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Behaviour of safety fuels in firing tests

The demand for the safety fuel arose, as O. Holdelfer mentioned in his paper, from the urgent need for protecting crew and aircraft against fire through an awkward emergency landing, or in combat through being fired on by explosive and incendiary ammunition. Safety from fire in the event of crashing is provided, in our experience, by gas oil, but safety from shooting up makes much greater demands, which have been adequately fulfilled especially by the TZ fuels of I.G. The nature of safety fuels is best shown by firing tests, and for this reason I am making this report on our Gatow tests.

The test programme is very extensive, covering the following points:-

1) The creation of an experimental condition of "safety from shooting-up nil" as a standard of comparison, and as a link with our practical experiences with gasoline. We made the condition that a container filled with gasoline should burn at once when fired on.

As we wished to burn as little gasoline as possible, a small container (fig. 1) was used. It has a cubic content of 2½ litres, and for being shot at repeatedly it has a large target area with small depth (5 cm.). But incendiary bullets pierced this thin layer so quickly at the short firing range that the mixture did not ignite at all. So we placed a few centimetres in front of the container an iron plate of 2 mm. thick. This reduces the speed of the projectile and lengthens the effective time the incendiary charge remains in the fuel. It also rips open the covering of the bullet, and exposes the incendiary charge. Thus the splitting plate increases the effect of the projectile, and imitates the actual conditions of fuel containers in an aircraft, where the projectile must crash through several obstacles to reach the fuel or the gas space. For firing at the gas space of low boiling fuels the container had to be closed with a lid. The dead space round the container in the wing or fuselage is represented by a shock-absorbing trough. Each shot fired was photographed.

2) An extended series of tests was made with this installation to obtain data. Eleven different fuels ranging from gasoline to safety fuels were fired on with infantry incendiary ammunition and infantry tracer ammunition, calibre 7.9 mm. one round at a time. These fuels were fired on at temperatures of $\backsim -14^{\circ}C$, $\approx +20^{\circ}C$, and $\approx +60^{\circ}C$, corresponding to tropical conditions. Also we made separate tests, in one of which we fired at the gas space above the surface of the fuel, in a partially filled container, while in the other we fired at the liquid fuel itself. Here we took partly individual photographs and partly small colour films at 64 frames per second.

(Fig. 1 - Test installation for rifle firing)

(Fig. 2 - Test installation for firing with explosive ammunition)

3) We are planning further tests on a selection of fuels with incendiary high explosive shells of calibre 15 and 20 mm. and 2-cm. cannon shells at a fuel temperature of ≈ -60°C. This temperature represents the worst conditions. Our 15 mm. incendiary h.e. shell has about the same effect as an English 20 mm. incendiary h.e. bullet, such as the enemy have been using for a long time. The test installation remained unchanged in principle (Fig. 2) but the dimensions had to be increased all round in accordance with the increased effect of the larger projectile. Also some safety measures had to be taken, such as electrical remote control of the firing apparatus, a firing screen to destroy unexploded rounds, and protection for the camera and the observer. The target consists of a piece of tube with an internal diameter of 300 mm. and holds 28 litres. Apart from the three ammunition types, the test parameters used here are the distance from the splitting plate which caused the detonation - this distance varies between 70 and 800 mm - and the thickness of the rubber composition on the target side of the container. On the front flange is a disc of the Raspe type made up of several layers of rubber, of alternatively 13 or 24 mm. In this way it is possible to study the safety of fuels against shooting up with the protection of containers in force today, and with the protective measures in process of introduction, at the same time taking into account developments in the ammunition of the enemy.

We are also engaged in trying out on this installation measures to eliminate the so-called fluid impact, to which we shall return later, so that these tests also assist in the development of containers.

The results were recorded on a slow-motion colour film (a selection of these photographs was shown at the end of this lecture).

Before turning to these results it would be to the purpose to follow the rifle bullet through the container. The conditions are quite different according as the bullet passes through the gas space or through the liquid fuel.

In general, the gas space represents a more or less saturated atmosphere. The round, forcing its way in, draws air in its train as it spins, and air may also enter through the hole made by the bullet. The numerous photographs show that on the near side the combustion caused by the rifle bullet is insignificant, as the round is directed against the flow. On the far side there is, however, generally a jet of flame, which is quickly extinguished, as the round carries fuel vapour out with it. Thus we have here an ignitable mixture, which is ignited by the round. In the container itself the fuel vapour and the air mix more slowly, so that the fuel in the container is first ignited, if at all, by the fire at the far side. This either causes a proper fire, or else a mixture fire, which dies out of itself after a short time.

Several rounds failed to take effect when the gas space above gasoline was fired into, on account of the excessive saturation.

Firing through liquid fuel (Fig. 3) involves other conditions, as here it is a question of a very rapid process in an incompressible medium. At its impact with the wall of the container the bullet causes a pressure disturbance, which spreads out in spherical form with the speed of sound in the liquid forming a shock wave. The speed of sound in gasoline at 17°C is 1166 m/s; the speed of the projectile is considerably lower. The thrust wave therefore gets ahead of the bullet, and is reflected back by the walls of the container. Also, an area of very high pressure is created in front of the bullet. I am able to show these stylised sketches as the result of ballistic Schlierin investigations by Struth and Maecker from the Ballistic Institute of the Technical Academy of the German Air Force. Therefore, the far side of the container is first subjected to a correspondingly high mechanical stress as the bullet approaches it, after which follows its destruction by the bullet, and finally the thrust wave, which has been reflected back and forth several times, hurls a considerable volume of fuel through the tulip-shaped opening of the far side. In containers as short as ours this sometimes occurs at supersonic speeds, and thus is observed in the frontal wave in the escaping liquid. The resistance of the container walls depends not only on their strength, but also, in view of the speed of the process, on their mass inertia.

In this liquid impact, as we call the behaviour on the far side for short, the ejected fuel is atomised more or less finely according to its viscosity, and here begins ignition by the incendiary bullet. The less the viscosity of a fuel, the more finely is it atomised and the easier it is to ignite. For the rest, it is only a question of flash point and boiling point whether the following fuel, which is in the form of a jet, is ignited or not by the burning liquid. The bullet cannot cause a fire during its passage through the funnel in the container, since there is not sufficient atmospheric oxygen available. An empty cavitation space is formed behind the bullet.

We have only now to consider two measures connected with construction. The first concerns the material for the container. Great damage is caused to metal containers by the spreading outwards of the holes which will not close, and lead to great losses of fuel. Therefore we use for war purposes only containers made up of several layers of rubber, which to a large extent are impervious to damage. So long as the bullets or splinters do not actually punch out a hole, the leaks will close themselves for the most part through the pressure of the fuel against a particular layer of rubber.

The second measure is with regard to the form of the dead space between the container and the outer skin of the aircraft. These spaces collect the leaking fuel and feed the fire, especially as they are screened from the air stream. They are a source of considerable danger.

(Fig. 3 - Firing through liquid)

Plans were discussed by the Technical Department of the German Air Ministry for placing the fuel container directly against the outer skin, as that the dead space ceases to exist, at least as regards the main direction of firing.

Our first large series of tests was made, as we have said, on 11 fuels of different boiling points and viscosities. The results were arranged according to size of flame and duration of burning as shown in the photographs without respect to other material properties. This clearly revealed that safety against firing increases with the flash point and the height of the boiling curve, and also with the viscosity (Fig. 4). The "safety scale" is a subjective one, based on the impression gained from the tests. The reference points safety 0 for B4 and safety 1 for YZ 900/5.0 and SS 3051 were chosen at random. The picture is merely intended to show in a concise and clear manner the essential results of the tests.

(Fig. 4 - Results of firing tests with rifle)

It also appeared that a high fuel temperature, such as would be encountered in the tropics, increases the danger of burning. The comparatively low boiling fractions of gasoline and gas oil are dangerously inflammable. The ignition oil R300 is also within this group, but is better than gasoline and also better than its predecessor R110. The second group begins with coal tar middle oil, and includes lubricating oil, followed by the satisfactory safety fuels of I.G. Farben and Ruhrchemie. Firing into the liquid results in mixture fires which become progressively smaller towards the end of the series. Firing on the gas space is less serious than firing on the liquid in every type of fuel, as a burning mass of liquid, in consequence of the greater weight of fuel, releases a far greater volume of heat than a cloud of gas.

In the tests with infantry tracer ammunition, burning only occurred on firing into the gas space of gasoline at $\approx 60^{\circ}C.$, and then only in a plentiful air supply. Otherwise, tracer ammunition is not dangerous.

Shooting up with incendiary bullets caused fires for the most part on the far side in models and also in full size containers in the aircraft. This was evident from observation of the passage of the bullet through the container. The weak fire on the near side is of no significance. On the other hand, with explosive ammunition the fire occurs on the near side of the container. The explanation is obvious. The bullet explodes prematurely at the outer skin of the airframe, the splinters scatter at an angle of 90 to 100°, pierce the wall of the container, and again cause thrust waves, which are reflected back from the opposite wall, and, on returning to the near side wall, expel fuel through the holes made by the splinters in the opposite direction to the line of fire. The atomised fuel is ignited by the detonation flame, which still persists, and which expands mainly behind the detonation front, especially if the bullet exploded a little late. The influence of the slip stream cannot therefore be great, even when infantry incendiary ammunition is used, as long as there continue to be dead spaces round the fuel container.

The nature of the incendiary h.e. shell is evident from its name. It has a decided splintering effect. The 2 cm. cannon shells, on the contrary, depend less on splinter effect than on blast. They therefore have thin walls with a relatively large H.E. charge and an incendiary charge of aluminium. Its splinter effect comes, not from the covering of the bullet but mainly from the fuse and the base. Of the three types of ammunition used, the cannon shell was the most effective.

So far, we have fired at the coal tar middle oil 3636H, and the safety fuel TZ 900/5.0 with H.E. ammunition at $\approx 60^{\circ}C$. Coal tar causes very large mixture fires: the expelled fuel burns away to a considerable extent. But the flame does not run along the jet of fuel which is seeping out, nor does the fuel inside the container burn. Meantime the rubber composition begins to burn. This fuel cannot be considered safe against H.E. ammunition, but it provides more protection against infantry ammunition and fire on crashing than gas oil does and may therefore qualify as an intermediate stage on the way to a safety fuel.

TZ 900/5.0 causes on the whole very much smaller mixture fires; the expelled fuel only burned in exceptional cases, and the fires go out by themselves in a short time. We have also used 2 cm. incendiary H.E. shells, which detonate inside the container. No fire occurred, though the test was repeated several times. Only the mixture fires were larger.

As regards the effect of the distance between the splitting plate and the container: at short distances the effect of the bullet on the rubber wall is greater. Admittedly the same effect can be obtained at greater distances of the splitting plate from the container by using a fuse with a suitable delay. The protection improves as the rubber composition becomes thicker, as the liquid impact and the spilling loses are reduced thereby. Also, because of its greater mechanical strength it offers added protection against the jagged holes radiating from the splinter marks: i.e. there is increased protection against large leaks. The tests are not complete yet, but one may safely say that the thick composition considerably reduces the size of the flame, and that we can observe here the influence of the distance of the splitting plate on the size of the flame. At distances of 800 - 400 mm. the flames are small, at least with TZ 900/5.0, only increasing at lesser distances. With the thin composition the distance of the splitting plate hardly affects the size of the flame.

It will hardly be possible to achieve real safety from shooting up with H.E. ammunition, that is to say, complete resistance to the formation of flames owing to the properties of the fuel. We must therefore content ourselves with finding a practical optimum, balancing safety from fire against fitness for use in an engine.

Further developments in ammunition and increases in calibre look like ending in the complete destruction of the aircraft with a single direct hit. Under these circumstances, safety fuel is only a part, if a large part, of the passive defence of the aircraft.

This series of tests showed that the comparatively low ~~boiling fuels in the~~ range from gasoline to gas oil are inflammable, and therefore are of no use as safety fuels. The fuels from coal tar middle oil to TZ 900/2 are suitable within limits, and are a partial solution. The still more viscous fuels such as TZ 900/5.0 and SS 3051, possess a degree of safety from firing which is practically adequate; also the lubricating oils in this stage of viscosity (Aero shell heavy) are within the safety requirements. From the point of view of safety from firing, it appears to be worth while to continue engine tests for the purpose of introducing viscous safety fuels.

Afterwards the film showing excerpts from the tests was shown.