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EFFECT OF PARAMETERS ON THE COMBUSTION
RATES OF HOMOGENIOUS SOLID ROCKET FUELS

By

D. Draskovic

EDITED TRANSLATION

FTD-ID(RS)T-1953-79 14 February 1980

MICROFICHE NR: FTD-80-C-000212

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English pages: 40

Source: Naucno-Tehnicki Pregled, Nr. 4,
1974, pp. 13-40

Country of Origin: Yugoslavia
Translated by: SCITRAN
F33657-78-D-0619
Requester: FTD/TQTA

EFFECT OF PARAMETERS ON THE COMBUSTION RATES OF HOMOGENIOUS SOLID ROCKET FUELS

Experimental investigation of causes of disturbances in the combustion rate of solid rocket fuels.

PART II

by

Dusan Draskovic

629.76-66:623.473-66:621.454.3:536.46(047) = 861/862

We discuss problems in experimental investigations of combustion rates of solid rocket fuels. Selection of the method was based on consideration of investigation procedures that would enable research of this phenomenon under realistic conditions of combustion and under some simplified conditions. The economic factors had some influence in the method selected as these type of investigations are relatively expensive and the number of experiments under realistic conditions is relatively small in comparison with the number of experiments involving fuel samples.

In the choice of domestic types of solid homogenious rocket fuels we started with the requirement to include the most important domestic compositions and to record the behavior of these fuels under various combustion conditions.

Selection of the test method

For the purpose of selection of a most convenient method for investigating changes in the rate of combustion due to various factors, an analysis of papers on this problem reported to date was carried out. First investigations were carried out by Wimpress [1] using a double-based rocket fuel JPN. He was the first to propose a linear dependence of the combustion rate disturbance as a function of the flow rate in the well known form:

$$\varepsilon = 1 + k_2(U_{p.s} - U_{pr})$$

which is used in practice to date.

Next, a more general investigation was reported by L. Green [3] using a composite fuel employing a real engine with a cylindrical charge burning only on its internal surface. He determined the rate of combustion using a combustion interruption method. He measured the time of combustion and the thickness of the combusted layer of the charge. The results obtained by Green are consistent with the above linear equation. Further investigations of this problem were reported by T. Marklund and A. Lake [4]. In contrast with Green, these authors carried out their experiments using fuel samples which were combusted in a controlled gas flow. As in Green's case, the tests were made using only composite fuels.

Among theoretical works, reports by Robillards and Lenoir [7] may be noted. They approached the problem with the assumption that the heat flux which acts upon the burning surface represents the basic parameter that regulates the combustion process of a solid rocket fuel.

Analysis of results and methods in the above mentioned investigations lead to the following conclusions:

- experimental results to date are generally consistent with the linear effect of flow rate.

- the Green method should be accepted only with some serious reservations because of the following reasons: First, the method of combustion interruption leads to errors in determination of the combustion time. It includes the time required for the extinguishing and lighting processes; second, the charge burns radially whereas the rate of combustion changes continually due to a continually increasing pressure. Therefore, it is difficult to distinguish this effect from other factors.

- in tests by Marklund and Lake the fuel samples are placed practically in the boundary layer of the gas stream. Yet the combustion rate is calculated on the basis of the average value of gas velocity in the channel.

Taking into consideration the advantages and faults of previous investigations, the accepted methods had to fulfill the following requirements:

- test conditions using real engines must be carried out for constant combustion pressure. Only in this case is the initial rise in pressure a consequence of the change in the combustion rate due to secondary effects.

- tests with fuel samples must enable the sample to be placed as much as possible outside the boundary layer of the basic gas stream. The form of the sample must be such that it causes a minimal disturbance in the basic flow of the stream.

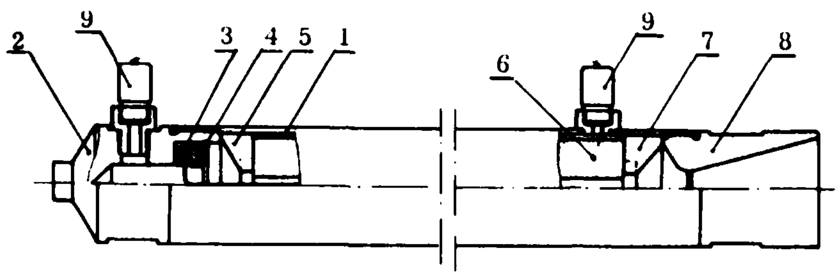
<u>Tests with the real engine</u>

In order to approach real conditions under which the combustion process takes place and in order to enable a comparison with results obtained by testing fuel samples, a proper test rocket engine has been designed.

The engine had to fulfill the following conditions:

- combustion at p = const.
- provide combustion pressurs of 50-150 kp/cm^2.
- provide a flow rate of combustion products of 300 m/sec at the end of the power charge.

An engine designed in this way is illustrated in Figure 1.



1. chamber
2. lever
3. lighter
4. limit control
5. screen
6. charge
7. screen
8. nozzle
9. pressure sensors

Figure 1. View of the rocket engine used for testing of erosion effects in real engines.

The length of the chamber for combustion and charge can be changed in order to satisfy requirements for the pressure level and flow of the stream. The charge has a cylindrical form and burns on its internal and external surface to assure p = const.

Combinations of various nozzles and lengths of the charge and the chamber permit obtaining the rquired values of pressures and velocities of combustion products in the exhaust. In order to analyze pressure drops along the length of the engine, pressure sensors are placed at both ends of the chamber. The charge is lighted by a lighter placed at the front end of the engine.

In the real engine the tests were made using two main compositions of double-base rocket fuels which have the broadest application in real designs. A significant number of tests were made using composition type A which appeared to be very sensitive to the disturbance phenomenon of combustion rates in actual designs. Composition B was used for only a few tests, mostly to confirm previous knowledge about the behavior of this composition.

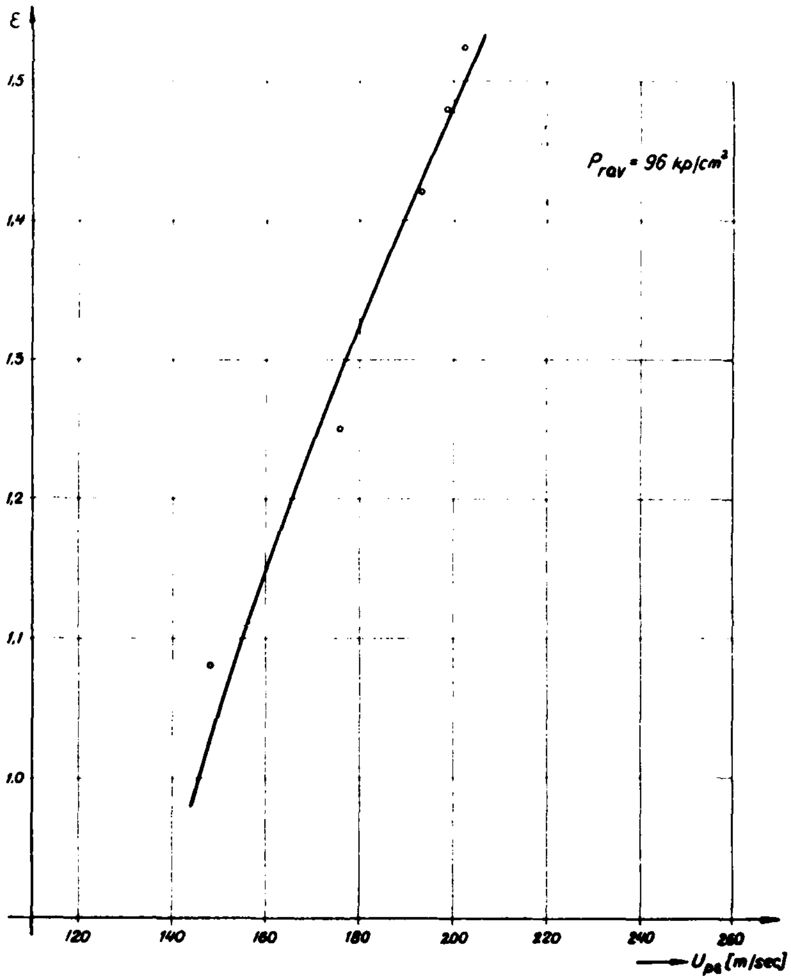

ε
1,5
1,4
1,3
1,2
1,1
1,0
P_{rav} = 96 kp/cm²
120
140
160
180
200
220
240
260
U_{pa} [m/sec]

Figure 2.

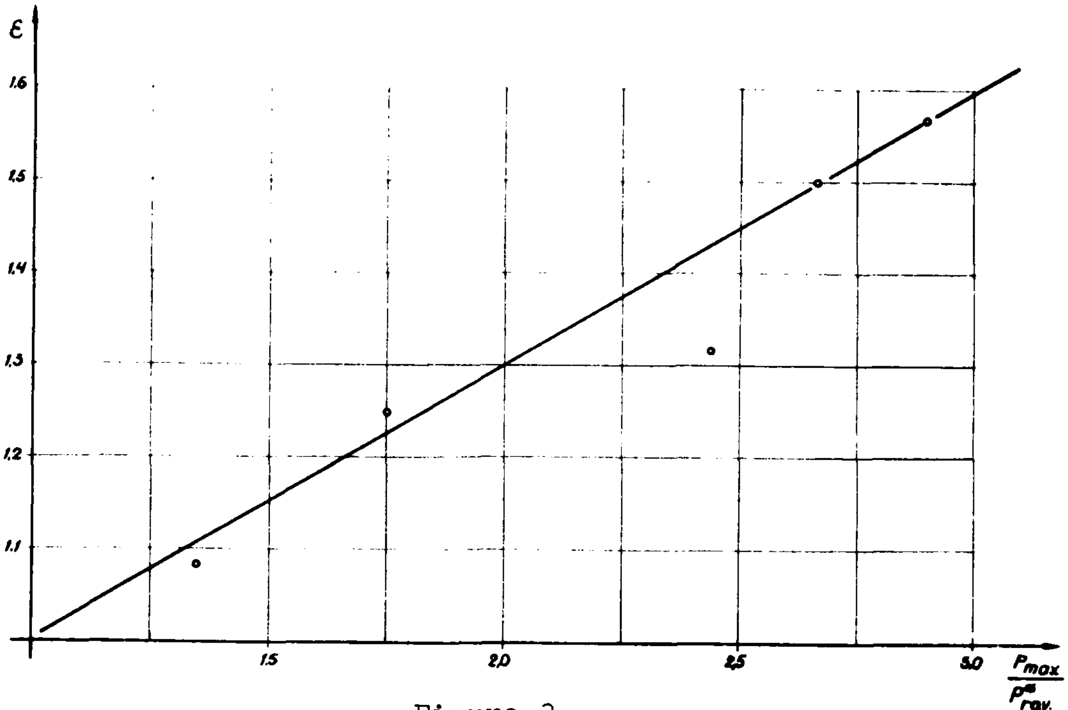


Figure 3.

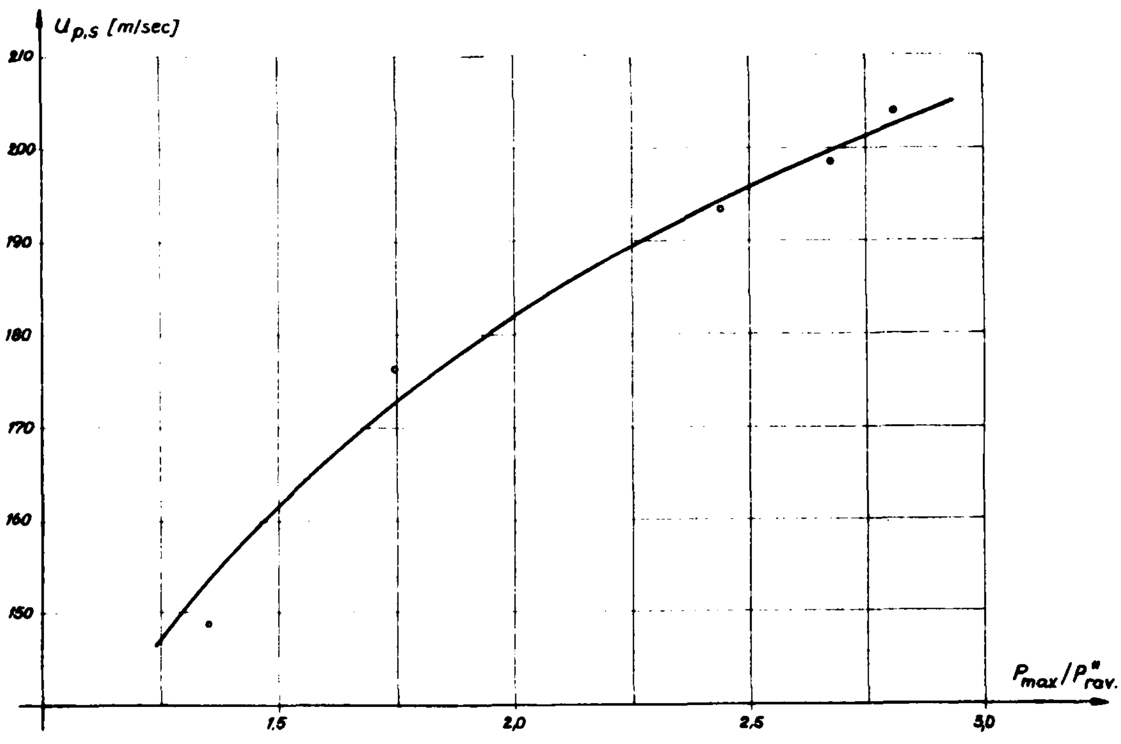


Figure 4.

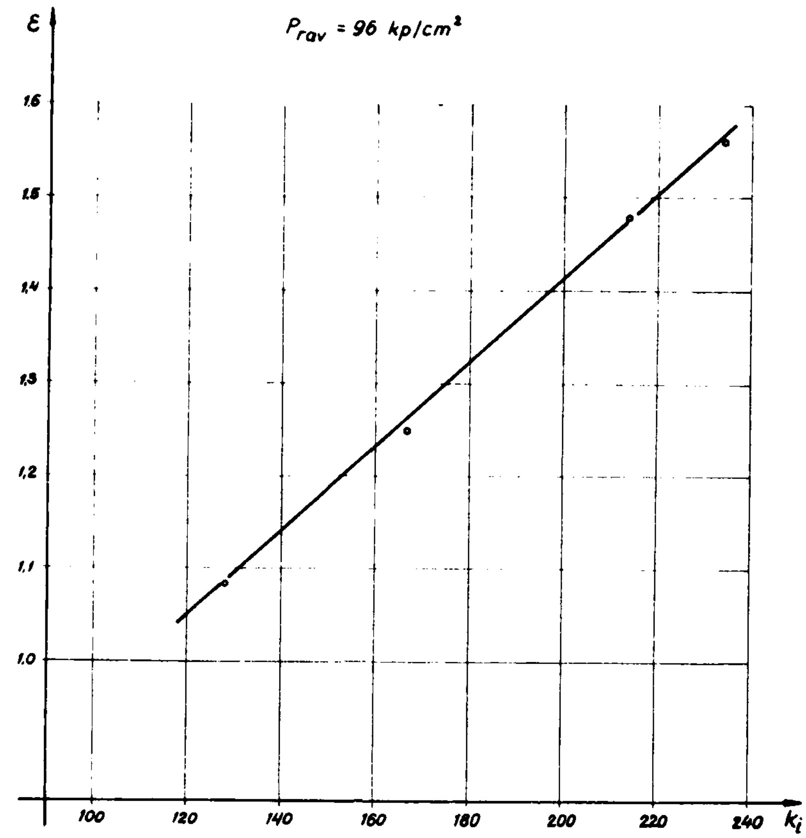
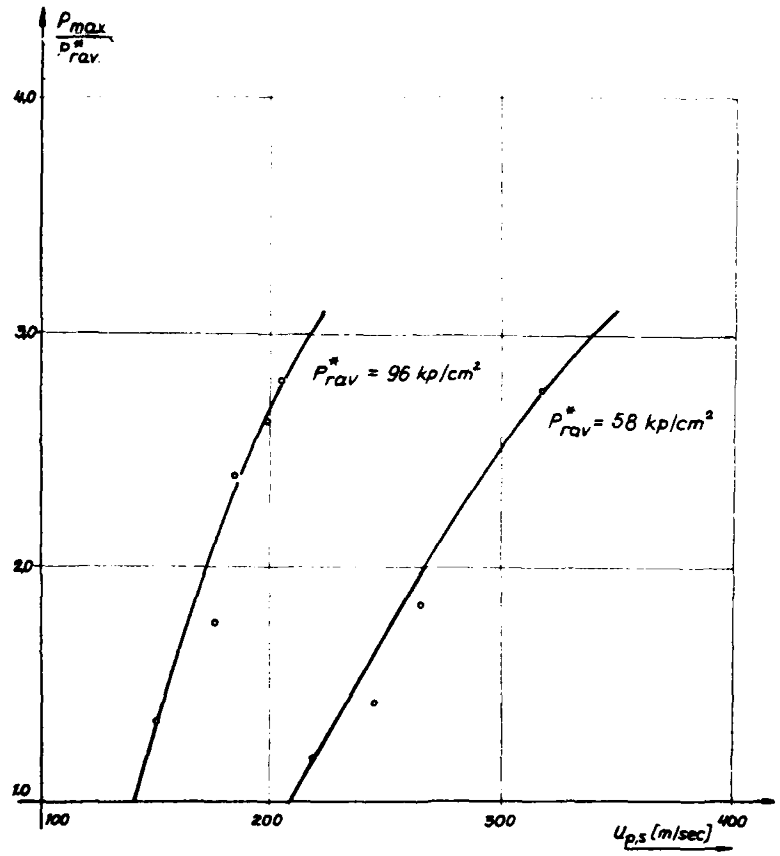


Figure 5.

Using the composition type A, a series of tests were carried out at two equillibrium combustion pressures. All calculated values are related to the conditions ahead of the nozzle. For a more accurate and easier analysis, along with the increase of the rate of combustion expressed by the quantity ε, analysis is also given for the dimensionless parameter of the initial rise in the combustion pressure. Taking into consideration the sensitivity of the tested composition during the initial pressure jump, which is most important for real designs, it is possible to determine the limits of allowable disturbances in combustion rates for each design from parameters of the rocket engine.

The results of investigations in a real engine are shown in Figures 2-8 for composition A and in Figures 9-10 for the composition B.



$\frac{p_{max}}{p^*_{rav.}}$
4.0
3.0
2.0
1.0
100
200
300
400
$u_{p,s}$ (m/sec)
p^*_{rav} = 96 kp/cm²
p^*_{rav} = 58 kp/cm²

Figure 6

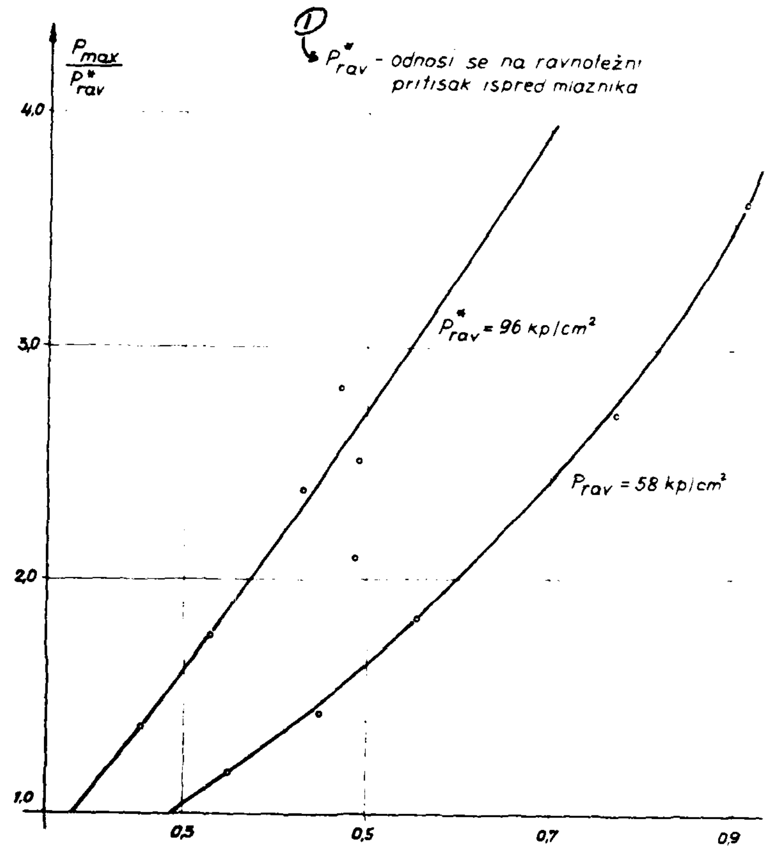


Figure 7

Key: 1--related to the equillibrium pressure of the nozzle.

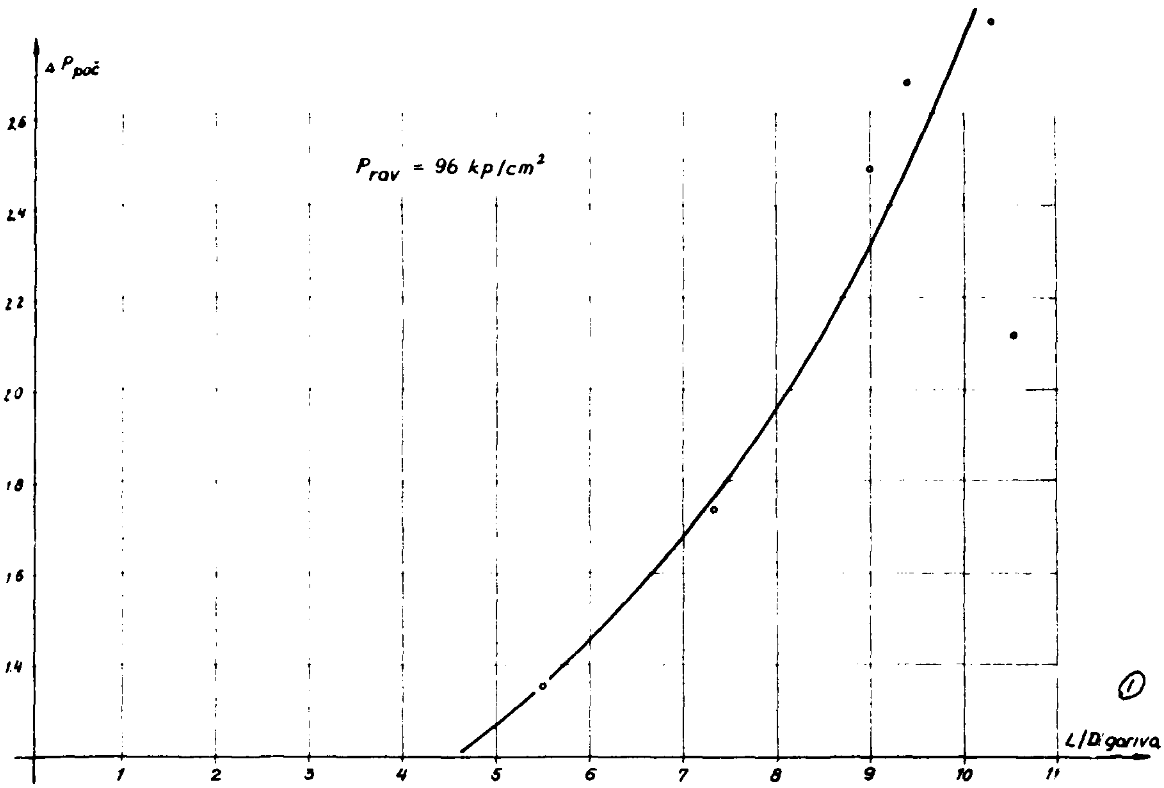


Figure 8

Key: 1--fuel

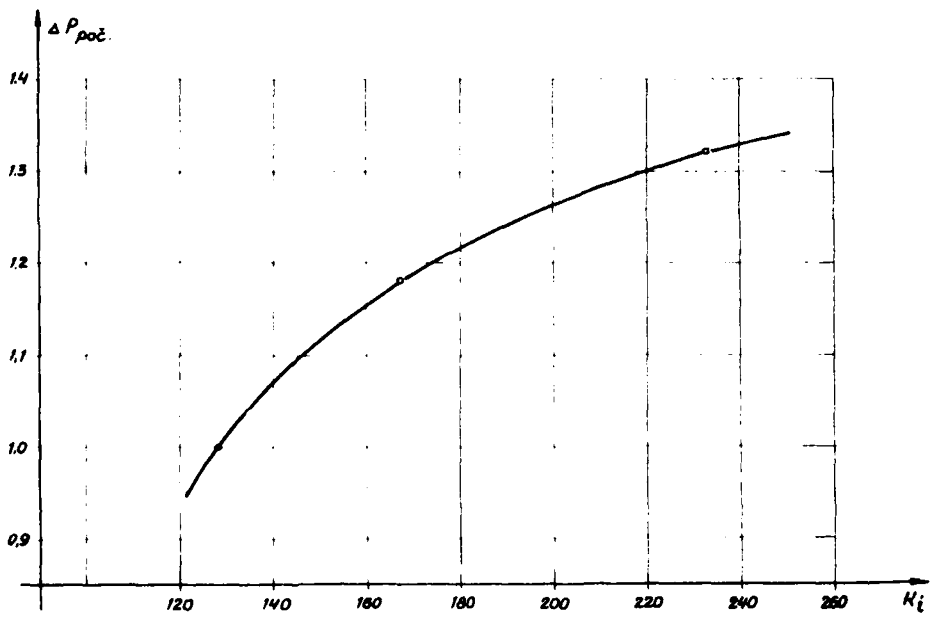


Figure 9

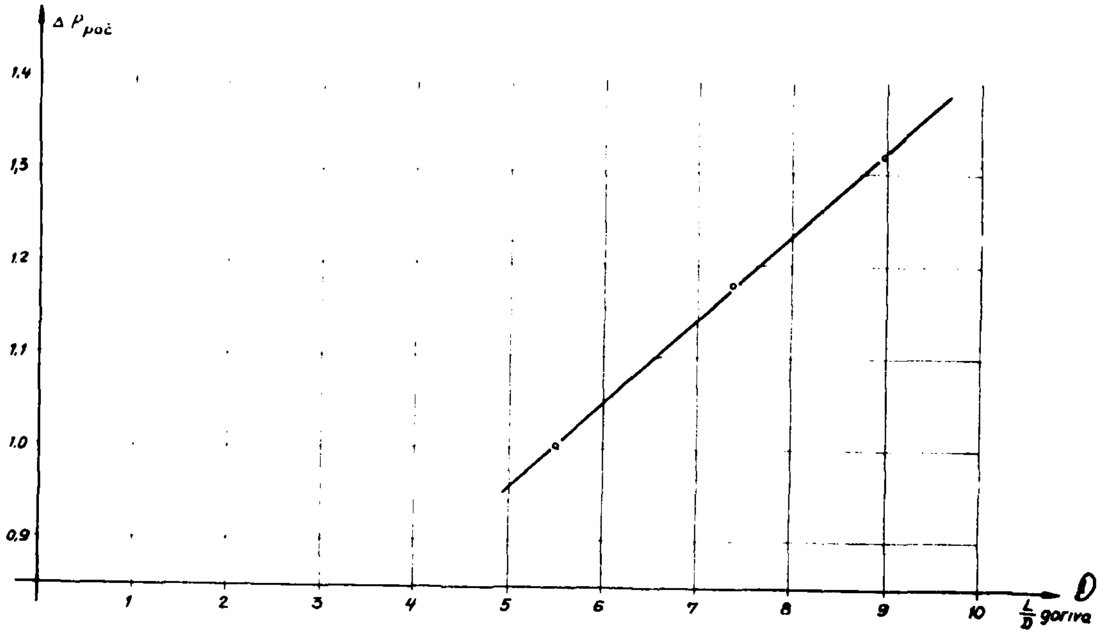


Figure 10

Key: 1--fuel

The critical values where a positive disturbance of the combustion rate of type A composition rocket fuel takes place at an equilibrium combustion pressure of 96 kp/cm^2 are:

$$U_{pr} = 144 \text{ m/sec}$$
$$I = 0.15$$
$$R_{ekr} = 1.5 \times 10^5$$

The obtained values are presented in the diagrams as $\varepsilon = f(U_{p.s})$, $\varepsilon = f(\Delta P)$, $U_{p.s} = f(\Delta P)$, $\varepsilon = f(K_i)$, $\Delta P = f(U_{p.s})$ and $\Delta P = f(L/D)$.

They show that the tested composition is very sensitive to disturbances in the rate of combustion, particularly at higher values of equilibrium combustion pressures. Consequently, this fuel is not suited for applications in the so called "strained" designs.

The degree of positive disturbance in the rate of combustion expressed by the dimensionless parameter ε rises rapidly with the flow velocity of the combustion products. At the combustion products flow rate of 200 m/sec, the parameter ε reaches a value of 1.5, which is considered to be a very high value.

The results of investigations show that the value of the parameter ε can be very significantly reduced by selecting a low equilibrium combustion pressure. This is a very important information for selecting optimum parameters for the rocket engine.

The diagrams that give relations between the initial jump in the parameter ε, flow velocity of the combustion products and the dimensionless (internal-ballistic) parameter K_i are particularly very practical diagrams for cross-checking the design of rocket engines.

Only three tests in a real engine have been carried out using rocket fuel type B. The tests were made to obtain insight into the sensitivity of this composition to changes in the fuel combustion rates.

On the basis of previous knowledge, it was expected that this composition is less sensitive to this phenomenon and this was confirmed in these three tests.

In this case the equilibrium combustion pressure during the tests was significantly higher than in the case of compositon A and corresponded to the value of 180 kp/cm^2. As the test results show (illustrated in Figures 9-10) the rise in the intial pressure (as a function of the dimensionless parameter K_i and the ratio L/D) is significantly lower and of a more suitable character than was found in the case of composition A.

<u>Testing with fuel samples</u>

The equipment for testing disturbances in the combustion rate using fuel samples inserted into a controlled gas stream is illustrated in Figure 11. The equipment consists of a gas generator, a channel for settling the gas stream, a test section

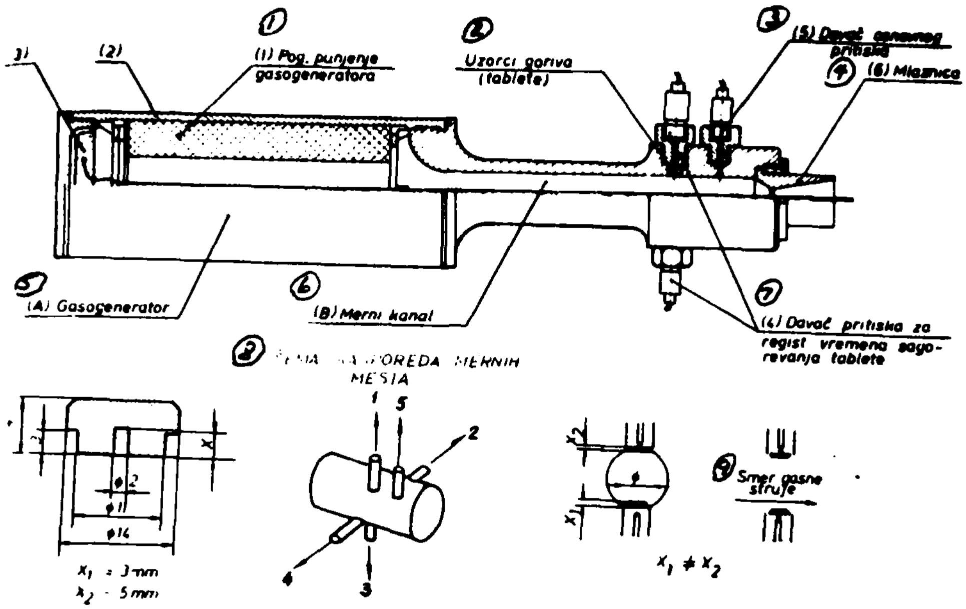


Fig. 11. Measuring device for testing fuel samples.

Key: 1--power charge for the gas generator; 2--fuel samples (tablets); 3--basic pressure sensor; 4--nozzle; 5--gas generator; 6--measurement channel; 7--pressure sensors for recording combustion time; 8--scheme of distribution of measurement locations; 9--direction of the gas stream

for measurements and an expansion section. The gas generator represents the classical rocket engine without the expansion section. The combustion chamber and the power charge section have variable lengths to enable obtaining the desired gas stream velocities in the test section. There are five pressure sensors built into the test section. Four of them have attached fuel samples and record time of the combustion sample. The fifth sensor serves for measuring the basic pressure in the channel.

By combining various nozzles and power charges, one can assure the required conditions of pressure and velocity of the gas stream in the test channel over the combustion samples. The fuel samples are attached to pressure sensors and because they are used in pairs of different thicknesses, the time for a sample combustion can be obtained. The total rate of combustion for a tested system is determined from the known dimensions and time.

Two pairs of fuel samples were tested in parallel to reduce measurement errors. The fuel samples were inserted into the gas stream to the degree possible because of the effect of disturbance of the basic gas stream. The pressure sensors operated on the principle of a recording chart where the measured value is recorded through a corresponding electronic system using a pen.

A large number of tests have been carried out using this equipment for compositions of rocket fuels designated as types A, B and C.

Tests with samples of type A composition

We have carried out 27 tests using rocket fuel samples of composition type A. The results obtained are shown in Figures 12-16. The analysis of results is represented in the figuress as:

$$U^{x}_{sag} = f(P), \quad \epsilon = f(U_{p.s}), \quad \epsilon = f(K_1) \text{ i } \quad \epsilon = f(J)$$

The following conclusions can be drawn:

1. The total combustion rate of samples increases with the increase of the flow velocity of combustion products. The increase in the combustion rate is not linear as was assumed so far according to the expression:

$$\epsilon = 1 + K_1 (U_{p.s}/U_{pr})$$

Instead the function appears to be exponential and its character is determined (aside from the combustion rate) also by the working pressure and physico-chemical characteristics of the rocket fuel. The empirical equation derived may be written in the following form:

$$\epsilon = A + \sqrt{B\, U_{p.s}\, e^{CP} - D}$$

In the case of the rocket fuel type A, this equation may be written as:

$$\epsilon = 0,85 + \sqrt{0,0015\, U_{p.s}\, e^{0,0075P} - 0,08}$$

Figure 13 shows curves for two equilibrium pressures of combustion calculated according to this empirical equation. The test results agree with this relationship to a satisfactory degree.

2. An increase in the equilibrium pressure of combustion at $U_{p.s}$ = const. also increases the total rate of combustion of the rocket fuel and more significantly so at higher velocities of the gas stream.

3. The critical values for the flow velocities of the combustion products and for the dimensionless parameter K_i at which a positive disturbance of the combustion rate takes place are substantially lower than those found in tests with the real engine.

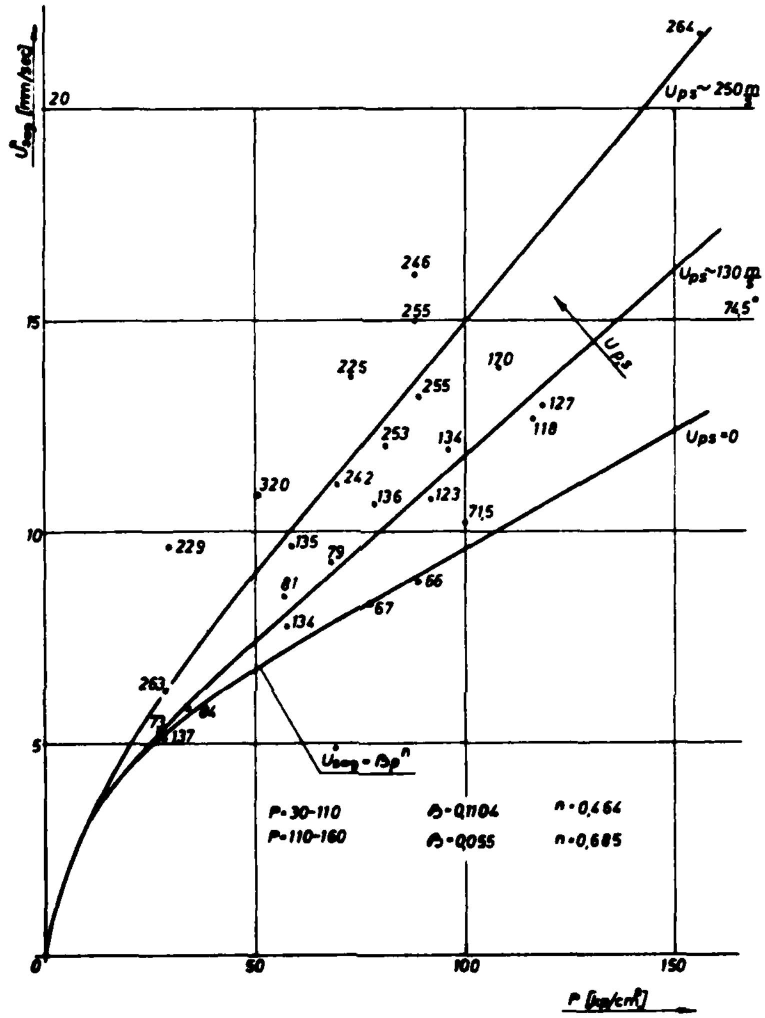
4. The gradient of change in the value of ε is significantly milder than found in tests of the same composition in a real engine.

Figure 16 shows calculated curves $\varepsilon = f(U_{p.s})$, with a family of curves for P = const. and K_1 = const. and another family of curves for P = const. and $K_1 \neq$ const. The test points are in good agreement with the calculated values.

5. Some of the dispersion of the test points is probably the consequence of errors in measurements and the manner in which the measured values are calculated.

<u>Tests with samples of composition type B</u>

Two series of tests were made using composition type B. In the second series of tests a modification of the law of combustion was made by changes in the type of soot and by addition of Pb-stearate. These modifications were intended to show that certain additives affect the sensitivity of the rocket fuel under various conditions of combustion.



U_{avg} [mm/sec]
20
15
10
5
0
50
100
150
P [kg/cm²]
Ups~250 m/s
Ups~130 m/s
74.5°
Ups
Ups=0
$U_{avg} = \beta p^n$
P=30-110
P=110-160
β=0.1104
β=0.055
n=0.464
n=0.685

Figure 12

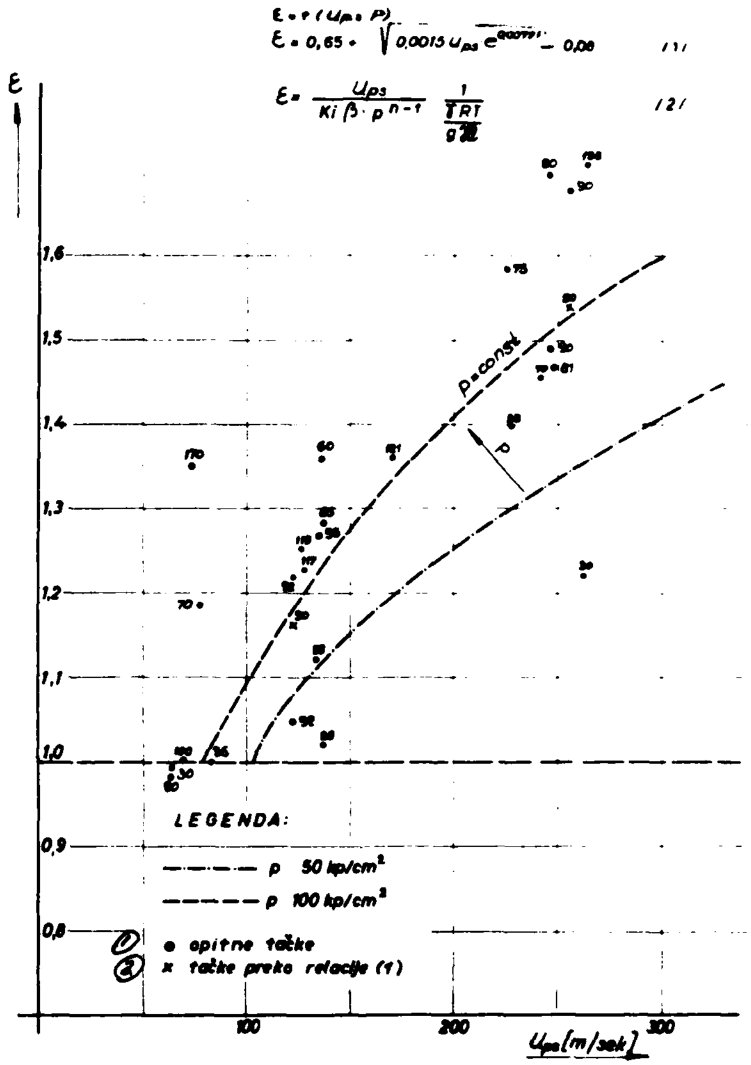


Figure 13

Key: 1-- • test points
2-- x points according to equation (1)

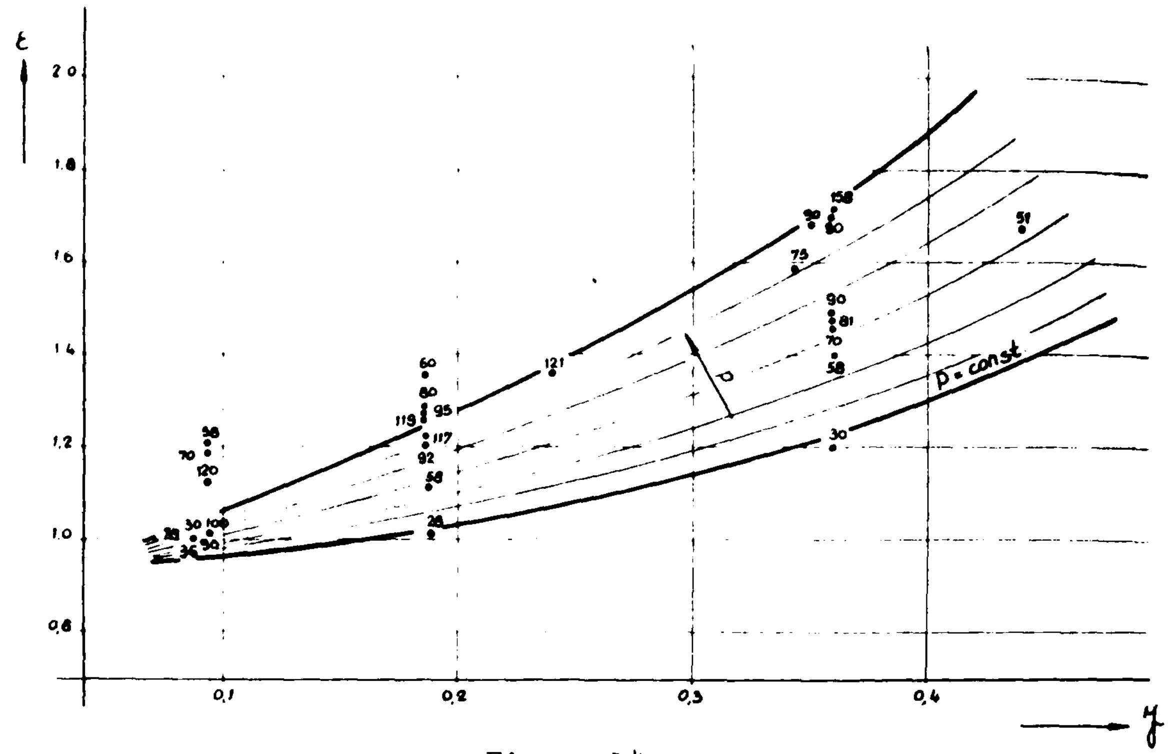
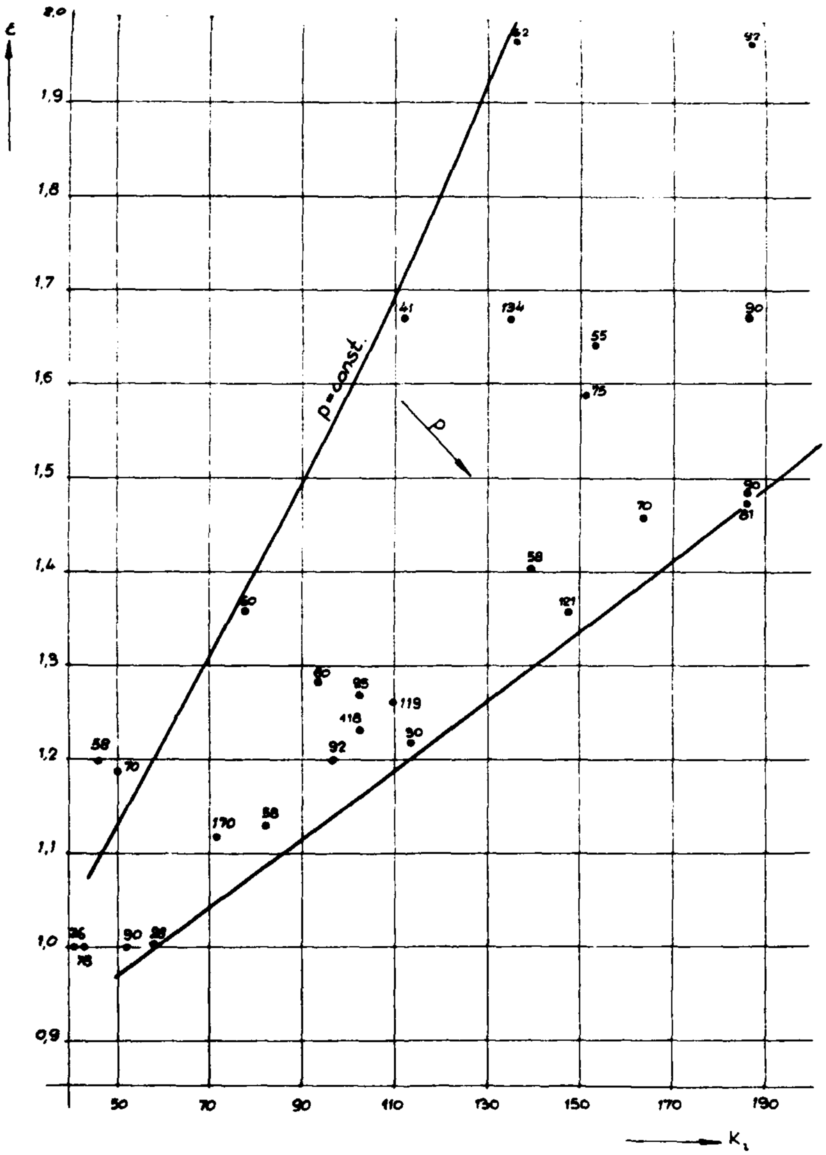


Figure 14

The first series of 15 tests were carried out using the same composition used for the tests with a real engine. In this way the results obtained for combustion of the rocket fuel under conditions of a real engine could be compared with those obtained using samples in a controlled gas flow.

The results of these tests are shown in Figures 17-21. The results shown in Figures 17-18 illustrate that the effect of pressure at a given flow velocity of the combustion products is almost negligible. These results, as well as the results obtained by tests with a real engine, show that this composition is very suitable for more severe operating conditions of rocket engines.

The second series of 15 tests was carried out with a modified composition. In this composition there was an increased amount of the Pb-stearate, and the Japanese soot was replaced with an



ε
2,0
1,9
1,8
1,7
1,6
1,5
1,4
1,3
1,2
1,1
1,0
0,9
50
70
90
110
130
150
170
190
p=const.
p
K

Figure 15

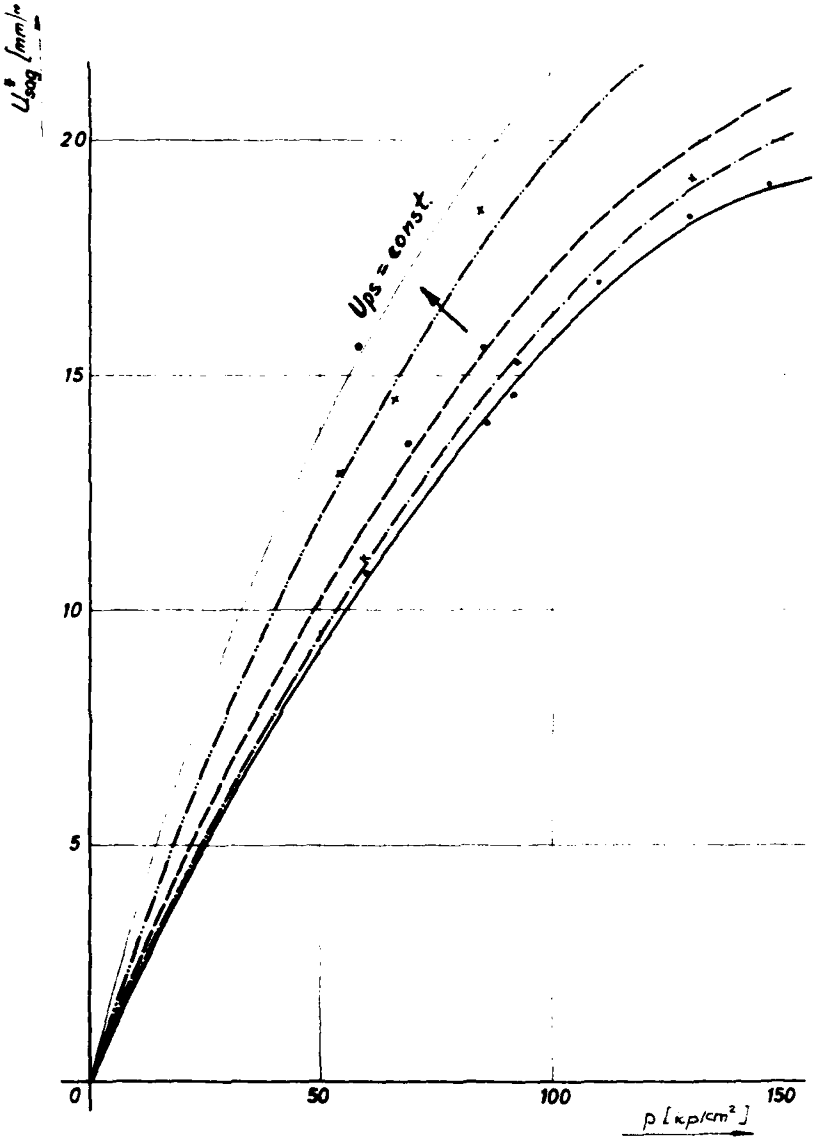


Figure 17

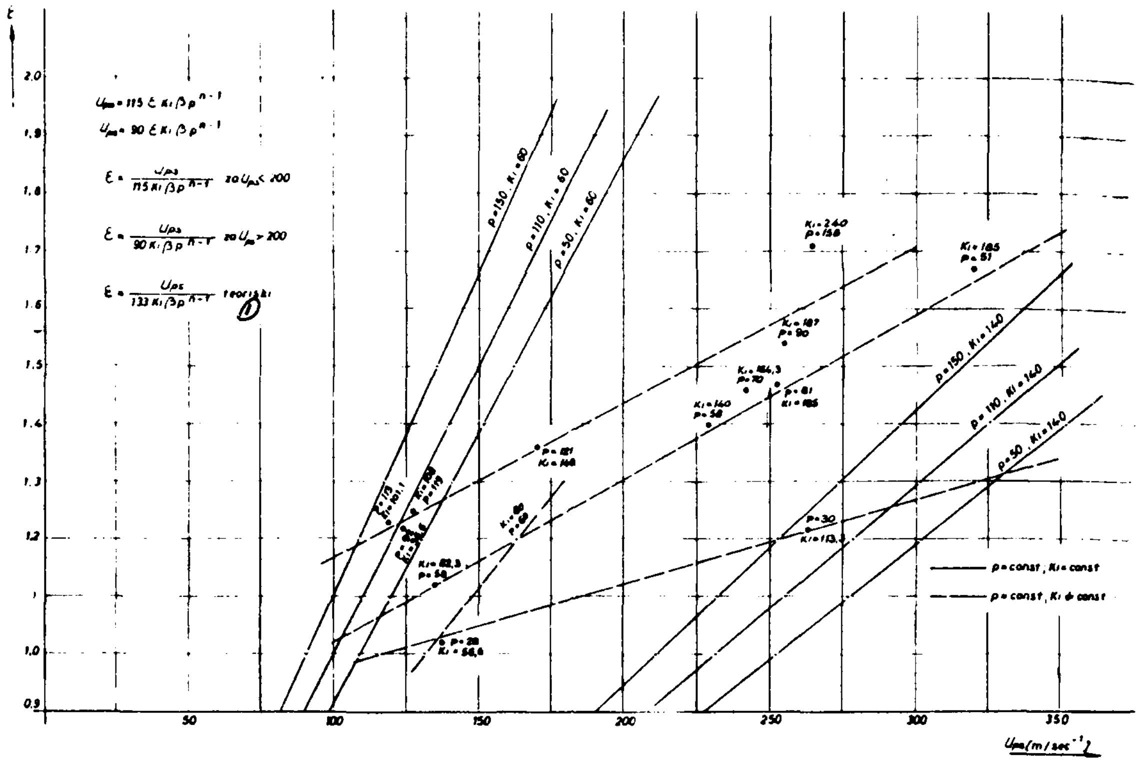


Figure 16

Key: 1--theoretical

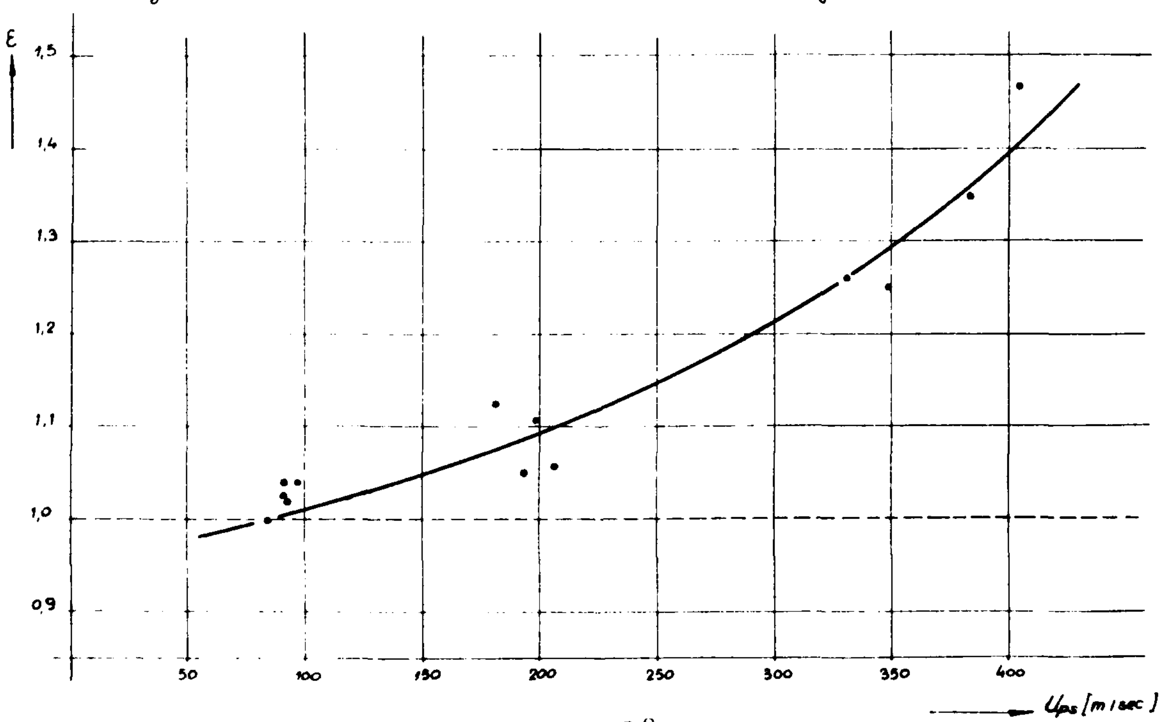
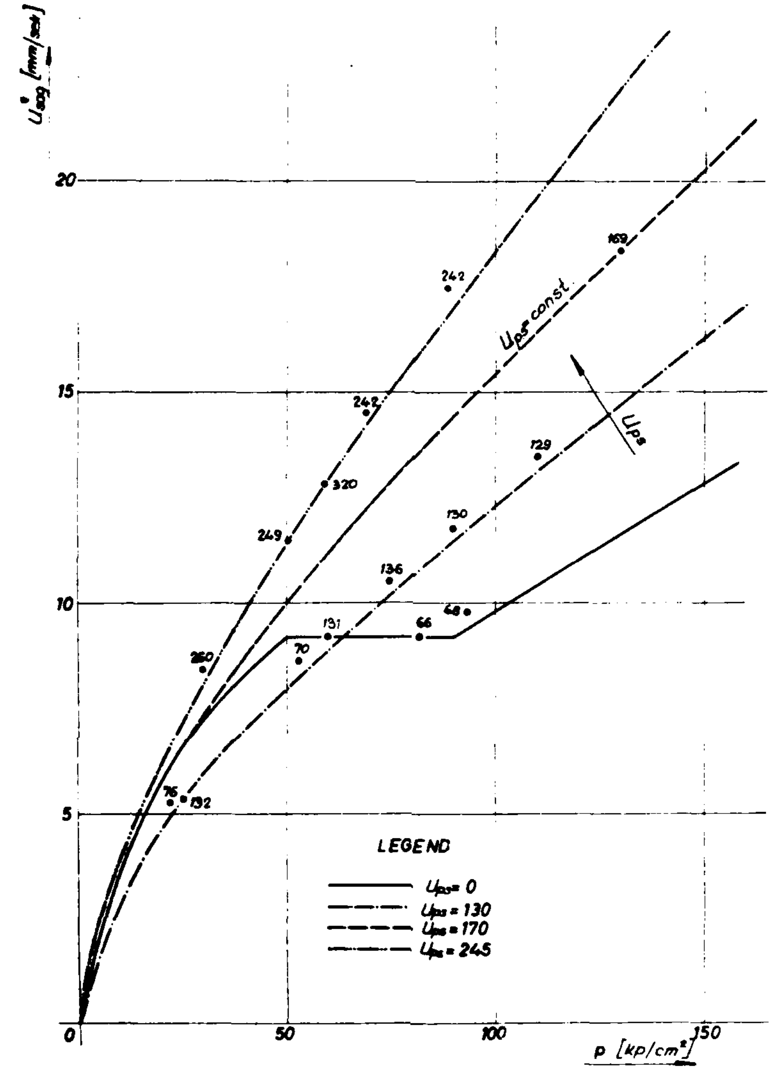


Figure 18



20
15
10
5
0
50
100
150
p [kp/cm²]
Ups= const.
Ups
LEGEND
Ups= 0
Ups= 130
Ups= 170
Ups= 245
242
169
248
320
249
129
130
136
131
66
68
70
250
76
132

Figure 19

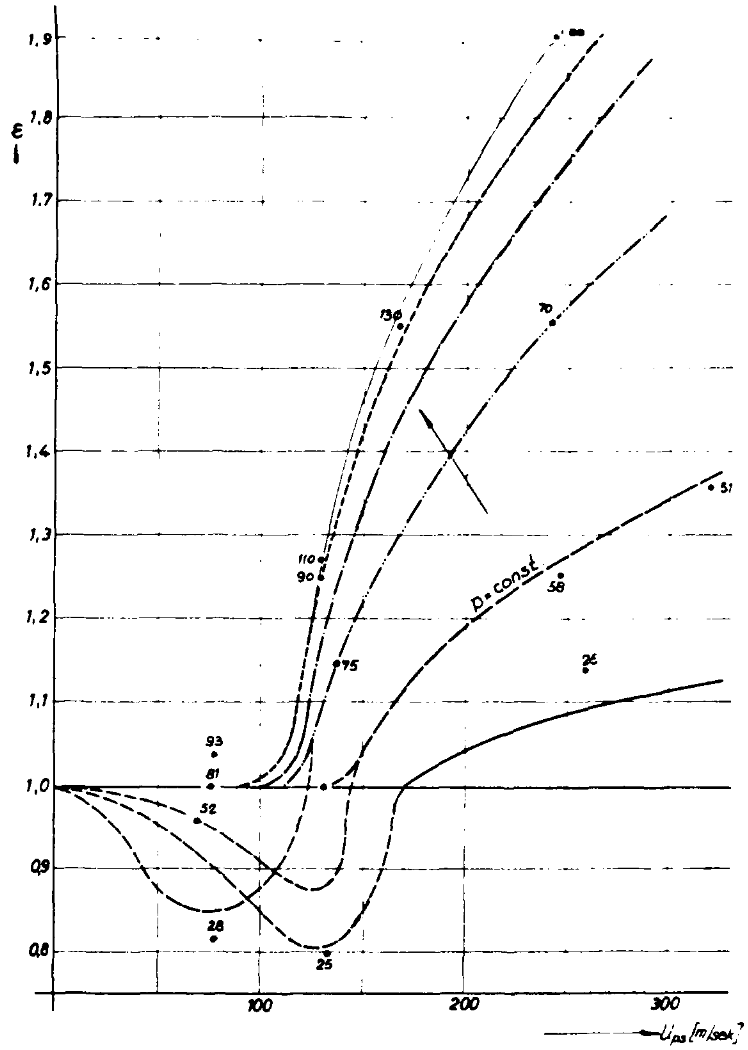

ε
1,9
1,8
1,7
1,6
1,5
1,4
1,3
1,2
1,1
1,0
0,9
0,8
100
200
300
U_{ps} [m/sek]
p = const.
130
70
51
110
90
58
75
93
81
52
28
25

Figure 20

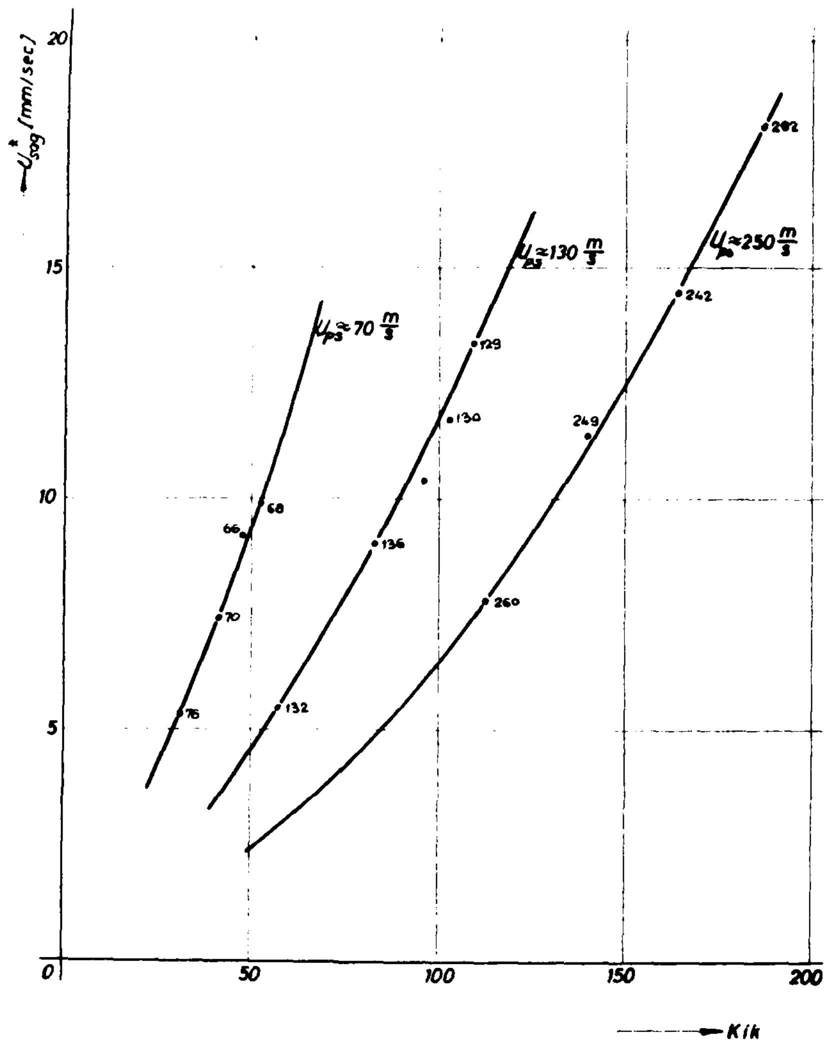


Figure 21

ordinary soot in the same quantity (0.5%). This composition has a "plateau" effect in the pressure range of 50-90 kp/cm^2.

The results of this series of tests are shown in Figures 19-21.

Analysis of these figures can point to the characteristic phenomenon of a negative increase in the combination rate of the fuel. Thus, in the region of lower pressures (below 70 kp/cm^2) and at a flow velocity of products of under 160 m/sec, the change in the rate of combustion as a function of the working pressure appears to be negative, i.e., $\varepsilon < 1{,}0$. This phenomenon is probably caused by the increased thickness of the gas zone and the quiet zone which results in reduction of the heat flux which acts upon the surface of the solid phase. This regulates the rate of decomposition, i.e., the rate of combustion of solid fuel. This phenomenon was noted also in previously published works though no explanation was offered.

The results illustrated in Figure 21 show the curves for $U_{p.s}$ = const. relating the total combustion rate and the parameter K_i. This figure shows clearly the effect of changes in the velocity of the stream of the combustion products on changes in the combustion rate.

Tests using compositions of type C

The composition type C is actually the basic composition of type B but without additives for the "plateau" effect which was obtained in composition type B.

This composition was used in 27 tests divided into two series of different fuel charges. In this way the differences between different series could be observed as a function of variation in the amounts of components and variations in technical procedures for preparing the power charge. In both test series a negative increase of the combustion rate was obtained for the gas flow rates below 100 m/sec and was a function of the equilibrium combustion pressure. Differences in results obtained by these two series are noticeable. It is probable that, in a way, the method of testing also has an effect on this difference. In the second series the test method was improved by using twice as many samples during the tests.

Results of the first series of tests are shown in Figures 22-25.

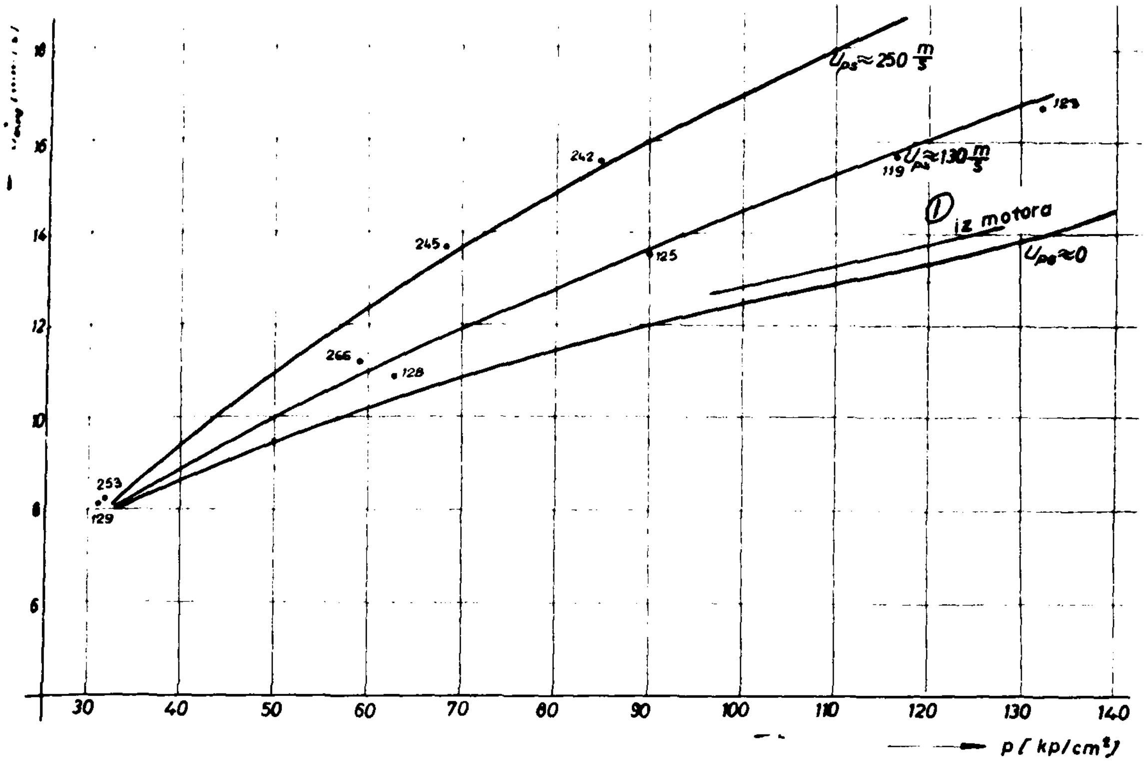


Figure 22

Key: 1--from the engine

Figure 23 shows curves $\varepsilon = f(U_{p.s})$ which are sufficiently consistent with the equation:

$$\varepsilon = 0,862 + \sqrt{\frac{8,62.10^{-4}\ U_{p.s}}{0,55 + 3,22\ e^{0,0032\ P}} - 0,067}$$

for the range of pressures and rates of flow within limits of:

$$60 < P < 130$$

$$80 < U_{p.s} < 250$$

Figure 24 shows how increases of the flow velocities of gases result in a significant increase of the critical value of the dimensionless parameter K_i. This finding indicates that it should be possible to design rocket engines with relatively high flow velocities of combustion products, provided that the equilibrium combustion pressure is kept relatively low.

The results of the second series of tests are shown in Figures 26-28.

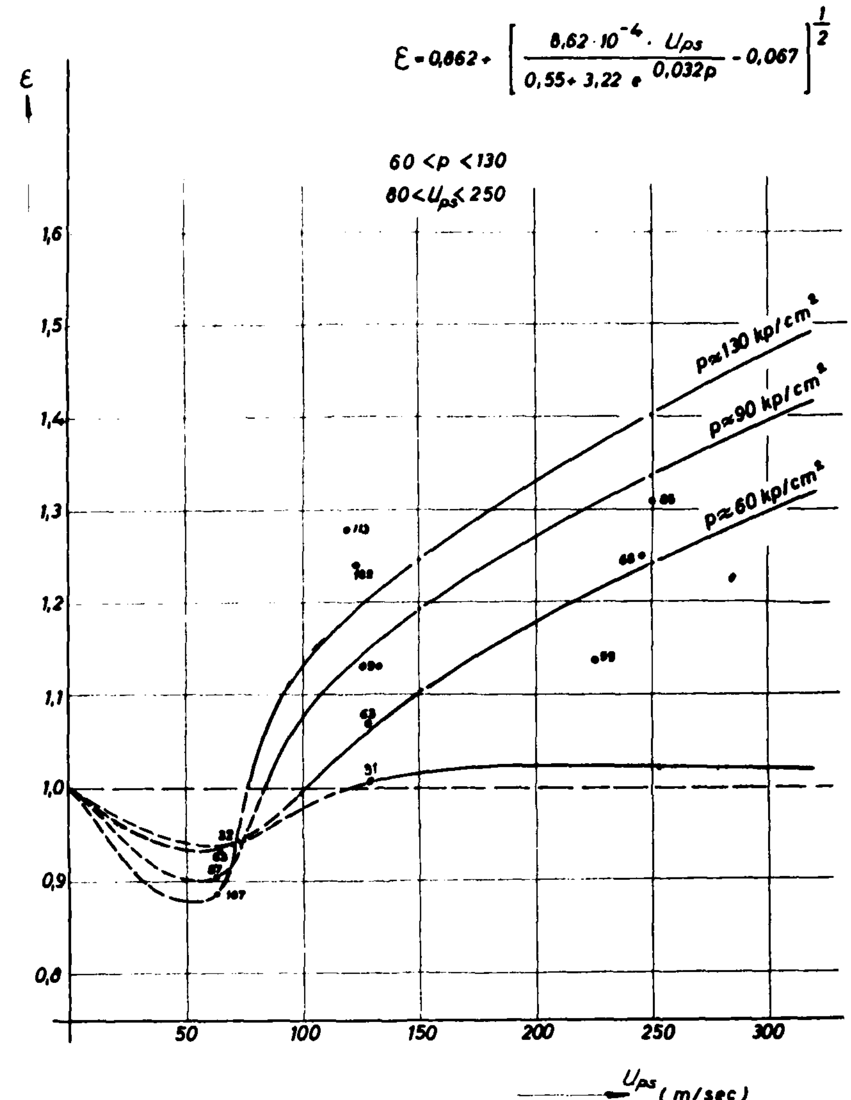


Figure 23

The obtained results are analogues to the first series and show the same relationship between the flow velocity, equilibrium combustion pressures and dimensionless parameters ε and K_1. In this case the flow velocity of gases below 70 m/sec gives a negative increase in the combustion rate of solid fuels.

The results shown in Figure 29 are interesting and show a relation between the so called "threshold" flow velocity of the combustion products and the coefficient K by the relation:

$$\varepsilon = 1 + K_2(U_{p.s} - U_{pr})$$

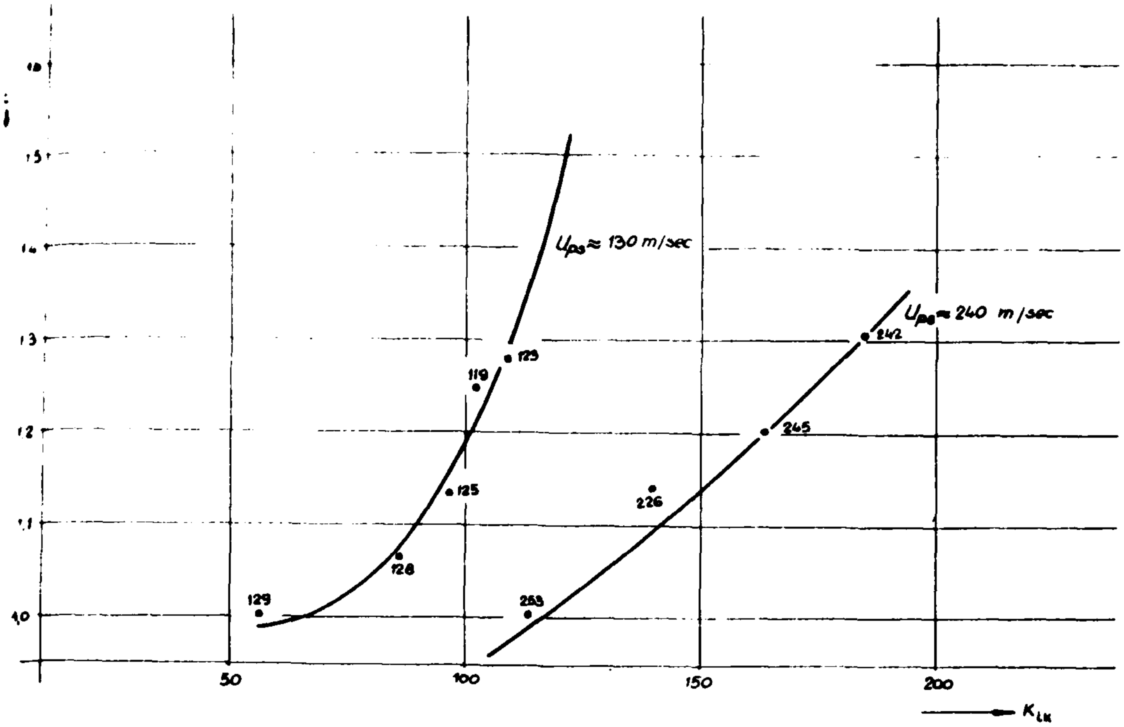


Figure 24

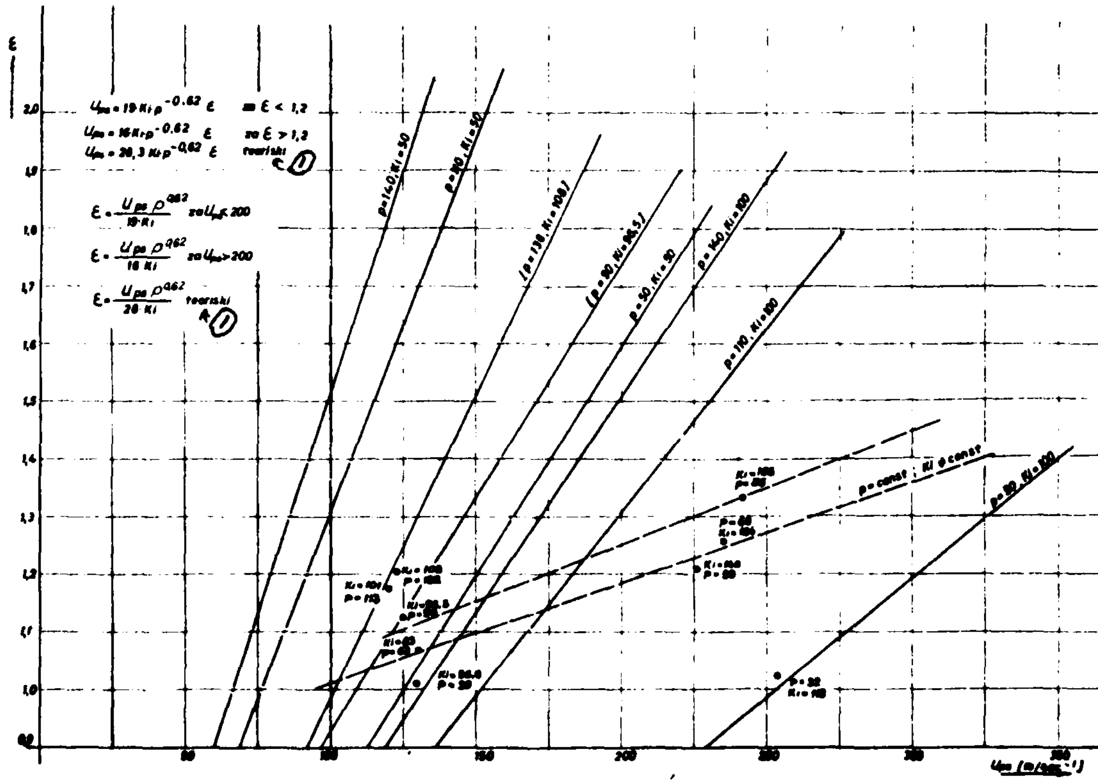


Figure 25

Key: 1--theoretical

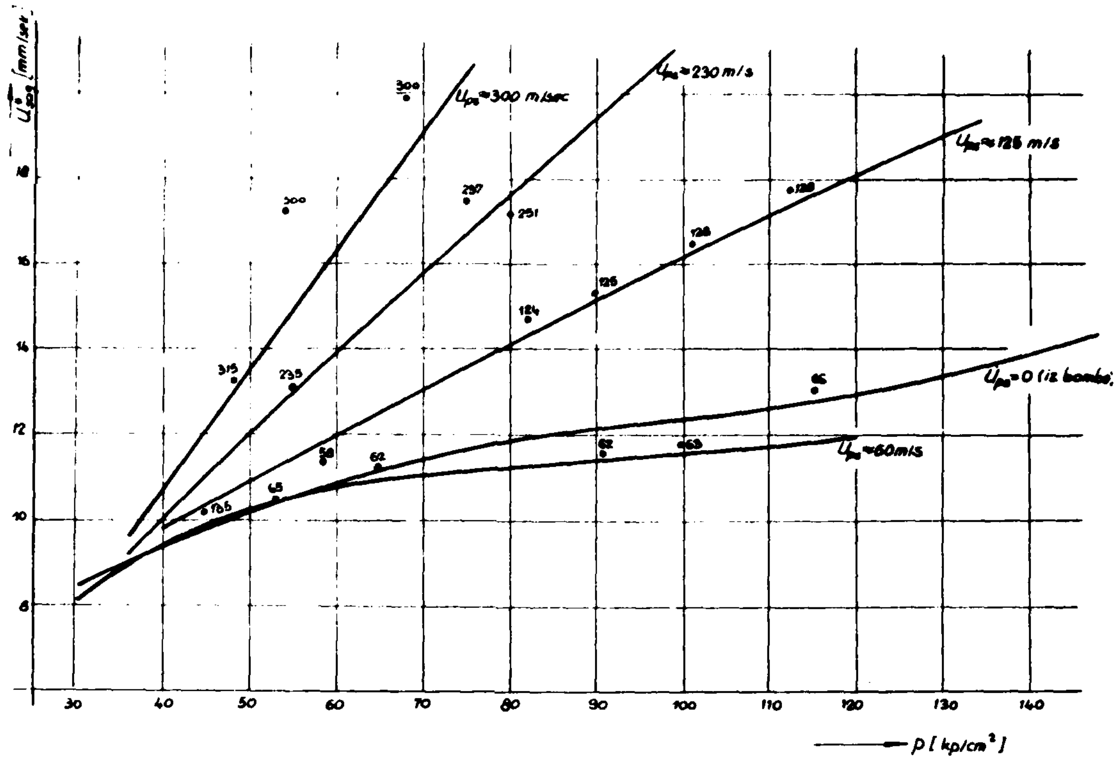


Figure 26

The results show that K is not a constant as presumed by the linear equation for the relation between the flow velocity and the combustion rate, i.e., it does not depend only upon the fuel type but also upon many other factors. In order to compare the experimental results with theoretical assumptions given in the first part of this work we have worked out the proper diagrams (using equations (24), (30), (33) and (38) which are presented in Figures 30-33.

The plotted experimental values show a sufficiently good agreement between the tests and the theoretical values. In plotting the diagrams we have used some determined values, others have been obtained by thermochemical calculations and some have been obtained from literature. Thus:

λ = 0.1936 kcal/mh°C - calculated

T_{sag} = 2480°K - calculated

C_p = 0.35

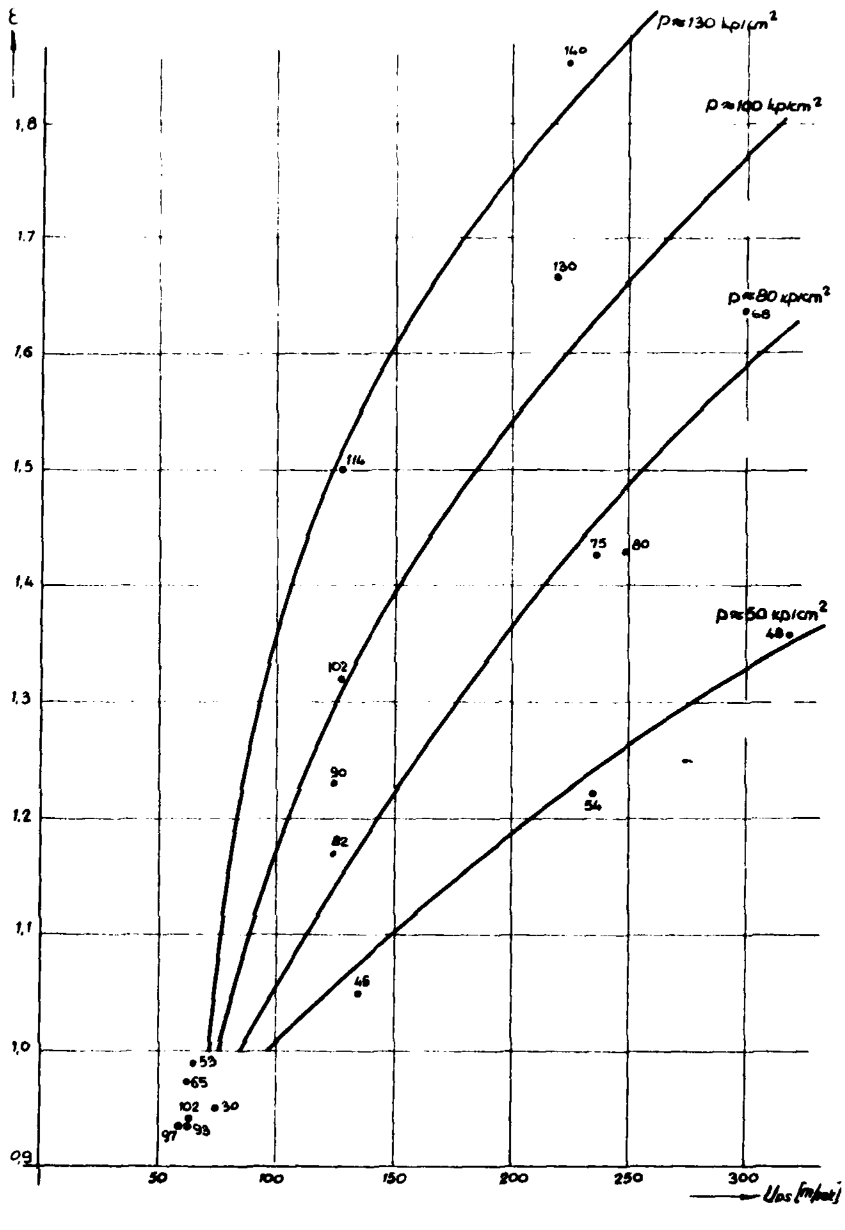
T_1 = 1200°K

T'_1 = 550°K - accepted

T''_1 = 453°K

Certain errors in results shown in Figures 30-33 have been introduced by accepting the temperatures T_1, T'_1 and T''_1 assuming that they remain constant for all conditions of working pressures. This is probably not correct. During the work some consideration has been given to the possibility of measuring these quantities. However, because the zones of decomposition and gasification are very thin (in the order of 10 microns) and because the process is violent, attempts to determine these values have been abandoned.

Yet, in spite of these deficiencies, the obtained results are satisfactory and probably provide an answer to the phenomenon of disturbance in the combustion rate of solid rocket fuels. This is the case from a positive point of view, i.e., about the decomposition of the gas layer as well as from the negative point of view, i.e., about suppression of the heat flux which acts upon the solid phase of the fuel. Thus, the determination of combustion laws of rocket fuels is made by combusting a test sample in a Crawford bomb where the sample burns along a front in a still atmosphere and at P = const. In this case all factors disturbing the process have been eliminated. When fuel samples are combusted in a gas stream of low velocity, the thickness of the gas phase increases so much that the process is suppressed together with a degradation of the solid phase which, in fact, controls the combustion rate of the sample. At high stream velocities the thickness of the gas zone is reduced and the still zone practically disappears. The heat flux acting upon the solid phase thus increases and causes a rise in the combustion rate of the fuel.



ε
1,8
1,7
1,6
1,5
1,4
1,3
1,2
1,1
1,0
0,9
50
100
150
200
250
300
Ups [m/sec]
p≈130 kp/cm²
p≈100 kp/cm²
p≈80 kp/cm²
p≈50 kp/cm²
140
130
68
116
75
80
48
102
90
54
82
46
53
65
102
30
97
93

Figure 27

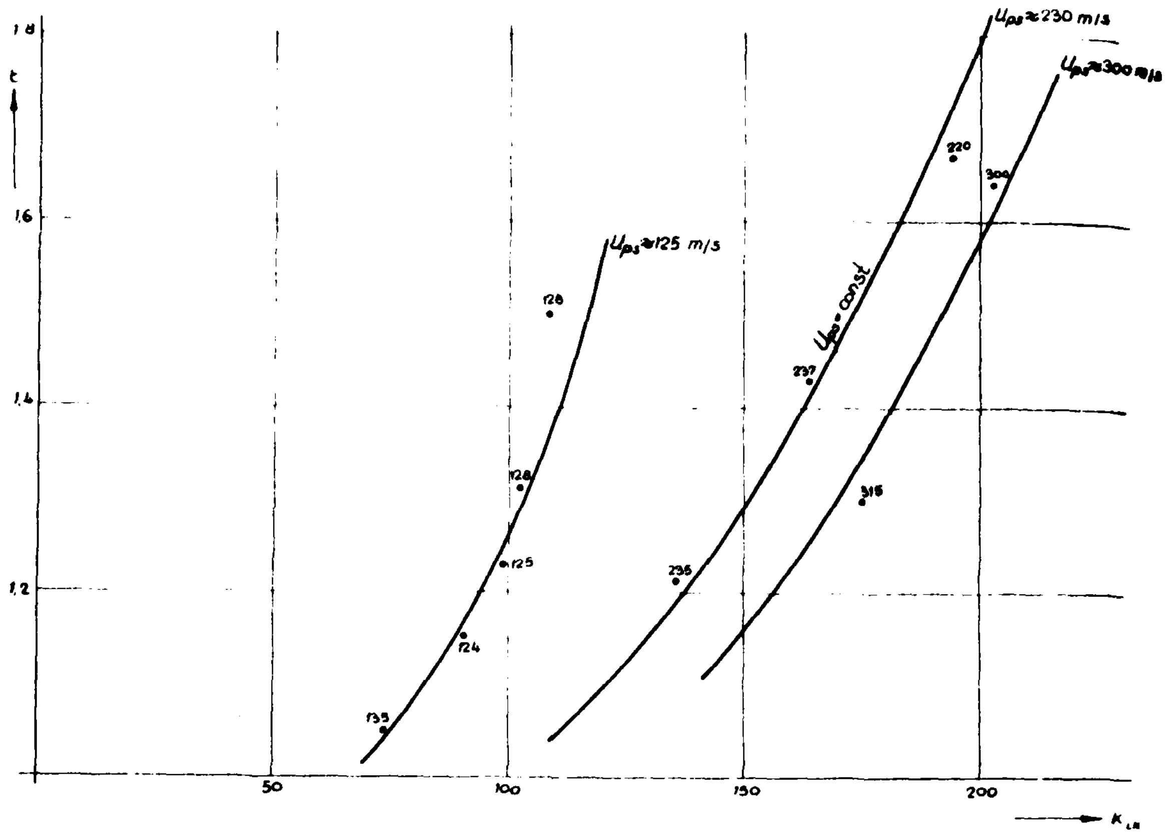


Figure 28

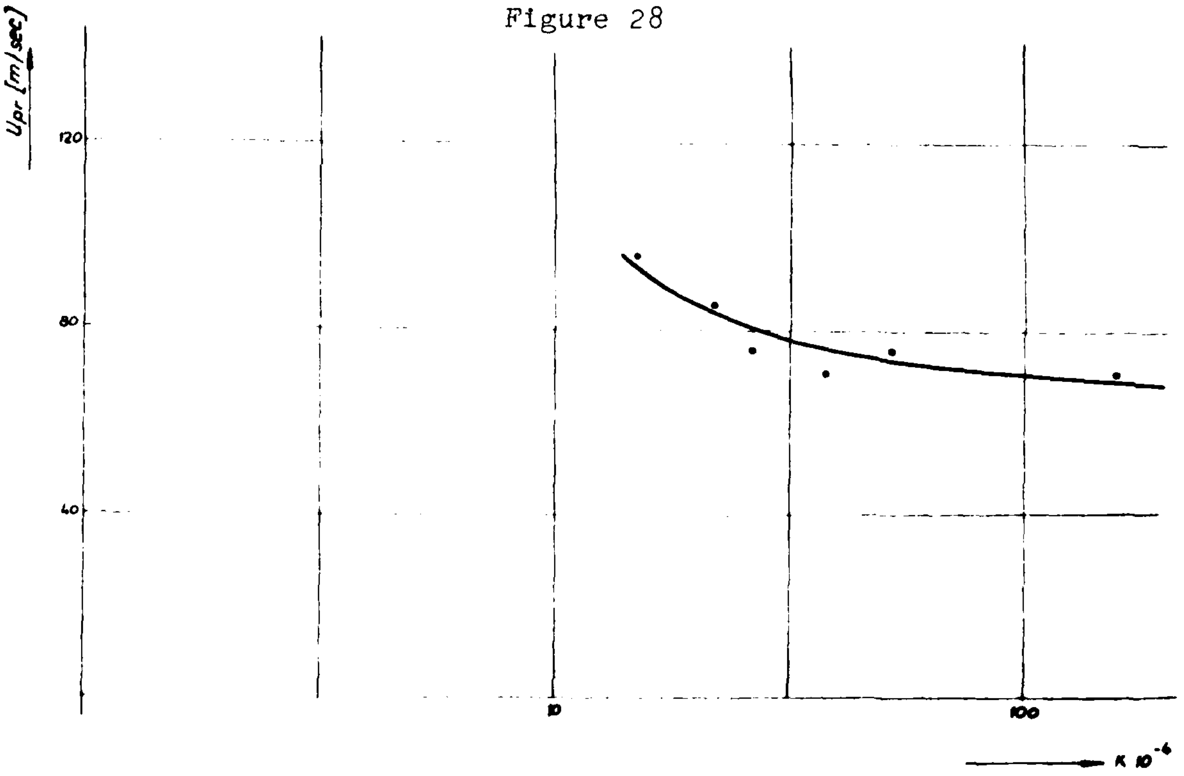


Figure 29

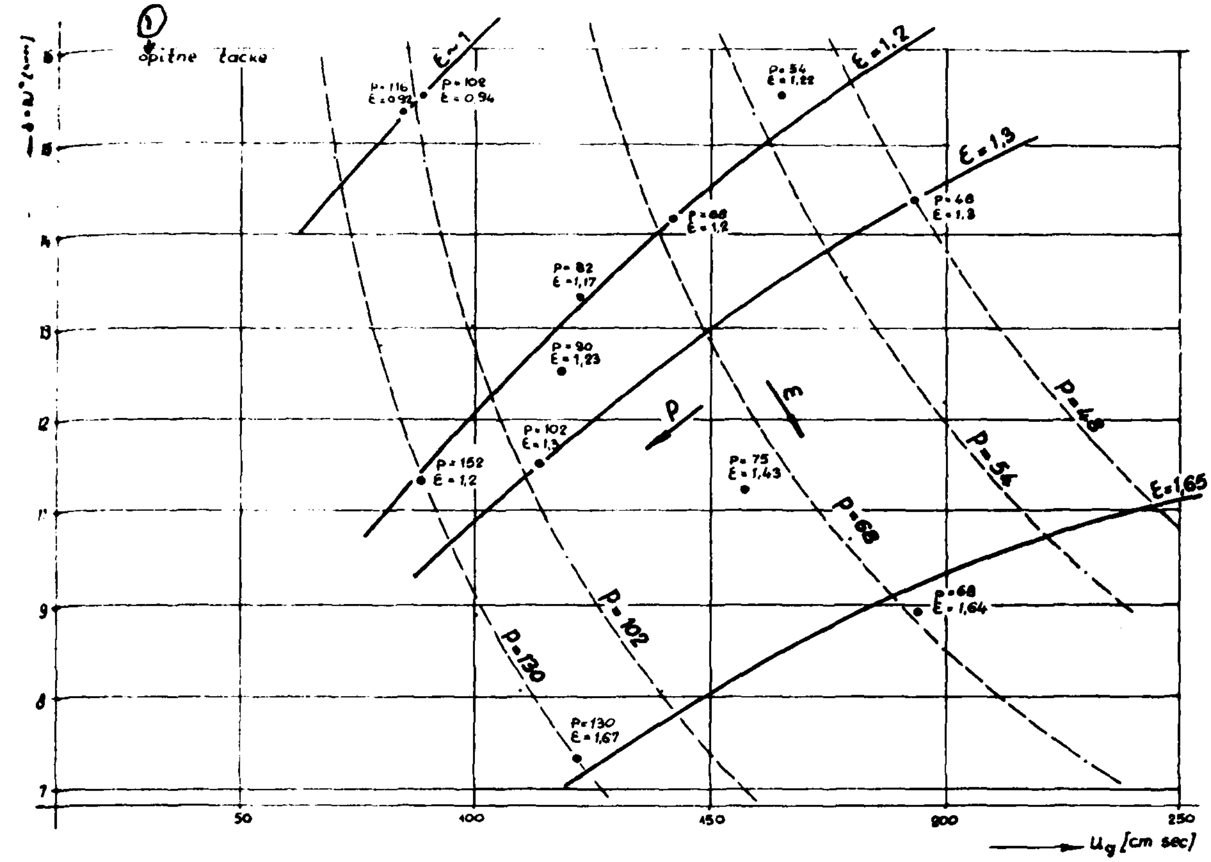


Figure 30

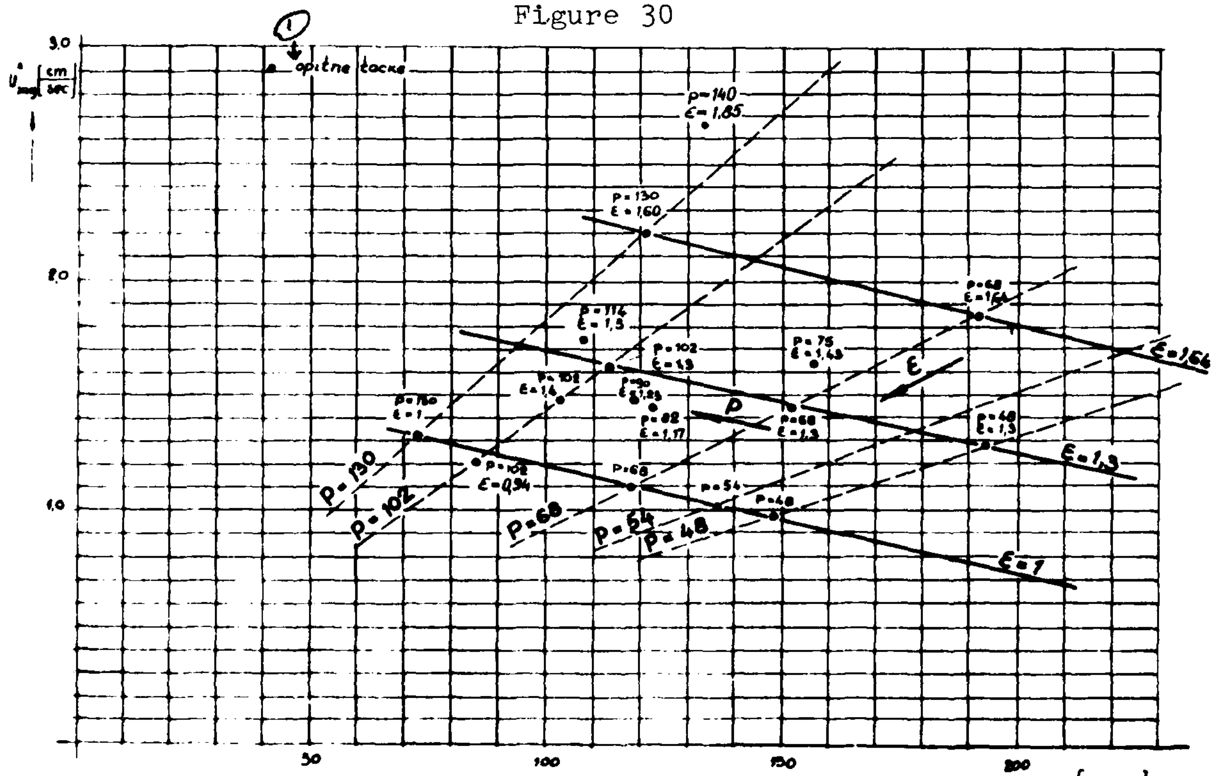


Figure 31

Key: 1--test points

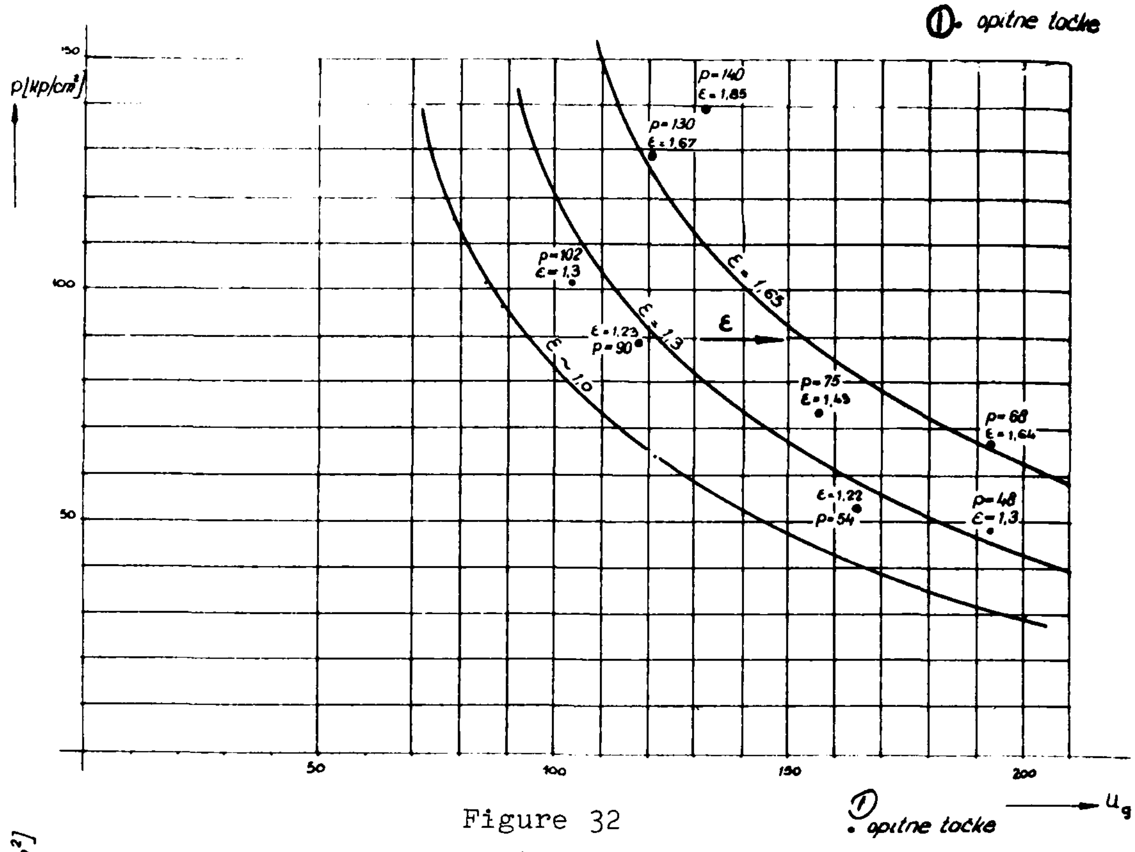


Figure 32

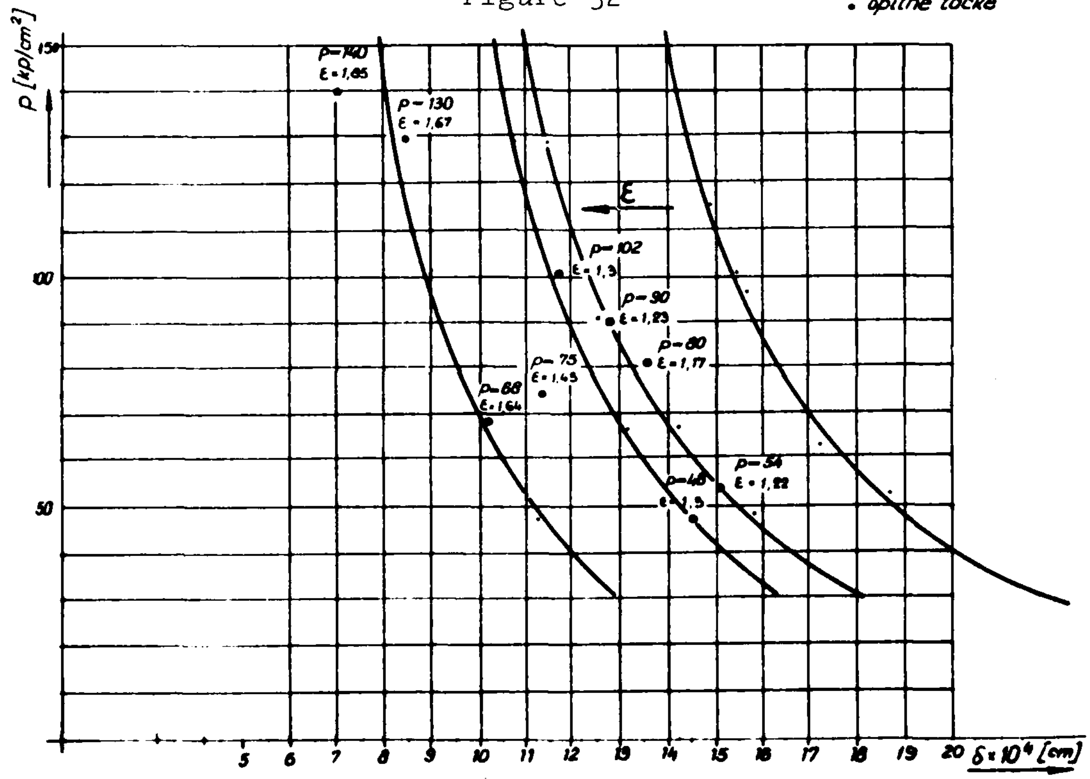


Figure 33

Key: 1--test points

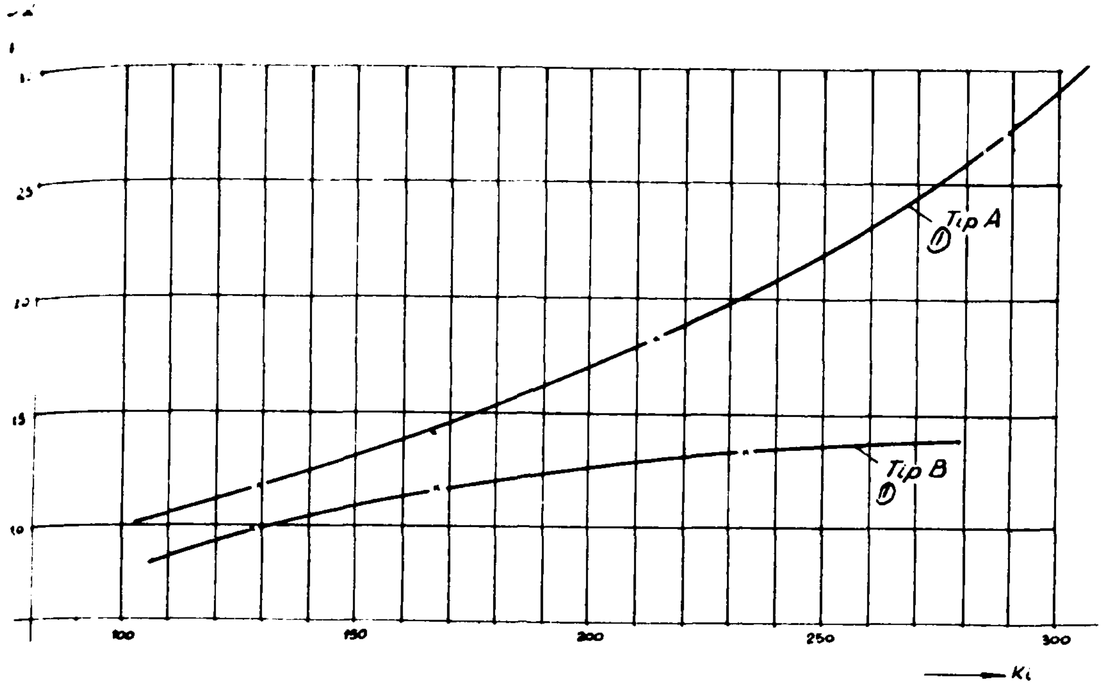


Figure 34. Comparative testing with a real engine
Key: 1--type

It could be concluded from the above that there is only one thickness of the gaseous phase where the process takes place regularly and that changes in this thickness to one or the other side leads to disturbances in the combustion rate. It must, however, be pointed out that the effect of this change is more intensive in the direction of increase of the combustion rate due to decrease of the thickness of the gaseous phase.

From the above we deduce:

$$\delta > \ \rightarrow \ U_g >$$
$$\delta > \ \rightarrow \ U_g >$$
$$\delta < \ \rightarrow \ U_g <$$

$$\left[\delta_{rav}\right]^{\delta_{max}}_{\delta_{kr}} \longrightarrow \left[U_{rav}\right]^{U_{sag\,kr}}_{U_{sg.mot.}}$$

Figure 31, 32 and 33 show that the reduction in the thickness of the gaseous phase and increase of the equilibrium pressure of combustion results in an increased positive rise in the combustion rate, i.e., the degree of erosion ε.

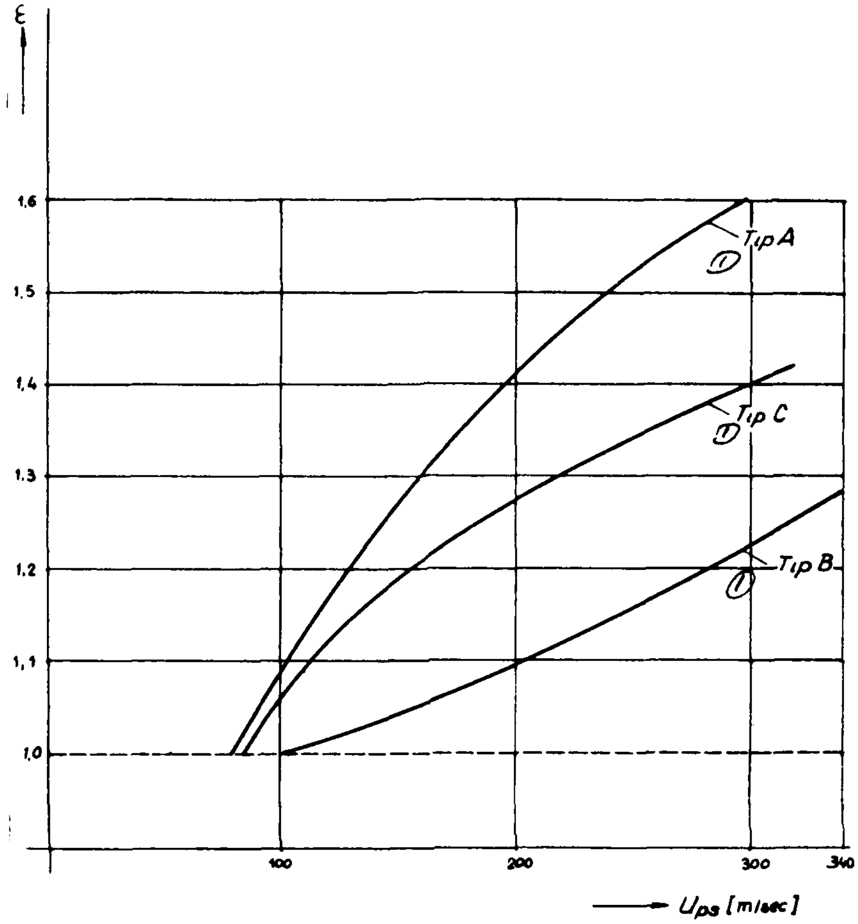


Figure 35. Comparison of tests using fuel samples.
Key: 1--type

Comparative results of testing compositions A, B and C

Results have been compared for the purpose of obtaining a clearer picture of the sensitivity of tested double-base rocket fuels of composition A, B and C on the erosion effect. The comparisons have been made separately for test results obtained in a real rocket engine and separately for test results obtained using fuel samples inserted into a controlled gas stream. Figure 34 shows results of tests using a real rocket engine with compositions A and B. The results are illustrated in the form:

$$\Delta P_{initial} = f(K_i)$$

As mentioned earlier, tests with a real engine were carried out at various levels of equilibrium combustion pressure. The working pressure for composition A was about 100 kp/cm^2 and for the composition B it was about 180 kp/cm^2. Because of a significant difference in the working pressures at which the tests were carried out and because of the effect of pressure on the intensity of the disturbance, a lower difference in the erosion effect should have been expected. The obtained results show that the composition B is much less sensitive to disturbances in the combustion rate than composition A and that this composition is more suitable for design of the rocket engines that use high charge levels.

Tests using fuel samples were made using the same equilibrium pressure for all three compositions (A, B and C), i.e., at P = 100 kp/cm^2.

The results of these tests are shown in Figure 35.

As may be seen in Figure 35, the difference obtained for the degree of sensitivity between compositions A and B are analogous to those obtained in real engines.

However, differences have been established for absolute values between tests in real engines and with fuel samples.

Thus for the composition A, U_{pr} = 120 m/sec in tests with a real engine and U_{pr} = 30 m/sec for tests with fuel samples. Analogous differences have been obtained for the composition B.

It is of interest to note that the "threshold-velocity" values are approximately the same for all three compositions. Other aspects of disturbances in the combustion rate are significantly different for the three compositions of the tested rocket fuels.

Conclusion

On the basis of theoretical considerations of problems of combustion of homogenious solid rocket fuels and conditions for the appearance of disturbances in the combustion rate and on the basis of tests made using conditions of real combustion as well as those of combusting fuel samples in controlled gas streams, the following conclusions can be drawn:

1. The phenomenon of erosive combustion, i.e., positive disturbances in the combustion rate in the solid rocket fuel appear as the consequence of the breakdown of the gas zone, the disappearance of the still zone and increase in the flux which acts from the reaction zone on the surface of the decomposition zone.

2. The derived relations between the disturbance in the combustion rate and the tickness of the boundary layer, coefficient of heat transfer and flow velocity of the combustion products, which are given in the form

$$\varepsilon = \phi' P^{1-n} \frac{a_g}{\delta_g^x} \ln \frac{T_1 - T_1'}{T_1' - T_1''}$$

$$\varepsilon = 1 + C \frac{\delta}{\delta^x} \rho_{\check{c}} C_{\check{c}} \left(\frac{T_1' - T_1''}{T_1 - T_1'}\right) e^{\delta^x U_{sg}^x \cdot K}$$

can be used to determine the magnitude of the increase in the combustion rate of solid fuels.

3. The empirical relation between the velocity of flow of the combustion products and the disturbances in the combustion rate which are, for the composition A, given in the form

$$\varepsilon = 0,65 + \sqrt{0,015\, U_{p.s}\, e^{0,0072\, P} - 0,08}$$

and for the composition C, are given in the form

$$\varepsilon = 0,862 + \sqrt{\frac{8,62 \cdot 10^{-4}\, U_{p.s}}{0,55 + 3,22\, e^{0,032\, P}} - 0,067}$$

shows that there exists an exponential relationship and that the velocity of the gas flow is not the only factor affecting disturbances of the combustion rate.

4. The linear relationship, presently used by many authors for the flow velocity of combustion gases and changes in the combustion rate

$$\varepsilon = 1 + K_1 \frac{U_{p.s}}{U_{pr}} \qquad i$$

and

$$\varepsilon = 1 + K_2 (U_{p.s} - U_{pr})$$

can be used only as the first approximation, because the values K_1 and K_2 are not constants. They are values dependent upon the pressure, flow velocity and internal ballistic parameters as confirmed by our tests.

These findings were mentioned by M. Barrere [9] who defined the increase in the combustion rate as a function of the unit flow in the form

$$\varepsilon = 1 + K (\dot{G} - \dot{G}_{pr})$$

$$\varepsilon = 1 + K (\dot{G}^b - \dot{G}^b_{pr})$$

where

$$G = \rho U.$$

For laminar conditions, the coefficient b is 0.5 and for turbulant conditions, it is 0.8.

Value K is defined by Barrere as a function of pressure in the exponential form

$$K = K_o P^c$$

where the magnitude of K_o depends only upon the form of the central cross-section of the flow of the combustion products.

5. The methods used for determining disturbances in the combustion rate in a real engine as well as using fuel samples, are quite sensitive to measurement errors. Thus the measured values show considerable dispersion. However, it appears to be very difficult to set up a method that would establish the real conditions during combustion of fuel in an engine and the conditions around the samples during combustion in the gas stream.

6. Evaluation of disturbance of combustion by analysis of the initial jump of the combustion pressure appears to be a most reliable and simplest method of registering a positive disturbance in the combustion rate of a solid rocket fuel.

7. The effect of various additives (stabilizers, catalysts, etc.) on the phenomenon of disturbance in the combustion rate, was not analized in this work. Their effect on this phenomenon is definitely significant and should be the object of another study.

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