ELUCIDATION OF COMBUSTION INSTABILITY IN SOLID PROPELLANT ROCKETS

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Summary—With special reference to combustion instability the behaviour of solid propellants is studied to such a periodic heating as results from the gas oscillation in rocket motors. The present paper describes one of two methods devised to perform periodic heating of solid propellants. A small piece of solid propellant is subjected to radio heating in a capacitor of a VHF (40 MC) oscillator. The piece of solid propellant can be heated periodically by modulating the VHF oscillation with an audio- or ultra-audio frequency. The time required for ignition is measured for various frequencies of periodic heating. The first part of the time required for ignition, solid state, is not affected by heating frequency. On the contrary, it seems that the later stage of heating, solid-liquid state, is increased selectively at about 19 KC.

1. *Introduction*

THERE have been a few previous papers on the phenomenon of combustion instability in solid propellant rockets. Nevertheless, the mechanism of the phenomenon is not fully known at this time, especially from lack of experimental knowledge of the subject. This phenomenon is commonly understood as that related to a coupling of the oscillatory gas flow with the combustion process in gas or condensed phase of solid propellant. In the theoretical treatment of this phenomenon, a simplified model of a burning solid propellant is set up, i.e. some hypotheses are introduced about the combustion process of solid propellant. However, some of these hypotheses are rather artificial or mathematical, and are not always supported by experimental facts. Moreover, there are still other possibilities to explain this phenomenon. In the light of this situation, it is thought needful to know more precisely about each individual phase of the combustion process of solid propellant without adhering to former theories. From this point of view, it is of particular interest to study how solid propellants behave to such a periodic heating as results from the gas oscillation in the rocket motor.

Two methods were devised to perform periodic heating of solid propellants. In one method, which is described in this paper, a small piece of solid propellant is subjected to radio heating in a capacitor of a VHF oscillator. The piece of solid propellant can be heated periodically by modulating the VHF oscillation with an audio or ultra-audio frequency. In the other method, sunbeams or a powerful arc-light is focused on a small piece of solid propellant through a lens system. The beams are interrupted by using a motor-driven multi-perforated disc. Frequency of periodic heating of the piece of solid propellant can be controlled by adjusting motor speed.

In this paper the author is presenting a study on the ignition of solid propellants by modulated radio heating, which is done to know the effect of periodic heating on the solid phase reaction beneath the burning surface.

Prior to these experiments, an experiment was conducted for the purpose of identifying any frequency sensitivity in the periodic heating of solid propellants. In this preliminary experiment was investigated the effect of alternating electric stimulus on decomposing solid propellants. A test piece of a double base solid propellant, 11 mm diameter and 2.8 mm thickness, is sandwiched in between two metallic parallel plates connected to a low frequency oscillator. The electric circuit was also arranged so as to measure the electric resistance of the test piece by using an oscillograph. Such a test piece was subjected to relatively slow heating in a furnace till ignition occurs. With increasing temperature of the test piece, which was determined as the temperature of the metallic plate, its electric resistance was found to decrease gradually and to begin to fluctuate at a certain temperature before ignition. This temperature was very well defined, probably corresponding to bubbling of the liquefied propellant. Electric field (a.c. or d.c.) of about 10 V/cm was effective to make the bubble formation remarkably fine. Under a fixed condition of the furnace, the time required for ignition was measured for various frequencies and output voltages of the oscillator. The results were obtained as follows:

The time required for heating the test piece till the bubbling temperature is not affected by the frequency of alternating electric field, with the exception of the gradual change due to the change of impedance and hence Joule's heat. On the contrary, the time from start of bubbling to ignition is increased selectively at about 25 kc. This tendency is noticed at about 1000 V/cm or more.

The author was encouraged by this fact to perform the experiment on the ignition of solid propellants by periodic heating.

2. *Apparatus and procedure*

In Fig. 1 is shown the circuit diagram of the apparatus for igniting a test piece of solid propellant by modulated radio heating. A VHF oscillation of 40 Mc produced by a 6C4 tube is transferred to two 807 tubes

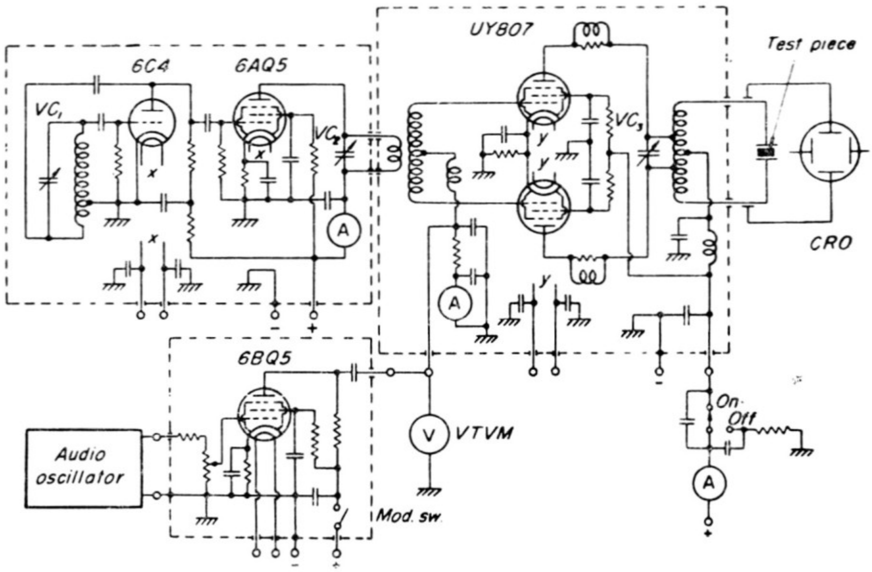

FIG. 1. Circuit for igniting solid propellant by modulated radio heating.

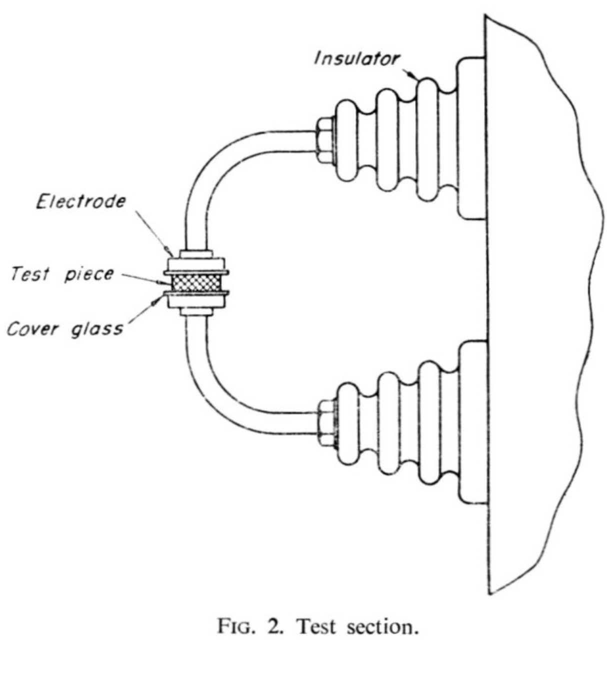

FIG. 2. Test section.

in push-pull through a buffer tube 6AQ5. The VHF power output is picked up from the 807 tubes in push-pull and applied to the test section, in which the test piece is heated dielectrically in a capacitor. Fig. 2 shows the detail of the test section. The capacitor is composed of two circular metallic plates of 14 mm diameter with a gap of about 4 mm. The test piece of solid propellant, 11 mm in diameter and 3.65 mm in thickness, is inserted in the gap of the capacitor together with cover-glasses of 15 mm diamet r and 0.2 mm thickness at both sides. These coverglasses are used to prevent

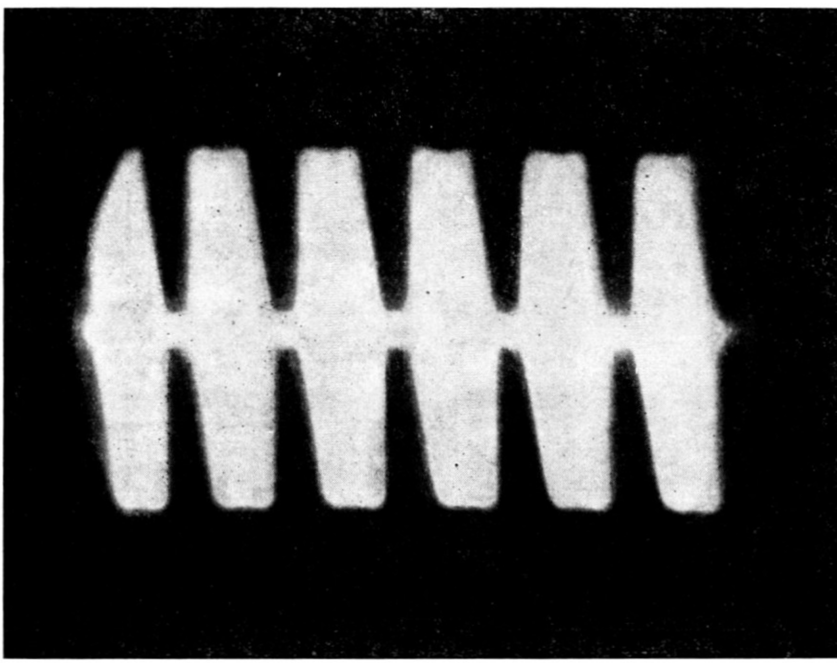

FIG. 3. Wave form of modulated VHF oscillation.

the capacitor from shorting and to weaken the heat transfer between the metallic plates and the test piece. The output voltage from a low-frequency oscillator is amplified by a 6BQ5 tube and applied to the grids of the 807 tubes to perform grid bias modulation. A constant modulation factor (over 100%) is secured by keeping the output voltage of the 6BQ5 tube constant. Two small electrodes extended from the deflecting plates of a cathode-ray tube are loosely coupled to the test section to watch the intensity and wave form of the VHF oscillation (Fig. 3). A 40 NC receiver shown in Fig. 4 is located near the test section to detect the field intensity of the VHF oscillation in the heating and ignition process. A microphone catches the sound of ignition and stops the current of the thyratron

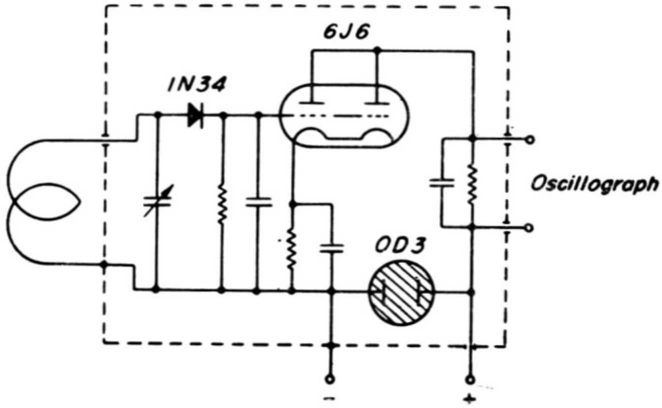

FIG. 4. VHF intensity meter.

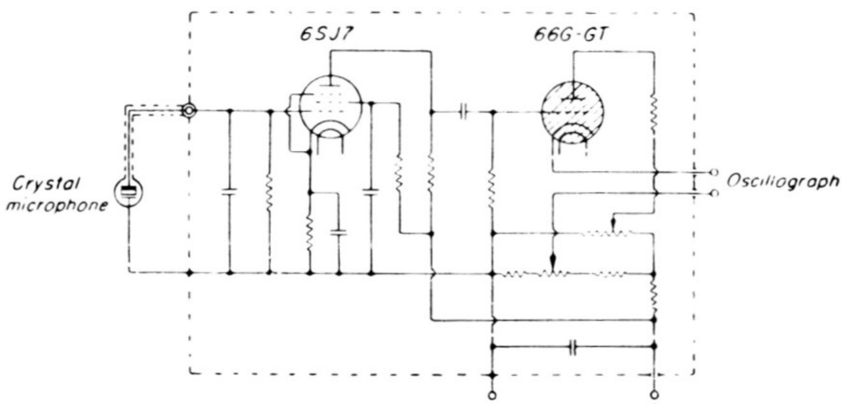

FIG. 5. Circuit for detecting ignition.

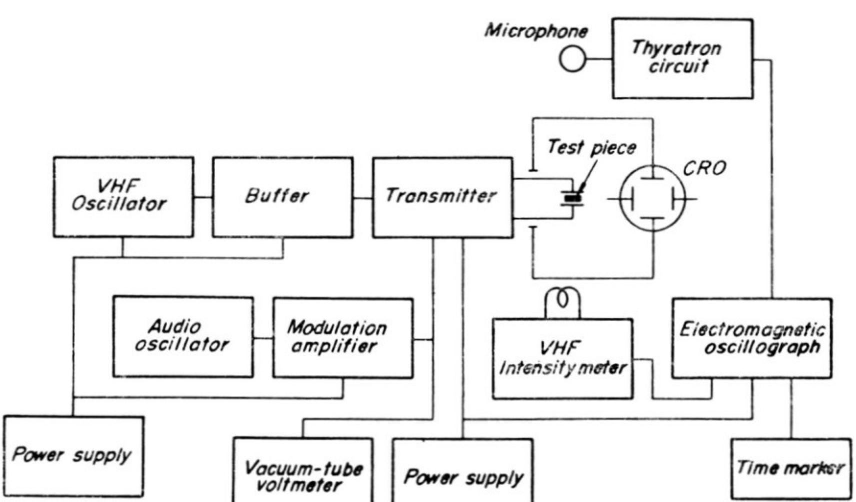

FIG. 6. Block diagram of apparatus.

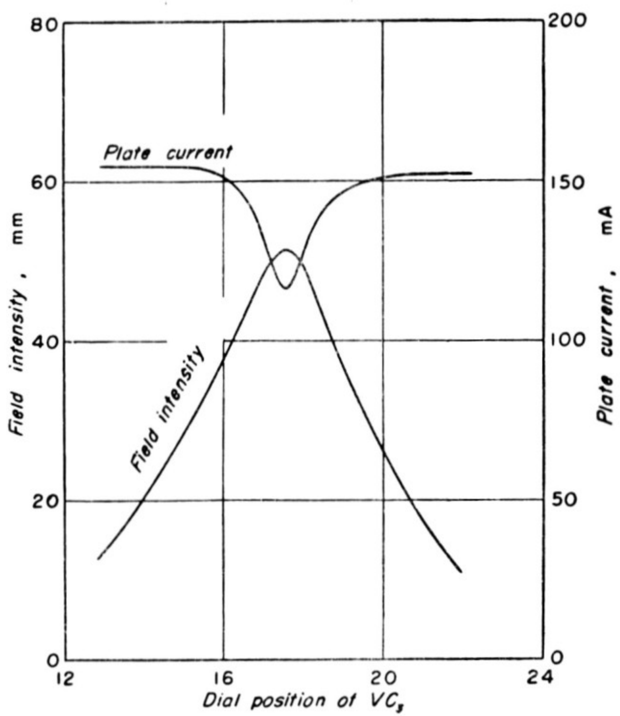

FIG. 7. Relation between VHF field intensity and dial position of VC_3.

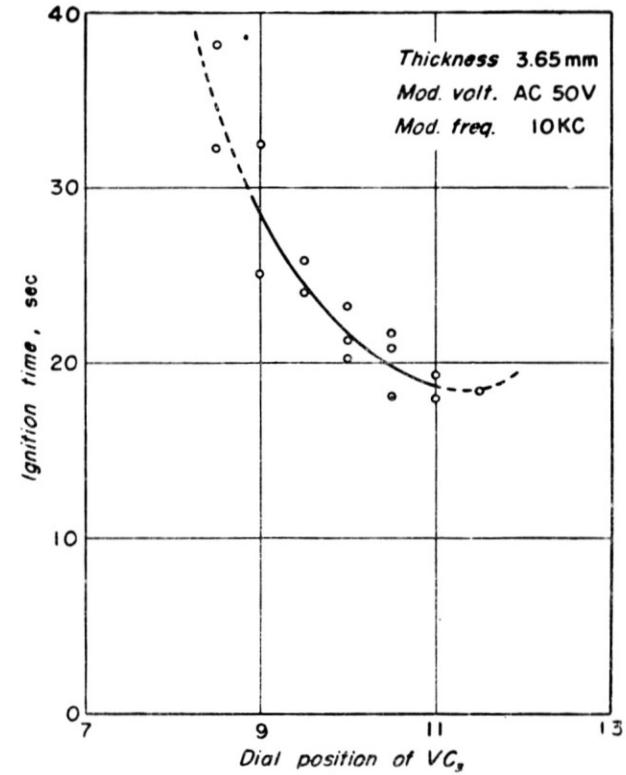

FIG. 8. Relation between ignition time and dial position of VC_3.

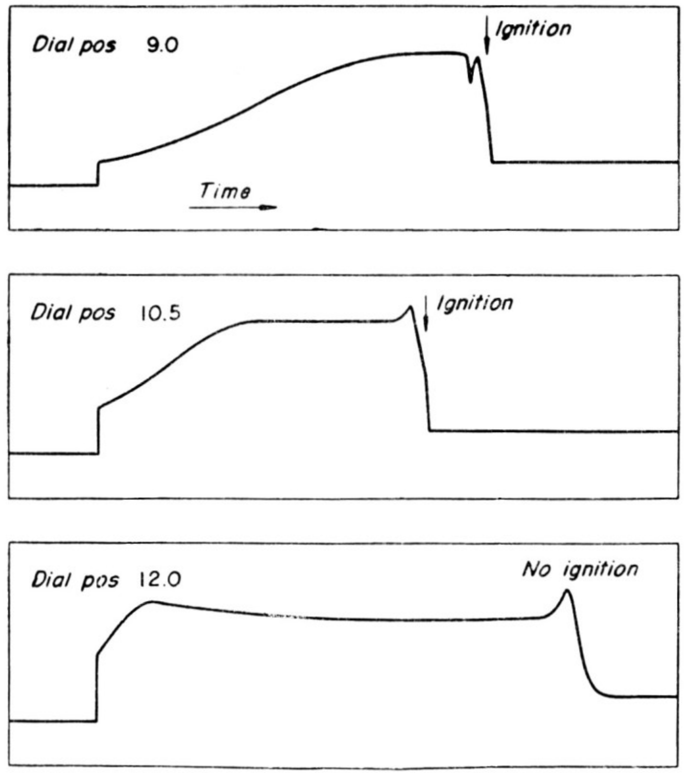

FIG. 9. Oscillograms of VHF field intensity corresponding three different dial position of VC_3.

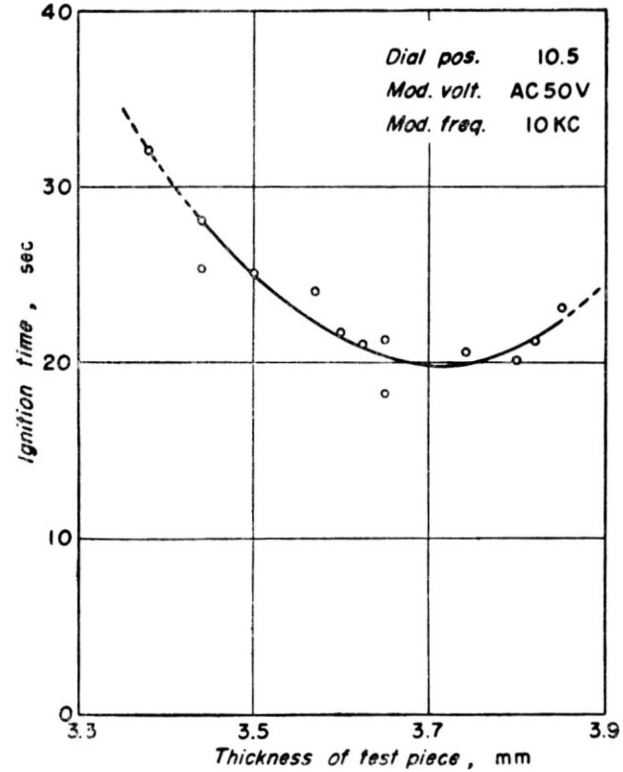

FIG. 10. Relation between ignition time and test piece thickness.

circuit shown in Fig. 5. Figure 6 shows the block diagram of the whole apparatus.

Radio heating of the test piece is initiated by making the plate and screen grid currents of the 807 tubes. In Fig. 7 is shown the relation between the VHF field intensity and the dial position of the variable condenser in the plate circuit of the 807 tubes. For a correct tuning, the variable condenser should be slightly adjusted, according to the capacity change of the test section in heating up the test piece. However, this is practically difficult to perform and, moreover, not desirable in view of reproducibility in experiments. As an alternative, the variable condenser is set so that ignition may occur as quickly as possible. The intensity of the VHF oscillation, the plate current of the 807 tubes and the time of ignition measured by the microphone are simultaneously recorded by means of an electromagnetic oscillograph.

Figure 8 shows the relation between the ignition time and the dial position of the variable condenser. The dotted line indicates the range in which ignition is liable to fail because of insufficient heating. Figure 9 shows oscillograms of the VHF field intensity corresponding to three different dial positions. The time required for ignition depends also upon the thickness of the test piece as shown in Fig. 10. In the greater part of experiments the thickness is 3.65 mm as mentioned above, the dimensional error being less then 0.02 mm.

3. *Results and discussion*

Figure 11 shows a typical oscillogram under the experimental condition used. In view of variation of the intensity of the VHF oscillation and the plate current of the 807 tubes, the time required for ignition can be divided into two parts. The intensity of the VHF oscillation increases with time in the first part t_1 and sustains almost a constant value in the second part t_2 until a peak appears before ignition. These two parts may possibly correspond to the solid state and the solid-liquid state, respectively. In Fig. 12 sectionalized test pieces are shown, whose heating has been interrupted at the time desired. The picture in top shows the state at the end of t_1, which is not essentially different from that at the initial temperature. The picture in bottom shows the state at the end of t_2, where one can find a hollow cavity due to the violent gasification. Furthermore, the peak of the VHF oscillation is supposed to correspond to a violent gasification, as well as the dielectric constant observed prior to ignition in the furnace heated experiment. When the VHF oscillation is too weak specially at the later stage of heating, ignition does not occur after the peak appears. In this case, however, it is found that the dielectric constant of the test piece has been quite different from the initial value. The

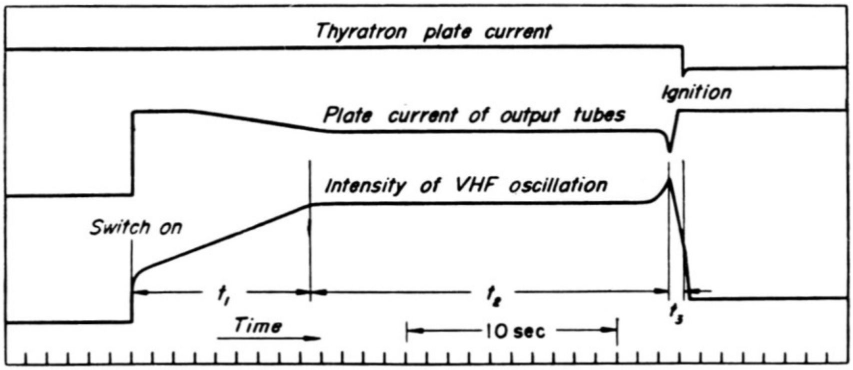

FIG. 11. Typical oscillogram under experimental condition used.

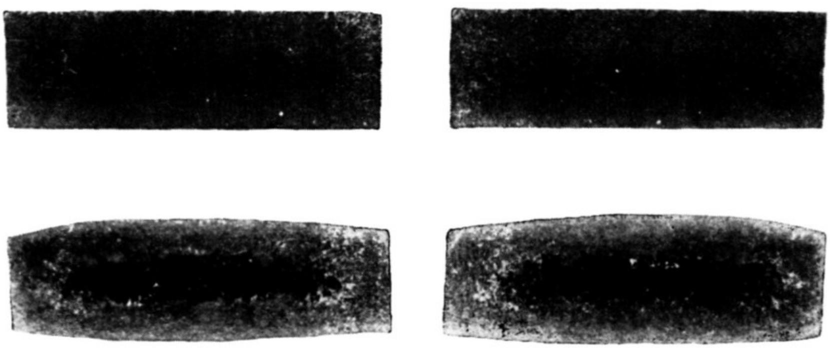

FIG. 12. Sectional views of test pieces at two different stages.

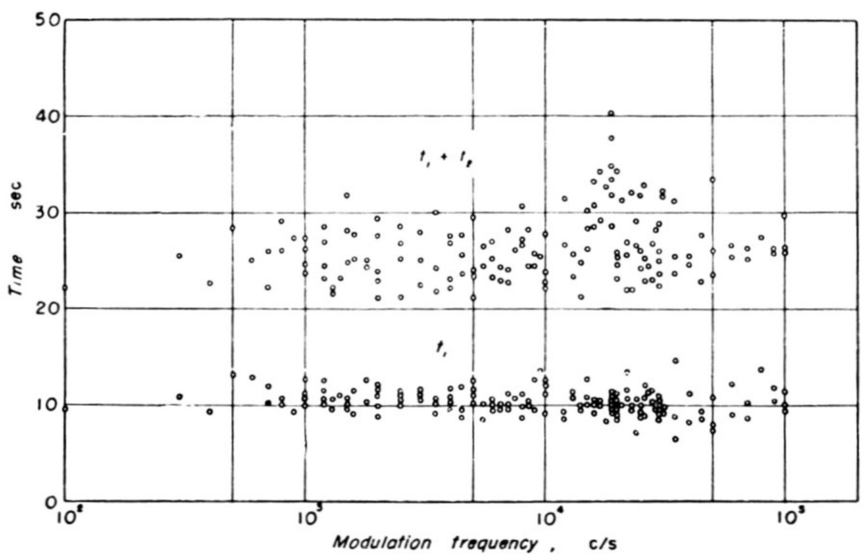

FIG. 13. Effects of modulation frequency on t_1 and t_1+t_2.

time lag between the peak and the acoustically determined time of ignition t_3 is relatively small compared with t_1 or t_2, depending upon uncontrollable factors. For this reason, the time of ignition is determined as the time of the peak of the VHF oscillation.

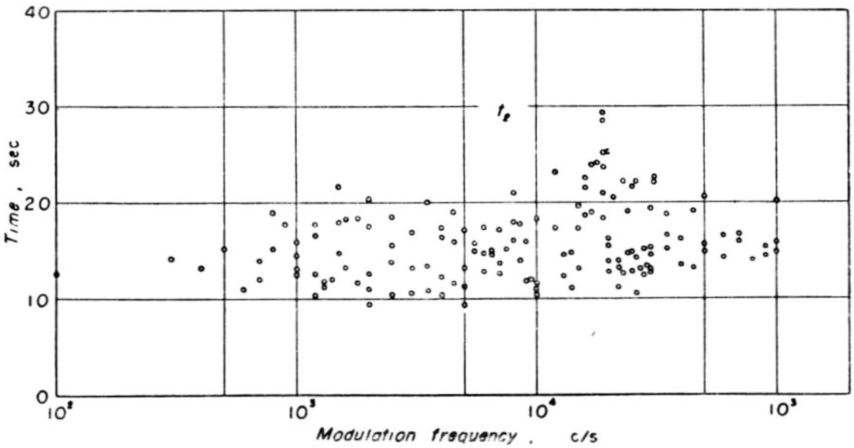

FIG. 14. Effect of modulation frequency on t_2.

Figure 13 shows the relation between modulation frequency and time of ignition of a double base propellant. It is not impossible to find some correlation between time of ignition and frequency of modulation or

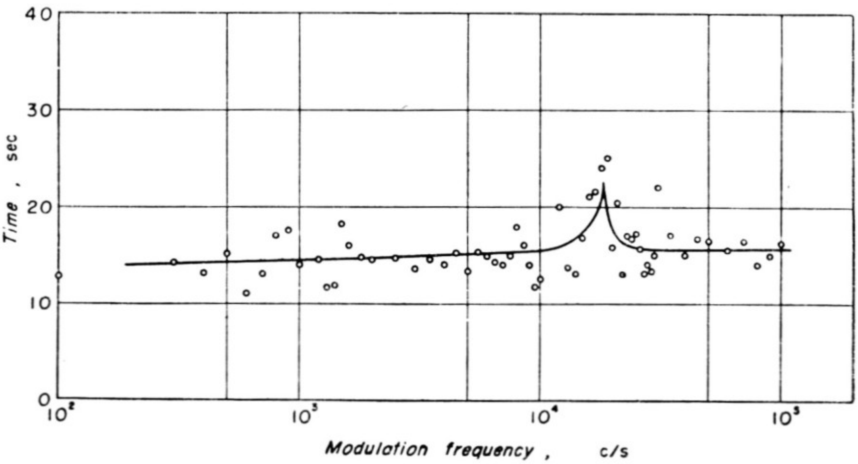

FIG. 15. Effect of modulation frequency on t_2 (mean).

frequency of periodic heating of the solid propellant, though observed values disperse considerably. The first part t_1 of the time required for ignition is not affected by modulation frequency with the exception of the gradual change. On the contrary, it seems that t_1+t_2 or t_2 (Fig. 14) is increased selectively at a frequency (about 19 kc). In Fig. 15 are averaged the observed values of t_2 at each frequency. Figure 16 shows the experimental result obtained at a dial position of the variable condenser slightly different from that for the above-mentioned experiment. The mean of t_2 at 18 kc is greater by 40% than that at 10 kc, the difference being significant.

Experiments on varying test piece size might serve to check whether such a selective frequency sensitivity in the periodic heating of solid propellants, especially at the later stage of heating, would be fundamentally characteristic of the combustion processes. Thus, similar experiments are performed for the test pieces of 2.0 and 5.2 mm thickness, respectively.

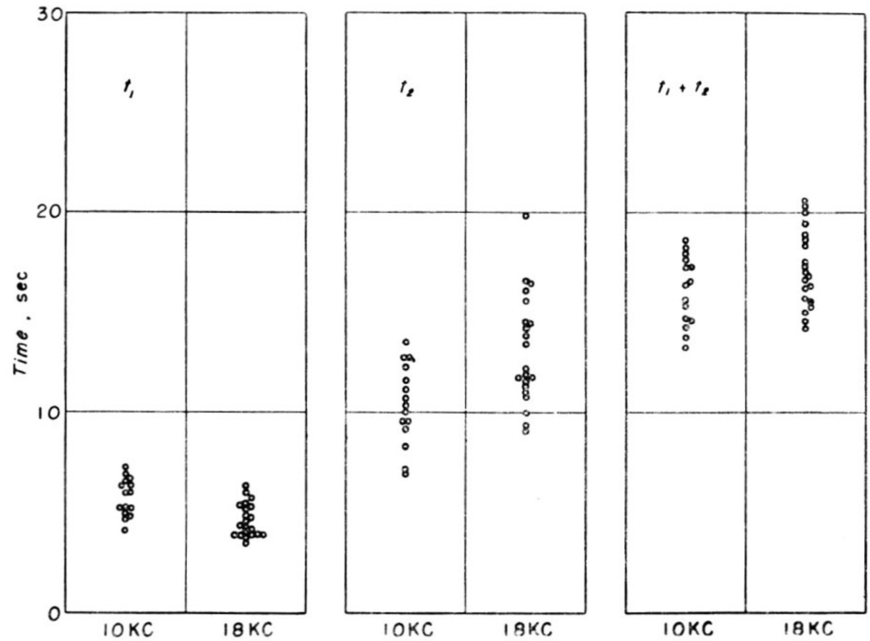

FIG. 16. Comparison of ignition time at 10 kc and that at 18 kc.

The test piece of 2.0 mm thickness is liable to fail to ignite, even though the variable condenser is set so that ignition may occur as quickly as possible. This is supposed to come from the fact that the cooling by the electrodes and the change of the dielectric constant or the tuned frequency becomes larger and results in an effect similar to the decrease of heating power.

The test piece of 5.2 mm thickness is found to ignite in a wider range of dial position of the variable condenser than the test piece of 3.65 mm

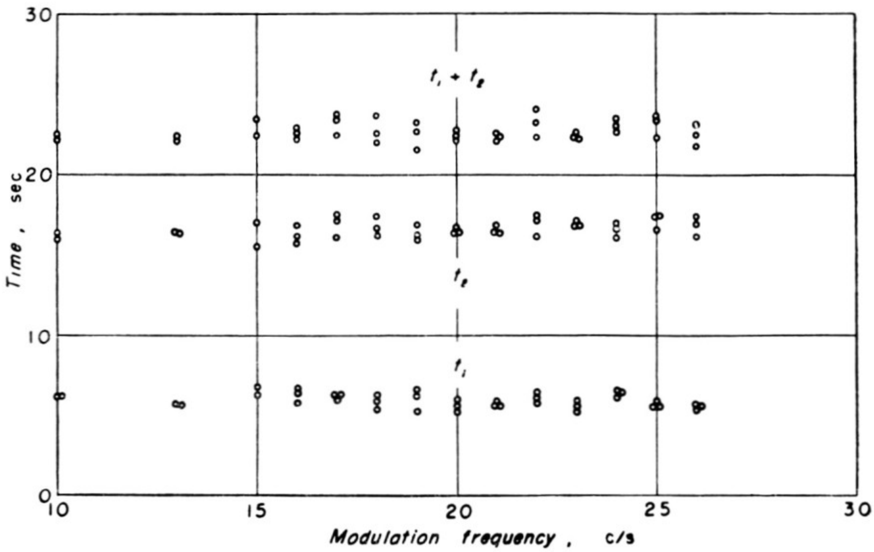

FIG. 17. Effect of modulation frequency on ignition time for test piece of 5.2 mm thickness.

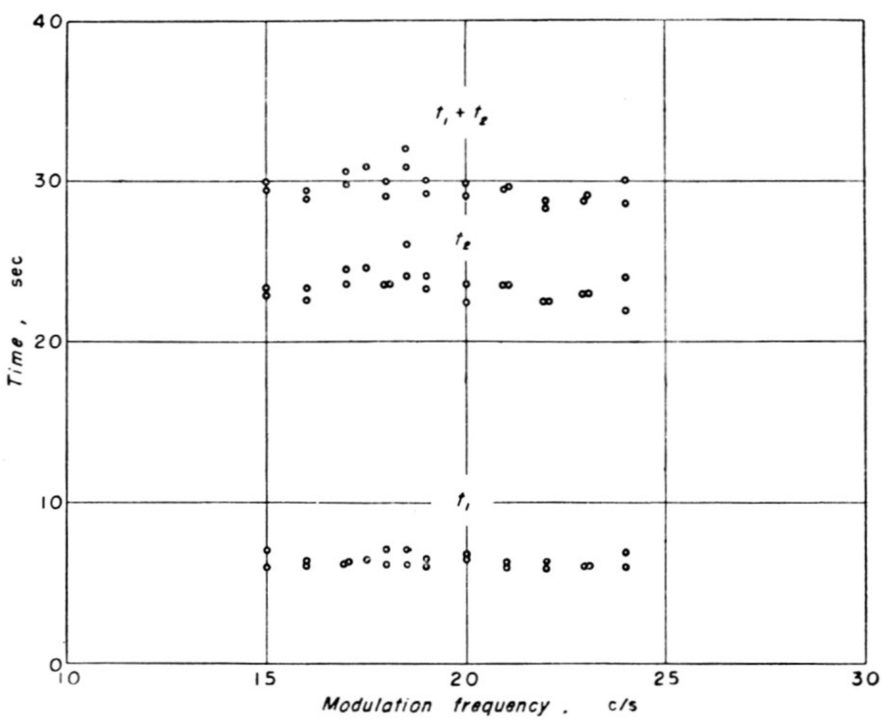

FIG. 18. Effect of modulation frequency on ignition time for test piece of 5.2 mm thickness with reduced heating power.

thickness. This is supposed to come from the fact that the cooling by the electrodes and the change of the dielectric constant or the tuned frequency become smaller and equivalent to the increase of heating power. Figure 17 shows the relation between modulation frequency and time of ignition for test pieces of 5.2 mm thickness. In this case also, the variable condenser is set so that ignition may occur as quickly as possible. No definite frequency sensitivity can be observed in the result shown in Fig. 17. Figure 18 shows the result of a similar experiment, where the range of dial position of the variable condenser for sure ignition is reduced to the extent of that for the test pieces of 3.65 mm thickness by lowering the plate voltage of 807 tubes. In this case, a selective frequency sensitivity of t_2 can be observed at 17 to 19 kc, though it is not so remarkable as for the test pieces of 3.65 mm thickness.

4. *Conclusion*

In the present paper by "ignition" is meant the initiation of a sustained decomposition reaction of solid propellant. The above-described experiments were conducted for the purpose of investigating the behaviour of solid propellants in the ignition by periodic heating.

A selective frequency sensitivity was noticed at 17 to 19 kc. On the other hand, a selective frequency sensitivity was also noticed at about 25 kc in the furnace heated experiment. The double base propellant used was of different composition and the condition of ignition was not the same, in the furnace heated experiment and the VHF heated experiment, respectively. It is important that a solid propellant in its ignition process behaves selectively to a certain frequency of periodic heating.

The author, of course, does not insist that such a phenomenon alone is responsible for instability of solid propellant rockets, but he thinks of it as one phenomenon which may possibly happen in the so-called unstable burning.

The accuracy of these experiments is still too low for quantitative discussion, because the same kind of solid propellant is unavailable in quantity for test pieces. Therefore, this conclusion should be qualitative. It is a future problem to explain this frequency sensitivity on the physicochemical basis. Anyhow, such a fact will be worthy of being considered in the study of instability in solid-propellant rockets.