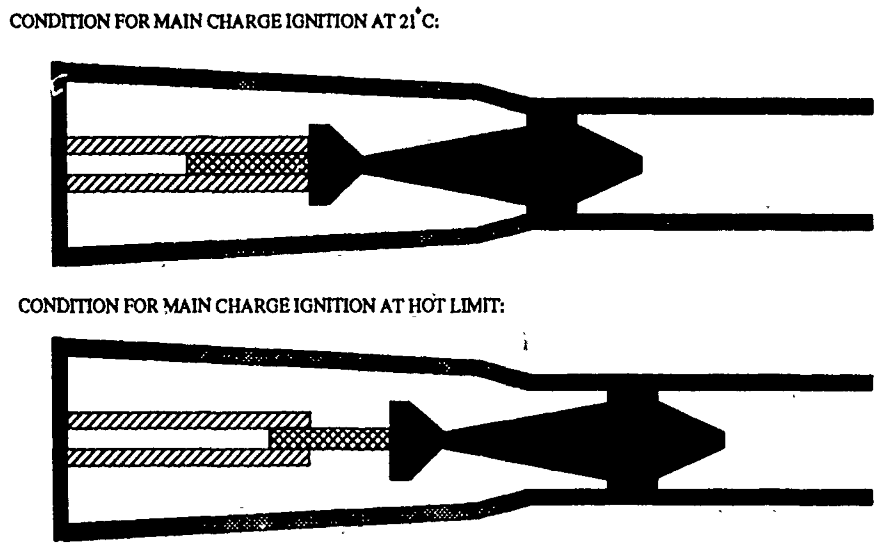

Figure 3. Control Tube Device Concept

propellant by moving the projectile forward just prior to igniting the charge itself. Figure 3 displays this concept in its generic form.

Recent firings of such a device demonstrated that this concept is feasible. Figure 4 shows some of these results.

Control tube concepts can be relatively complex in design. In addition, the fail-safe features of such devices remain to be proven.

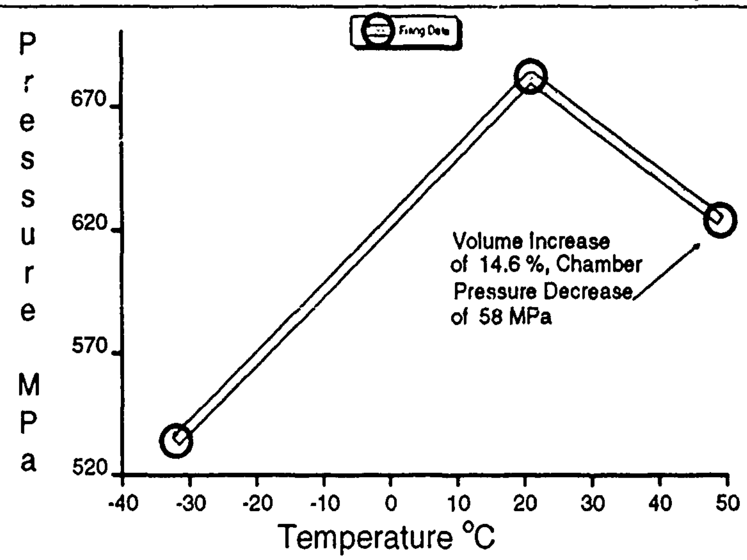

Figure 4. Control Tube Device Firing Data - 120-mm Cannon

3.3.2. Variable Volume Gun Tube

A concept currently under study by the author involves modifying the gun tube itself so that, in its ideal form, it is capable of adjusting the chamber volume of the weapon to neutralize the effects of temperature sensitivity.

This concept has several advantages over previously discussed techniques. First, it is relatively charge independent, meaning that the same mechanism would be able to correct for various charges, regardless of their peak performance or relative temperature sensitivities. This would solve many problems associated not only with varying performances of different type charges but with changes within lots of the same type charges.

Secondly, it would be capable of adjusting volume both up and down and could achieve true flat temperature sensitivity performance across any desirable range of temperatures. Finally the concept could be applied across a variety of weapons of quite different sizes and specifications.

How might such a system work? It might vary in complexity from a simple variable intrusion breech set by the soldier from sensor information in the charge stowage area, e.g., approximate charge temperature, to a smart chamber which is capable of sensing pressure rise rates and instantaneously adjusting chamber volume. In between these possibilities might be systems which employ barcode-like temperature sensors on charge components which are read just before or during charge insertion and either prompt the user to reset the chamber volume or communicate with an automated system to do it for him. Figure 5 displays two potential design concepts.

To explore the feasibility of such a concept a simple experiment was performed. The basic goal of this experiment was to determine what change in volume might be required to implement such a system.

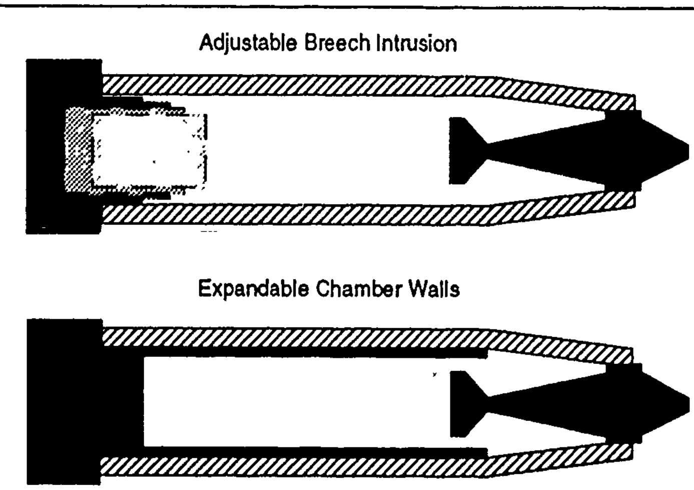

Figure 5. Variable Volume Gun Tube Concepts

Since a variable chamber volume system was not yet available a simple inverse compensation experiment was designed. In this experiment a charge was designed which was somewhat less than full chamber bore in size. Several of these charges were fired hot (63 °C) while chamber pressures and velocities were recorded. Then the same charge design was fired at ambient temperatures with full bore length spacers (volume compensators) inserted in the chamber. The procedure was repeated with increasingly larger spacers in an attempt to achieve the pressures obtained in the hot firings. It was felt that to a reasonable approximation this technique could be related to one for a expandable chamber system.

Several views of the test charges used are shown in Figure 6. Pressure increase versus volume decrease results as compared to the baseline hot charge case are shown in Figure 7.

Extrapolating the results of Figure 7 it can be seen that for this system a decrease of 18 percent in volume is required to reproduce the temperature induced pressure change which occurs during the hot firing. While this might on first look appear to be a considerable

Figure 6. Variable Volume Experimental Charge

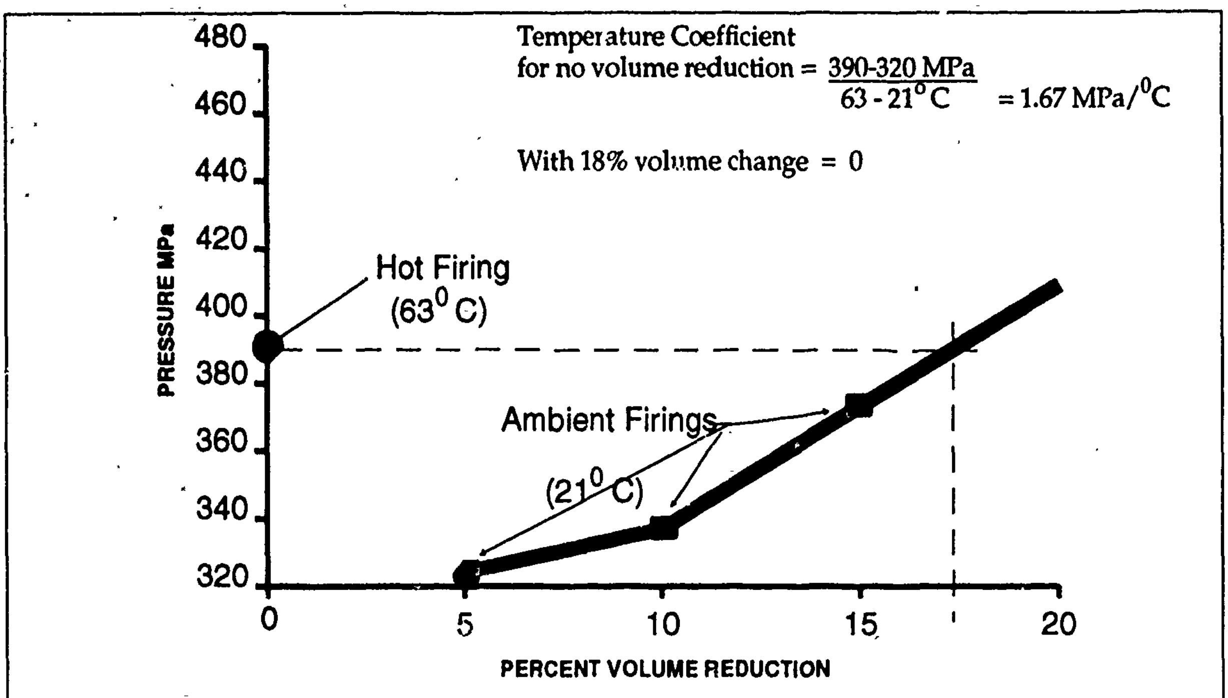

Figure 7. Variable Volume Experimental Data

volume change requirement, it should be noted that it could be obtained by a full bore axial length change of only 15 cm or a full chamber radial change of just 1.34 cm.

Future work in this area will concentrate on engineering prototype volume compensation hardware, most probably a variable intrusion breech. While the efforts in volume compensation for temperature sensitivity reduction are still in their infancy, it is a promising technique for increasing the performance of current conventional based propulsion systems.

4. SUMMARY

Chemical modification of propellant to reduce temperature sensitivity has to date met with success with only low pressure propulsion systems such as rocket motors. Temperature compensation through control of propellant mechanical properties and therefore surface availability has met with limited success in small to medium caliber systems to date. There seems to be no physical reason why these mechanisms cannot be reproducibly controlled and scaled up. However it is still unclear if these mechanisms can be made to work well at both ends of the temperature spectrum simultaneously. Volume control techniques are still in their infancy but hold the promise of a charge independent, broad temperature range solution.

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