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THE GASDYNAMICS OF SELF-REGULATION OF A SUPERSONIC PLUG NOZZLE

by

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ABSTRACT

(U) Experimental studies are presented of supersonic plug nozzles. The purpose of the study was to determine the nozzle performance at characteristic pressure ratios and to formulate a gasdynamic theory for variable nozzles. Cold air at 6 kg/cm (superscript 2) and 345 degrees K was used as the working medium. The static pressure was measured along the nozzle, the plug, and the nozzle inlet. In addition, the shadow method was used to visually examine the exhaust jet. Changes in the pressure ratio in the nozzle were determined from pressure variations at the inlet cross-section of the nozzle. The study included plug nozzles with single and multiple combustion chambers. In addition to rocket application, plug nozzles have potential application in turbojet and ramjet engines.

THE GASDYNAMICS OF SELF-REGULATION OF A SUPERSONIC PLUG NOZZLE

Dr. of Eng. Tadeusz Gajewski

The high power demanded of rocket engines creates a number of problems which relate not only to the design concept of the engine, but also to its fueling and cooling arrangements, combustion chambers and the exhaust nozzle. These problems must be solved so as to most efficiently utilize the power resources of the individual engine components and of the working fluid, simultaneously taking into account all the factors affecting the size and weight of these components.

A component whose dynamic characteristics, weight and size basically affect the engine's output is among others the exhaust nozzle. Each percent increase in the efficiency in accelerating the working fluid in the nozzle increases the engine thrust. A reduction in the dimensions and weight of the nozzle can have an appreciable effect on the rocket's range.

The basic type of the exhaust nozzle of rocket engines is the conventional de Laval nozzle. Most frequently its operating time is not adjustable, but it is sometimes equipped with an arrangement for controlling the direction of the thrust vector.

The exhaust nozzle is designed for some nominal flight altitude, which depends on the required range and flight path. Above and below this altitude a non-adjustable nozzle operates with incomplete expansion or with expansion [to] below-atmospheric pressure with an attendant loss of thrust.

This problem also exists in turbojet and [pure] jet engines which have such high pressure ratios in the nozzle when the rocket's Mach number exceeds 2, as to necessitate the use of converging-diverging nozzles instead of the previously used converging nozzles, and also require that the former be adjustable in accordance with flight and engine-operation conditions.

Control of the de Laval nozzle of a rocket engine consists in varying the area of the exhaust cross section, while in turbojet engines it consists also in varying the area of the throat section. All methods of regulating the conventional de Laval nozzle involve design difficulties as well as reduction of operating reliability and this adds importance to self-regulating supersonic nozzles. One of such nozzles is one with a center plug and with mixed expansion in the supercritical region, i.e., expansion which takes place partially in the inner part of the nozzle and partially in the quasi-free flow past the centrally-located plug. The concept of such a nozzle is shown schematically in Fig. 1. The plug is situated coaxially inside the cylindrical nozzle passage and partially protrudes from it. This arrangement forms a convergent-divergent passage which is needed for obtaining supersonic exhaust velocity for supercritical pressure ratios in the nozzle.

Rarefaction waves, in which the flow expands, is accelerated and changes direction are produced when the working fluid flows past the convex part of the plug in the supercritical region. The differential equation of the potential of this flow is a hyperbolic-type equation, while its characteristic equation has two different real roots in the integral space. Two families of curves, which are regarded in their physical interpretation as Mach lines, appear in the plane of the flow. Henceforth we shall call these the characteristic curves instead of Mach lines.

In supersonic flow past the convex part of the plug these characteristics are incident on the cylindrical wall of the nozzle and after being reflected from it are incident on the tapered surface of the plug. This surface is shaped so that characteristics of the second family will not be reflected.

After passing through the first family of curves the stream moves in the direction of the nozzle axis; after passing through the second family of curves, the flow is deflected in the opposite direction, with the result that after passing curve AB (Fig. 1) the flow takes place parallel to the nozzle axis.

When the nozzle operates at the design pressure ratio (calculated for complete expansion) the bounding surface of the jet is generated by streamline AC (Fig. 1). The pressure at this surface is constant and equal to atmospheric pressure p_H at the given altitude H.

This article presents results of experimental work performed on models of supersonic plug nozzles. This work had as its purpose to determine the behavior of the nozzle when operating at characteristic pressure ratios and to work out on this basis the fluid-flow theory of the properties of self-regulating nozzles.

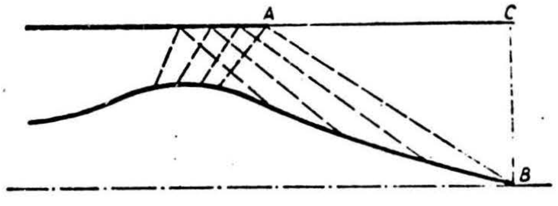

Fig. 1. Schematic of a supersonic plug nozzle.

The nozzle models were designed from a shape calculated graphically from characteristics curves. The working fluid consisted of cold air with initial parameters $p_0 = 6$ kg/cm^2 and temperature 245°K. The static pressure was measured along the generating line of the nozzle's cylindrical part and of its plug, the pressure at the nozzle inlet was also measured. In addition, shadow-graphs were obtained of the flow pattern in a region allowing qualitative determination of the exhaust jet. The pressure ratio in the nozzle was varied by adjusting the pressure at the nozzle's inlet.

The pressure ratio π_N in the nozzle is the ratio of the total pressure p_0 of the jet at the nozzle inlet to the static pressure p_N at the nozzle's outlet. The pressure ratio π_{Nc}, corresponding to complete expansion in the nozzle is the ratio of pressure p_0 to p_H, the atmospheric pressure at the given flight altitude H. And finally, the design pressure ratio in the nozzle π_{Nd} is the ratio of pressure p_0 to the atmospheric pressure p_H for which the nozzle has been designed. In accordance with the above we can write

$$\pi_N = p_0/p_N \qquad \pi_{Nc} = p_0/p_H \quad \pi_{Nd} = [p_0/p_H]_d$$

Using these pressure ratios we can define three characteristic modes of the nozzle's operation

1) $p_N > p_H \qquad \pi_{Nc} > \pi_{Nd}$
2) $p_N = p_H \qquad \pi_{Nc} \quad \pi_{Nd}$
3) $p_N < p_H \qquad \pi_{Nc} < \pi_{Nd}$

A. Operation of the Nozzle at Pressure Ratios $\pi_{Nc} > \pi_{Nd}$

When the nozzle operates at this mode, the static pressures along the generating surface of the cylinder's wall and of the plug decrease to above-atmospheric pressures. The distribution of these pressures is represented by the section of Fig. 2. The numbers on the schematic of the plug and the nozzle's cylindrical part denote measuring points. On the circumference of the exhaust section of the nozzle's cylindrical part, which is represented in Fig. 3 by points A_1 and A_2, the jet pressure is higher than atmospheric. The jet expands to atmospheric pressure in the pattern of oblique rarefaction waves. The fluid-flow pattern of the exhaust jet, which was analyzed similar to the others on the basis of shlieren photographs is represented in Fig. 3. In this figure the thin continuous lines denote compression waves, the dashed lines denote rarefaction waves, while the heavy lines denote shock waves.

In the pattern of rarefaction waves the streamlines are deflected from the axis of the jet which results in a corresponding distortion of the jet's surface at segment A_1D_1 (Fig. 3). Due to the influence of the pressure of the surrounding medium, this distortion changes direction until it is totally reversed at segment D_1C_1.

Weak compression waves emerge from the free surface of the jet. Since the parameters of the jet on its free surface are constant, the angle between this surface and the waves is the same. As a result of this, the compression waves which converge toward the axis of the jet intersect and thus form a shock wave in the shape of a surface of revolution with generating line A_1B_1. The strength of this wave increases as the nozzle's mode of operation moves away from the design mode. On a sufficiently great deviation this wave terminates on the axis of the jet in a wave normal to B_1B_2, past which the jet is subsonic. The wave at the curved generating line A_1B_1 changes its direction at the line of intersection with the normal wave and emerges onto the free surface of the jet at points $\underline{C}_1$ and $\underline{C}_2$ (in one of the flow-section planes).

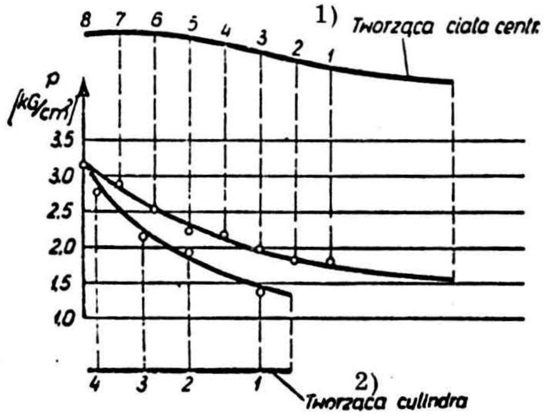

Fig. 2. Pressure distribution along the generating lines of the cylinder and of the plug. $\pi_{\underline{Nc}} = 4.5$, $\pi_{\underline{Nd}} = 3.7$.
CODE: 1) Generating line of the plug; 2) generating line of the cylinder.

The plug is located in the region where the jet's pressure is above atmospheric. From this it can be concluded that the nozzle in question produces the same thrust losses in the case of operation with $\pi_{\underline{Nc}} > \pi_{\underline{Nd}}$ as a conventional de Laval nozzle due to incomplete expansion.

B. Operation of the Nozzle at Pressure Ratios $\pi_{\underline{Nc}} = \pi_{\underline{Nd}}$

As the pressure ratios in the nozzle are brought closer to the design pressure (going down from above-design pressures) the strength of the shock waves is reduced and the normal shock wave also disappears, to be replaced by an oblique wave which emerges from the edge of the nozzle's cylinder. Atmospheric pressure is obtained at the last rarefaction wave incident on the plug's nose. The streamlines of the jet behind this wave are parallel to the nozzle axis (see Fig. 1). The pressure distribution along the nozzle walls when the nozzle operates with complete expansion is shown in Fig. 4.

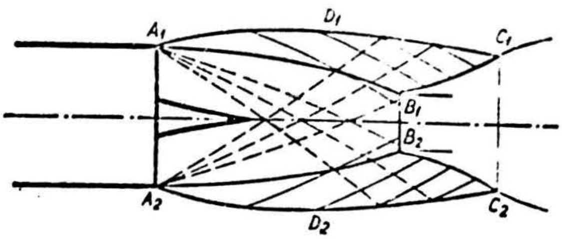

Fig. 3. Schematic of the flow pattern of the jet in the vicinity of the plug. $\pi_{\underline{Nc}}=4.9$, $\pi_{\underline{Nd}}=3.7$.

C. Operation of the Nozzle at Pressure Ratios $\pi_{Nc} < \pi_{Nd}$

When the pressure ratios in the nozzle are lower than the design pressure, the pattern of oblique shock waves comes closer to the exhaust of the nozzle's cylinder and thus moves into the region of the plug's influence. As follows from measurements, the static pressure of the jet along the nozzle's cylindrical part drops to below-atmospheric pressure.

Due to the effect of atmospheric pressure on quasi-free jet (exhaust jet, interacting with the plug) the latter cannot expand to below-atmospheric pressure. Due to this expansion to atmospheric pressure, which is obtained on the circumference of the plug section, takes place along the plug. On this circumference the oblique shock wave which emerges from the edge of the nozzle cylinder comes into contact with the plug. The pressure distribution along the cylinder and the plug for this mode of operation is shown in Fig. 5. The corresponding flow-pattern structure of the jet is shown in Fig. 6.

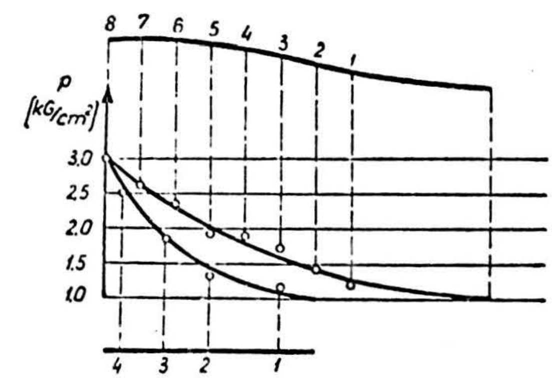

Fig. 4. Pressure distribution along the generating lines of the cylinder and of the plug. $\pi_{Nc} = \pi_{Nd} = 3.7$.

An oblique shock wave with generating line A_1B_1 emerges from the edge of the cylindrical part, is reflected from the plug's wall on the circumference represented by points B_1 and B_2 and emerges on the surface of the quasi-free jet at points C_1 and C_2. Here it is again reflected from the free surface of the jet in the form of rarefaction waves. A step-wise pressure increase to above-atmospheric pressure takes place at the circumference at which the oblique shock wave comes into contact with the plug.

Figure 7 shows the pressure distribution along the wall of a balanced, conventional de Laval nozzle operating at a specified pressure ratio. As can be seen from the figure, the pressure on the end segment of the nozzle wall is below atmospheric. This denotes loss of thrust relative to that obtained under design conditions. The segment of the de Laval nozzle subjected to below-atmospheric pressure produces negative thrust. This is illustrated by Fig. 8.

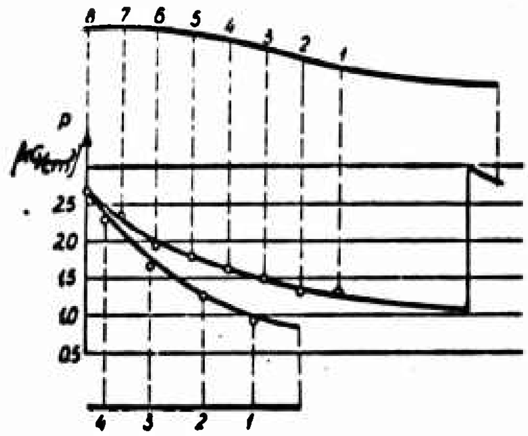

Fig. 5. Pressure distribution along the generating lines of the cylinder and the plug. $\pi_{Nc} = 3.04$, $\pi_{Nd} = 3.7$.

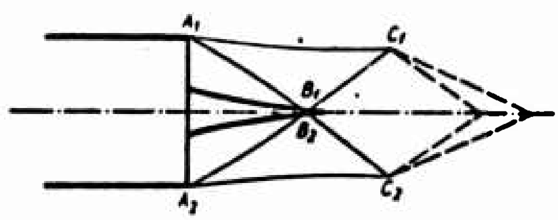

Fig. 6. Schematic of the fluid-flow pattern of an exhaust jet in the space formed by the plug. $\pi_{Nc} = 3.04$, $\pi_{Nd} = 3.7$.

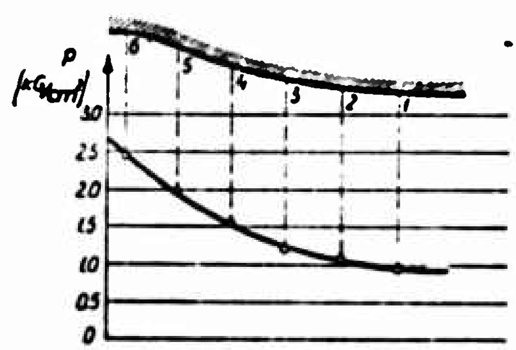

Fig. 7. Pressure distribution along the wall of a conventional de Laval nozzle.

$\pi_{Nc} = 3.04$, $\pi_{Nd} = 3.7$.

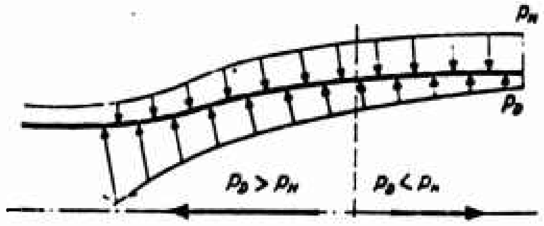

Fig. 8. Thrust of a de Laval nozzle operating at a lower-than-design pressure ratio (in the region of aerodynamically similar flows).

Due to the effect of the ambient pressure on the quasi-free exhaust jet of a plug nozzle, the nozzle becomes in this region self-regulating, reducing the thrust losses as compared with those which would in this case prevail in a de Laval nozzle. It is true that below-atmospheric pressure regions arise along the wall of the cylindrical part of the plug nozzle, but this does not affect the thrust, since the cylinder does not contribute to the thrust.

As the pressure ratios in the nozzle continue to vary, the angle of the secondary oblique wave becomes greater than its value corresponding to maximum jet deflection angle. This produces a bridge-type pattern of shock waves, which consists of an oblique wave closed by a normal wave, from the ends of which the following oblique wave emerges. A schematic of the fluid-flow pattern of the exhaust jet under specified operating conditions is shown in Fig. 9, while Fig. 10 represents the corresponding pressure distribution along the nozzle walls. The self-adjustment mechanism of the nozzle is principally similar to that described above.

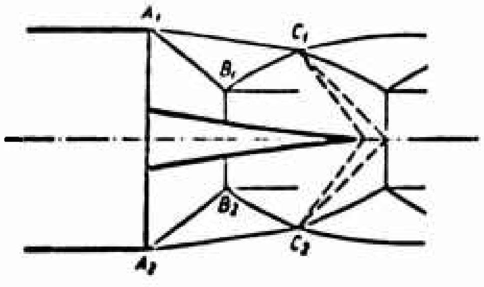

Fig. 9. Schematic of the fluid-flow pattern of an exhaust jet in the region of the plug. $\pi_{Nc} = 2.4$, $\pi_{Nd} = 3.7$.

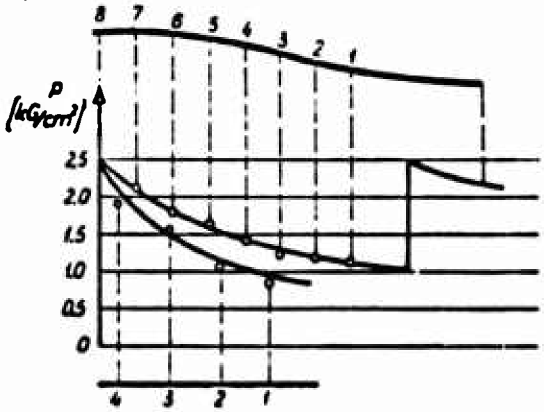

Fig. 10. Pressure distribution along the wall of the cylindrical part and of the plug. $\pi_{Nc} = 2.4$, $\pi_{Nd} = 3.7$.

When the pressure ratio in the nozzle drops further, the region of the subsonic jet past the normal wave which is in contact with the nozzle expands, while the supersonic region contracts. Simultaneously the normal shock wave comes ever closer to the outlet section of the cylindrical part. For a sufficiently low pressure ratio the normal shock wave occupies almost the entire outlet section, while the wave pattern of which it is a part is situated near the outlet section of the cylindrical part. A schematic of this fluid-flow pattern of the exhaust jet is shown in Fig. 11.

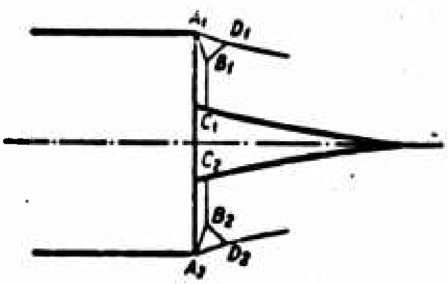

Fig. 11. Schematic of the fluid-flow pattern of an exhaust jet in the region of the plug. π_{Nc} = 2.6, π_{Nd} = 8.

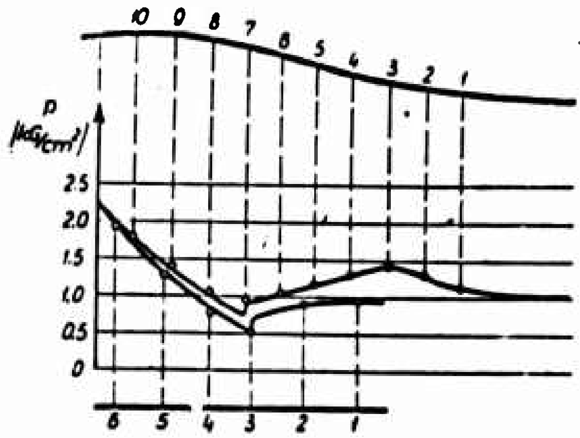

Fig. 12. Pressure distribution along the wall of the cylindrical part and the plug. π_{Nc} = 2.4, π_{Nd} = 8.

The sequential reduction in the pressure ratio in the nozzles causes the normal wave to move deeper inside the nozzle. The jet past the normal wave is obviously subsonic which means that it is compressed past it as a result of increasing areas of the flow passages. The quasi-free subsonic jet emerging from the cylindrical part of the nozzle expands to atmospheric pressure. In the nozzle segment between the throat section and the section in which the normal shock wave exits the jet is expanded to below-atmospheric pressure. This means that the nozzle efficiency drops to the same extent as in a conventional de Laval nozzle. The pressure distribution along the nozzle walls in the case under study is represented in Fig. 12.

The basic period of nozzle operation with self-regulation proceeds until the normal shock wave approaches the exhaust section of the nozzle's cylindrical part. In the case of one of the nozzles that were tested this took place at a pressure ratio of 2.4, while the design pressure ratio was 7.8. This means that self-regulation of the nozzle in the free space of the plug section stops only after the ambient pressure is reduced by a factor of 3.25. This would correspond to a design altitude of about 10 km and would denote a faster increase in a thrust of a jet engine with such a nozzle as compared to one with a conventional de Laval nozzle. This ceiling can be effectively increased if we take into account the fact that always the efficiency of a nozzle decreases insignificantly when passing the design pressure ratio in the direction of increase of the latter.

The theory of self-regulation of a plug nozzle with composite expansion is valid also for a plug nozzle with outside expansion. Due to this it serves as a basis for future studies of plug nozzles.

Figure 13 shows the design schematic of the concept of a rocket engine with a plug in which the turbine utilizing the energy of combustion products [exhausted] from the combustion chamber drives the pumps of the fueling system, with the latter located inside the plug.

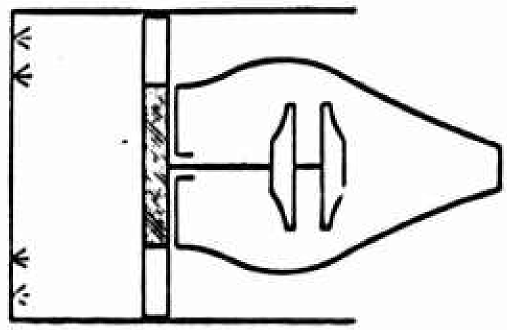

Fig. 13. Schematic of the idea behind a single-chamber rocket engine with a plug.

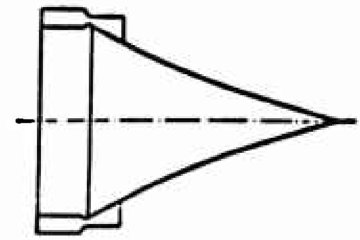

Fig. 14. Schematic of the idea behind a multi-chamber rocket engine with a plug.

Figure 14 presents a schematic of a multi-chamber rocket engine with a center plug. The parallel-operation combustion chambers are located around the plug. The products of combustion exhausted from all the combustion chambers flow past the plug. The advantage of this solution is the feasibility of cutting out certain engines and to thus control the direction of the thrust vector. Another advantage of this type of engine is also the feasibility of designing an engine with a sufficiently high thrust on the basis of a multiply reused single engine design. This eliminates the problem of incomplete combustion which arises when single-chamber engines are proportionally enlarged (in order to increase the thrust).

Among shortcomings of rocket engines with external or mixed expansion we can count difficulties in cooling the plug. The danger also exists that there will appear a radial thrust component in the case of lack of axial symmetry in the flow past the plug which, for example, may be due to nonuniformity of the jets exhausted from the different combustion chambers.

In considering the concept of a jet engine with such a nozzle provisions are also made for the use of a plug with a truncated end. This truncation may be justified by a number of considerations. The end part of the plug does not produce appreciable additional thrust due to the smallness of the surface interacting with the jet. In addition, the thrust loss that does occur can be compensated by the bottom pressure of the truncated plug. This truncation is also favorable from the point of view of weight reduction and also reduces the difficulty in cooling a small surface with an appreciable heating load.

It is to be expected that plug nozzles will come into use also in turbojets[1] and in [pure] jets.

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[1]See Footnotes, p. 10.

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FOOTNOTES

p. 9. [1]Ed. note. Such a nozzle was actually used in the Pratt and Whitney J52 turbojet engine, used to drive the "Hound Dog" air-to-surface missile.