CHAPTER 5

INTERNAL BALLISTICS OF THE GRAIN

5.1. INTRODUCTION

As already described in chapter I the reason for the strange shape of the thrust diagrams - i.e. degressive instead of progressive - was not well understood until all tests were finished and a detailed study was made.

It was always thought that these diagrams resulted from deformation of the grain under high pressure and temperature. In fact it was not possible to relate deformation with thrust shape. Moreover ,any type of propellant grain burned a typical way as is shown now.

5.2. TYPICAL THRUST DIAGRAMS

Following typical grain configurations were tested:

- cylindrical hole- casted - no coating;
- cigarette grain- casted - no coating;
- cylindrical hole - casted - and coated;
- crucifix hole - casted - and coated;
- cylindrical hole- centrifugated - and coated.

It will be shown later that in fact the grain type "crucifix hole" has to be split in a CANDY-GX type and a NEBEL type curve.

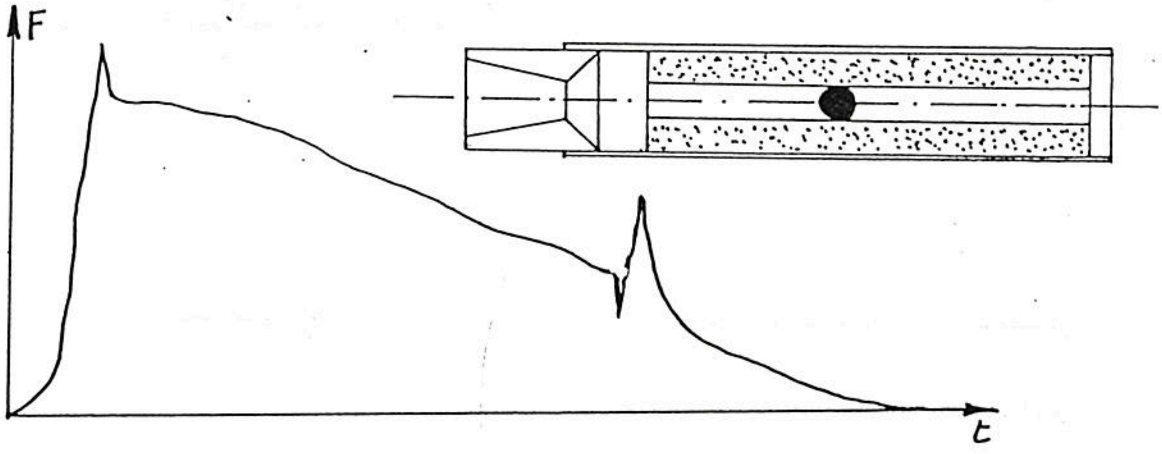

Fig.5.1. Cylindrical hole - casted - no coating.

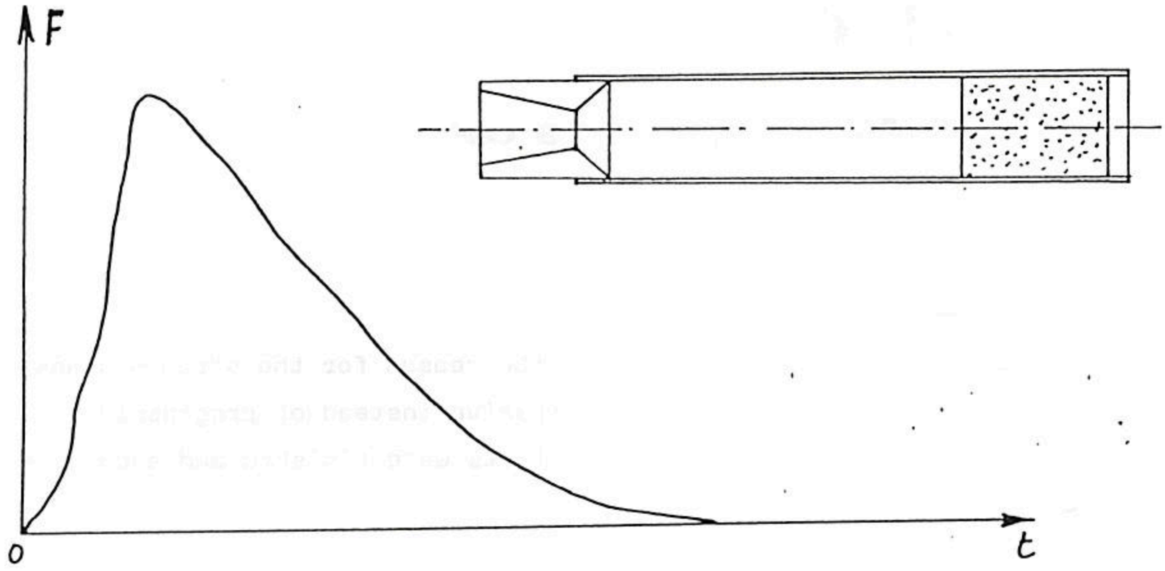

Fig.5.2. Cigarette grain - casted - no coating.

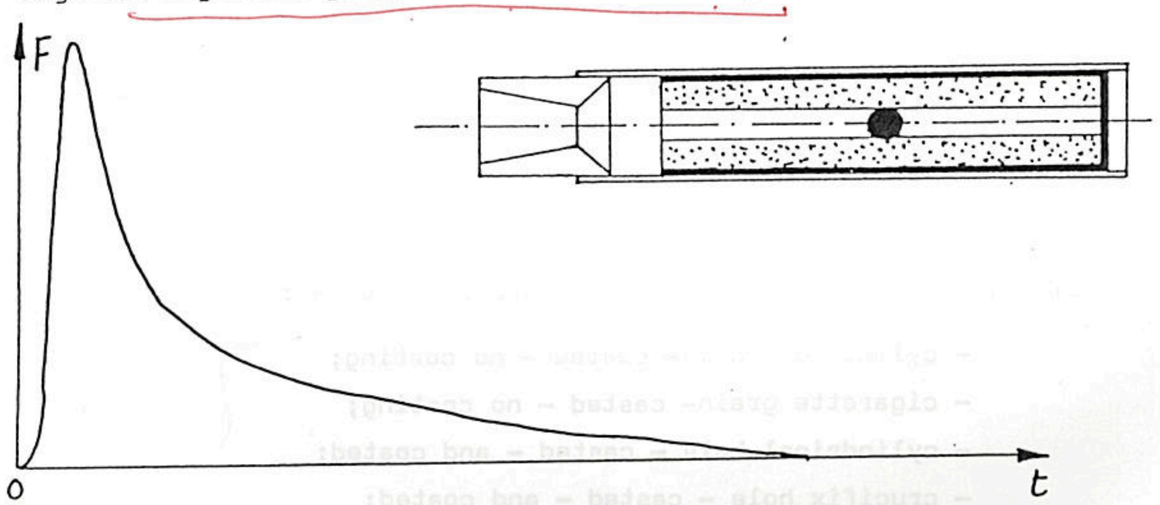

Fig.5.3. Cylindrical hole- casted - coated

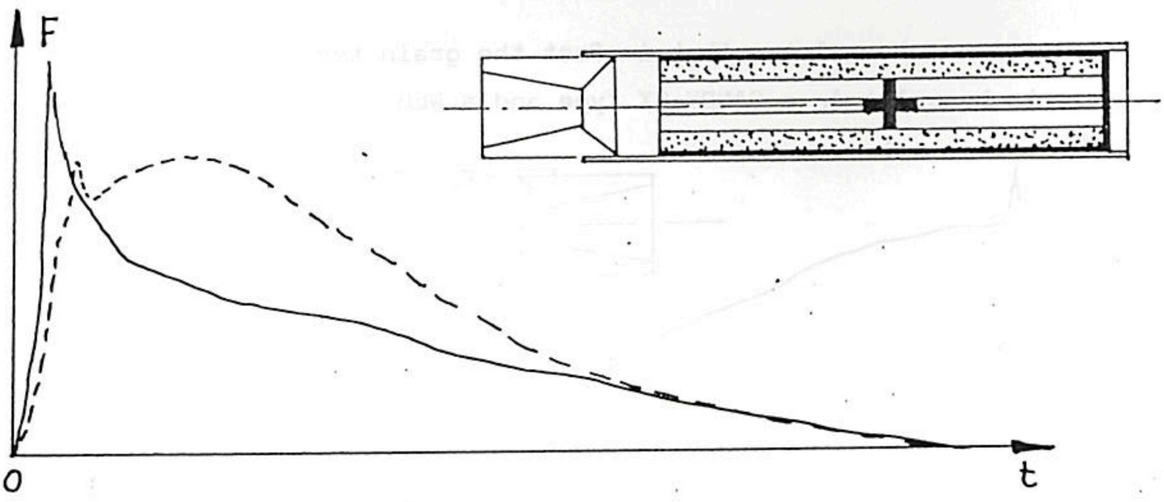

Fig.5.4. Crucifix hole - casted - coated

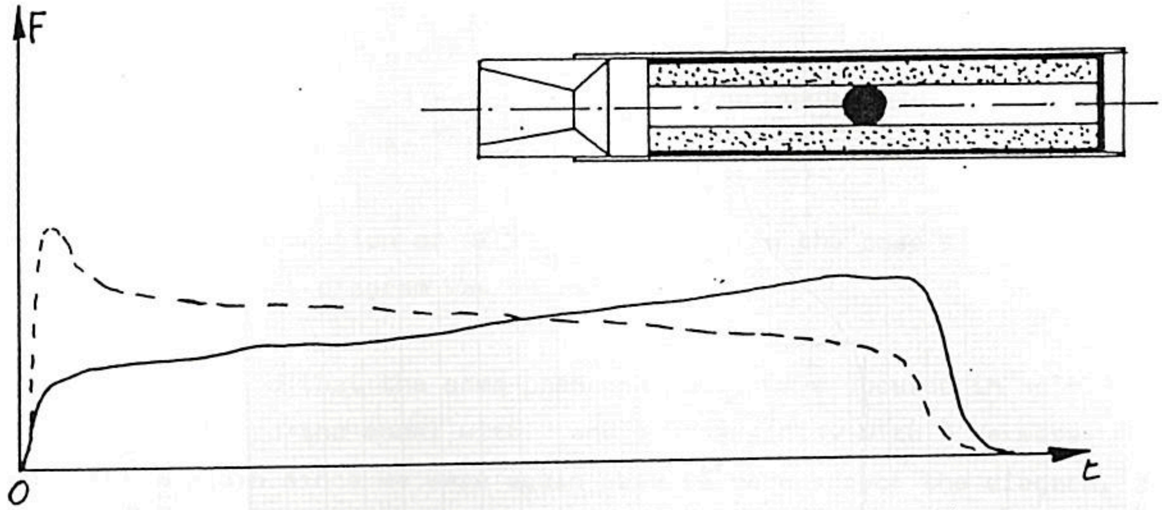

Fig.5.5. Cylindrical hole -centrifugated - coated

5.3. ANALYSIS OF THE DIFFERENT THRUST SHAPES

5.3.1. cylindrical hole - centrifugated - coated.

It was not until a stress analysis of the grain in the case of cylindrical perforations was made that we found the solution for one of the **types**.

It was shown that under certain conditions - i.e. when the inner diameter is small- the inside region of the propellant is subjected to stress, while the outer part is under pressure. This means that when the tensile strenght of the propellant is small, the grain can break along the axis.

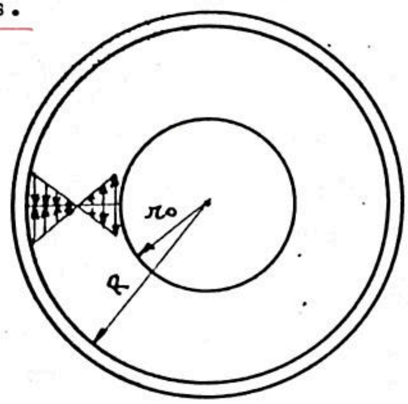

Fig.5.6. Stress in a cylindrical perforated casebounded grain.

This possibility was mathematically tested, and we discovered that the shape of such a thrust diagram **was one** of the kind of NEBEL 3.

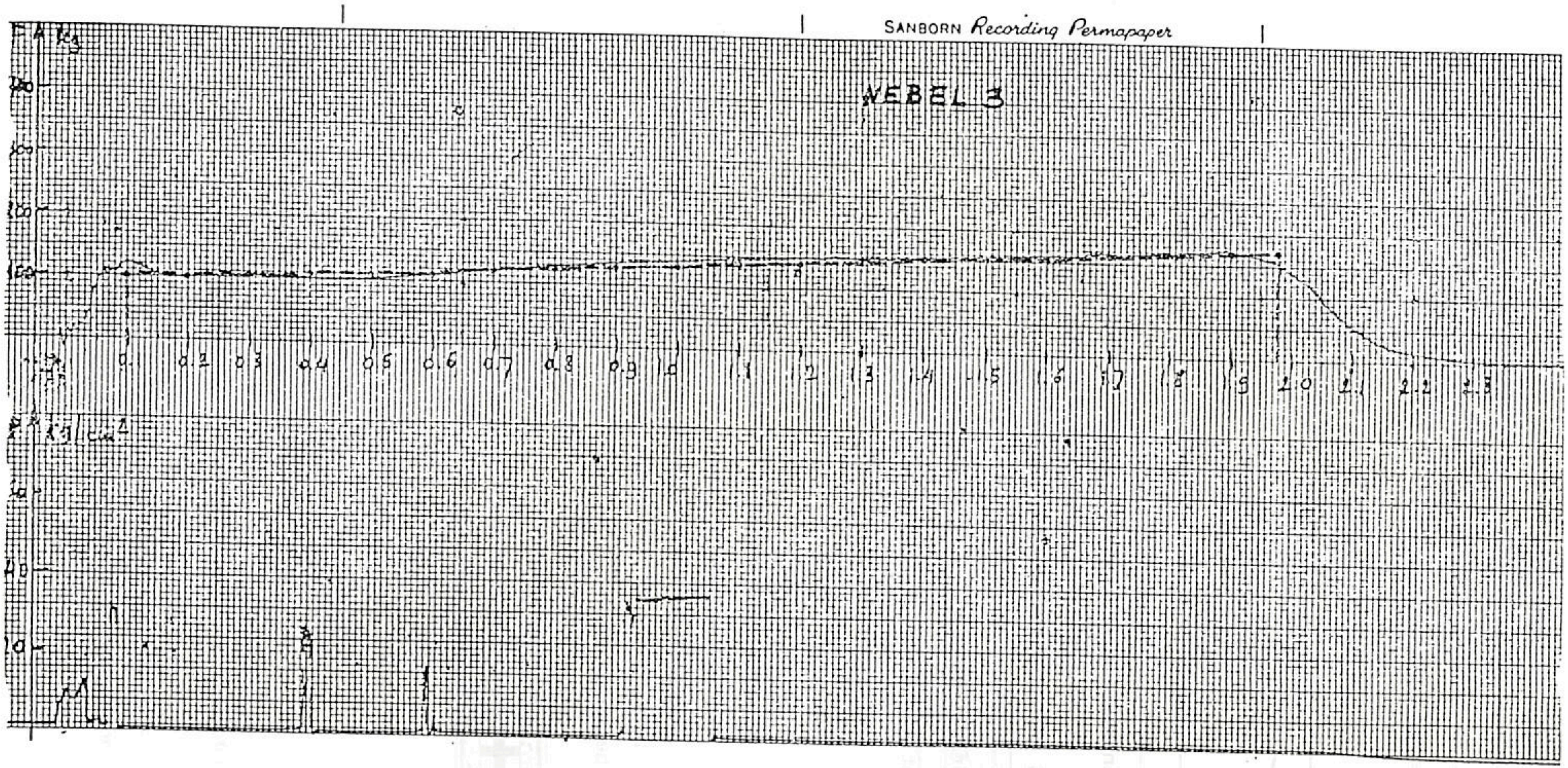

Fig.5.7. Simulation of NEBEL 3 according to the burning mechanism described in figure 5.9., with n = 0,42 and k = 0,215 cm/s

When the model was correlated with the thrust curve of this rocket we found that with k=0,215cm/s and n=0,42 the curves almost perfectly cover each other (fig. 5.7).

This was the explanation of NEBEL 3, but what in the case of NEBEL 2 where the thrust diagram was degressive!

Since we believed that the same phenomena must have occured in both rockets, we tried the model with 2 and 3 breaklines. With 3 we were successful again since we were again able to reconstruct the diagram. For this rocket we got: k=0,205cm/s and n= 0,41, which was very close to the values for NEBEL 3. (Fig.5.8).

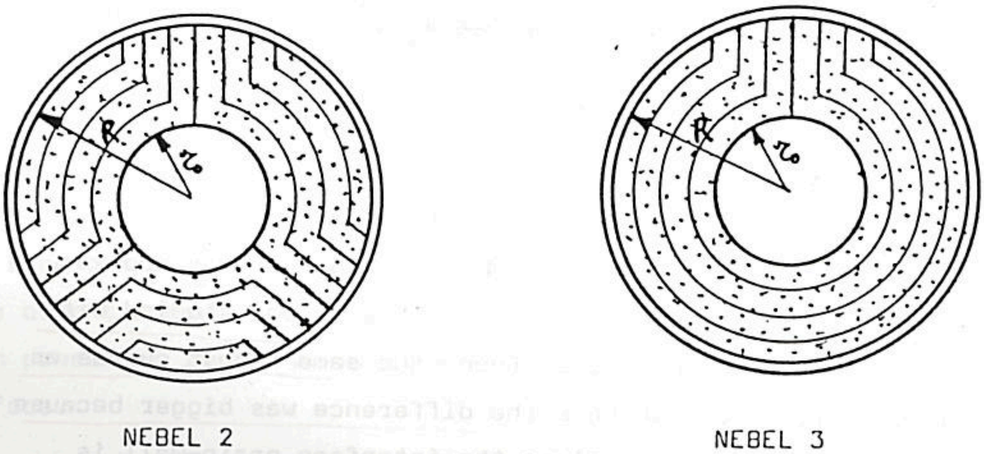

Fig.5.9. Progression of the burning surface for NEBEL 2 and 3.

5.3.2. cylindrical hole - casted - coated

Increasing the number of breaklines changes the thrust curve towards more and more degressive diagrams. This explains why in the case of grains that were casted with cylindrical perforation - i.e. grains with low density and consequently low tensile strenght - the thrust curves are very degressive. The grains are so weak that the propellant breaks into many pieces. Such grains will never show a sudden decrease in pressure or thrust at the end of burning.

It is clear that it is impossible to check the number of breaklines and the burning rate expression for all these grains since the difference in behaviour when the number of breaklines increase, disappear.

Figure 5.10. shows what happens when the number of breaklines is increased. To establish this figure the mathematical model was used.

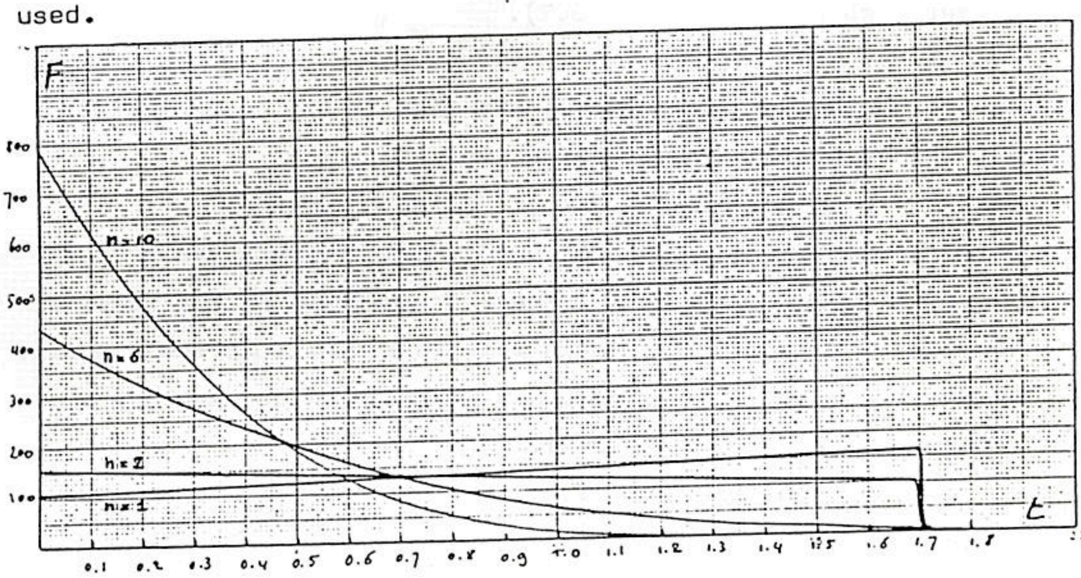

Fig.5.10. Influence of the number of breaklines on the thrust shape.

5.3.3. cigarette grain - casted - no coating.

From the test of GX-24 we knew that when no coating was applyed the grain could burn at all surfaces. When this was studied with the aid of the mathical model, we found the same thrust curves as we measured them. Of course here the difference was bigger because the mechanism of the burning along the interface grain-wall is so complex that it was impossible to model.

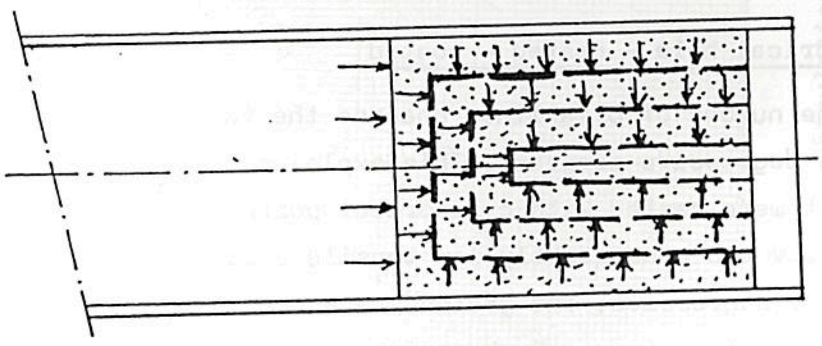

Fig.5.11. Progression of the burning surface for cigarette grains - casted - and without coating.

5.3.4. cylindrical hole - casted - no coating.

Based upon the results of 5.3.3. it was easy to describe what happened with this kind of grains. It is certain that burning occured between wall and grain.

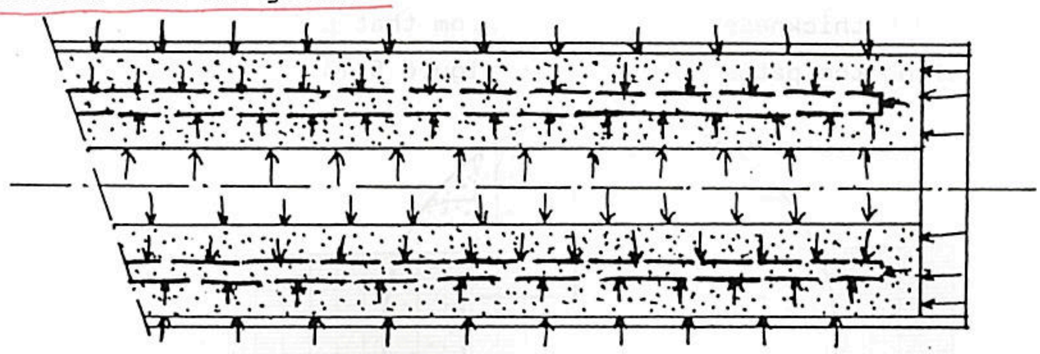

Fig.5.12. Progression of the burning surface in grains with cylindrical perforation that were casted but not coated.

At the end of the burning this type of rockets always shows a pressure or thrust increase. This might be due to the fact that part of the propellant grain breaks because the propellant web thickness was becoming too small.

It is now easy to understand why this type of rockets were so difficult to ignite. In order to work properly the grain had to separate from the wall otherwise the burning area was too small. When this didn't happen the rocket showed chuffing. Only at sufficient high pressures it was possible for the gases to penetrate the interface.

5.3.5. crucifix hole - casted - coated

The internal ballistics of this kind of grain configuration seem to be much more complicated than of the other types. First of all the difference in the first phase of the thrust curve between inner wall diameters of 80 - 81 mm (GX and CANDY) and 87 (NEBEL) is remarcable. This means that outer grain diameter plays an important role in the first tents of seconds. In all cases of CANDY and GX rockets with this configuration, the rocket reached its top thrust at the very beginning of burning. In all NEBEL rockets it happened after 0,3 seconds. The fact itself that this happens after exactly 0,3 seconds is remarcable and indicates that the process is each time reproduced.

For the second phase of the thrust curve, i.e. the degressive one, the situation is more clear. One can assume that from a certain moment the combustion reaches the coating on those sides where the propellant web thickness is smallest. From that point burning will continue along the paths described in figure 5.13.

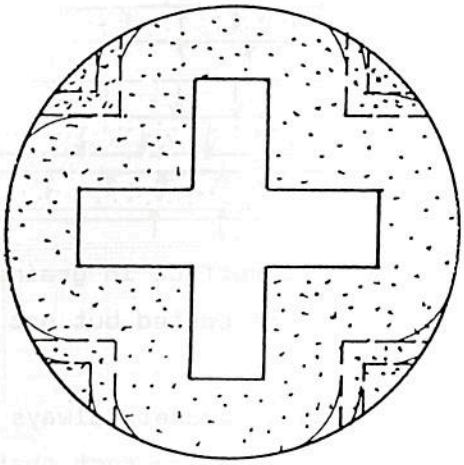

Fig.5.13. Burning mechanism during the last part of the thrust curve

It should however be noticed that the shape of the grain in the neighbourhood of the coating is not clear. This of course will depend upon what happened before. For this reason it is very difficult to simulate this phase.

In the case of CANDY 2 where the thust decreases immediatly and very fast, a good simulation could be found. This simulation that is shown in figure 5.14 yielded a $k = 1{,}95\ 10^{-5}$ m/s with a $n = 0{,}41$.

In fact other simulations with higher n and lower k, also gave good results. When drawn in the same figure one can see that even with a n of 0,8 the combustion rates do not differ that much. (see figure 5.22).

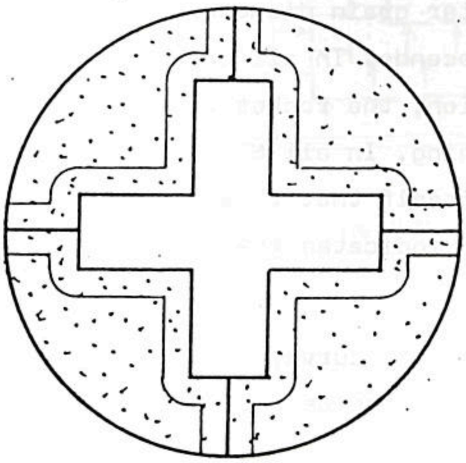

Fig.5.16. Progression of the burning surface for CANDY 2

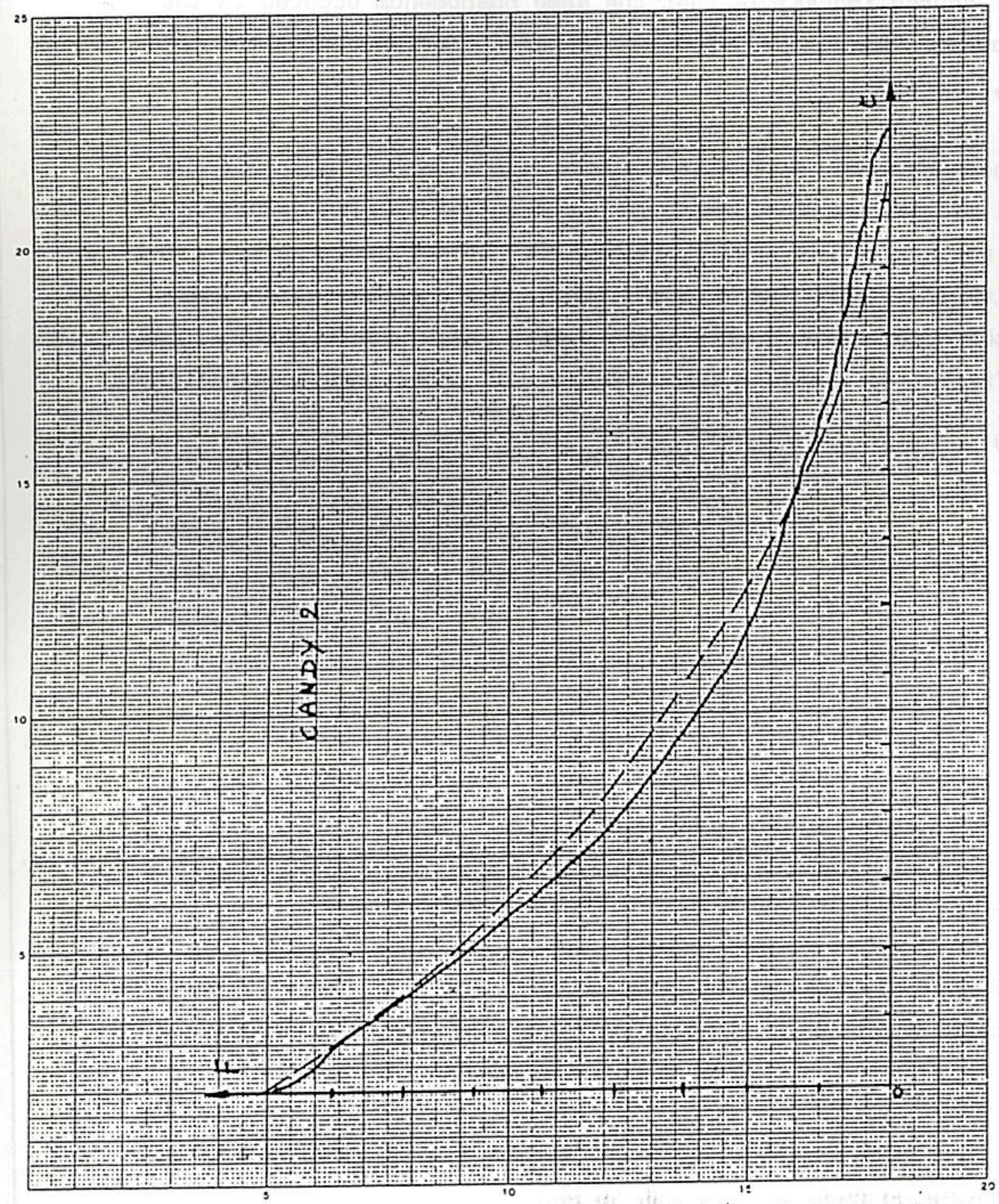

Fig.5.14. Simulation of CANDY 2 (dotted line)

The mechanisms assumed for CANDY 2 are shown in figure 5.16. It is based on the idea that from the moment of ignition the grain breaks on its 4 pointsand that the burning proceeds according to it.

It is of course impossible that the same phenomenum occured in the NEBEL rockets, since it would never explain the top of the thrust after 0,3 seconds.

Differences between one thrust diagram to another are probably due to small differences in burning rate and in the burning mechanism. Indeed, one can assume that other kinds of breaks occur at the sa me time, with almost the same probability, and a real thrust diagram can be the combination of different types, which also means that it will difficult to simulate them. Figure 5.17 shows some possibilities.

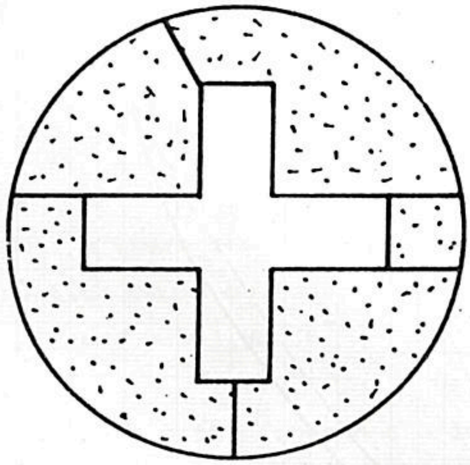

Fig.5.17. Possible breaks in the crucifix type grain.

This mechanism is however not applicable to the NEBEL rockets,where the thrust diagrams in the initial phase are almost identical, meaning that each time the same phenomenum occurs.

We have tried to find the exact mechanism, but we came very soon to the conclusion that this is not so easy.

When we started from the idea that the grain burned the normal way, we found a thrust time diagram like figure 5.18. The progression of burning would than be like figure 5.19.

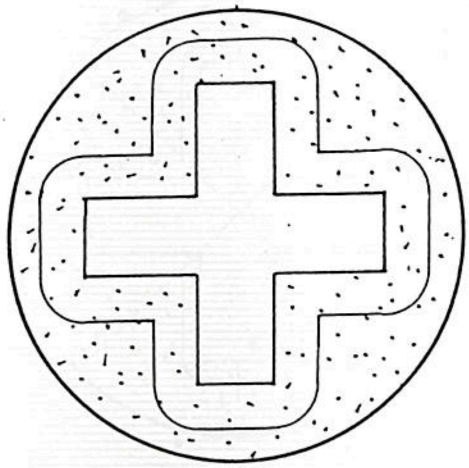

Fig. 5.19. Burning mechanism under normal conditions.

It means the following things:

- It is impossible to find the maximum of the thrust after 0,3 seconds (here it is 0,7 - 1 s).
- Part of the degressive phase does not appear.
- The thrust increase in the real case is even faster than in the simulation (k= 0,23 cm/s, n = 0,41).
- In the simulation the thrust increase accelerates, while in the real case it decelerates.

We have tested different possibilities, but none of them gave the goed shape, the biggest problem being the top of the thrust after 0,3 seconds.

In our immagination only one possibility seem to exist. It is that at ignition the grain breaks in the 4 points, but not the whole way to the coating (see figure 5.20).

This can explain the top after 0,3 seconds, although with n=0,41, the thrust increase is to low. However it is not impossible that n is larger for these propellants (casted), and than it would be a good possibility. A weak point is the fact that we don't know why it should happen that way, and why each time.

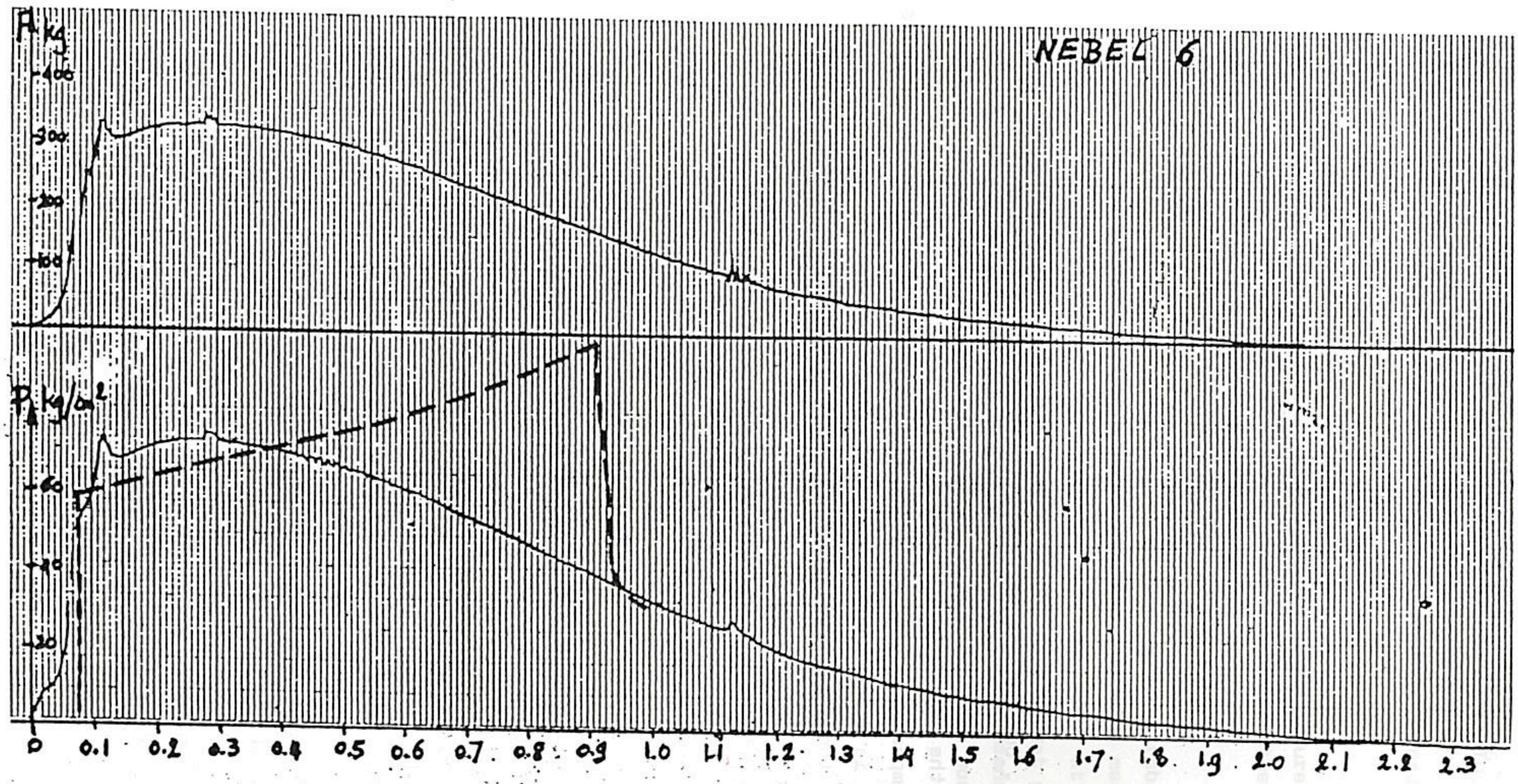

Fig.5.18. Simulation of NEBEL 6 according to the burning mechanism represented by figure 5.19 (no abnormalities).

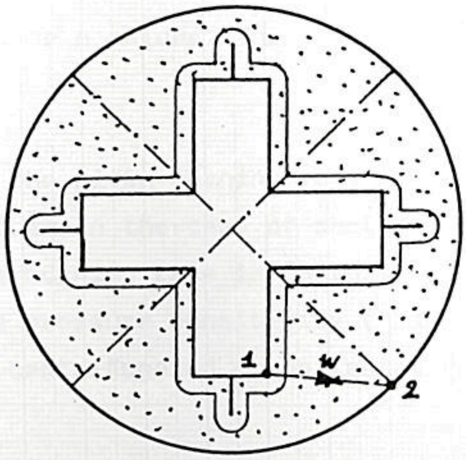

Fig.5.20. Possible burning mechanism for crucifix grains in NEBEL rockets.

In order to have some information about the burning rate expression, which in turn can lead to the understanding of the internal ballistics, we have also used an other approuch.

In any case, k and n are lincked by the fact that the burning distance is well known and fixed. It is the distance between point 1 and 2 (= w) in figure 5.20. So one can write the following expressions:

$$\int_0^{t_b} r \, dt = w$$

since $r = k\,P^n$

$$k \int_0^{t_b} P^n \, dt = w$$

or

$$k \sum P^n \Delta t = w$$

Since P is known, being the combustion pressure, the relation between k and n can be calculated. It is represented in figure 5.21. If in all cases the same expression for the burning rate would hold, it would be the point where all curves coincide. One can see however that only the curves of GX-44 and NEBEL 6 have one point in common. It is where n = 0,7 and k = 0,11 cm/s (when P in bar).

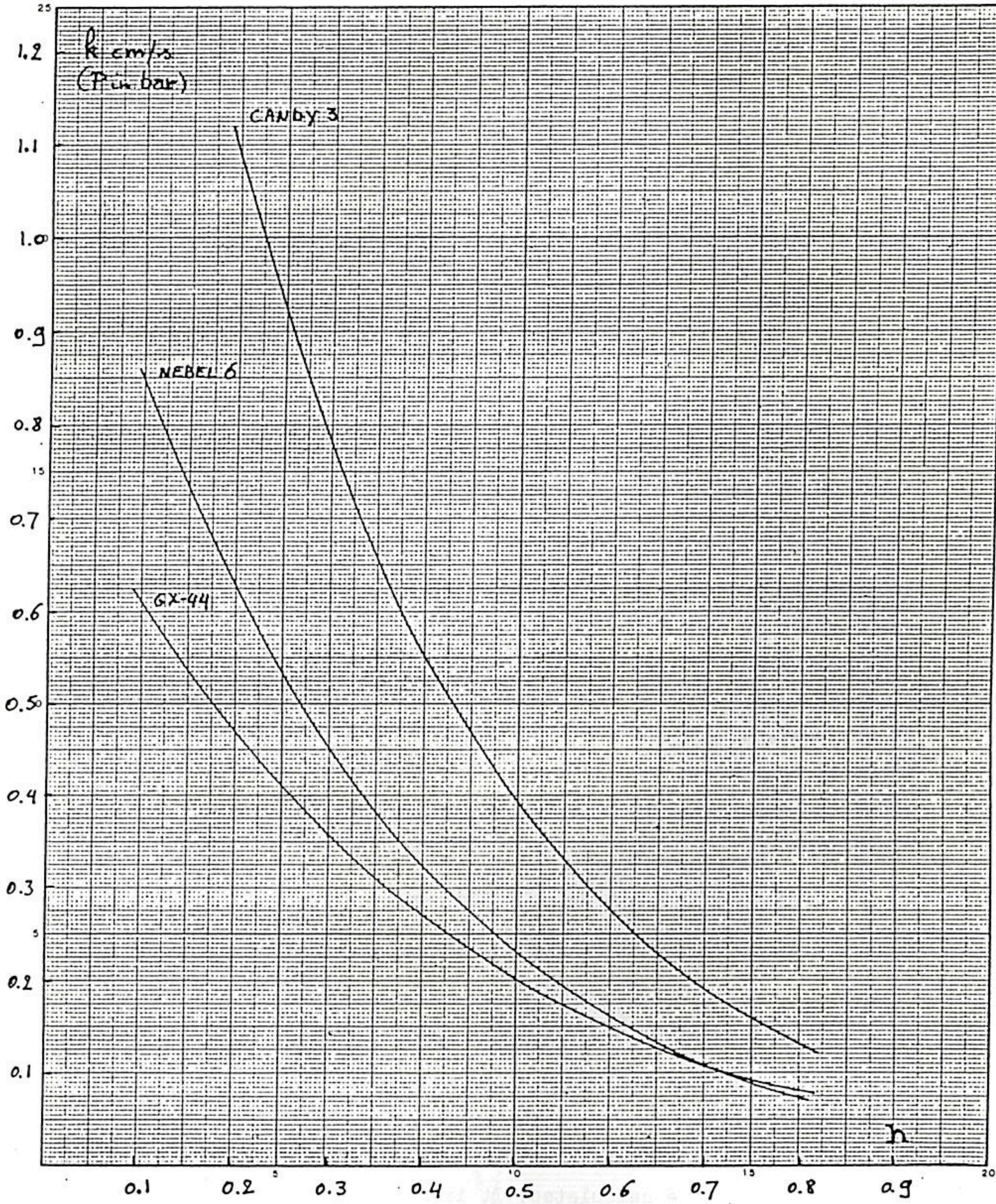

Fig.5.21. Relation between n and k for tree different tests

CANDY 3 deviates a lot from these two curves, although it comes nearer for higher n values. The reason for this deviation is not understood.

It seems that the given burning rate expression is acceptable. It indicates that in the case of casted propellants:

- the burning rate is faster;
- the pressure sensitivity (higher n) is higher ,

compared with centrifugated propellants.

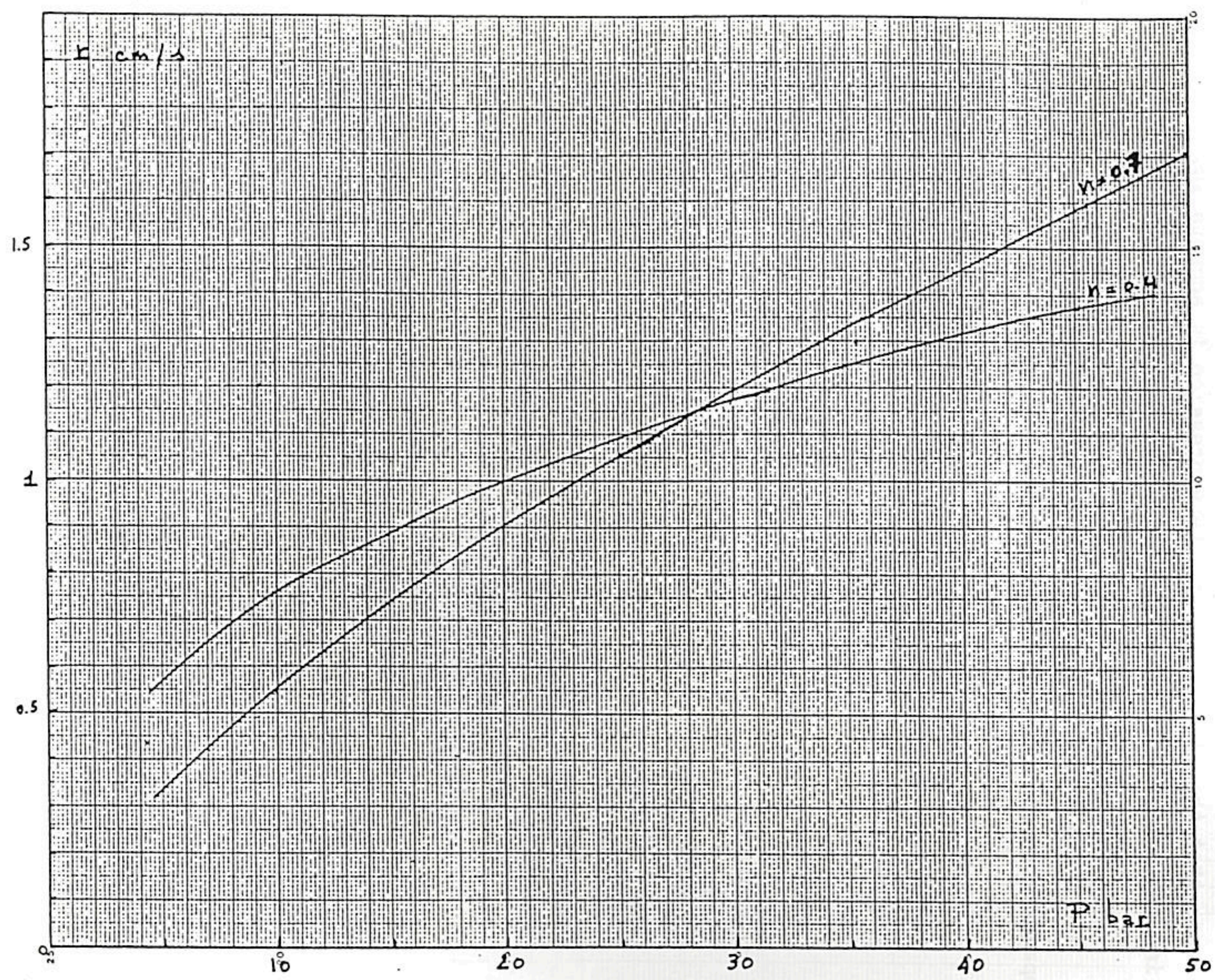

Fig.5.22. Burning rate curves according to the relation between n and k for GX-44.