OPTIMUM NOZZLE CONTOURS FOR AEROSPIKE NOZZLES USING THE TDK 99^{TM} COMPUTER CODE

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ABSTRACT

The Two-Dimensional Kinetics (**TDK**) Computer Program is a primary tool in applying the JANNAF liquid rocket thrust chamber performance prediction methodology. Over the past decade work has been completed which extends the applicability of TDK to high expansion ratio space engines, scramjet engines, axisymmetric and linear aerospike nozzles, tangential slot injection into the exhaust nozzle and transpiration cooling of the nozzle wall. Among the many recent improvements incorporated in the **TDK 99^{TM}** Computer Program[1], the implementation of the **N**ozzle **C**ontour **O**ptimization (**NCO**) procedure now allows the code to be used as a powerful design tool, as well as an analysis program.

The conventional approach to design a nozzle configuration incorporates a RAO[2] technique, which generates an optimum nozzle contour for an inviscid flow for a perfect gas with a constant isentropic exponent. An alternative method uses an optimum truncated 'perfect' nozzle solution. Both of these methods ignore the effects of kinetics, boundary layer losses, base pressure, and external flow interaction. The recent interest in the linear aerospike engine emphasizes the need to include the preceding effects when optimizing for system performance, since the interaction of the free stream with the inviscid flow and boundary layer tend to dominate the overall performance. In this paper, the **NCO** option of the **TDK 99^{TM}** Computer Program was used to optimize the performance of a linear aerospike configuration, including the effects of kinetics, base pressure, boundary layer flow, and free stream environment.

INTRODUCTION

The **TDK 99^{TM}** computer program is a continuously improved and updated superset of the Two-Dimensional Kinetics (**TDK**) Computer Program[3]. Recent improvements to the code allow the user to generate an optimized nozzle contour, including the effects of kinetics, boundary layer flow (incorporating regenerative cooling, transition, tangential slot injection, transpiration cooling, radiation equilibrium, etc.), base pressure, and external flow interaction. The linear aerospike engine offers advantages over conventional converging-diverging bell shaped nozzles, such as thrust vector control, altitude compensation, throttleability, and reduced weight. But unlike the conventional nozzle, the flowfield of an aerospike nozzle strongly interacts with the external environment, which can significantly alter the performance. Therefore, it is extremely critical to optimize the performance of an aerospike nozzle including the above effects.

Optimization techniques used to design rocket nozzle contours have been utilized since 1955, as discussed by Guderley and Hantsch[4]. Rao[2] simplified the analysis with a design technique that is widely used today. Humphreys, Thompson, and Hoffman[5] recognized the need to include the boundary layer loss and base pressure, but their analysis did not include the full interaction with the free stream flow or kinetic losses. The **TDK 99^{TM}** computer program includes kinetics, base pressure, boundary layer losses, and free stream interaction. The optimization procedure employed allows the search to span a specified search grid or seek a solution based on a direct search algorithm, or a combination of both. Until recently, the direct search optimization technique would have been prohibitively expensive. But the increased performance and reduced cost of modern computers allows this procedure to be very attractive. The optimization parameters include attachment angle, exit lip angle, length, and radius. For the following study and for demonstration purposes, the optimization procedure was applied for a fixed exit point and power head.

PROCEDURE

The **NCO** option of the **TDK 99^{TM}** computer program was used to design an optimum performing linear aerospike exhaust nozzle at three representative flight conditions for a fixed power head and exit lip point. Although **TDK 99^{TM}** incorporates several analytic functions to characterize the nozzle wall geometry, the skewed parabola was used for this optimization study because it is the most general, and can degenerate to most of the other options. The analysis considered the effects of kinetics, boundary layer loss, free stream interaction, and base pressure. Each design configuration was subsequently analyzed at the off-design flight conditions. The design analysis consisted of two parts: first the grid search option was employed to investigate the general characteristics of the nozzle performance, and the second analysis used the results of the grid search as a starting point for the direct search optimization. Although the direct search algorithm could have performed the entire optimization in one step, the grid search option allows the user to look at the bigger picture, and start the direct search optimization near a solution. Quite often, physical constraints must be also factored into the search regime, and this two step procedure allows better implementation of these constraints. The appealing aspect of this approach is that the user does not have to anticipate the complicated interaction of the kinetics, boundary layer, inviscid core, free stream, and base pressure. Upon detailed evaluation of the final solution, it usually becomes apparent how the interactions behave.

RESULTS

The design analysis at sea level conditions is unique to all regimes because the free stream air is quiescent. Therefore, the interaction between the inviscid core flow and the external environment does not involve turning the free stream flow. Relatively large steps were taken in the grid search procedure, which indicated that the solution regime was relatively flat. The subsequent direct search optimization procedure quickly converged, as shown in Table 1. It should be noted that rapid convergence was due to a reasonable first guess provided by the grid search results. Examination of the characteristic mesh associated with the converged solution indicates an extremely complicated flow pattern, as shown in Figure 1

Table 1. Results of Direct Search Optimization Procedure at Sea Level Conditions

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ATTACH     EXIT    AXIS      EXIT    NOZZLE  ISP(TDK)  DISP(BL)  BASE   ISP(NET)
 ANGLE    ANGLE   ANGLE    RADIUS    LENGTH    SEC       SEC      SEC     SEC

30.000    6.482    0.00   -1.0000   50.0000   447.240   6.767 -59.344   381.129
30.500    6.454    0.00   -1.0000   50.0000   447.035   6.737 -59.239   381.059
29.500    6.506    0.00   -1.0000   50.0000   447.711   6.618 -59.584   381.509
29.500    6.665    0.50   -1.0000   50.0000   447.888   6.631 -59.674   381.583
29.500    6.826    1.00   -1.0000   50.0000   448.271   6.784 -59.869   381.618
29.500    6.729    0.70   -1.0000   50.0000   448.100   6.625 -59.782   381.693
29.000    6.754    0.70   -1.0000   50.0000   448.344   6.629 -59.907   381.808
28.500    6.779    0.70   -1.0000   50.0000   448.607   6.797 -60.041   381.769
29.377    6.735    0.70   -1.0000   50.0000   448.162   6.735 -59.814   381.613
29.000    6.914    1.20   -1.0000   50.0000   448.640   6.789 -60.058   381.794
29.000    6.596    0.20   -1.0000   50.0000   448.056   6.781 -59.760   381.515
29.000    6.826    0.93   -1.0000   50.0000   448.447   6.779 -59.959   381.709
28.500    6.779    0.70   -1.0000   50.0000   448.607   6.797 -60.041   381.769
29.500    6.729    0.70   -1.0000   50.0000   448.100   6.625 -59.782   381.693
28.877    6.760    0.70   -1.0000   50.0000   448.383   6.644 -59.927   381.813
28.877    6.920    1.20   -1.0000   50.0000   448.686   6.637 -60.081   381.968
28.877    7.084    1.70   -1.0000   50.0000   448.988   6.644 -60.235   382.109
28.877    7.421    2.70   -1.0000   50.0000   449.490   6.798 -60.491   382.201
28.377    7.439    2.70   -1.0000   50.0000   449.655   6.771 -60.575   382.308
27.877    7.458    2.70   -1.0000   50.0000   449.853   6.838 -60.676   382.338
28.431    7.437    2.70   -1.0000   50.0000   449.660   6.844 -60.578   382.238
27.877    7.628    3.20   -1.0000   50.0000   450.012   6.869 -60.757   382.386
27.877    7.802    3.70   -1.0000   50.0000   450.201   6.884 -60.854   382.463
27.377    7.818    3.70   -1.0000   50.0000   450.344   6.889 -60.927   382.529
26.877    7.835    3.70   -1.0000   50.0000   450.590   6.629 -61.001   382.960
26.877    8.009    4.20   -1.0000   50.0000   450.528   6.855 -61.021   382.653
26.877    7.665    3.20   -1.0000   50.0000   450.330   6.635 -60.920   382.775
26.877    7.799    3.59   -1.0000   50.0000   450.425   6.884 -60.968   382.573
26.377    7.852    3.70   -1.0000   50.0000   450.610   6.828 -61.063   382.719
27.377    7.818    3.70   -1.0000   50.0000   450.344   6.884 -60.927   382.534
26.778    7.838    3.70   -1.0000   50.0000   450.498   6.866 -61.005   382.626
26.877    8.009    4.20   -1.0000   50.0000   450.528   6.855 -61.021   382.653
26.877    7.665    3.20   -1.0000   50.0000   450.330   6.635 -60.920   382.775
26.877    7.799    3.59   -1.0000   50.0000   450.425   6.884 -60.968   382.573

26.877    7.835    3.70   -1.0000   50.0000   450.590   6.629 -61.001   382.960
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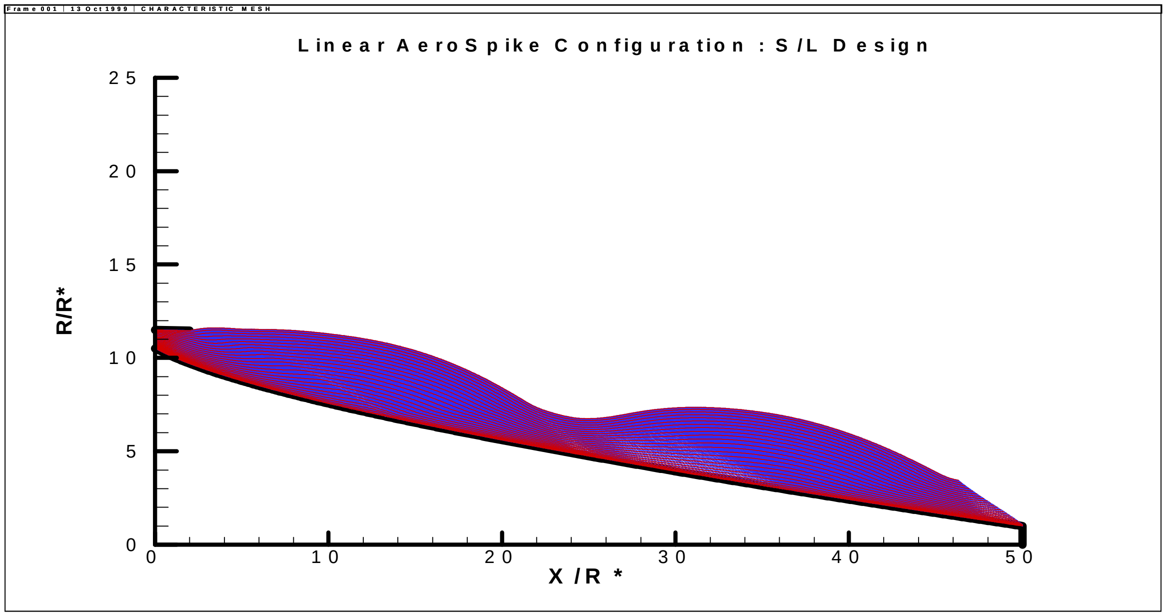

Figure 1. Characteristic Mesh for Sea Level Design

The interaction between the quiescent air and the inviscid core flow indicates a strong compression or shock wave, followed by an expansion, another compression, etc. The corresponding boundary layer analysis shows a significant increase in heating rate and shear stress due to the compression waves. Although the inviscid performance is enhanced by the compression waves, the boundary layer loss is significantly increased. The total performance is the result of a delicate balance of all the components that contribute to the engine thrust. It is not the purpose of this analysis to explain the significance of this complicated flow field, but rather apply these results in a comprehensive procedure to optimize total system performance. The sea level configuration was subsequently analyzed at the 50,000 feet and 100,000 feet flight conditions. The resulting characteristic mesh, shown in figures 2 and 3, show a significantly different flow field than the design point. Although the free stream Mach number is increasing with altitude, the pressure is dramatically decreasing, resulting in an expanded flow field.

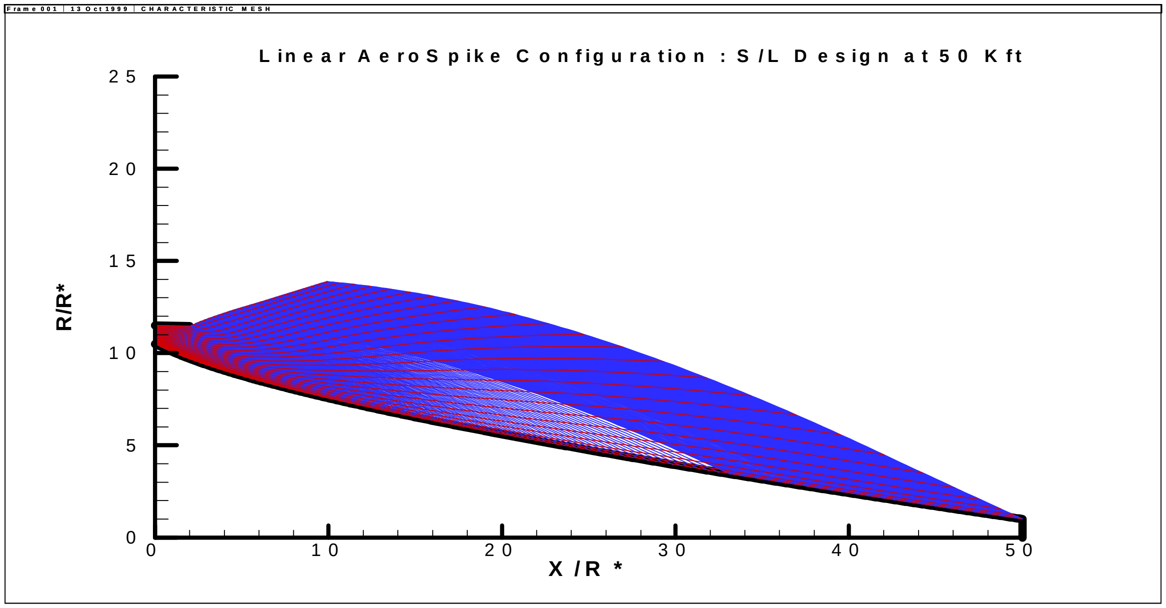

Figure 2. Characteristic Mesh for Sea Level Design at 50,000 Feet

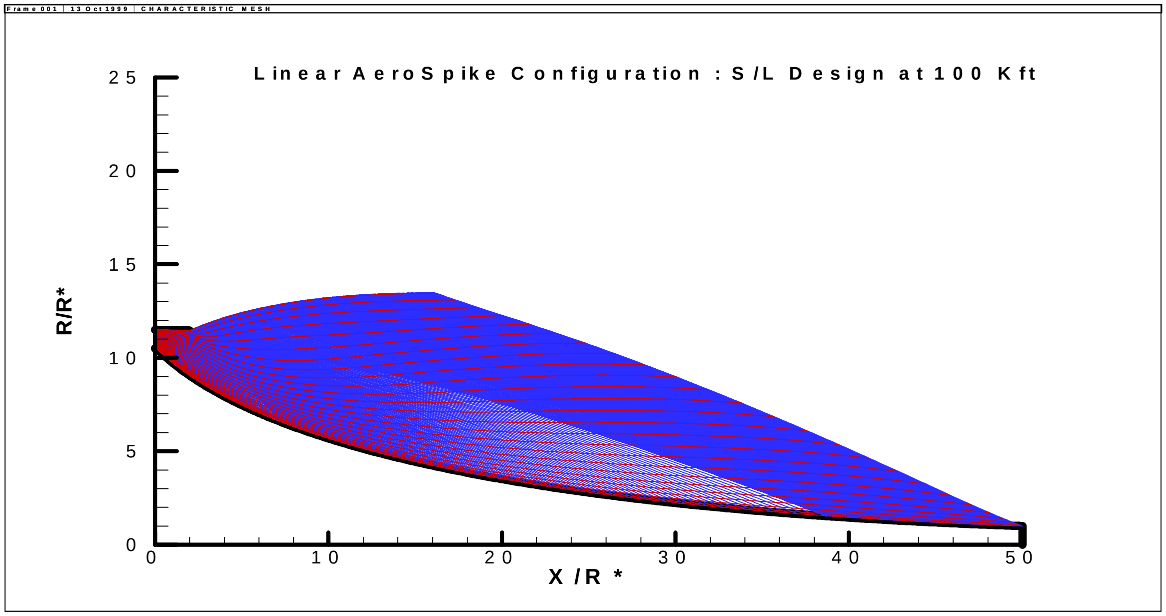

Figure 3. Characteristic Mesh for Sea Level Design at 100,000 Feet

The grid search option and the direct search optimization procedures were repeated for the 50,000 feet flight condition. The characteristic mesh associated with this design point is shown in Figure 4. The resulting configuration was subsequently analyzed at sea level and 100,000 feet. The corresponding characteristic mesh plots are shown in Figures 5 and 6. It should be noted that the characteristic mesh profiles indicates that the flow field is highly dependent on both the flight conditions and nozzle wall geometry. Therefore, the off-design performance can be significantly effected by seemingly minor geometry changes

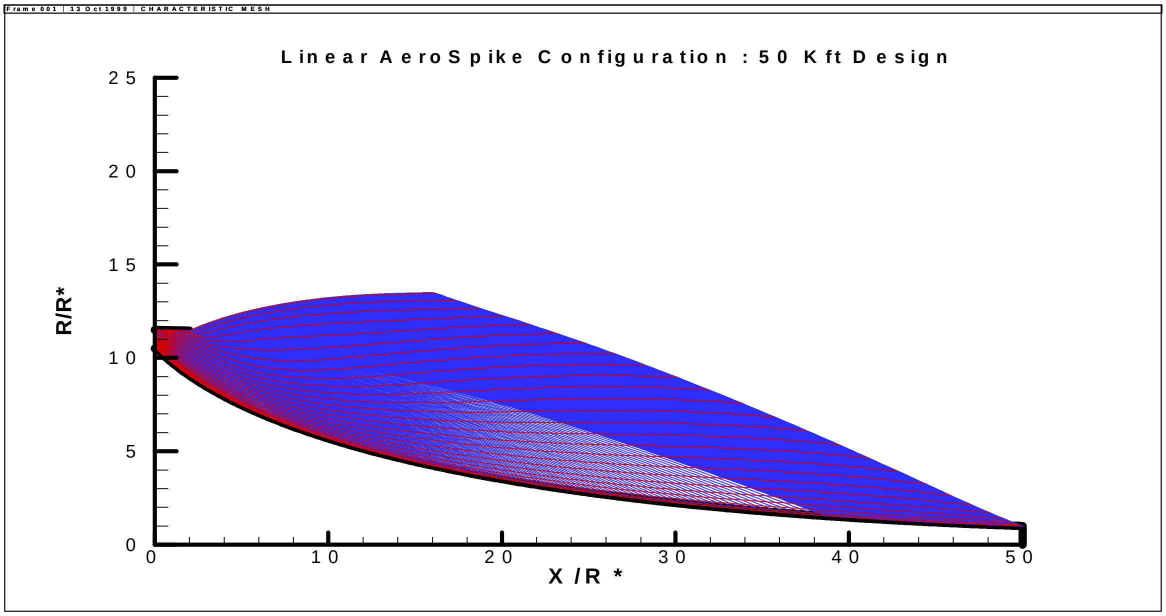

Figure 4. Characteristic Mesh for 50,000 Feet Design

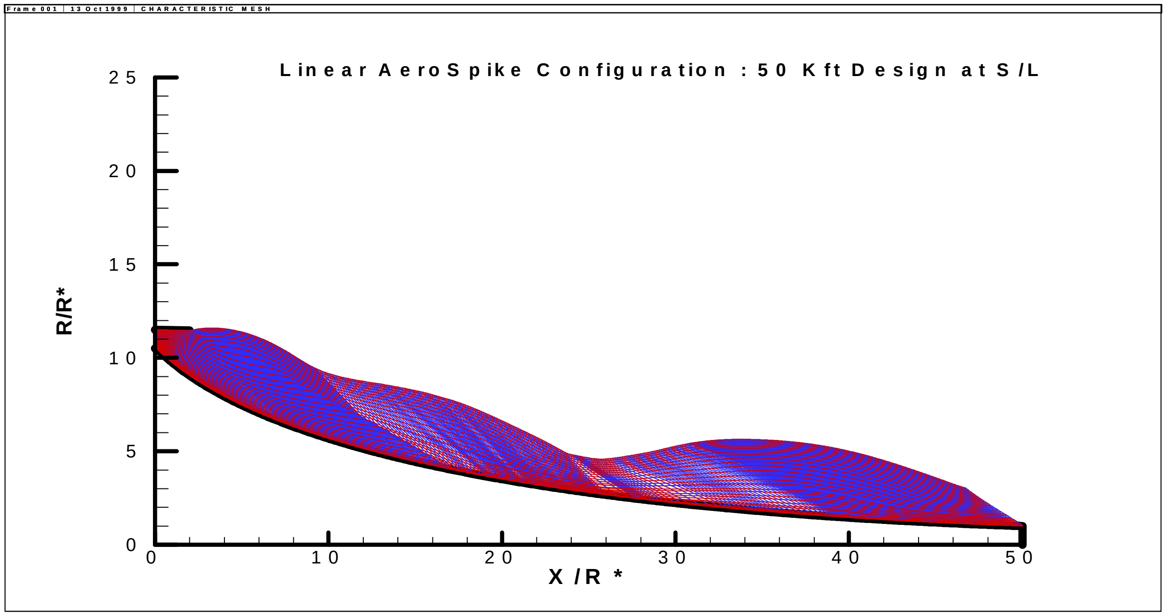

Figure 5. Characteristic Mesh for 50,000 Feet Design at Sea Level

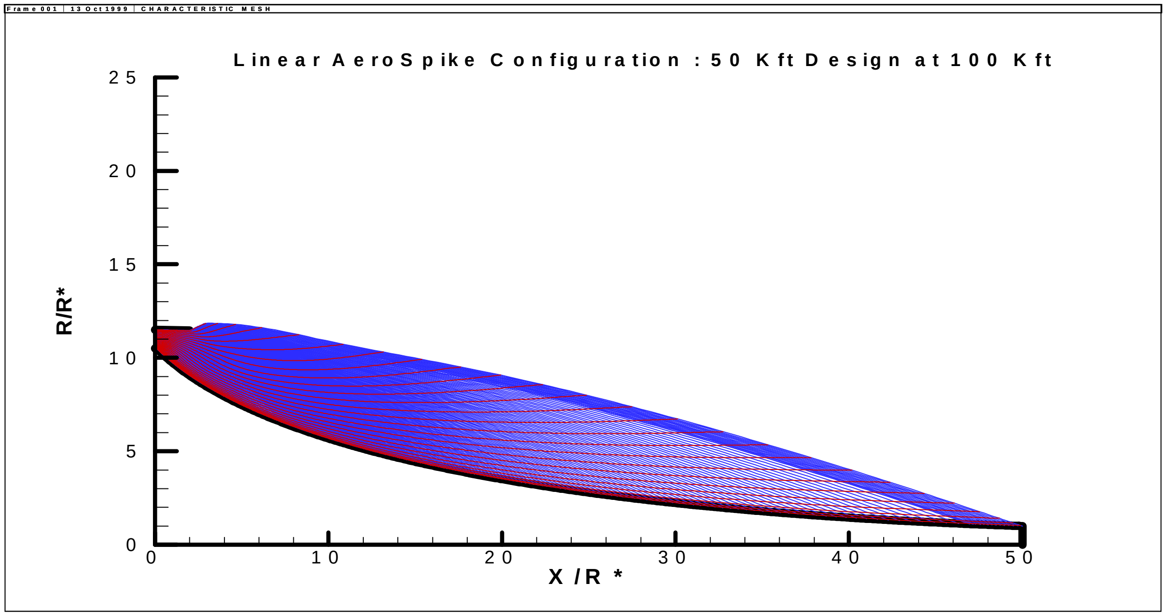

Figure 6. Characteristic Mesh for 50,000 Feet Design at 100,000 Feet

The above design procedure was applied to the 100,000 feet design condition, followed by a subsequent analysis at sea level and 50,000 feet. The resulting characteristic mesh plots are shown in Figures 7 through 9. Although the flow fields may look quite similar at first, each geometry and flight condition displays different characteristics.

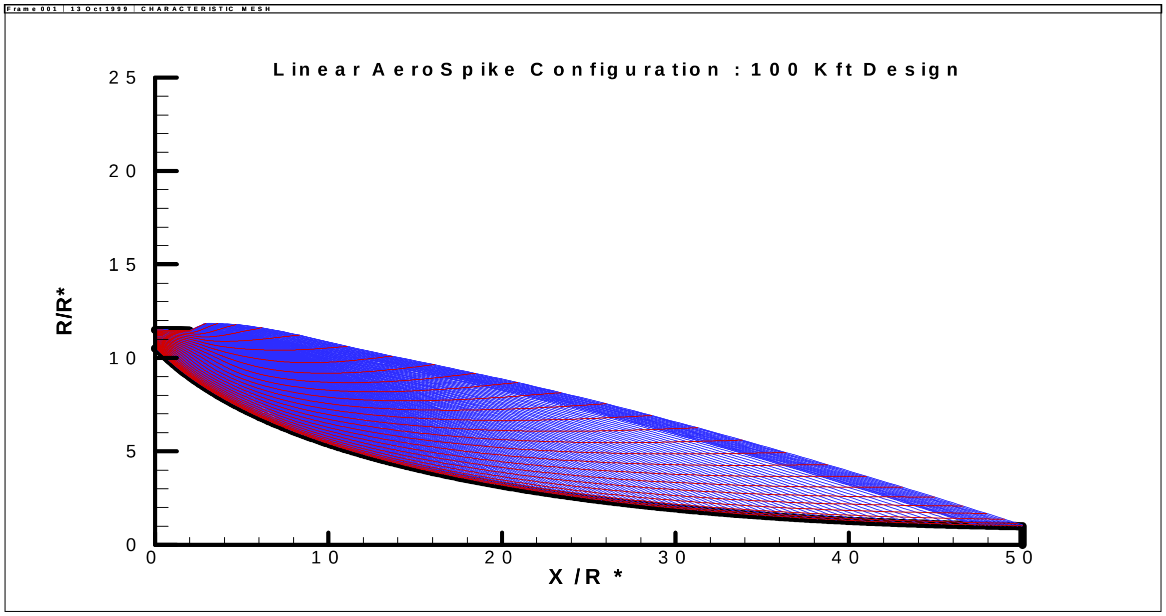

Figure 7. Characteristic Mesh for 100,000 Feet Design

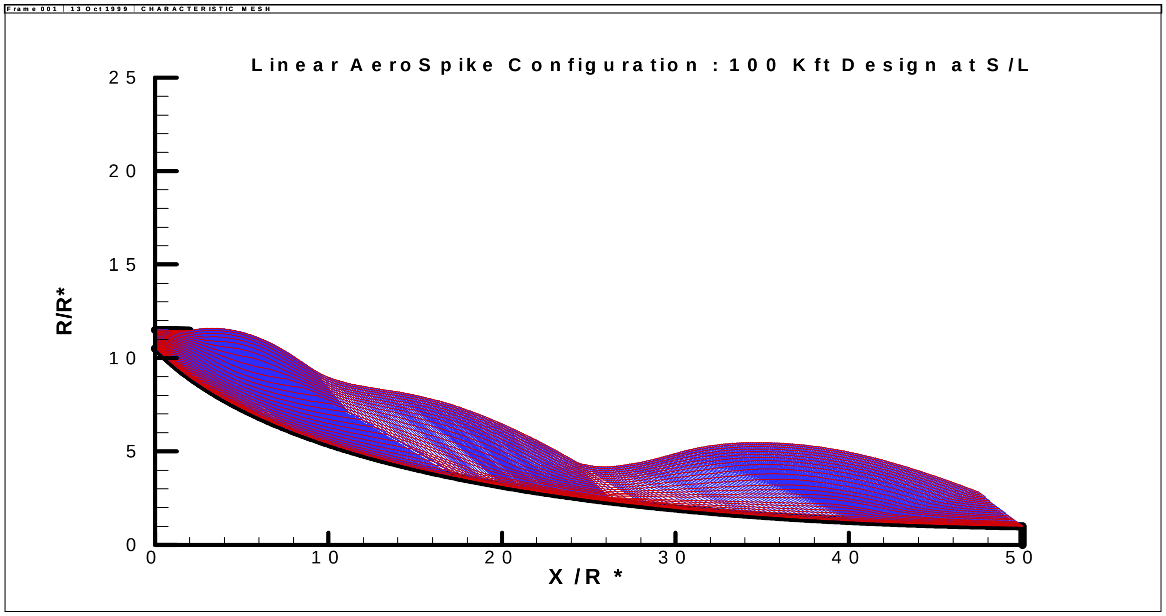

Figure 8. Characteristic Mesh for 100,000 Feet Design at Sea Level

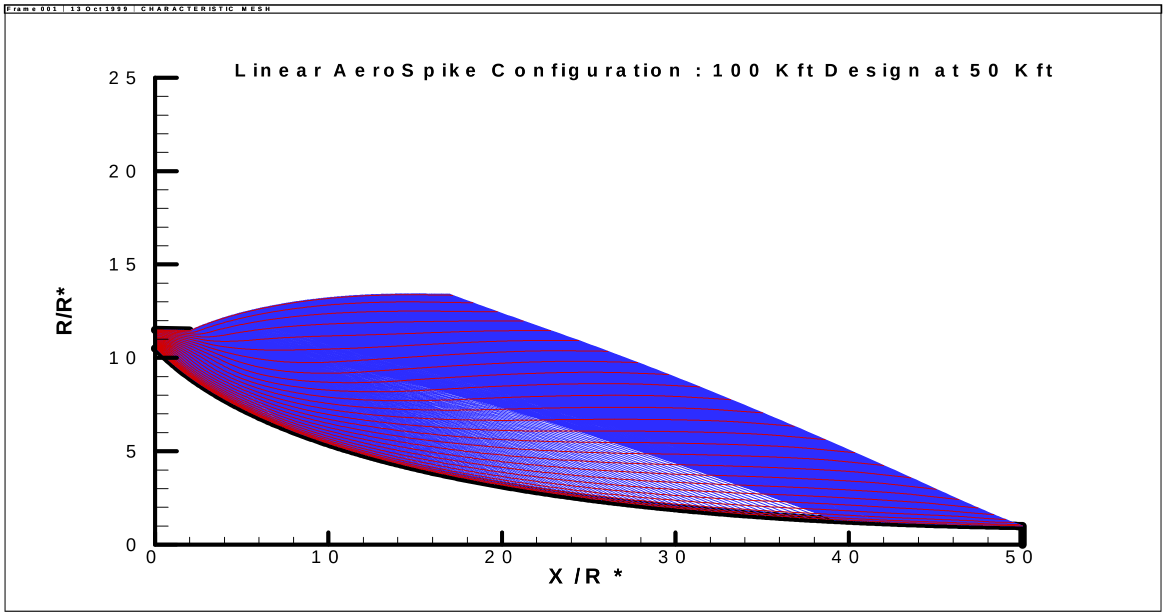

Figure 9. Characteristic Mesh for 100,000 Feet Design at 50,000 Feet

The geometry parameters for a skewed parabola resulting from this **NCO** study are shown in Table 2. The corresponding wall profiles are shown in Figure 10. The resulting specific impulse performance values are summarized in Table 3. As a point of comparison, the above designs are compared to Isp predictions for the Space Shuttle Main Engine (SSME) in Table 4.

Table 2. **NCO** Skewed Parabola Geometry Parameters

Design Point	Attachment Angle (Degrees)	Lip Angle (Degrees)	Parabola Skew Angle (Degrees)
S/L	26.877	7.835	+3.70
50 Kft	42.233	1.851	-11.99
100 Kft	43.215	0.802	-15.01

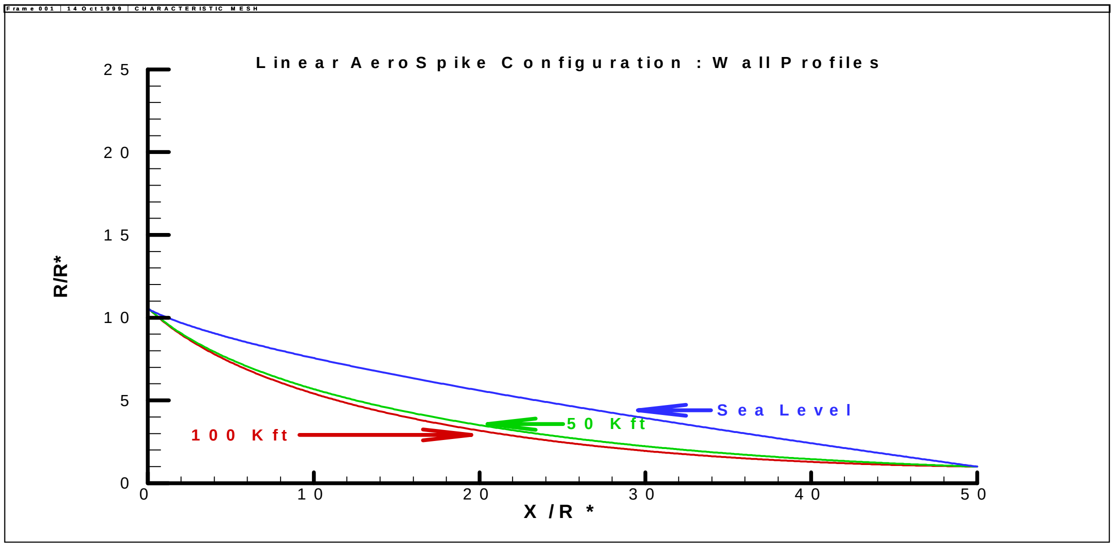

Figure 10. **NCO** Linear Aerospike Wall Profiles

Table 3. NCO Performance Summary

Design Point	**Operation Point**	**Isp(TDK) (Sec)**	**ΔIsp (B/L) (Sec)**	**ΔIsp (Base) (Sec)**	**Isp (Net) (Sec)**
S/L	S/L	450.49	-6.53	-61.00	382.96
S/L	50 Kft	351.70	-3.53	+10.96	359.13
S/L	100 Kft	351.00	-3.24	+27.07	374.83
50 Kft	S/L	421.63	-6.51	-46.29	368.83
50 Kft	50 Kft	367.69	-3.83	+2.80	366.66
50 Kft	100 Kft	367.42	-3.67	+18.70	382.45
100 Kft	S/L	415.39	-6.30	-43.10	365.99
100 Kft	50 Kft	368.47	-3.88	+2.41	367.00
100 Kft	100 Kft	368.81	-3.74	+18.25	383.32

Table 4. Comparison of Optimal Linear Aerospike Designs to the SSME

Design Point	**Isp(Sec) S/L Design**	**Isp (Sec) 50 K ft Design**	**Isp (Sec) 100 K ft Design**	**Isp (Sec) SSME**
S/L	**382.96**	368.83	365.99	374.44
50 K ft	359.13	**366.66**	367.00	448.46
100 K ft	374.83	382.45	**383.32**	457.13

CONCLUSIONS

It has been demonstrated that the **TDK 99™** Computer Program can be used to optimize a exit nozzle contour including the effects of kinetics, boundary layer, base pressure, and external flow interaction. Although the linear aerospike configuration inherently has altitude compensating features, it is apparent from this study that this may be a two edged sword. A complete system design must optimize the configuration based on a given flight trajectory. An optimal design will be a compromise geometry, which deliveries the maximum impulse over the entire flight. Any diversion from the flight trajectory may severely degrade the overall delivered impulse. This restriction may severely limit the utility of a flight system.

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