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High Altitude Towed Glider

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Symbols

A_t	Tow Line Projected Area
c	Distance above $y=0$ where a Theoretical Catenary Curve will be Horizontal
C_d	Tow Line Drag Coefficient
C_f	Tow Line Coefficient of Friction
D	Drag Force
D_g	Glider Drag
d	Tow Line Diameter
FoS	Factor of Safety
Δh	Vertical Separation Distance Between the Glider and Tow Aircraft
L/D	Lift to Drag Ratio
T	Tension in the Tow Line
T_{max}	Maximum Tow Line Tension
T_0	Tension in the Tow Line at the Location $y=c$
s	Tow Line Length
Δs	Incremental Tow Line Length
W_g	Glider Weigh
W_p	Payload Weight
W_t	Weight of the Tow Line
V	Velocity
y	Vertical Coordinate Distance
ϕ	Angle Between the Horizontal and the Local Normal Vector to the Tow Line
ρ	Atmospheric Density
ρ_t	Tow Line Material Density
σ_u	Ultimate Strength of the Tow Line
θ	Tow Line Angle with Respect to the Horizontal at the Glider Location
ω	Distributed Load on the Tow Line

Introduction

The desire to sample the atmosphere at altitudes of 24 km or higher from a subsonic instrument platform has been expressed by the atmospheric science community. The ability to do this would allow for better understanding of the upper atmosphere in order to determine if any environmental damage has been or is being done. The upper atmosphere is of prime interest to atmospheric scientists due to the large amount of active chemistry that takes place in this region. The most widely known aspect of this is the ozone layer whose recent thinning due to interaction with chlorofluorocarbons is the cause of great environmental concern.

The main obstacle to producing an aircraft that can fly subsonically above 24 km has been the

powerplant. The ability to supply enough thrust to keep the aircraft at these altitudes for a reasonable amount of time (on the order of 4 hours) has proven to be a fairly difficult task. There are a number of approaches that have been proposed to accomplish this. They range from multiple stage turbocharged engines to semi-closed cycle engines to rocket driven turbines. Each of these methods and the many others that have been suggested have their strong points as well as weaknesses. However, regardless of which method is considered, the main obstacles are always the same - trying to extract oxygen from and / or reject heat to an extremely rarefied atmosphere. The atmospheric density at 80,000 ft is 1/25th that at sea level.

One possible method of avoiding these problems is to use a glider and a tow aircraft. The tow aircraft would remain at a lower altitude, around 20 km, while the glider would ascend to the desired altitude. The glider and tow aircraft would be connected by a tow line. This scheme allows for the operation of the tow aircraft power plant in a much denser atmosphere while enabling the sensors and sampling equipment to attain the desired altitude. Although this concept eliminates the problems with operating a power plant at very high altitudes it brings in a host of new issues and concerns which must be addressed in order to determine if this concept is a valid alternative to a powered high altitude aircraft. The obvious concern with the tow aircraft / glider approach is the characteristics and operation of the tow line between them. This paper examines how the properties of the tow line, such as material strength and density, drag, and glider / tow plane separation distance, affect the feasibility of this concept.

Analysis

There are three main areas of interest in the analysis of this concept. They are the glider aircraft, the tow line, and the tow aircraft. For the present analysis the main concern is the operation and design of the tow line. The major forces that govern its shape and design are the drag and gravitational forces. The actual loading on the tow line would be the vector sum of these forces. The following diagram shows the glider / tow aircraft arrangement and forces on the tow line.

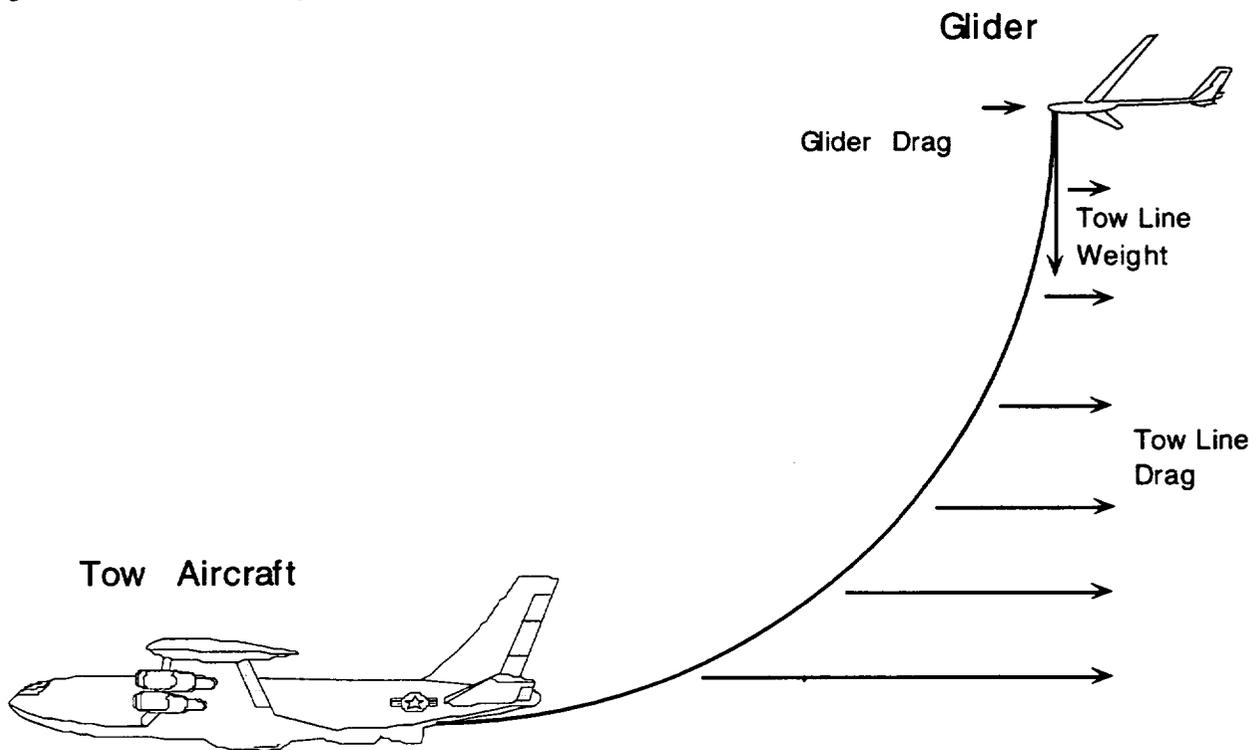


Figure 1 Tow Aircraft / Glider Configuration

For this initial analysis it is assumed that the tow line will take the shape of a catenary curve. This is not completely accurate because the shape of a catenary would ideally result when a uniformly distributed load is placed on the tow line. In this case however, the load is not uniformly distributed because the drag load decreases with altitude. Therefore, the actual tow line shape would not be a true catenary. Using the assumption of a catenary shape however, allows for the fairly easy calculation of the tow line length which in turn is used to calculate a reasonable estimate of the lifting load placed on the glider by the weight of the tow line.

The initial information and assumptions made in the analysis are as follows;

1. Glider / Tow Aircraft Vertical Separation Distance (Δh)
2. Glider Aircraft Lift / Drag (L/D)
3. Tow Line Drag Coefficient (C_d)
4. Tow Line Friction Coefficient (C_f)
5. Tow Line Factor of Safety (FoS)
6. Tow Line Material Characteristics (ρ_t, σ_U)

With this initial information the tow line length and weight can be calculated as follows. The angle the tow line end makes with the horizontal at the glider (θ) is first arbitrarily chosen. With this angle the catenary curve constant, c , can be calculated (equation 1). This constant is then used in determining the tow line length and weight (equations 2 and 3 respectively).

$$c = \Delta h \cos(\theta) / (1 - \cos(\theta)) \quad (1)$$

$$s = (\Delta h^2 + 2 \Delta h c)^{0.5} \quad (2)$$

$$w_t = \pi (d/2)^2 s \rho_t 9.81 \quad (3)$$

For the calculation of the tow line weight, an initial thickness for the tow line is chosen. With the initial tow line thickness and the known spacing between the aircraft, the drag force on the tow line can be calculated. The drag is comprised of two components, the form drag which is based on the locally normal component of velocity and frontal area and the frictional drag which is based on the parallel component of velocity and the wetted area¹. The drag is expressed in the following equation.

$$\Sigma D_i = 0.5 V^2 \Delta s d (\Sigma \sin^2(\phi_i) \rho_i C_{di} + C_f \pi \Sigma \cos^2(\phi_i) \rho_i) \quad (4)$$

The atmospheric density (ρ) varies significantly from the tow aircraft to the glider. Therefore the drag on the tow line must be done incrementally as a function of vertical distance between the two aircraft. The drag coefficient of the tow line is also a function of Reynolds number. This relationship can be found from empirical data for an infinite cylinder and is given in reference 2.

Using the given thickness of the tow line and its ultimate strength, the allowable load the tow line can carry can be calculated. This value is then checked against the tension due to the drag force on the glider and tow line and the gravitational force on the tow line. Since the drag force act in a horizontal direction and is a maximum at the tow aircraft while the gravitational force acts in a vertical direction and is a maximum at the glider, these forces are checked independently against the maximum allowable tension in the tow line. If the tow line tension caused by either the drag or gravitational force exceeds the tension allowable in the tow line, the thickness of the tow line must be increased. This thickness is increased incrementally until the maximum allowable tension exceeds that produced by the forces on the tow line. The drag force and weight of the tow line have to be recalculated with each iteration.

$$T_{\max} = (\sigma_U \pi (d/2)^2) / \text{FoS} \quad (5)$$

The glider drag can be estimated from the glider, payload and tow line weights and the assumed lift / drag ratio of the glider. This is given by the following equation.

$$D_g = (w_p + w_g + w_t) / L/D \quad (6)$$

With the glider drag and the tow line weight now known, the end angle of the tow line at the glider is calculated from the vector sum of these two forces. This angle is then compared to the initial end angle assumed at the beginning of the analysis. If they are different, a new end angle is used and the calculations are repeated until there is no change in this angle between the initial and final values. A flow chart describing the calculations is given below.

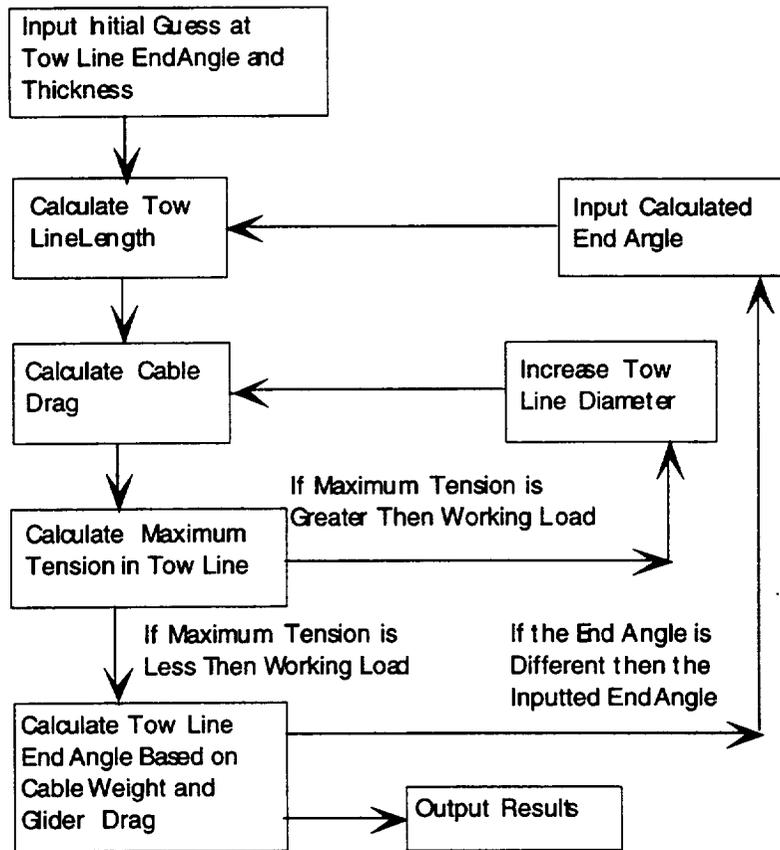


Figure 2 Analysis Logical Flow Chart

Results

The assumptions used in the analysis are as follows. The results include variations on some of these assumptions in order to demonstrate how they effect the drag and weight of the tow line.

Glider Weight	194 kg (428 lb)
Payload Weight	227 kg (500 lb)

Glider L/D	26
Glider Mach Number	0.4 (approximately 119 m/s or 390 ft/sec)
Tow Line Factor of Safety	2
Tow Line Material:	Carbon VHS Composite
	Density 1530 kg / m ³ (95 lb / ft ³)
	Ultimate Strength 1.9 GPa (275 ksi)

The assumed tow line drag coefficient can significantly effect the results. If one assumes the tow line can be approximated by an infinite cylinder then the drag coefficient can be determined from experimental data based on Reynolds number. Since the Reynolds number is a function of the atmospheric density and viscosity it will vary with altitude. To determine what effect this variation will have on the drag coefficient, data was generated on Reynolds number versus altitude for various glider / tow aircraft separation distances. The procedure to determine the operational Reynolds number for each separation distance was an iterative one. This is because as the separation distance increases the required diameter of the tow line necessary to withstand the drag force increases. This in turn effects the Reynolds number thereby effecting the selected drag coefficient. The following graph shows the Reynolds number for various separation distances and the required tow line diameter. By comparing the range of Reynolds numbers in this graph (1100 to 4700) to the empirical data of Reynolds number versus drag coefficient for an infinite cylinder, it was determined that the drag coefficient for the tow line would be approximately 1.0 throughout the complete Reynolds number range. So the results presented are based on a C_D of 1.0. The coefficient of friction of the tow line was estimated to be 0.001.

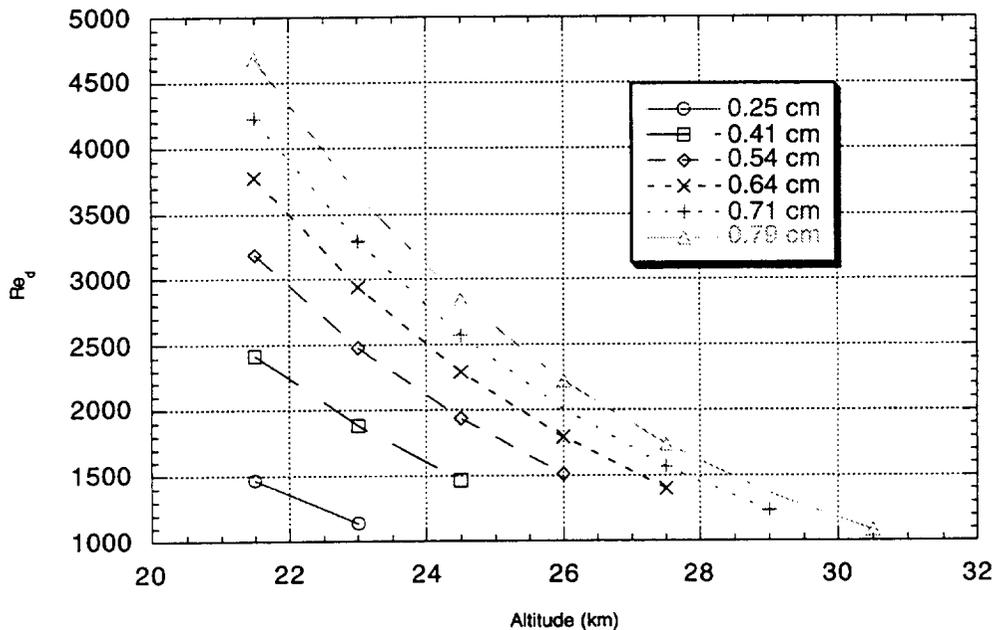


Figure 3 Reynolds Number Versus Altitude for Various Diameter Constant Thickness Tow Lines

These results are summarized in the following table for a tow aircraft altitude of 20 km. Comparisons were also made with different tow aircraft altitudes and are shown in figures 4 and 5.

Glider Altitude km (ft)	23 (75,460)	24 (78,740)	25 (82,020)	26 (85,300)	27 (88,580)	28 (91,860)	29 (95,140)	30 (98,430)
Tow Line Weight kg (lb)	16 (35)	31 (68)	52 (114)	78 (172)	110 (242)	145 (319)	184 (405)	224 (493)
Tow Line Drag N (lb)	939 (211)	2255 (507)	4082 (918)	5859 (1317)	7469 (1679)	9068 (2039)	10,683 (2402)	11,970 (2691)
Tow Line Length m (ft)	7795 (25,574)	7187 (23,579)	7234 (23,734)	7763 (25,469)	8583 (28,159)	9450 (31,004)	10,245 (33,612)	11,184 (36,693)
Tow Line Diameter cm (in)	0.132 (0.052)	0.188 (0.074)	0.245 (0.096)	0.290 (0.114)	0.326 (0.128)	0.358 (0.141)	0.387 (0.152)	0.409 (0.161)

Table 1 Tow Line Specifications

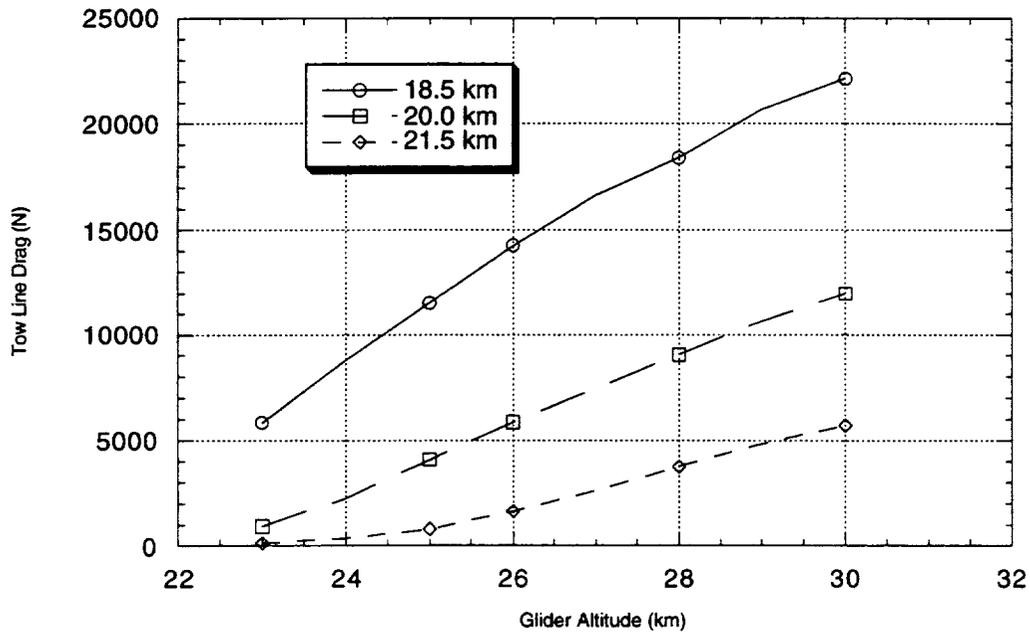


Figure 4 Tow Line Drag as a function of Glider Altitude for Various Tow Aircraft Altitudes

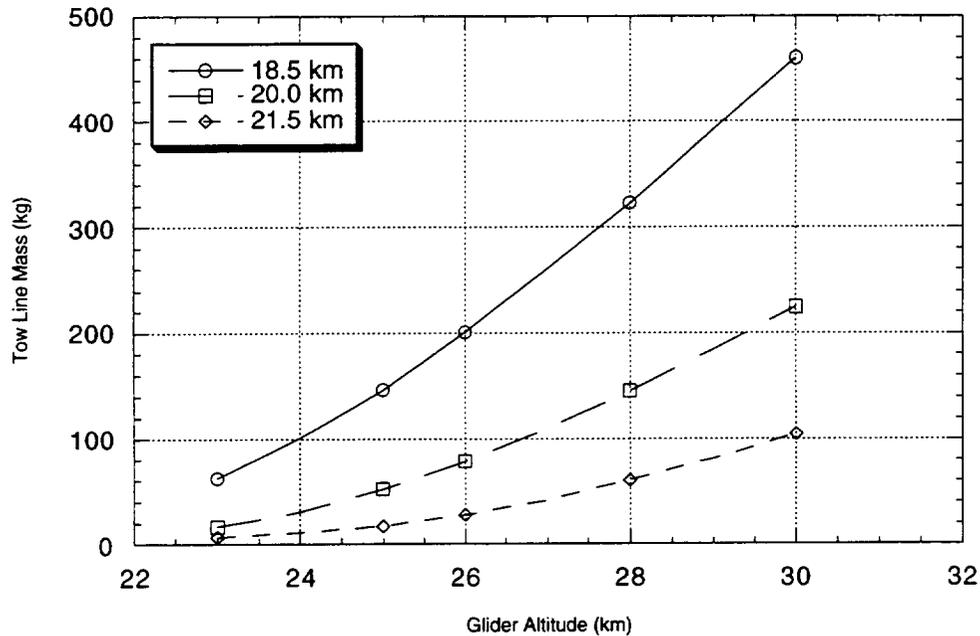


Figure 5 Tow Line Weight as a Function of Glider Altitude for Various Tow Aircraft Altitude

To determine what effect each of the assumptions had on the tow line results, cases were generated with reduced values of tow line drag coefficient and coefficient of friction, tow line material factor of safety and glider Mach number. These results are shown in figures 6 through 8. The reduction in drag coefficient may be accomplished by designing a more aerodynamic tow line and adjusting for any low Reynolds number effects, such as boundary layer separation. The reduction in material factor of safety can be thought of as either a more aggressive use of the material stated or as an increase in material strength. The final set of results, shown in figure 9, were generated using the most optimistic values for each of the assumptions.

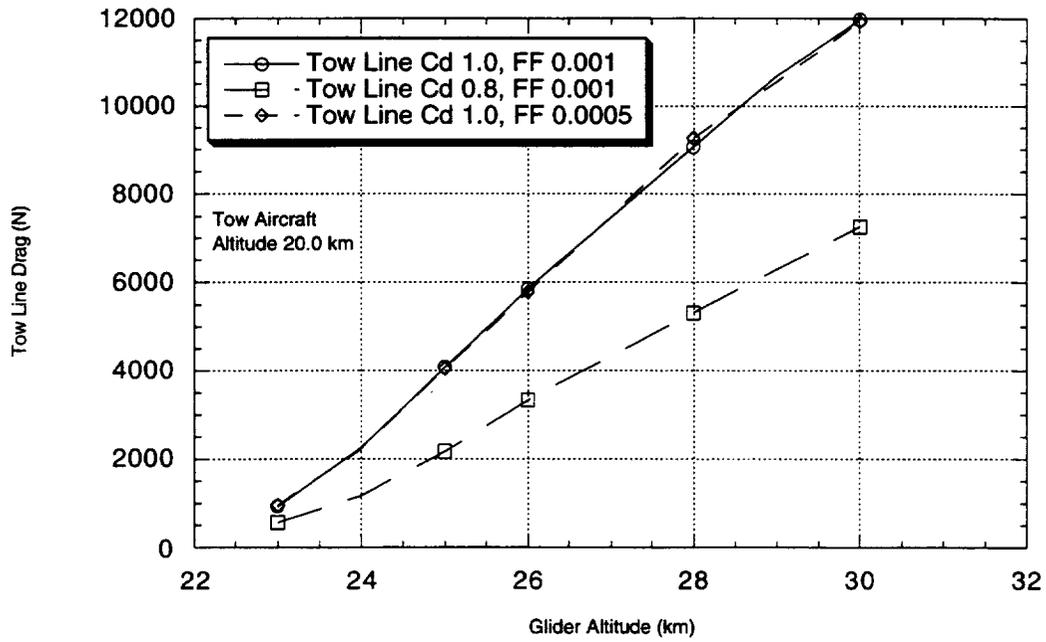


Figure 6 Tow Line Drag Versus Glider Altitude for Various Tow Line Drag Coefficients and Coefficients of Friction

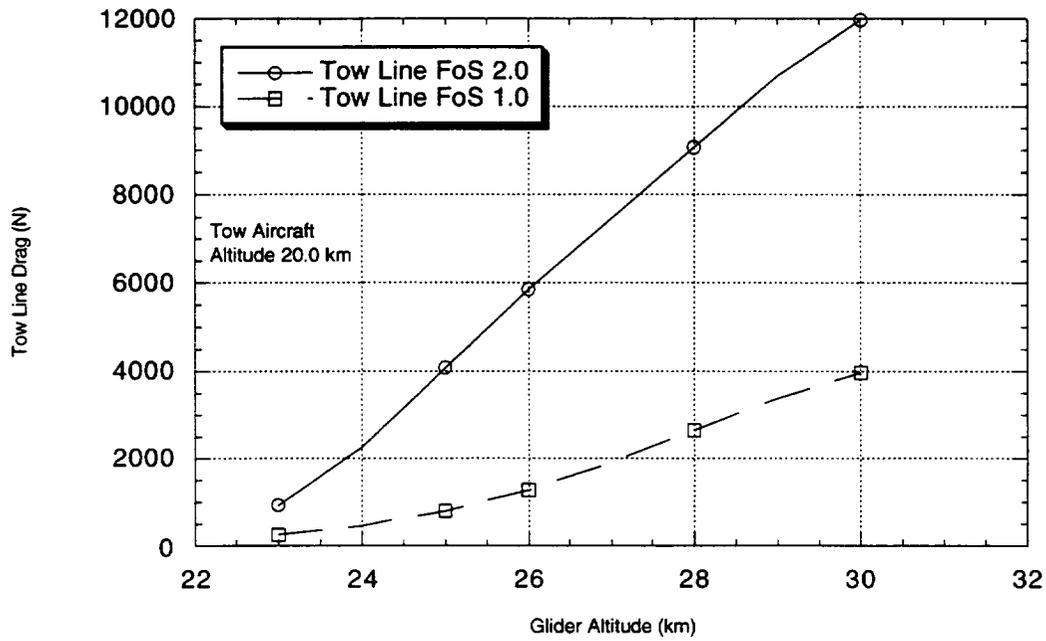


Figure 7 Tow Line Drag Versus Glider Altitude for Various Tow Line Material Factors of Safety

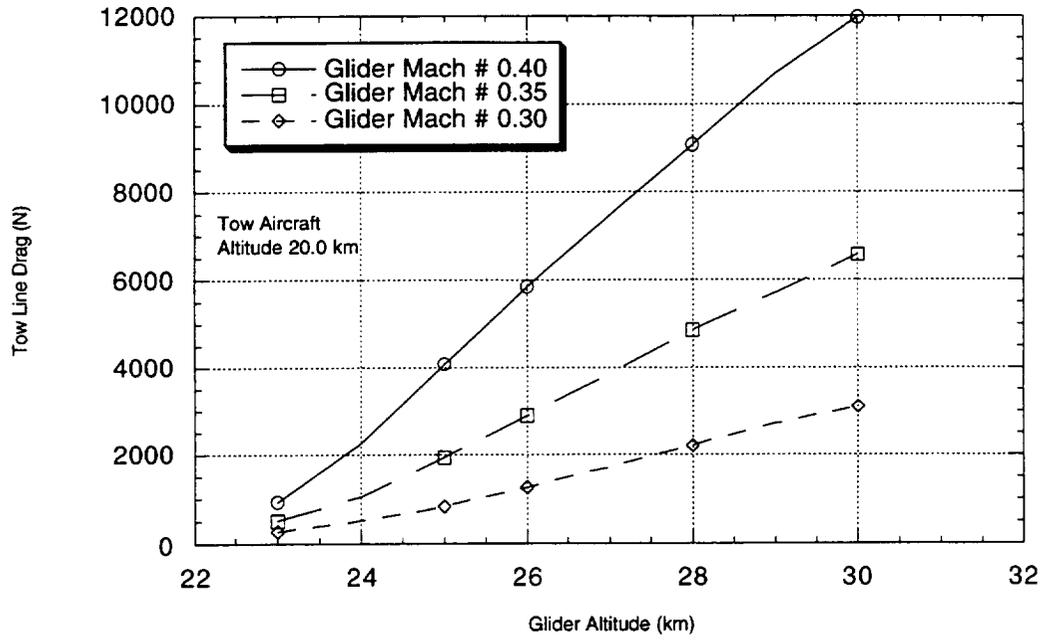


Figure 8 Tow Line Drag Versus Glider Altitude for Various Glider Mach Number

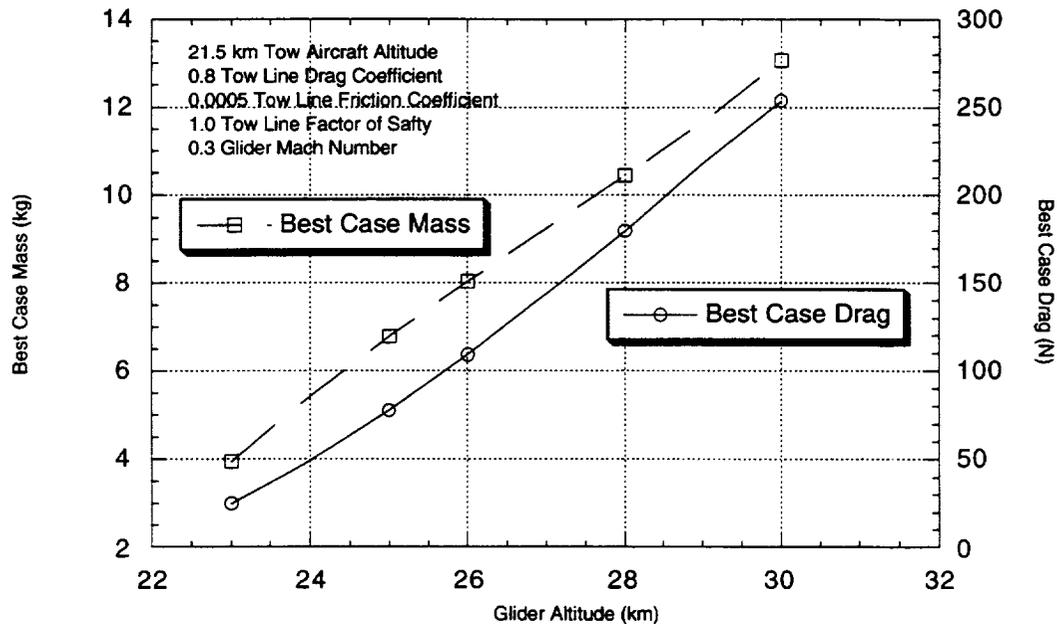


Figure 9 Tow Line Drag and Weight Versus Glider Altitude for the most optimistic assumptions

Conclusion

The concept of towing a glider to high altitudes is an unconventional approach to solving the problem of producing power and rejecting heat in a rarefied atmosphere. By examining the results one can see that for the base case assumptions the tow line drag increases significantly with tow aircraft / glider separation, as would be expected. The tow line drag values represent excess thrust that the tow aircraft must be capable of generating at altitude. For glider altitudes above 24 km the excess thrust needed becomes prohibitively large. The results show that by varying some of the initial assumptions significant reductions in tow line drag and weight can be obtained. The variables which had the greatest effect on reducing the tow line drag were the decrease in tow aircraft / glider separation distance, the increase in tow line strength and the decrease in glider Mach number. The reduction in tow line drag coefficient did reduce the drag but it wasn't as significant a reduction as obtained by the other factors mentioned.

By increasing the tow aircraft altitude this reduces the tow line length. This reduction in length is from the portion of tow line in the densest atmosphere. Both of these factors result in a significant reduction in drag. However the problem of producing a subsonic aircraft that can generate excess thrust at this higher altitude could be as substantial as developing a powered aircraft to fly the mission directly.

The increase in the tow line strength was accomplished by decreasing the factor of safety used in the strength calculations. This indicates that any improvement in the structural material properties can have a significant effect on drag reduction. However, The ability to construct an operational tow line with a 50 to 100% strength increase over the baseline carbon material cannot be considered a realistic requirement for the development of this concept. The selection of a material will also have to take into account the ability to build a tow line out of it of uniform strength with a length of 4.5 km or more and to be able to manage its winding and unwinding from the tow aircraft.

The final factor that had a significant impact on the tow line drag was the glider Mach number. The slower the glider flies the lower the drag of the complete system. As the glider flies slower the wing loading must decrease in order to be capable of supporting itself and any payload at these lower velocities. This produces a lighter more fragile aircraft which is a concern since the glider has to be towed to altitude through the denser lower atmosphere. Also, a reduction in the glider velocity also corresponds to a reduction in the tow aircraft velocity which makes it more difficult for the tow aircraft to produce excess thrust at high altitudes.

The final portion of the analysis shows a significant reduction in tow line drag when a combination of these drag reduction approaches are used. This suggests that by taking small steps to reduce drag in a number of areas, the combined effect would produce a reduction in drag greater than the sum of each individual improvement. Based on the initial assumptions the practical use of this concept is limited. If, however, some type of drag reduction method or methods, such as ones previously suggested were capable of being successfully incorporated then the concept would seem viable.

Reference

1. Hoerner, S.F., "Fluid Dynamic Drag," published by the author, 1965.
2. White, F.M., Fluid Mechanics, McGraw-Hill, 1979.
3. Beer, P. and Johnston, R. Jr., Vector Mechanics for Engineers: Statics and Dynamics, McGraw-Hill, 1984.

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