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DESIGN QUALIFICATION OF A SINGLE-GRAIN ROCKET MOTOR FOR SHELF LIFE EXTENSION PROGRAM OF MULTI-GRAIN ROCKET MOTOR

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ABSTRACT

A single grain rocket motor was designed to be used in a shelf life assessment and extension program for a solid double-based propellant multi-grain rocket motor. The qualification of the single-grain rocket motor has been performed through several static firings to measure the different ballistic characteristics at different temperatures. The purpose of such qualification firings was to approve the suitability of the design of the single-grain rocket motor to give comparable ballistic performance to the multi-grain rocket motor, which should match the original specifications of such motors.

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1. Introduction

Shelf life of a rocket motor based on solid propellant is defined as the time for which all functions of a propellant charge remain intact within given tolerances, although some aging processes have already occurred. This can be divided into: i) safe storage life and ii) safe use life. The first determined by chemical reactions, whilst the second is determined by a more complex physico-mechanical interrelationship (1-4).

The service life (safe use life) of a rocket motor is at an end when it reaches any critical condition for its functioning. The critical condition may correspond to the point at which a change in ballistic functioning brings ballistic parameters outside required limits. Ability of rocket motors to function satisfactorily at the high and low extremes of the service temperature range must be taken as the most valid criterion of serviceability, and it would seem to be the prime purpose of all the development, environmental testing and surveillance work to ensure maximum success in these terms (5). Moreover the shelf life of rockets depends mainly on the deterioration of the characteristics of its vital components. The most known components which drastically affect the performance of rockets are those which contain propellant and pyrotechnic compositions.

It was proved (4,5) that the rocket motors which contain these compositions if not regularly checked for their different characteristics would cause many problems to the user airing storage and usage of these rockets. It is known that the characteristics of solid propellant – based rocket motors, especially those of double base type, undergo self- degradation during its storage even at normal temperatures. This was proved because of the autocatalytic decomposition nature of double base propellant main constituents, nitrocellulose (NC) and nitroglycerine (NG). The scope of work of this paper is created from the desire of the user of the stock to carry out assessment investigations of a multi-grain rocket motor. The purpose of such investigation is to define the current characteristics of these rocket motors in order to determine the extent of suitability of these rocket motors to be used or even stored.

The difficulties in carrying out such an assessment program were defined as follows: i) the rocket motors available are of different ages, ii) the rocket motors are stored in different climatic conditions, and of the most importance is that the original characteristics of these rocket motors are unknown. At the same time it is recognized that carrying such investigation to assess the current status of the different characteristics certainly requires the firing of many multi-grain rocket motors which consequently causes a lot of losses of the current stock. From this point of view the current investigation is based on a design of a single-grain rocket motor to be used for the required static firings. This piece of work is not discussing the design of the rocket motor, but only investigating the extent of suitability of such design (i.e qualification) to give comparable ballistic performance to that of the multi-grain rocket motors.

2. Experimental

The multi-grain rocket motor consists of 14 grains of double base solid propellant composition. The dimensions of the grain is as follows: (length: 1740 mm, outer diameter: 140mm and inner diameter: 36mm) with a total weight 39.7 kg.

The single-grain rocket motor was designed in another investigation which is concerned with testing the validity of such design to perform life assessment program of the multi-grain rocket motors.

Chemical and mechanical characterization of the double base propellant single grain was performed through the conventional testing procedures in order to assess the extent of suitability and safety of such grains to be ballistically tested.

The different characteristics of the investigated solid propellant were tested as follows:

2.1 Characterization of chemical properties

The chemical properties of double base propellant samples, selected from 13 multi-grain rocket motors, have been tested through conventional testing procedures:

- Chemical stability by Heat test and Hanzen test methods
- Calorific value using calorific bomb.
- Determination of main nitric ester ingredients, NC and NG.
- Determination of ignition point.
- Determination of density,
- Determination of moisture content.

2.2 Characterization of mechanical properties

The mechanical properties of samples of double base solid propellant of single grains have been tested through conventional tension and compression testing procedures. The parameters measured were as follow: (maximum strength, yield stress, and elongation).

2.3 Characterization of ballistic properties

The ballistic properties of both single-grain and multi-grain rocket motors were statically measured. The parameters measured were as follows: burning time, maximum pressure, total thrust and specific impulse.

3. Results and Discussion

3.1 Testing of Multi-Grain Rocket Motors

The multi-grain rocket motors under investigation were characterized by measuring the different properties (viz. chemical, mechanical and ballistic properties). The data obtained for these characteristics were as follows:

3.1.1 Visual and X-ray inspection of the solid grains

The propellant grains of the multi–grain rocket motors under investigation were examined for any defects (cracks, scratches, flaws, and other external and internal defects) using X-ray testing. Examining 10 rocket motor grains, no defects were noticed.

The dimensions and weight of such grains were measured, and found to be as follows:

- Length: 1740 ± 20 mm
- Outer diameter: 140 ± 2 mm
- Inner diameter: 36 ± 1 mm
- Weight of the 14 grains forming the multi–grain rocket motor was 547 ± 10 kg

3.1.2 Chemical Properties Testing

The chemical properties of the double base propellant of the grains of the multi–grain rocket motors were investigated. Thirteen (13) grains were sampled from thirteen (13) rocket motors, a grain from each. The obtained chemical properties were as follows:

- Chemical stability: 66-90 hrs for the 100˚C heat test, and a pH of (3.5-4.5) of Hanzen test at 110˚C,
- Ignition point: 183 -186˚C,
- Soluble constituents: 39.5-40%,
- Calorific value: 870 - 885 cal/g,
- Density: 1.6 g/cm^3, and
- Moisture content: 0.3-0.7%

As mentioned above the original chemical properties of the newly manufactured grains were unknown, nevertheless comparing the obtained properties with that of similar formulations, especially the determining factor, viz the ratio of NG/NC content, would indicate that these properties were not significantly changed with respect to the original manufactured one. This is supported by: i) the pronounced high chemical stability of the investigated propellant, and ii) the investigations (6,7) carried out on similar double base propellant rocket motors, which concluded that the changes in chemical properties of such formulation having low NG/NC ratio and of a simple geometrical design, small web thickness were not significant.

3.1.3 Mechanical Properties testing

The mechanical properties of the propellants under investigation were tested. The tension and compression properties were tested at two temperatures, 24˚C and 50˚C. The average values of the investigated properties were as follows:

a) Compression testing at 24˚C and 5000 kp:
Yield force (average): (1300-1400) kp
Yield force (maximum): (2700-3500) kp
Yield strength: (75-100) Kp
Compression strength: (190-260) kp/cm^2

b)Tension testing at 24˚C:
Maximum force: (75-93) kp
Tensile strength: (190-235) kp/cm^2
Elongation: (16-20) mm with 29-37%

c) Tension testing at 50 ˚C:
Maximum force: (77-80) kp
Tensile strength: (190-200) kp/cm^2
Elongation: (16-18) mm with 24-30%

The aforementioned values for mechanical properties, especially comparison of the properties for tension testing at the two different temperatures 24˚C and 50˚C, would indicate the stability of mechanical properties of the investigated solid propellant grain for the multi–grains rocket motors. Further more comparison of the aforementioned data with that obtained from other investigations(6), would clearly indicate that significant changes in mechanical properties of propellant grain like that under this investigation, especially of that simple geometrical shape and chemical composition, are unexpected especially if they are well stored.

3.1.4 Ballistic Properties testing of the multi-grain rocket motors

Selected samples of multi-grain rocket motors were statically fired to examine the current status of the ballistic performance of such rocket motors. The firings were performed on rocket motors conditioned at 20˚C. The average ballistic performance obtained from the firing of 7 full rocket motors, of 10 years age, from the well stored stock was as follows:

- Time of burning: (3.78-3.84) sec,

- Maximum pressure: (87-99) kp/cm^2,
- Average pressure: 66 kp/cm^2,
- Integral of pressure- time curve: 251 kp/cm^2,
- Average thrust: (258-262) kp,
- Specific impulse: (198-199) sec

3.2 Testing of Single-Grain Rocket Motors

A single-grain rocket motor was designed for the purpose of performing shelf life assessment program of the multi-grain rocket motors in order to avoid great losses of the stock of rockets. This is based on that the shelf life assessment program requires testing of huge quantities of rocket motors of different ages and storage at different climatic conditions. A ballistic performance data would be reliable only if it is obtained from the firing of a minimum of 3-5 rocket motors. Moreover, during performing such assessment program one would carefully consider the safety aspects along with the availability of simple tooling and equipment when carrying such extensive programs, of course the single-grain rocket motors is much favorable in the mentioned restrictions.

The design considerations of the single-grain rocket motors were carefully considered such that, comparable ballistic characteristics values would simulate that of the multi-grain rocket motors. This investigation is not dealing with the design stages, the design details were presented in a classified technical report (3). From this point of view the purpose of this investigation is only restricted to test a single solid propellant grains, selected from different multi-grain rocket motors. This was performed in several phases of testing. Three phases of testing were carried out and accompanied with some modifications of the design, until reaching very close to the ballistic performance of the multi-grain rocket motors.

The preliminary phases for testing were not presented for simplicity. These phases were followed by two phases to assure the qualification of the designed rocket motor to be suitable for carrying out several firings required for the prospected shelf life assessment program of the full multi-grain rocket motors. If the similarity is obtained between the performance characteristics of both the single and multi-grain rocket motors, this would imply that the designed motor is qualified for such static firings.

3.2.1 The first phase for testing the single-grain rocket motor

Ten (10) multi-grain rocket motors were selected from the well-stored stock. Fifteen (15) grains were sampled for static firings using the designed single-grain rocket motor. These tests were carried out at three different temperatures as follows (5 grains at +40˚C, 5 grains at +20˚C and 5 grains at -30˚C). The average ballistic performance data are presented in Table (1).

Table 1 clearly shows that the difference in ballistic performance between the two extreme temperatures +40˚C and -30˚C is not significant. Although the time of burning at the higher temperature is smaller than that at the lower temperature, the other ballistic determining parameters (viz the total thrust and specific impulse) are a little higher at the lower temperature -30˚C. The available data cannot explain this abnormality. Further investigations (8) were carried out in a trial to clarify this.

3.2.2 The Second phase for testing the single-grain rocket motor

Another fifteen (15) grains were sampled, from the same sampled multi-grain rocket motors, for static firings using the designed single-grain rocket motor. These tests were carried out as well at three different temperatures as follows (5 grains at +40˚C, 5 grains at +20˚C and 5 grains at -30˚C). The average ballistic performance data are presented in Table (2).

Table 2 presents the ballistic performance of the fired grains. The results obtained from these firings support those obtained from the first phase of firings. Moreover, the insignificant changes between the ballistics at the two extreme testing temperatures would be related to the following: i) the chemical composition of the double base propellant grains, mainly the determining factor the ratio of NG/NC, this is in agreement with a previous investigation of similar composition (6) which had indicated the stability of such composition with low nitroglycerine content to significant variations by time and temperatures. It would be expected that the more energetic double base propellants containing higher percentages of nitroglycerine (viz 40%) are subject to significant changes not only in ballistic properties but also in chemical storage age.

Meanwhile the geometric shape and design of the solid propellant grains would certainly enhance the effect of testing the grains at different temperatures. The solid propellant grains under this investigation are of a very simple design and shape, so it wouldn’t be strange to predict the insignificant changes in ballistics of such grains tested at different temperatures. This is supported by the similarity in all the measured ballistic characteristics (viz time of burning, pressure, total thrust and specific impulse).

3.3 Comparative Analysis of the Ballistic Performance of both Single-Grain and Multi-Grain Rocket Motors

Comparison of the results for the ballistic properties obtained from single and multi-grain rocket motors clearly indicates that there are great similarities in all the ballistic characteristics, especially the vital ones (viz the pressure, total thrust and specific impulse), the only exception is identified in the time of burning. The single-grain rocket motor time of burning is within the range of (3-3.4) s at 20˚C, while the multi-grain rocket motors time of burning was in the range of (3.78-3.84) s at +20˚C and (3-3.6) s at 27˚C. This deviation, which is about 15%, would be attributed to the following: i) it is very difficult to expect quite similar modes of burning of a single grain in either the single-grain rocket motor or in the multi-grain rocket motor, certainly the burning of the other 13 grains in the same multi-grain rocket motor would significantly affect the mode of burned grain, and ii) the multi-grain rocket motor has firing tables which determine the nozzle adjustment at every testing temperature in order to obtain the optimum ballistic performance, the facility which is not available in the single-grain rocket motor for the present investigation. This is because such adjustment would require the firing of a huge amount of motors at different temperatures which forms a cost burden at the current investigation.

Nevertheless, such changes in ballistic modes of burning between the single-grain and multi-grain rocket motors wouldn't significantly affect the function and purpose desired from the designed single-grain rocket motor. The main purpose of such motor is to be used in carrying out comparative static firing testing of different properties of multi-grain rocket motors, such difference had arisen from the different manufacturing ages and the storage of the stock of such motors at different climatic conditions. These firings will constitute the heart of data required to make shelf life assessment program of the multi-grain rocket motors (8).

4. Conclusions

A single-grain rocket motor, designed for the purpose of carrying out an assessment program of the shelf life of a multi-grain solid double based-propellant rocket motor, was qualified for such program. The qualification was performed through several static firings of both the single-grain and multi-grain rocket motors. Comparative analysis of the ballistic performance for each motor has led to verification of the suitability of the designed single-grain rocket motor to give the required ballistic performance of the real motor.

5. References

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Table 1. The First Phase of Single-Grain Rocket Motor Static Firing

Group	T ($^{\circ}C$)	Wt. (kg)	T_b (S)	$T_{0.7p}$ (S)	P_{max} (Bar)	IF (Ton.S)	I_s (s)
1	+ 40	38.3	4.27	0.09	56.36	7.48	194.30
2	+ 20	38.2	3.39	0.1	71.92	7.71	201.60
3	- 30	38.25	4.62	0.13	59.04	7.53	201

Table 2. The Second Phase of Single-Grain Rocket Motor Static Firing

Group	T (^{o}C)	Wt. (kg)	T_b (S)	$T_{0.7p}$ (S)	P_{max} (Bar)	IF (Ton.S)	I_s (s)
3	+ 40	38.5	4.23	0.05	66.6	7.246	192.0
4	+ 20	38.0	2.99	0.04	85.4	7.383	198.3
5	- 30	38.1	4.56	0.08	59.2	7.259	194.4