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# DUAL-BELL ALTITUDE COMPENSATING NOZZLES

M. Horn and S. Fisher

Rocketdyne Div., Rockwell International

## BACKGROUND

All large liquid rocket booster engines in use today rely on fixed geometry bell nozzles. These nozzles limit engine performance, since they operate at optimal efficiency at only one point along the flight trajectory. Thus, during the design process, a compromise must be made between sea level and vacuum performance in order to best meet the demands of the mission within the nozzle performance limitations. An addditional constraint is the nozzle expansion ratio, which must be limited to prevent the nozzle flow from separating at sea level, resulting in separation sideloads. Engine lift-off thrust requirements, weight and packaging issues may also limit the nozzle size. These factors all contribute to the limitations in the vacuum performance of an engine.

Conversely, a nozzle capable of varying effective expansion area ratio can optimize delivered impulse throughout the entire flight trajectory, resulting in dramatic performance gains. The ideal Altitude Compensating Nozzle (ACN) would continuously vary nozzle exit area ratio such that the nozzle is always pressure matched. In pursuit of these performance gains, ACN's have been investigated numerous times, but always, weight, cost, mechanical complexity and cooling issues have precluded their implementation on a real vehicle.

One ACN concept which avoids many of these design difficulties is the dual bell nozzle. The dual bell nozzle relies on an inflection point in the nozzle to force the flow to separate from the nozzle wall at the desired location, thus increasing sea level thrust. Since the flow separation is symmetrical and controlled, no sideloads are generated by the flow separation. During the ascent profile, the plume gradually expands until it finally attaches to the nozzle wall downstream of the inflection point, as depicted in Figure 1. Once the flow is attached and the nozzle exit pressure exceeds ambient pressure, the higher effective area ratio results in increased performance for the remainder of the ascent. For the ideal case, the net effect is that of having two nozzles, each optimized for a different portion of the flight trajectory. Mission studies have demonstrated that the performance of this two-stage ACN comes very close (within 1 to 3%) to the optimal efficiency for an ideal ACN of a given maximum area ratio.

In reality, however, the dual bell nozzle concept has several inherent inefficiencies which reduce its performance from the theoretical optimum. Figure 2 compares the actual performance of a dual bell nozzle to the optimum dual bell. The optimum dual bell nozzle, for this case, would follow the 16:1 Rao optimum nozzle thrust coefficient curve as the vehicle ascended, and then, at the performance cross-over point, switch to the 40:1 Rao optimum nozzle thrust coefficient curve for the remainder of the mission. However, during sea level operation with an actual dual bell nozzle, the separated region of the nozzle results in "aspiration drag". The relative impact of this aspiration drag on nozzle performance is evident in region A on the graph. By lowering the effective wall pressure at the inflection point, this aspiration effect also triggers transition before the optimum performance cross-over point, as seen in region B. Then, once transition occurs and the flow is fully attached in the nozzle, the inflection point results in losses due to a non-optimal contour, illustrated by region C on the graph.

Despite these losses, the dual bell nozzle still provides a significant net impulse gain relative to either the 16:1 or the 40:1 fixed Rao optimum nozzles. It should also be noted that most ACN concepts suffer from similar losses due to non-optimal contours, induced drag, etc.

## DISCUSSION OF TESTING

The primary objective of this cold flow test effort was to assess the performance characteristics of dual bell nozzles and to obtain preliminary design criteria by testing a number of configurations. Characteristics of interest included low altitude performance, high altitude performance and the flow transition process. In combination with this performance data, other factors such as cost, weight, fabricability and vehicle related issues could then be traded to establish the feasibility of the concept.

The testing was carried out in Rockwell's altitude test chamber located in El Segundo, California. Figures 3 and 4 show the layout of the facility. The test chamber is approximately 5'x5'x16', with 3' diameter windows on either side of the test section to allow viewing of the flow field. Air flow is supplied to the chamber by an air compressor capable of an output of 12 lb/sec at 300 psia. Altitude chamber evacuation occurs through a variable supersonic diffuser connected to a 26,000 cu ft vacuum sphere. The vacuum sphere is continuously evacuated by five vacuum pumps and an air ejector. Additionally, the flow through the model at the exit plane acts as a jet pump, further reducing the ambient pressure in the altitude chamber.

The nozzle configurations were mounted on a balance to measure axial thrust loads. Pressures and temperatures were also measured along the length of the nozzle. Schlieren imaging was used to visualize the plume flow field at the exit of the nozzle. This allowed real time evaluation of the flow field to determine nozzle transition characteristics.

Four different dual bell nozzle configurations were tested in this effort, along with two baseline nozzles to allow for performance comparisons. Figures 5 and 6 compare the contours tested. The baselines were 16:1 and 40:1 Rao optimum nozzles, which represented the low and high area ratios of the dual bell nozzles tested.

The 16:1 Rao optimum nozzle was used as the base nozzle for all of the dual bell contours. All of the extensions were of the same axial length, with an exit area ratio of 40:1. The test matrix varies the pressure gradient in the extension, since this is known to be the primary factor affecting both nozzle performance and flow transition characteristics. The conical extension provides a negative pressure gradient, as does the Rao optimum extension. The constant pressure extension has a zero pressure gradient, while the overturned extension provides a positive pressure gradient. Figure 5 illustrates the nozzle wall pressure gradients as a function of contour. Controlling the pressure gradient along the nozzle also controls the contour turn angle at the inflection point. The greater the turn angle, the better the anticipated transition performance; however, this benefit comes at the cost of decreased high altitude performance. The exploration of this trade was a primary goal of this activity.

## RESULTS OF TESTING

During testing, it was observed that the conical and Rao optimum dual bells did not provide smooth flow transition from the low to high area ratio mode. In both cases, the flow attachment was unsteady over a range of pressure ratios. The constant pressure and the overturned extensions, however, both exhibited excellent transition characteristics, with transition occurring in less than 30 msec* and at repeatable nozzle pressure ratios. The high altitude and low altitude performance of the configurations were also quantified using the test results.

Based on these results, the constant pressure extension was selected as the baseline dual bell nozzle contour, since it provided the best high altitude performance of the two contours with acceptable transition characteristics. The high altitude performance of the overturned contour was degraded by the more severe nozzle geometry.

Figure 7 depicts the nozzle thrust coefficient versus the pressure ratio for the constant pressure dual bell nozzle. At low pressure ratios, the nozzle flow separates at the inflection point. This separation results in a higher thrust coefficient than for the full flowing nozzle, until the flow transitions. The flow transition consistently occurred at the same pressure ratio, although, as expected, the transition takes place before the optimum performance cross-over point. At higher pressure ratios, the full flowing constant pressure dual bell nozzle provides improved performance relative to the baseline 16:1 nozzle, as illustrated by region C in figure 2.

Figure 8 illustrates the nozzle pressure profiles in both the separated and attached flow cases. In the case of separated flow in the extension, it is seen that the relative pressure in the extension is lower than the ambient pressure due to aspiration of the nozzle extension by the flow. This results in the observed performance loss relative to the 16:1 nozzle case. In the attached flow cases, it can be seen that when the nozzle is underexpanded, the nozzle pressure profiles all lie on top of each other, as predicted by basic nozzle theory. However, in the case of overexpansion with attached flow in the extension, it is seen that nozzle wall pressure in the extension increases with increasing ambient pressure. This behavior is attributed to the zero pressure gradient condition along the nozzle wall, and is believed to be a contributing factor in the excellent transition characteristics of this contour.

Low altitude performance losses due to aspiration drag, high altitude performance losses due to a non-optimal contour and early transition all reduce the dual bell nozzle's efficiency below the theoretical optimum. Even with these losses, however, the dual bell nozzle has shown significant gains over a single bell nozzle in mission studies. For a three engine SSTO vehicle based on the SSME engine, the use of a dual bell nozzle of the same area ratio as the baseline SSME nozzle resulted in a 12.1% increase in payload to L.E.O. The use of a larger area ratio

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* (Framing speed of video camera)

nozzle yields even more significant payload gains, with the added advantage of allowing a larger area ratio nozzle to be used at lift-off without suffering undue transient sideloads due to flow separation.

## CONCLUSIONS

While certain inefficiencies are inherent in the dual bell nozzle concept, it is seen that there are still clear performance advantages to using a dual bell nozzle for certain mission applications. While other altitude compensating nozzle concepts offer similar advantages, they typically suffer from mechanical complexity, difficulty of cooling and ultimately, high weight and cost. The dual bell nozzle offers a unique combination of performance, simplicity, low weight and ease of cooling, and thus warrants continued investigation.

## RECOMMENDATIONS

Follow on testing is planned which will provide more detailed information on the performance and flow transition process for the dual bell nozzle. In addition to this testing, analytical modeling to investigate detailed aspects of the flow field and assist in design optimization is also desirable. While the attached flow case is readily addressed using a variety of currently available codes, modeling of the separated flow case and the flow transition process will likely require significant effort. The experimental data will allow validation of the models developed, so that they may be used as design tools for the dual bell nozzle and other separated, transient nozzle cases of interest.

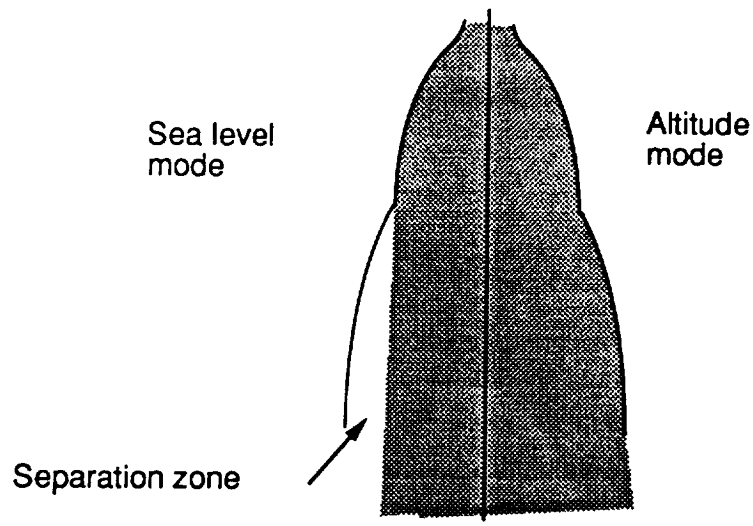



**Figure 1 - Flow separation at the inflection point provides increased sea level thrust**

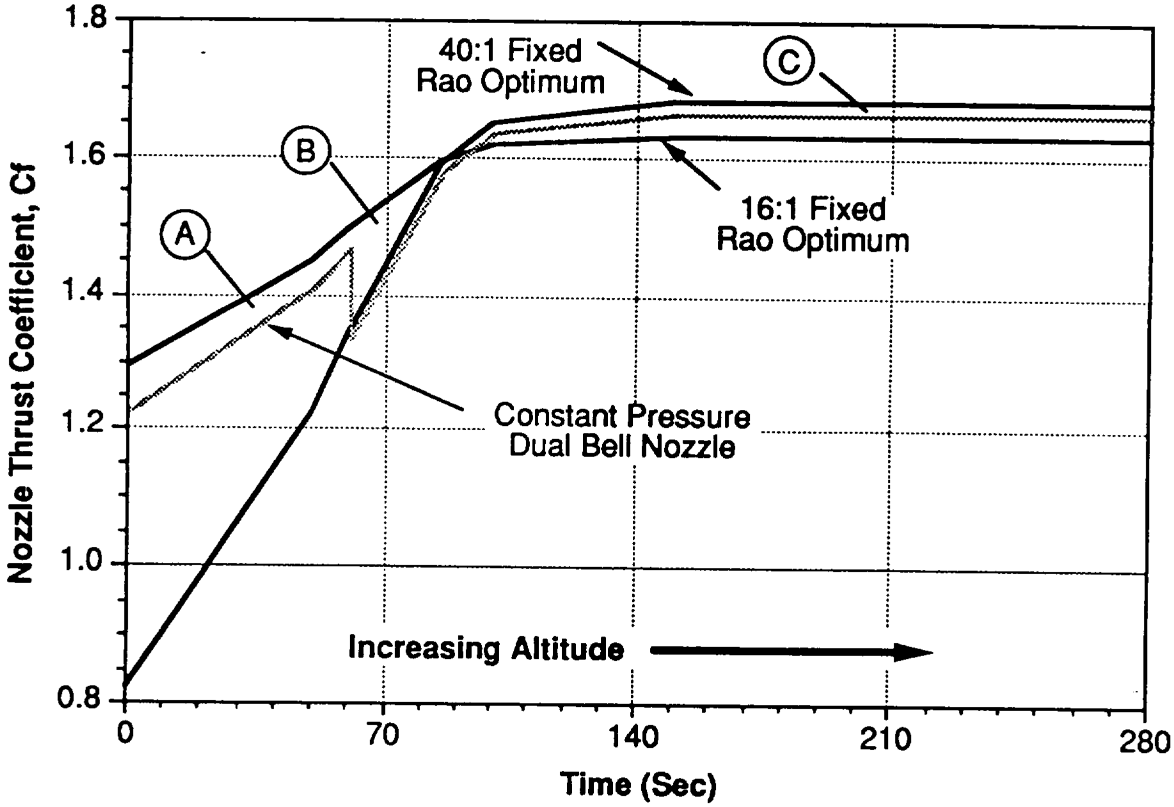



**Figure 2 - Comparison of nozzle thrust coefficient vs time for a typical mission using a dual bell nozzle**

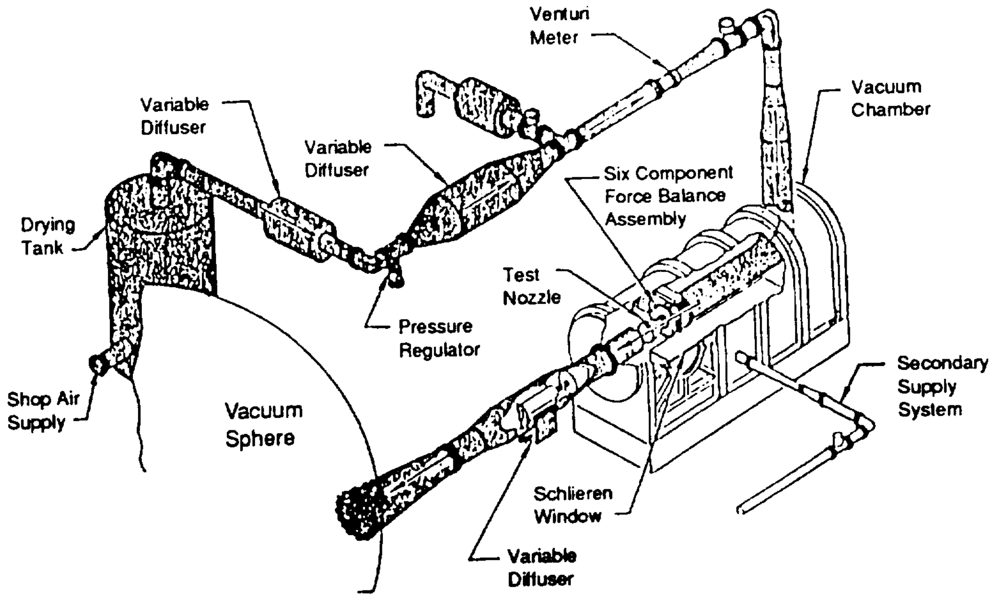



**Figure 3 - Schematic of altitude test facility at NAA**

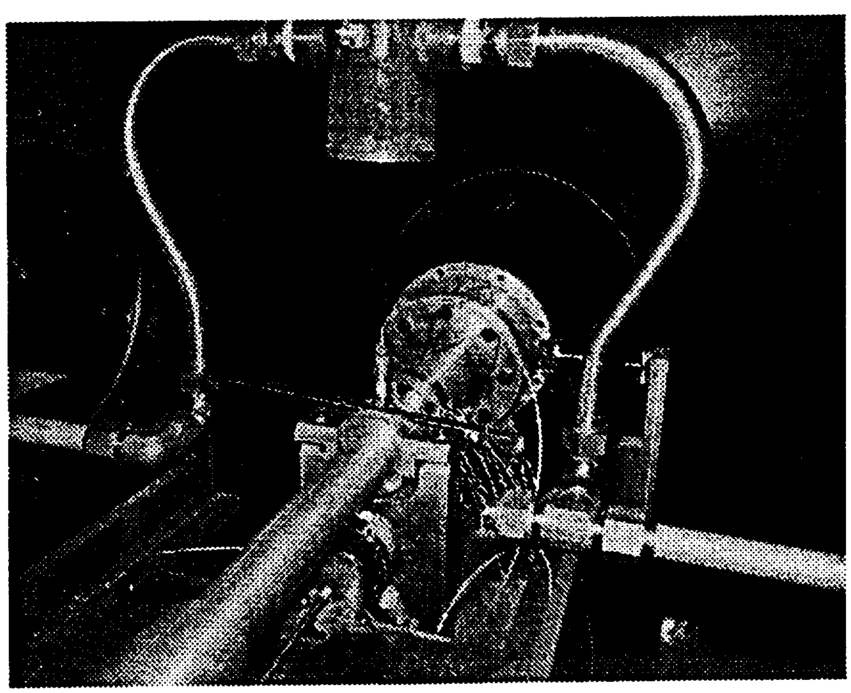


**Figure 4 - Dual bell nozzle test hardware installed in altitude test chamber**

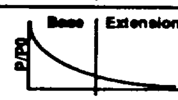
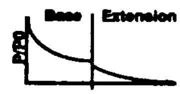
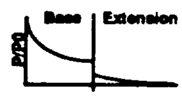
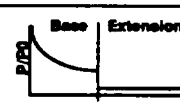
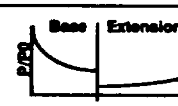
| Configuration | θ Turn | Pressure Profile |
|---|---|---|
| 16:1 Rao Optimum (baseline) | — |   |
| 40:1 Rao Optimum (baseline) | — |   |
| 16:1 Rao Opt Base, 40:1 Conical Extension | 14.5° |   |
| 16:1 Rao Opt Base, 40:1 Rao Opt Extension | 18.5° |   |
| 16:1 Rao Opt Base, 40:1 Constant Press Extension | 22.5° |   |
| 16:1 Rao Opt Base, 40:1 Overturned Extension | 26.5° |   |

**Figure 5 - Dual bell nozzle configurations tested**

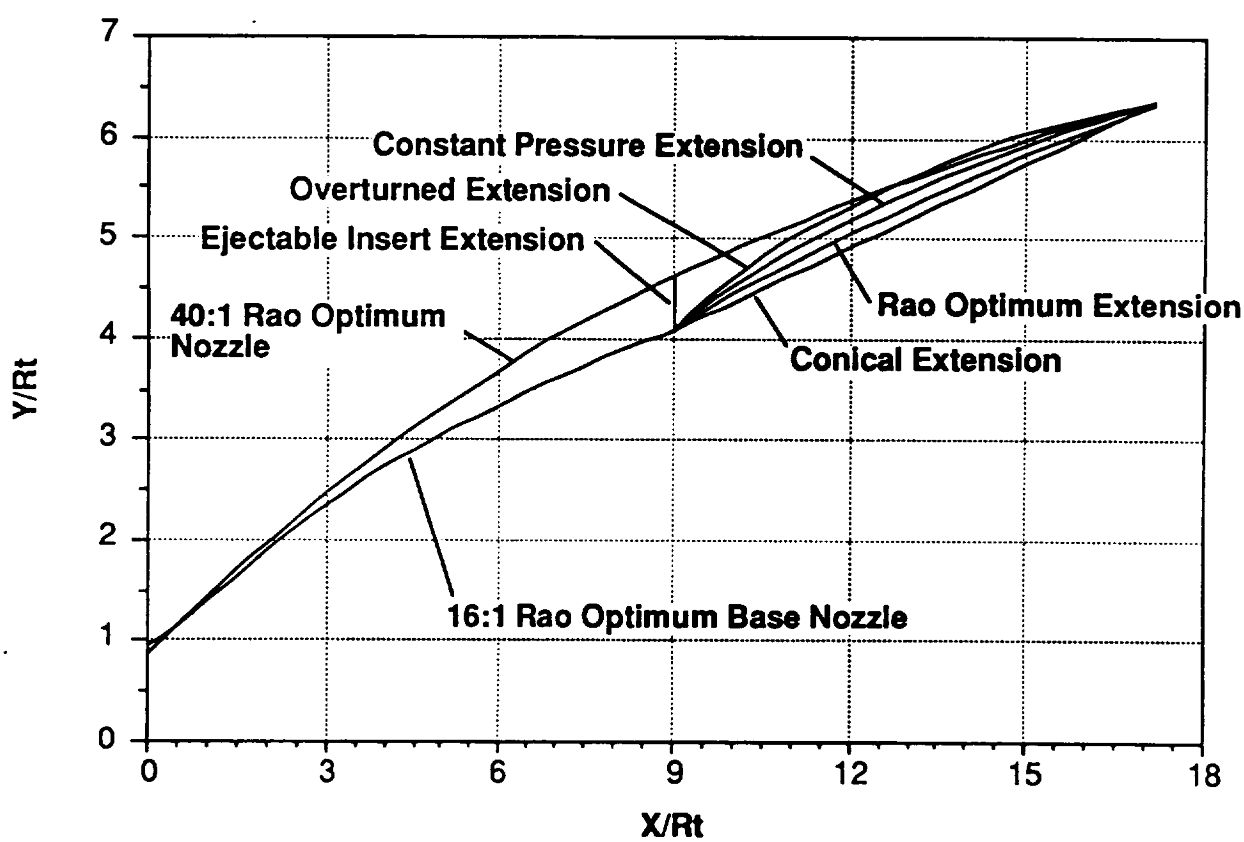



**Figure 6 - Comparison of dual bell nozzle contours**

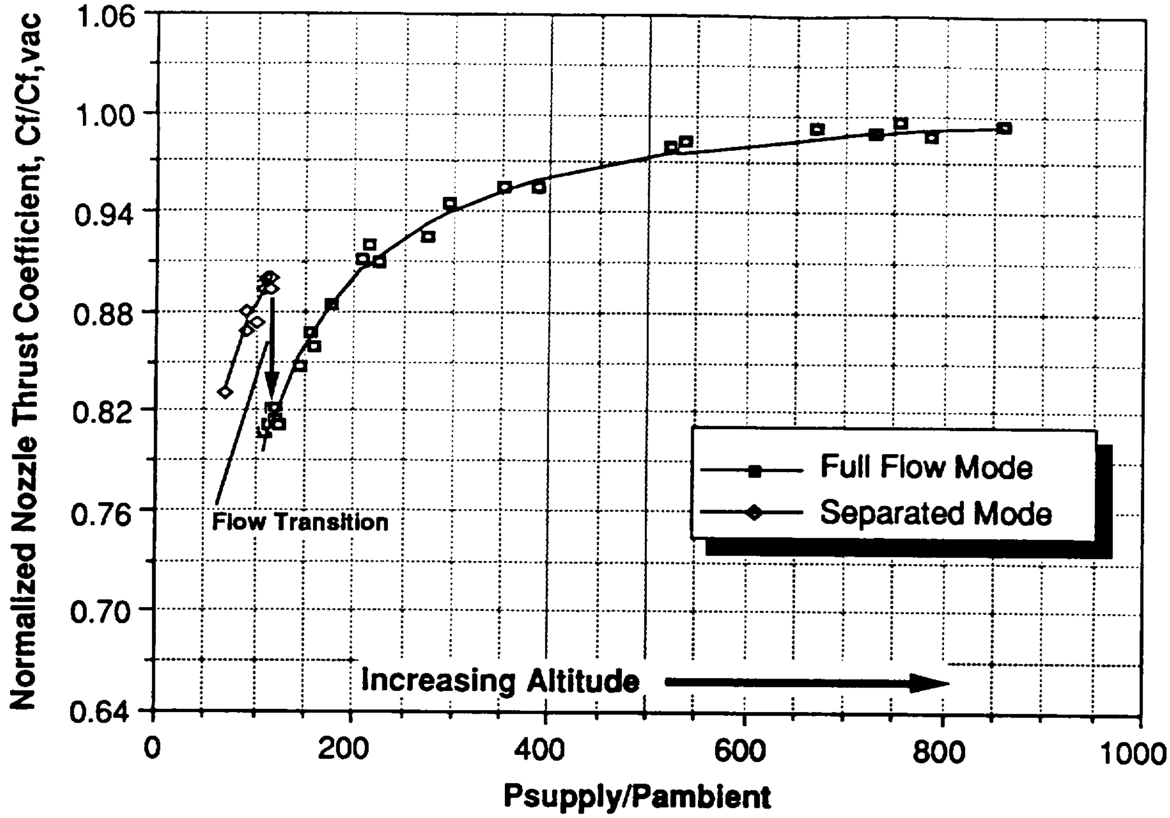



**Figure 7 - Thrust coefficient vs pressure ratio for a constant pressure dual bell nozzle**

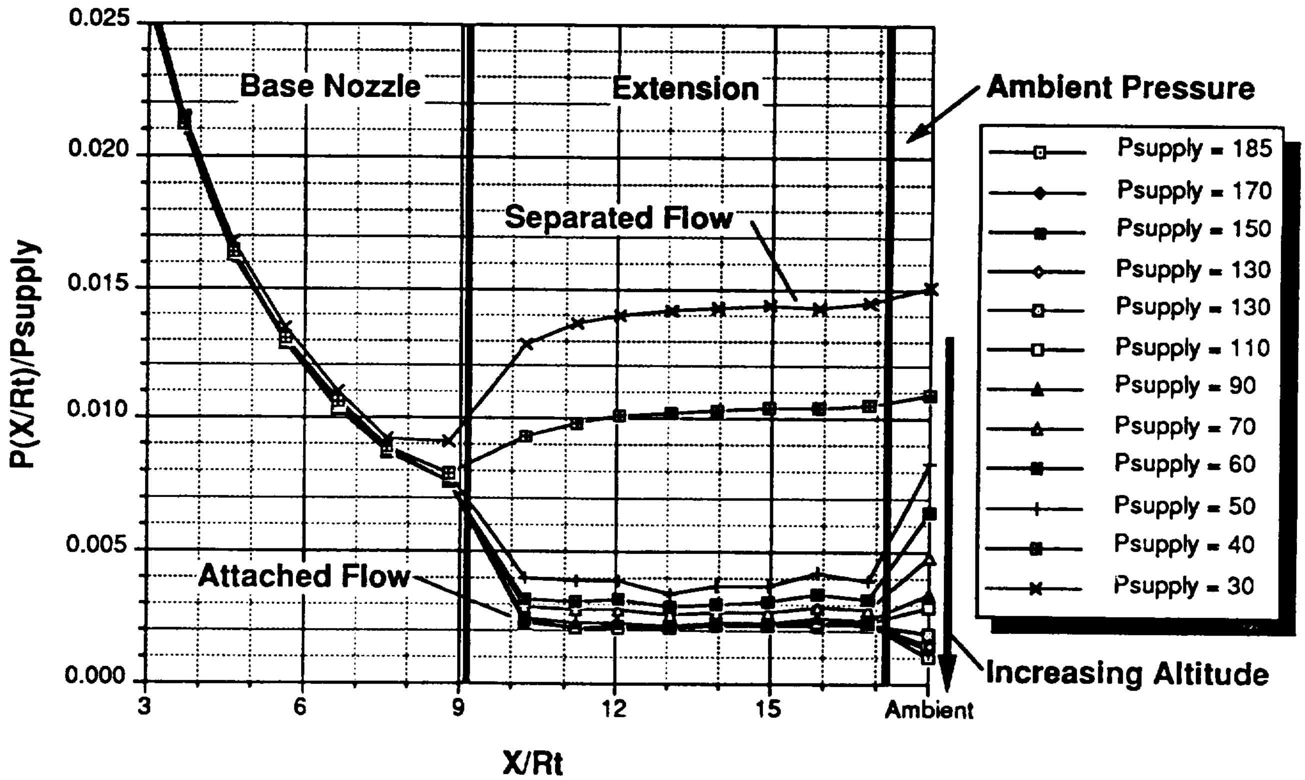



**Figure 8 - Nozzle pressure ratio vs axial distance from throat for constant pressure dual bell nozzle**