# Base Flow Analysis for a Dual-Engine Booster

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## Theme

A METHOD of predicting average base pressure and temperature of a dual-engine booster of cylindrical shape is presented. Very good agreement of the analytical prediction with the available flight data for the Titan III Booster has been obtained.

## Contents

The convective base heating of multiple-engine boosters results mostly from the hot exhaust gas which is reversed toward the base as plume interaction occurs. Prediction of convective heating requires knowledge of the base gas temperature and the heat transfer coefficient. The latter depends on base gas density and, therefore, on base gas pressure and temperature.

Several methods on the multiple-engine base flow analysis have been developed in the past based on the integral method of Korst's theory and have shown reasonably good results. However, these methods were primarily intended for three or more engine configurations and are not readily applicable to a two-engine configuration. This limitation occurs because most of these methods use either the "choked flow" condition through the vent area between two adjacent nozzles as the criterion for a unique solution, or the reverse jet impingement model, thereby neglecting the effect of freestream jet-exhaust jet-plume interaction. In a dual-engine configuration, no such vent area can be defined nor is the jet impingement model adequate. The dual-engine base flow solution is also affected by the mass and energy entrainment capability of the plume interaction between the freestream jet and the portion of the exhaust jet facing the freestream side. A typical dual-engine base flowfield is depicted in Fig. 1.

The present base flow analysis of dual-engine booster is taken from the backup report,[1] where a general method of analyzing the multiple-engine base flow has been developed, and is presented here to show that a satisfactory base flow prediction can be obtained for a dual-engine configuration as well if all the important effects are properly accounted for. The analysis consists of a) the reverse flow analysis for the region between the two engines (inner base region) and b) the mass and energy entrainment analysis for the freestream-exhaust jet interaction region (outer base region). The method is limited to the case where all the mixing layers involved are fully turbulent and both the freestream and the exhaust jet stream are supersonic.

In the inner base region where the neighboring exhaust plumes interact, the recompression pressure rise which results from this interaction reverses some of the lower energy portion of the shear layer. Because of this direct reversal of the lower energy exhaust gas, the initial boundary layer at the nozzle exit becomes important. It has been observed that the nozzle exit thermal boundary layer affects the base convective heating rate in multiple-engine configurations. The nozzle exit boundary-layer characteristics may be calculated by any one of the available methods.

As the initial boundary layer separates from the nozzle lip into the base region, a new initial shear layer profile emerges. Determination of this shear layer profile can be made conveniently by streamtube analysis. The virtual origin of this layer is determined by satisfying conservation of both the mass and the momentum between the actual layer and the equivalent fully-developed layer of an error function shape; thereby, the often used mixing analysis of a similar velocity profile of the error function shape can be applied directly.

A control volume is established for the relatively constant pressure region bounded by the nozzle exit plane location and the axial station where the reversal of the flow begins. Following the method of Ref. 2, the downstream boundary of the control volume is set at midway between the nozzle exit plane and the rear stagnation point. The jet boundary streamline (a streamline which separates the oncoming mass at the nozzle-exit from the recirculating mass) within the mixing layer is then determined from mass and momentum considerations. The total enthalpy within the mixing layer may be related to the velocity by Crocco's energy relation. As is done in many previous analyses, the recompression pressure rise is assumed to be equal to the pressure rise of the inviscid plume boundary going through an oblique shock at the intersection point of the two inviscid plume boundaries. The discriminating (or reattaching) streamline within the mixing layer is then determined by selecting the streamline which has a dynamic pressure equal to the pressure rise. Integration of the mass and energy between the jet boundary and the discriminating streamlines gives the reverse flow mass and energy which later escape into the outer base region and into the downstream flow.

The analysis for the outer base region is similar to the method developed in Ref. 2 for a single engine booster. The interaction between the external freestream and the exhaust jet streams has been analyzed by treating the two-engine configuration as an

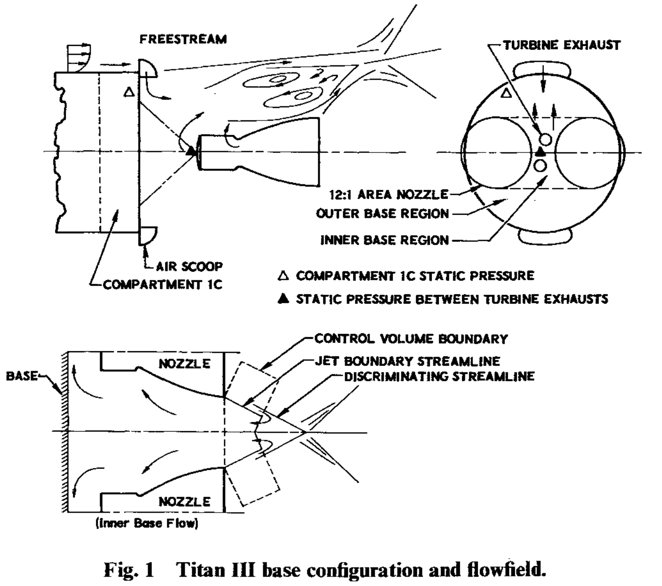


**Fig. 1 Titan III base configuration and flowfield.**

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equivalent single engine so that the single-engine analysis can be applied directly. The diameter of the equivalent single engine is determined by setting its peripheral length equal to the effective peripheral length of the two engines which would be obtained if the two engines were connected by two parallel dashed lines (as shown in the rear view of Fig. 1) separated by a distance equal to the engine diameter. The effect of initial boundary layer in a single-engine booster analysis is relatively unimportant and, therefore, has been neglected in this part of the analysis.

The analysis begins with an initial trial value of the base pressure which is assumed to be common to both the outer and the inner base regions. This assumption is valid because there are no flow restrictions in a dual-engine configuration. For this selected value of the base pressure, the mass and the energy originating in the inner base region are calculated. The mass and the energy entrainment in the outer base region is determined for a range of values of the base gas temperature. The base pressure and the base gas temperature are then iterated until the mass and energy coming from the inner base, the mass and energy entrained by the freestream jet-exhaust jet interaction, and the mass and energy bled into (or out from) the base region from other sources, if any, are all balanced.

The available Titan III flight data[3] obtained during the STB-1 and STB-2 flights have been used to determine the validity of the method. Two sets of base pressure data, namely, the compartment 1C pressure and the static pressure between turbine exhausts (see Fig. 1) have been selected for comparison with the analytical results. These data represent the pressure at both the upstream and downstream portions of the base region. The base gas temperature was obtained by Martin Marietta Corp. from the measured convective heat flux, the base pressure, and the reverse flow gas Mach number by solving simultaneously the Nusselt-Reynolds equation and the convective heating equation.[3] As shown in Fig. 1, two air scoops are mounted on the vehicle

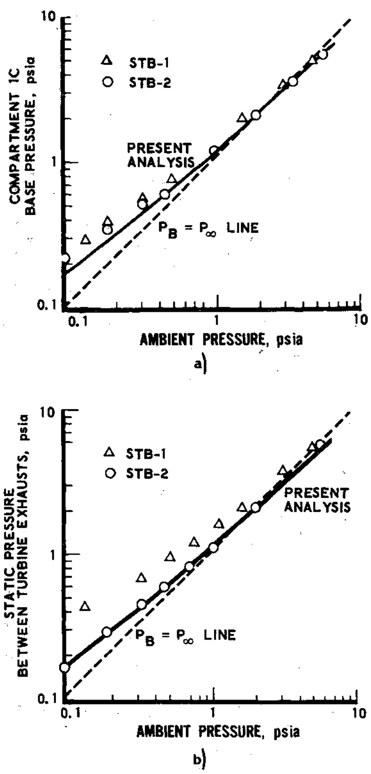


Fig. 2 Base pressure comparison.

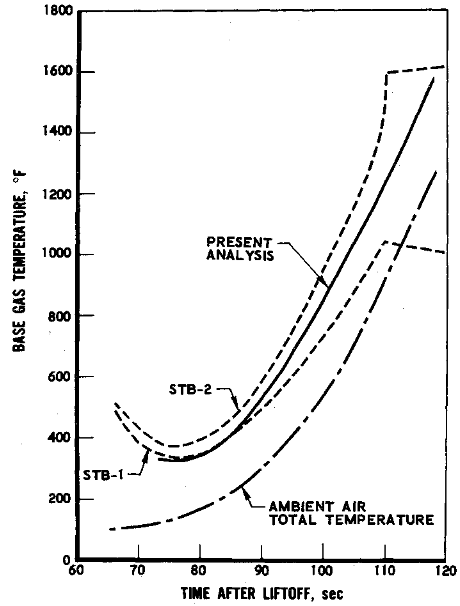


Fig. 3 Base gas temperature comparison.

at the base corner to deflect some of the boundary-layer flow along the vehicle skin into the base region. The net effect is a reduction in base gas temperature and an increase in the base pressure. The fraction of the boundary-layer mass and energy which is introduced into the base region was calculated from a boundary-layer analysis and the vehicle external skin temperature. At high altitude, impingement of the turbine exhaust gas jet on the nozzle external surface results in a localized reverse flow. However, the amount of this reversed flow is negligible compared with the reversed flow from the main engine exhaust jets and, therefore, has not been included in the present analysis.

The Titan III boosters use Aerozine-50 and $N_2O_4$ as propellants. Thermodynamic properties of the exhaust-jet gas used in this analysis have been determined at a mixture ratio (oxidizer/fuel) of 2.2. The results of analysis are compared with the data in Figs. 2 and 3. In Fig. 2, the predicted base pressure is compared with measurements made both at compartment 1C and at a location between turbine exhausts. Good agreement of the base pressure prediction with STB-2 data is shown in the figure. A slight disagreement with STB-1 data may possibly be due to the larger angle of attack ($-6° \sim 4°$) of STB-1 than the STB-2 ($-3° \sim 0°$) during the range of flight time analyzed. Comparison of the predicted base gas temperature with the flight-deduced data of STB-1 and STB-2 is shown in Fig. 3.

It is shown that a satisfactory prediction of the base flow of a dual-engine booster can be made by coupling a reverse flow analysis of the inner base region with the outer base flow analysis where the two-engine configuration is substituted by an equivalent single-engine configuration.

## References

[1] Hong, Y. S., "Base Flow Analysis of Multiple-Engine Boosters," Rept. TR-0074(4901-01)-1, The Aerospace Corp., El Segundo, Calif.

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[3] Callahan, J. B. and Schmitt, D. A., "Titan III B Program, Stage I Base Heating Criteria Report (Preliminary)," MCR-69-608, Jan. 1970, Martin Marietta Corp., Denver, Colo.