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SUMMARY

Development of the 23KS20000 motor (thrust of 20000 lbf. for 23 sec.) for the Black Brant IIB vehicle was completed in September 1964. The motor has a diameter of 17 in., a parallel length of 180 in., and contains approximately 2100 lb. of CARDEPLEX (aluminized ammonium perchlorate/polyurethane) propellant. This paper traces the development history of the motor with emphasis on the internal ballistics.

Axial combustion instability was the factor which dictated the pace of the motor development. Experimental investigations led to a method of 'tailoring' propellant compositions to obtain optimum combustion stability characteristics at prescribed burning rates. This method was used in the selection of the propellant for the 23KS20000 motor.

INTRODUCTION

THE 17 in. diameter 23KS20000 motor is the propulsion unit for the Black Brant IIB high altitude research vehicle. In the nomenclature used to describe the motor, the 23 stands for the nominal duration (sec.) of the thrust and the 20000 is the nominal thrust level (lbf.); the S denotes that a solid propellant composition is used while the K indicates that the propellant is of the composite type. The CARDEPLEX propellant used in the motor is an aluminized ammonium perchlorate/polyurethane formulation.

In late 1959, when development of the 15KS25000 motor for the Black Brant IIA vehicle was progressing favourably, studies were commenced on a motor with a lower thrust and a longer burning time. The design did not appear to present any difficulties and it was thought that the requirement could be met by simply incorporating a burning rate depressant in the propellant formulation. After two successful preliminary firings, the core was redesigned to give a higher propellant loading density. The first firing with this new grain design took place in August 1960 and resulted in motor failure, owing to axial combustion instability. Following this occurrence, a crash propellant modification program was instigated in an attempt to develop a stable burning propellant with the required burning rate. The best propellant found was one which contained 19% of aluminum; in the fifth firing of the prototype 23KS20000 motor using this propellant, combustion instability was again encountered.

The pace of the 23KS20000 motor development was, in fact, dictated by the knowledge of combustion instability characteristics gained from experimental investigations carried out at CARDE[1,2]. A summary of the findings is presented.

LIST OF SYMBOLS

a,b	Regression coefficients
A_t	Nozzle throat area
c^*	Propellant characteristic velocity
D	Motor diameter
K_n	Restriction ratio
L	Motor parallel length
P_c	Chamber pressure
$\bar{P}_c$	Average chamber pressure
P_{cs}^*	Critical stable pressure
r	Burning rate
r_{1000}	Stable non-erosive burning rate at 1000 psia
S	Burning surface area
t_b	Burning time, measured from the time at which the chamber pressure initially rises to 100 psig (zero time) to the time when the pressure finally drops to 98% of the final maximum pressure
$t_{a,30}$	Action time, measured from zero time for t_b to the time at which the pressure finally drops to 30 psig
T_p	Initial grain temperature
Y	Ballistic parameter
ρ_p	Propellant density
μ	Micron

CHARACTERISTICS OF NONLINEAR AXIAL COMBUSTION INSTABILITY

Nonlinear axial combustion instability occurs when one or more strong compression waves propagate within the cavity of a motor. The interaction of the unsteady flow field with the combustion process produces an increase in the time-average burning rate and hence in the time-average chamber pressure and thrust. Initiation is nonlinear, a small but finite flow disturbance

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*Head, Rocket Motor Section

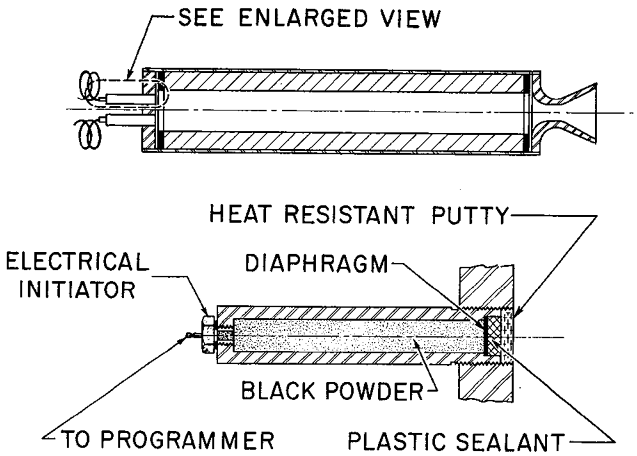

Figure 1
Pulse tube layout

being required to trigger instability; such disturbances can occur naturally, but to overcome the problem of random initiation, a pulse technique was developed[3] to inject flow disturbances at preselected times during burning. The pulse tube layout is shown in Figure 1 and representative high frequency pressure records in Figure 2. If a motor is operating in an intrinsically stable condition, a pulse will rapidly decay; on the other hand, if a motor is incipiently unstable, a disturbance will amplify to a level governed by the gain-loss balance of the system. The serious consequences of the non-linearity characteristic in a motor development program are readily apparent; thus it would be possible to perform a number of motor firings without realizing that a combustion instability problem existed.

For a fixed motor size and propellant composition, motors are stable at low pressures but, above a critical stable pressure level, P_{cs}^*, are capable of unstable operation (Figure 3). The abscissae in Figure 3 is the restriction ratio, defined as

$$K_n = \frac{S}{A_t} \tag{1}$$

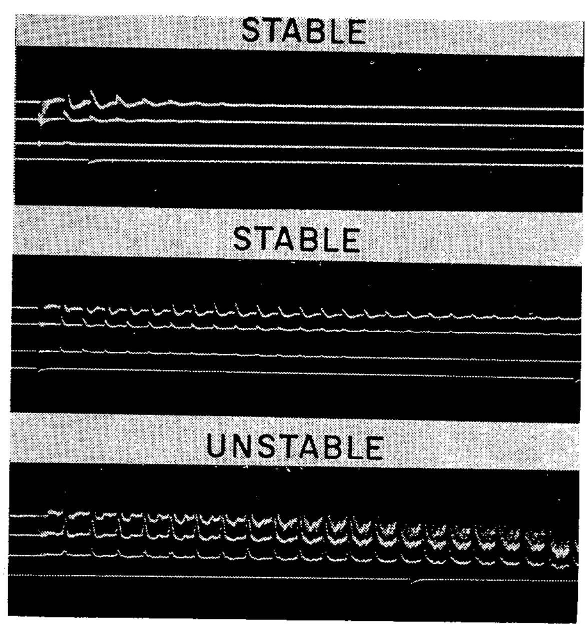

Figure 2
Representative high frequency pressure records

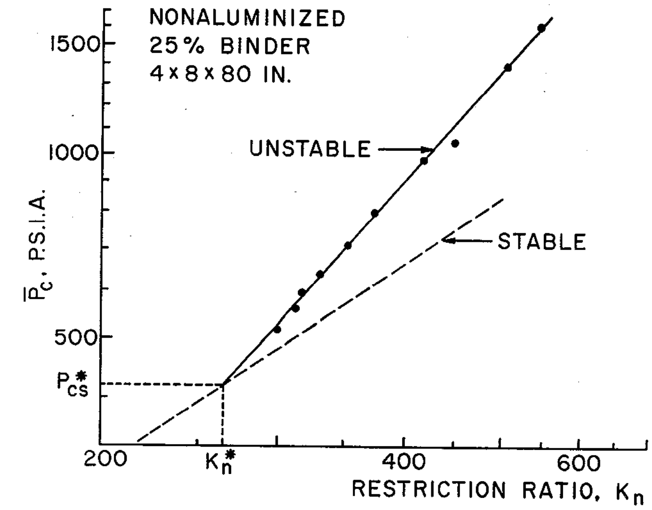

Figure 3
Typical pressure-restriction ratio relationship

where

K_n = restriction ratio
S = burning surface area
A_t = nozzle throat area

From the mass-balance and energy relations

$$K_n = \frac{P_c}{c^* \rho_p r} \tag{2}$$

where

P_c = chamber pressure
c^* = propellant characteristic velocity
ρ_p = propellant density
r = burning rate

The characteristic velocity, c^*, is essentially a function of the propellant properties, being only weakly dependent on the operating pressure level; under non-erosive conditions the burning rate is a function of pressure only. Consequently, for a fixed propellant, Eq. (2) gives a relation between P_c and K_n which is independent of motor size.

A decrease in the initial grain temperature leads to a reduction in P_{cs}^*, the amount being dependent on the propellant formulation. Therefore the likelihood (or degree) of instability increases at low grain temperatures.

With regard to the effect of compositional changes, it has been established that any single change which causes an increase in the stable burning rate leads to an increase in P_{cs}^*, and therefore tends to stabilize the design. An example, which illustrates the effect of varying aluminum level at a constant binder level (25%), is shown in Figure 4.

The influence of scaling on the unstable behaviour of motors is still imperfectly understood. Lower values of P_{cs}^* have been observed in motors 2 in. diam. × 20 in. long than in motors 8 in. diam. × 80 in. long. Motors with similar length/diameter ratios but with diameters greater than 8 in. have, in most cases, shown little difference in unstable behaviour; one important exception has been observed, however, with the propellant used for the final 23KS20000 motor.

There is some evidence that low values of the motor length/diameter ratio, L/D, promote stability. On the

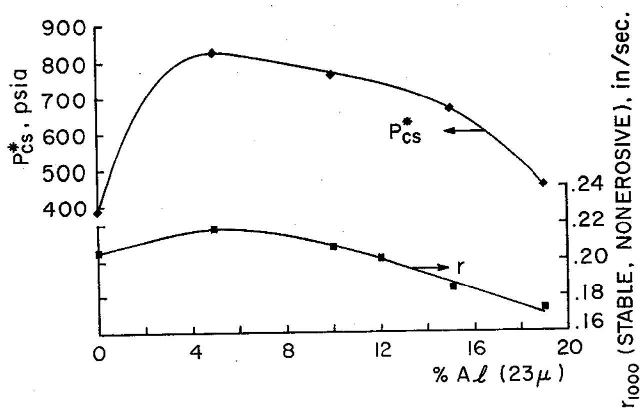

Figure 4
Stable burning rate and critical stable pressure versus aluminum content

TABLE 1

COMPOSITIONS AND BALLISTICS PARAMETERS OF CARDEPLEX PROPELLANTS

Formulation Code	A5	A12	B7	C2	F10
Polyurethane binder, % by wt.	25	25	25	25	27
Ammonium perchlorate, % by wt.	70	70	70	56	55
Aluminum, % by wt.					
SAX3 (40μ, 6% Mg)	5	–	5	–	–
SAX9 (40μ, 12% Si)	–	–	–	19	–
SA26 (23μ)	–	–	–	–	17
SA24 (7μ)	–	5	–	–	–
Lithium fluoride, added parts	–	–	1.8	–	–
Copper chromite, % by wt.	–	–	–	–	1
Flame temp., °K (theoretical)	2460	2460	2350	2680	2600
Burning rate at 1000 psia, in./sec.	0.22	0.24	0.15	0.15	0.20
Critical stable pressure, P_{cs}^* (8 in. × 80 in. motors), psia	760	≃1000	390	420	1300

other hand, increasing L/D from 10 to 15 had no effect on P_{cs}^*. Changing the web thickness, altering the nozzle end geometry of the motor and changing the grain cross-section had no effect on unstable behaviour.

HISTORY OF THE 23KS20000 MOTOR[4]

The 23KS20000 motor has a diameter of 17 in. and a casing length of 183 in. As noted in the previous section, this length to diameter ratio is too high for any stabilizing influence to be operative. The casing for the motor was essentially an off-the-shelf item so that the maximum allowable working pressure (approximately 1100 psi) was prescribed before the grain design was developed. Three requirements had to be met in the design:

(i) the performance specification and casing geometry led to the requirement for a low burning rate propellant,

(ii) to promote efficiency it was desirable to operate at a pressure level as close as possible to 1100 psi, and

(iii) the motor was required to function satisfactorily at 0°F.

In terms of the trends reported in the previous section, all of these factors were detrimental to combustion stability. Unfortunately these trends were not known at the commencement of the development program.

The first prototype of the motor was based on the propellant formulation B7 (Table 1) obtained by the addition of 1.8% of the burning rate depressant lithium fluoride to the formulation A5 (used in the 15KS25000 motor). The motor was designed to operate at 750 psi but was destroyed in the third (70°F) firing by self-excited axial instability (Figures 5 and 6). Subsequently it was found that P_{cs}^* for formulation B7 was only 390 psia in comparison with 760 psia for formulation A5 (Figure 7); hence this prototype 23KS20000 motor was operating well inside the pseudo-stable regime.

The second prototype was based on the formulation C2 (Table 1) with a design operating pressure level of 800 psi. In an 8 in. diam. × 80 in. long motor this formulation had exhibited mild combustion instability at 800 psi, but was the best of a number of formulations tested in a crash program. It was conjectured that the increase in scale would lead to stable operation and failing this, that instability could be eliminated by a small decrease in the operating pressure level. Both of these conjectures were incorrect; self-excited combustion instability was encountered during the fifth full scale firing at 70°F. During the development of a 9KS11000 motor for the Black Brant III vehicle, it had been found possible to eliminate combustion instability by a relatively small reduction in the

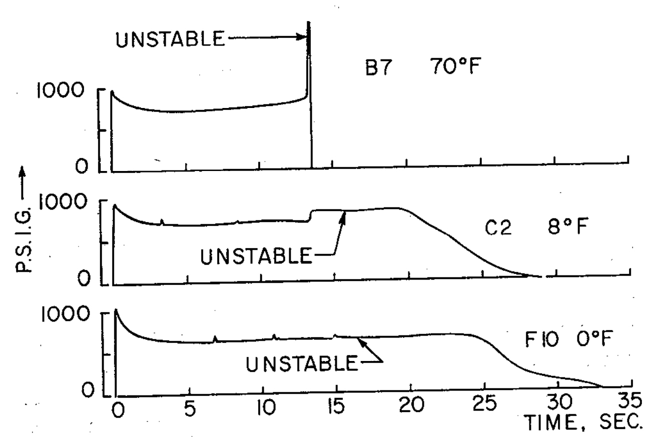

Figure 5
Low frequency response pressure records for the three prototype motors

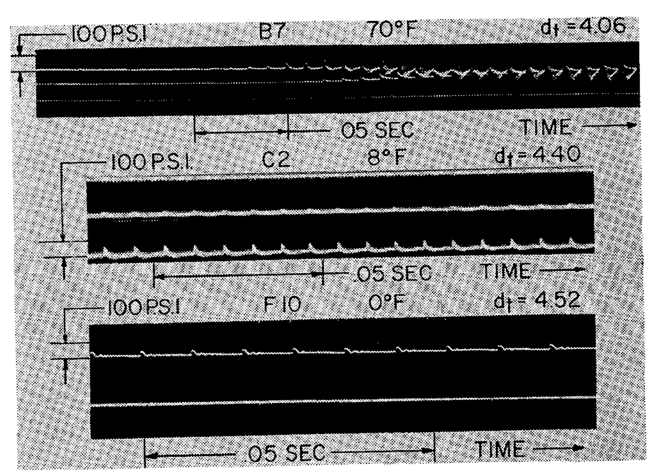

Figure 6
High frequency response pressure records for the three prototype motors

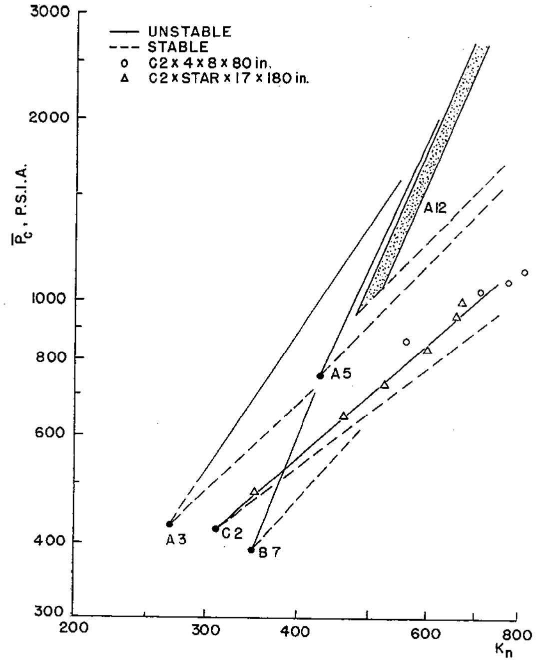

Figure 7
Pressure restriction ratio relationships for CARDEPLEX propellants

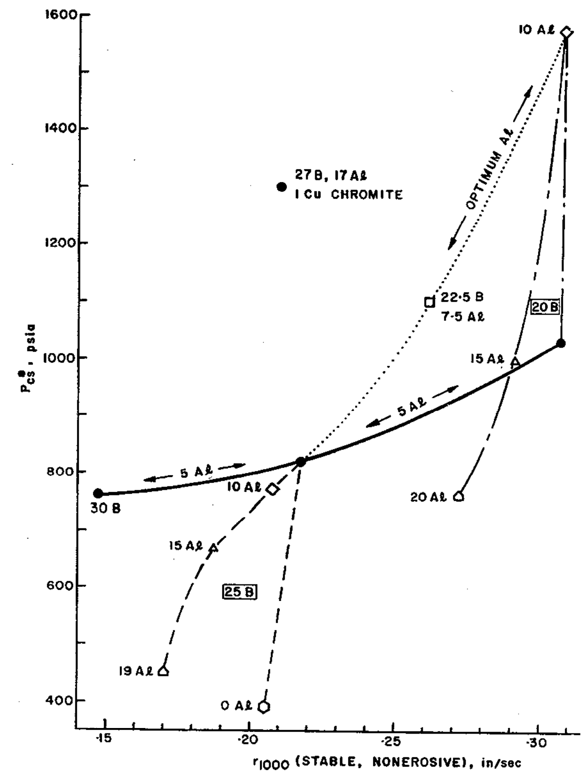

Figure 8
Effect of formulation changes on critical stable pressure

operating pressure level[5,6]; the formulation A12 (Table 1) was used in this motor. Figure 7 shows why this expedient was successful and also shows why the same method was unsuccessful for the C2 formulation. Although the instability encountered with this formulation was relatively mild, the small difference in slope between the unstable and stable $\bar{P}_c$ versus K_n curves did not allow stabilization by reduction in operating pressure level without a severe performance penalty; the P_{cs}* for C2 formulation was later found to be 420 psia. Figures 5 and 6 show the low and high frequency response records from a typical full scale firing. At this stage, sufficient results had been obtained from a systematic research program employing 8 in. diam. × 80 in. long motors to permit the 'tailoring' of propellants to yield improved values of P_{cs}* at certain burning rates, and the final design of the 23KS20000 motor was performed.

FINAL DESIGN

The final design of the 23KS20000 motor was based on the premise that a propellant could be formulated which would burn stably in the motor at a pressure level between 800 and 900 psi with a burning rate of 0.20 in./sec. These characteristics were selected as ones which could be achieved by formulation changes and which would, by appropriate grain design, still allow the performance specifications to be met.

Propellant selection

It had been observed[3] that the inclusion of a burning rate accelerator in a propellant formulation led to a marked increase in the critical stable pressure, P_{cs}*. This fact was used in the selection of a formulation for the motor. Increasing the binder level in a formulation gives a reduction in burning rate and in P_{cs}* (Figure 8). However, if a burning rate accelerator is now added, it is possible to obtain a net gain in P_{cs}* from the two combined changes. The formulation F10 (Table 1) was tailored to meet the requirements of 23KS20000 motor by this method, using copper chromite as the rate accelerator; the aluminum, binder and copper chromite levels were optimized to give the maximum value of P_{cs}*, based on results from 8 in diam. × 80 in. long motors (Figure 8).

Grain design

The formulation F10 had a higher burning rate than either of the formulations B7 and C2 used in the first two prototype motors. Consequently an increased web thickness was required in order to maintain the same burning time. This, in turn, led to a grain with a higher loading density and hence to a more severe erosive burning condition. To cater for this, the grain was designed with a thicker web at the nozzle end of the

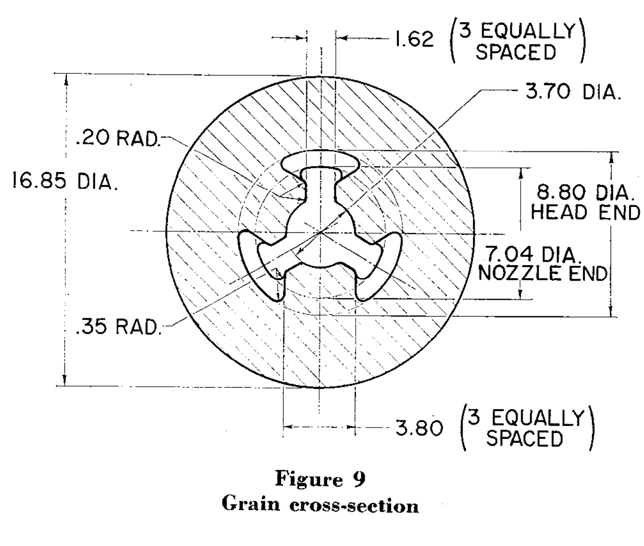

Figure 9
Grain cross-section

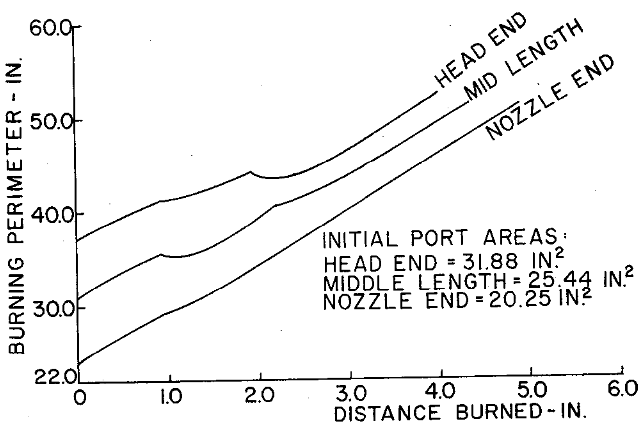

Figure 10
Burning perimeter versus distance burned

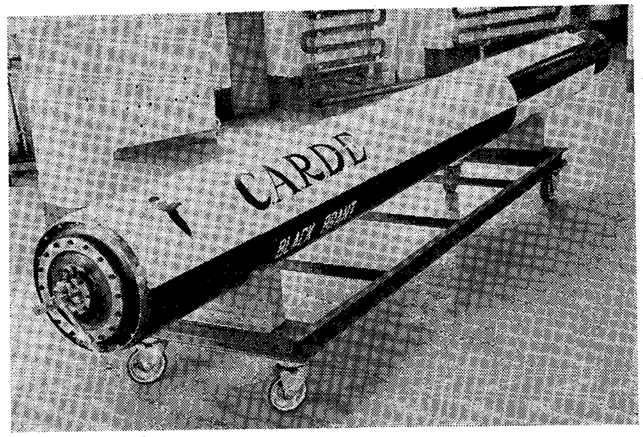

Figure 12
View of 23KS20000 motor from head end

motor than at the head end. Since the required port to throat area ratio for the design (1.25:1) was in a region for which no erosive burning data were available, an approximately half scale motor was designed with a tapered star-centre grain configuration. Two firings of this motor gave satisfactory pressure and thrust-time characteristics but, as a result of these firings, a tapered modified three leaf clover grain design was selected for the 23KS20000 motor (Figure 9). Figure 10 shows the variation of the burning perimeter with the distance burned at three positions along the length of the grain.

Motor design

The tapered grain cross-section necessitated a redesigned motor casing with an enlarged opening at the head end to enable the core to be extracted; the casings were manufactured by Bristol Aero-Industries Ltd. A layout of the motor is shown in Figure 11; the layout is similar to that used in earlier CARDE development projects[5,6]. Motor insulation weights were kept to a minimum and complete grain encapsulation was incorporated using the CARDE "boot" and "bonnet" technique. The nozzle development was completed in four firings; it consists of a steel housing (AISI 4340) and an AGSX graphite insert oversprayed with 0.055 in. of Rokide A (aluminum oxide). Figures 12 and 13 show views of the motor from the head and nozzle ends.

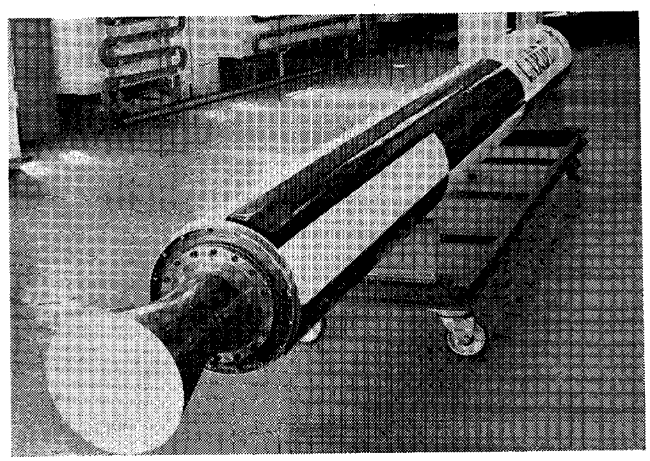

Figure 13
View of 23KS20000 motor from nozzle end

DEVELOPMENT FIRINGS

Development firings were commenced in April 1964. The CARDE pulse technique for combustion stability evaluation was used in the first firing and a mild degree of instability was initiated during the latter stages of burning (Figure 14). This occurrence was

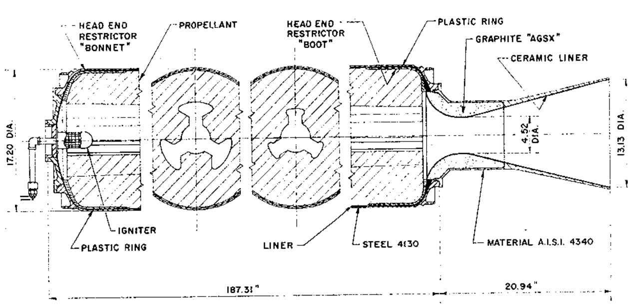

Figure 11
Layout of 23KS20000 motor

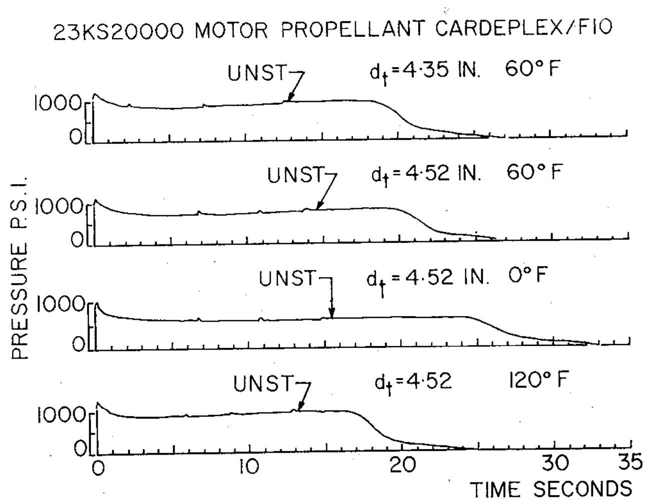

Figure 14
Pressure-time curves from 23KS20000 motor firings

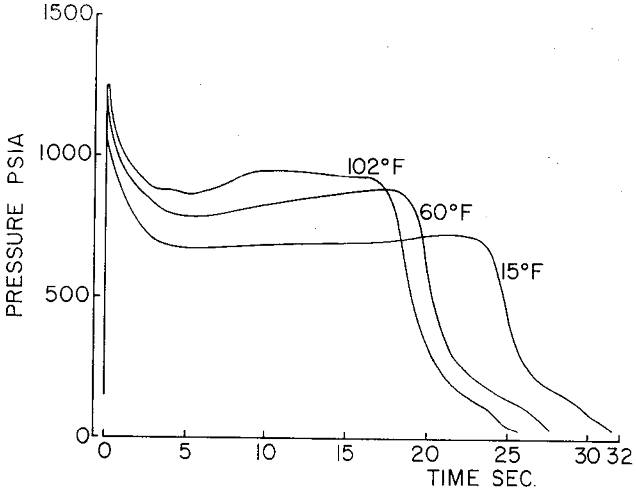

Figure 15
Pressure-time curves for 23KS20000 motor

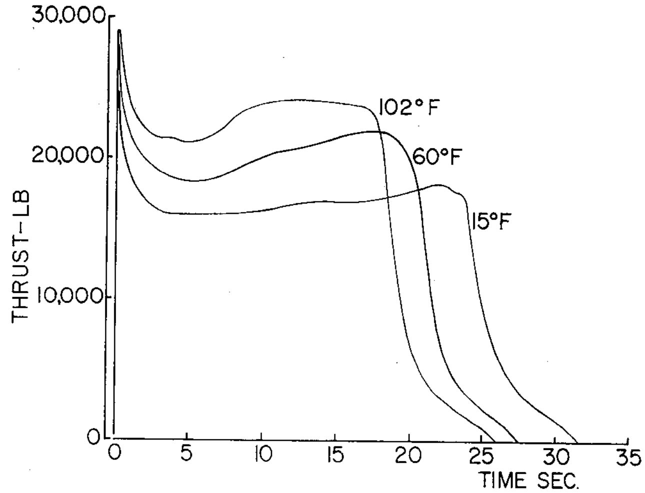

Figure 16
Thrust-time curves for 23KS20000 motor

contrary to experience with 8 in. diam. × 80 in. long motors; from these motors P_{cs}* was found to be 1300 psia whereas the average pressure in the first 23KS20000 motor was 960 psia. A reduction in operating pressure to 820 psia did not completely eliminate the instability but the jump in average pressure on initiation was approximately 3% (Figure 14). At this juncture the decision was made to operate at the lower pressure level and accept the possibility of mild combustion instability. In all, seven firings with the design nozzle throat diameter were performed with initial grain temperatures in the range from 0°F to 116°F. The increment in average pressure on initiation of instability was found in all cases to be less than 4%; Figure 14 shows the results at the temperature extremes.

The progressive improvement in instability characteristics obtained for the three propellant formulations which were employed during the development program is shown in Figures 5 and 6. From the high frequency pressure records it can be seen that the peak-to-peak amplitude of the oscillations in the final motor is approximately 35 psi. The corresponding thrust oscillations and the associated change in thrust level were considered acceptable by the vehicle designers.

Pressure and thrust versus time curves for the motor at three grain temperatures are shown in Figures 15 and 16. The ballistic reproducibility attained during the seven development rounds was excellent. Since firings were performed over a range of initial grain temperatures, it was possible to perform a linear regression analysis to determine the residual variation in the ballistic parameters; this gives an estimate of the performance scatter which could be expected in further firings of the motor. In addition, the analysis gives a linear relation between a ballistic parameter and the grain temperature in the form

$$Y = a + b\,T_p$$

where

Y is the ballistic parameter
T_p is the initial grain temperature (°F)
a,b are the coefficients determined in the analysis.

Table 2 lists the performance data for an initial grain temperature of 70°F, the coefficients a and b from the regression analysis, and the residual standard deviations as percentages of the mean values. An indication of the excellent reproducibility obtained is shown in Figure 17, where average thrust is plotted against the initial grain temperature.

TABLE 2

23KS20000 MOTOR PERFORMANCE DATA

Parameter	Value (70°F)	Coeff. a	Coeff. b	Residual Standard Deviation, %
Burning time, t_b, sec.	19.48	24.36	−0.0697	2.40
Action time, $t_{a.3p}$, sec.	27.41	32.27	−0.0694	2.01
Avg. pressure over t_b, lbf.	850	666	2.62	1.58
Avg. thrust over t_b, lbf.	20,770	15,870	70.0	1.06
Specific impulse, lbf.-sec./lbm.	216.3	210.7	0.0806	1.99
Total impulse, lbf.-sec.	449,300	438,600	151.8	0.55

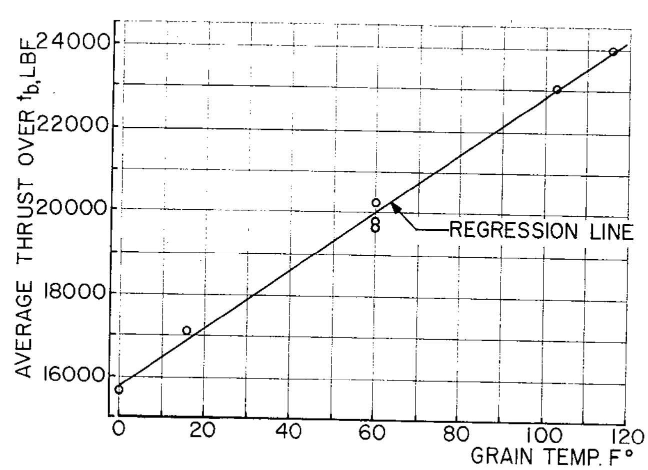

Figure 17
Average thrust versus grain temperature

TABLE 3
23KS20000 MOTOR WEIGHT DATA

Item	Weight, lb.
Casing and Insulation	385
Liner	68
End Restrictor	13.6
Propellant	2077
Nozzle	66.4
All-up-weight of motor	2610
All-burnt weight of motor	529

Representative weight data are presented in Table 3.

The motor development was completed in September 1964. Two dynamic firings were performed in October 1964 and two in January 1965. Three of these vehicles gave the predicted performance but a motor failure occurred during the final vehicle flight. An examination of the recovered pieces indicated that failure was due to overheating of the casing near the nozzle end of the motor; the time of failure was close to the motor burning time. A subsequent static firing also resulted in overheating of the casing, in the same area; a minor modification will overcome the design fault.

CONCLUSIONS

Perhaps the greatest benefit to accrue from the 23KS20000 motor development program was the knowledge gained of axial combustion instability. In particular, the method of 'tailoring' propellant formulations to yield optimum combustion stability characteristics is of great value to motor designers. In any vehicle development program it is obviously advantageous that the vehicle and motor designers cooperate at an early stage; a small compromise on, for example, motor diameter can lead to improved overall performance and speedier motor development.

ACKNOWLEDGEMENTS

The concerted efforts of a large number of CARDE personnel were required to develop the 23KS20000 motor. I would like to acknowledge these efforts and emphasize that, for the most part, I have described work performed by other people.

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