Structures for Stratospheric Particle Injection

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Summary

Large volcanoes periodically inject aerosols into the stratosphere, cooling the planet by scattering incoming solar radiation. Injection of suitable particles at 20 km has been identified as the least expensive geoengineering option to ameliorate the temperature rise associated with a doubling of CO_2 levels, and the technology most likely to be effective. This paper considers the engineering issues associated with two methods of conveying particles to 20 km (65,000 feet); building fixed towers or the use of pipes supported by tethered balloons. A fixed mast would need to be an order of magnitude taller than any structure built to date. It raises major issues of self-weight buckling and would require either new materials or an increase in production of high strength composites by many orders of magnitude. A balloon-supported tether to reach 20 km altitude does not have buckling issues and appears much more practicable with relatively small development costs. Various options for such a design are considered, including the material from which it might be fabricated and some of the technical problems that have to be overcome.

Keywords: *Towers, Cables, Aramid, Fibres, Balloons, Geoengineering*

1. Introduction

It is now widely accepted that man-made CO_2 is causing a rise in the Earth's temperature which, if allowed to continue, would have a range of adverse consequences. Some are gradual, such as water shortages for many of the world's poorest peoples, rises in sea level, increased frequency and intensity of hurricane typhoon damage and severe water shortages. Others are discontinuous: melting of tundra permafrost releasing methane, the release of methane hydrates from the ocean floor and the possible destruction of the Amazonian rainforest through reduced precipitation. Against such a background, the world needs to reduce its greenhouse gas production, but it is by no means clear that the political will exists to make the necessary changes in a sufficiently timely manner. The long planetary time constants mean that the achievable rate of reduction may not be sufficient to avoid extremely severe adverse consequences to humanity and the planet. In consequence, it is highly desirable to research options that would allow 'Geoengineering' of the planet in a more positive manner. A variety of possibilities have been suggested, ranging from the reasonably practical to some on the edge of science fiction. A recent Royal Society working group[1] concluded that the technology that was most likely to work, and most affordable, was Solar Radiation Management by Stratospheric Particle Injection.

The process would mimic the effect of volcanic eruptions, either by injecting SO_2 or H_2S which would form droplets, or by dispersing particles with a high refractive index. If these are of the right size they would scatter incoming solar radiation but not interfere with outgoing infra-red radiation. The net effect would be a reduction in solar heating and a temporary cooling of the planet. The particles need to be injected into the stratosphere (otherwise they are washed out very quickly), ideally near the equator, and can be expected to stay in the atmosphere for 1-2 years. Major volcanic eruptions near the equator such as Pinatubo or Krakatoa have been extensively studied, and the science has become reasonably well understood. Significant risks include reduction in the ozone concentration in the stratosphere and adverse regional impacts, such as reducing monsoon or Sahel precipitation.

The SPICE project (Stratospheric Particle Injection for Climate Engineering) is investigating this possibility and has three strands. 1) What particles should be injected? 2) How can they be delivered? and 3) Climate modelling to investigate regional impacts and the optimal siting of the injection points. This paper addresses the structural questions that arise in the second strand, but is informed by preliminary results from the other work.

2. Stratospheric Particle Injection

The particles need to be injected above the tropopause, which is at 20km altitude in equatorial regions and 12 km altitude near the poles, to achieve reasonable residence times. Volcanoes in the tropics (e.g. Pinatubo, 1991, 15ºN) have a greater effect on temperature than those at higher latitudes (e.g. Kasatochi, 2008, 52ºN[2] and Sarychev, 2009, 48ºN[3]). Preliminary modelling suggests that this is due to a higher solar radiation flux near the tropics and stratospheric circulation lofting particles injected near the equator to high altitudes, whereas particles injected nearer the poles have greater elutriation rates, mainly remaining close to the tropopause. Atmospheric currents distribute the injected particles E-W within weeks, but more slowly (months) N-S. However, injection height is important; the northern volcanoes only injected material into the lower stratosphere whereas Pinatubo's material reached 25 km. Early estimates show that 2 Mt to10 Mt of particles (depending on type) would need to be injected each year at a height of 20 km to achieve a 2ºC planetary cooling that would be roughly equivalent to reversing the effect of doubling atmospheric CO_2.

As part of the SPICE project, a study has been carried out and submitted to the Royal Society for publication into possible delivery methods, which includes artillery, re-usable or single use balloons, coilguns or aircraft [4]. Two of these concepts have a significant structural engineering component and are the subject of this paper:

(i) a fixed tower, which would have to withstand high winds, and

(ii) a tether kept in tension by a balloon at high altitude and either attached to a ship that could move to avoid the jet stream or land-based in tropical regions where jet stream velocities are much lower.

In one case the load is in compression, in the other it is in tension.

Figure 1 shows the maximum of the 6-hourly "instantaneous" data for the wind 33º N [5]. The jet stream at an elevation of about 11 km is clearly visible, as is the reduction to relatively steady conditions at 20 km. This data almost certainly underestimates the very short gusts that would have structural effects, and these figures do not include the effect of tropical storms that can cause very large wind speeds at low levels. The density variation is also important, falling to about a tenth of its surface value at 20 km.

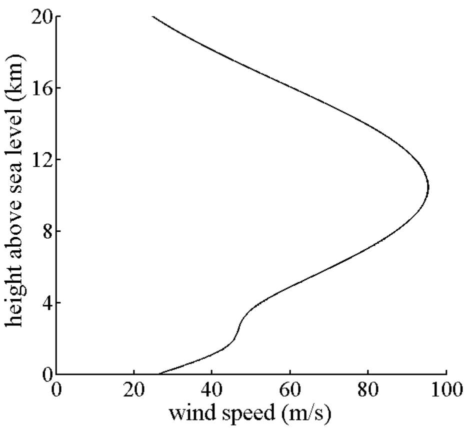

Figure 1. Variation of wind speed with height

Table 1. Material Properties

Material	Strength MPa	Density kg/m^3	Cost £/t
Aramid	2,760	1,440	20,000
PBO	5,800	1,560	80,000
PS. steel	2,000	7,860	---
Nanotubes	63,000	1,440	---
Structural steel	500	7,860	800
CFRP	1,500	1,500	4,000

3. Towers

Robock and others [6,7] have mentioned high towers as potential options for elevating and dispersing material to stratospheric altitudes. A tall tower must be strong enough that the materials do not reach their limiting stresses, and it must be stiff enough not to buckle. In the first instance, these criteria can be considered separately, and for illustration designs have been carried out in steel and in carbon fibre reinforced polymer (CFRP) with the material properties listed in Table 1.

A straight tower, of uniform cross-section, will fail in compression when the height is $\sigma / \rho_m g$, where σ is the material's strength in compression, ρ_m is its density and g is the acceleration due to gravity. This is a limiting factor for steel, giving a maximum height (without any safety factor) of about 6.5 km. However, this height can be exceeded if the tower tapers.

The predominant wind forces will be horizontal, so the tower will act primarily in flexure as a vertical cantilever. Two tower cross-sections are considered; one formed from a single hollow tube as shown in Fig. 2(a), the other from four legs with bracing, Fig. 2(b). Most tower configurations can be approximated to one or other of these cross sections.

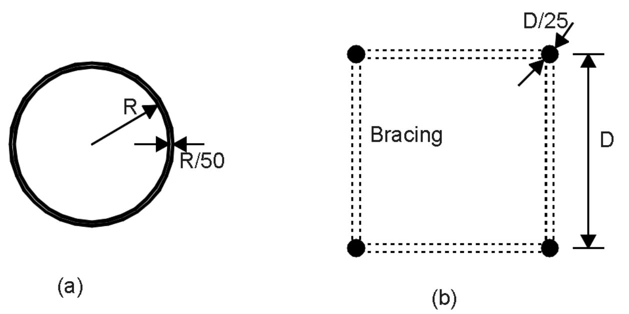

Figure 2. Alternative tower cross-sections. R and D vary with height.

The single tube will be thin-walled and it is assumed that the wall thickness t is $R/50$. Thin-walled tubes in compression are at risk from local buckling where the thin wall crumples. Stiffeners or internal bracing will probably be required but it is assumed they are light enough to be neglected in the calculation of tower mass. For the truss, a significant amount of bracing would be required. It will be assumed that this bracing weighs as much as the four main legs and attracts the same amount of wind load. The diameter of each leg d is related to the overall tower width D by taking D/d fairly arbitrarily as 25.

The wind force is given by $F = \frac{1}{2} \rho_a C_D v^2 A$, where F is the force, ρ_a is the air density, C_D is the drag coefficient, A is the area facing the wind and v is the wind speed taken from Fig. 1. To determine the section dimensions the loads are integrated from the top of the tower downwards, giving a vertical moment (from the wind) and an axial force (from the self-weight). The top of the cylindrical tower is assumed to have a radius R of 0.5 m, and the truss a width D = 1 m. By computing the sum of the axial stress and the bending stress and comparing this total with the limiting material stress σ_y, the required diameter at each level can be found. For the hollow tube design, the variation of R with height is shown in Fig. 3. For steel, the radius at the base is about 68 m with a total weight of steel of about 19 million tonnes. Using a lighter material such as CFRP (Carbon Fibre Reinforced Polymer), the width increases less rapidly, thus reducing the wind load, so R at the base is only 26 m with a total weight of 0.66 million tonnes.

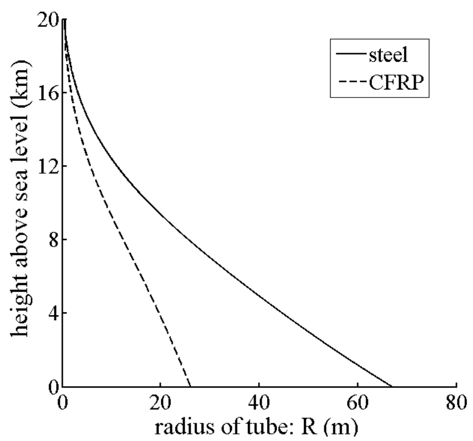

Figure 3. Variation of principal diameter of single tube to resist wind loads only

Similar effects are observed for the trussed form; the width of the steel truss increases quite rapidly towards the base, indicating that the self weight of the tower is starting to be a much more significant part of the load, although it is still possible to build a tower 20 km tall. The trussed steel tower would have a total weight of 16 million tonnes, half of which is assumed to be in some kind of bracing. There is much less weight in the CFRP tower (218,000 tonnes).

These dimensions, although large, give structures that are very slender. Even for the steel tube, the ratio of the height to the width at the base is about 150, so buckling is more likely to be critical. In the first instance buckling can be computed on the assumption that the towers have a uniform cross section for their entire height. Later, tapered towers will be considered.

The classical buckling load for a cantilever buckling under its own weight [8] is given by

$$(qL)_{crit} = \frac{7.837EI}{L^2} \qquad (1)$$

where q is the weight per unit length. The 7.837 factor can be compared with $\pi^2/4 = 2.467$ for the end-loaded cantilever column; clearly more load can be carried if it is distributed evenly along the length rather than being carried at the end. But the self-weight is related to the material density and its cross sectional area so the formula above can be rearranged to give:-

$$L_{crit} = 7.837\left(\frac{E}{\rho_m g}\right)\left(\frac{r}{L}\right)^2 \qquad (2)$$

where E is the Young's modulus of the tower material and r is the radius of gyration of the tower cross section. This formula conveniently separates the buckling load into a material factor and a shape factor. For a thin circular tube the radius of gyration r is $R/\sqrt{2}$ and notably is independent of the tube thickness. For a solid cylinder, $r=R/2$, so the self-weight buckling length would be half that for a thin tube of the same material. It is clearly better to maximise r by placing the material as far away from the centroid as possible. For the truss $r = D/(2\sqrt{2})$, allowing for the fact that half of the material is in the bracing that contributes to the weight but not to the overall stiffness of the tower. For that reason the truss design will not be considered further.

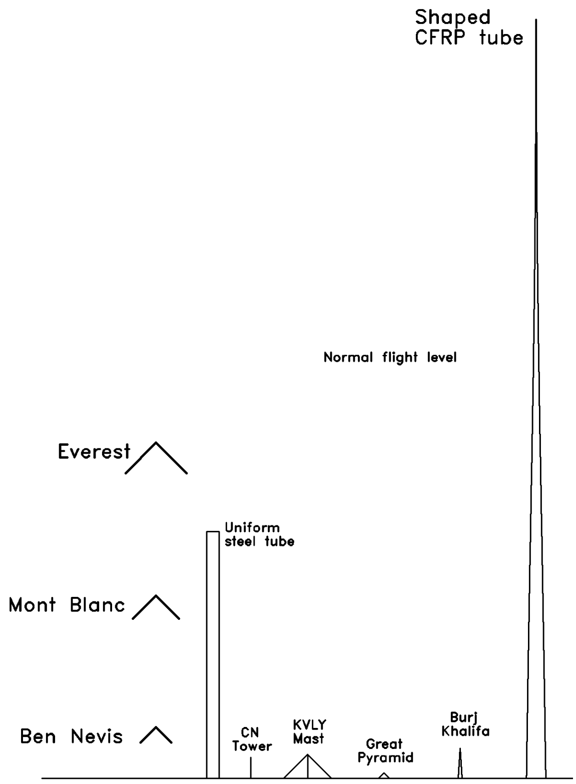

Figure 4. Comparison with notable tall structures (to scale).

For steel, the required dimensions for the uniform tube at 6.5 km tall would give r = 116 m whence R = 163 m for the tube. For a 20 km tower in CFRP, the radius of the uniform tube is 500 m. These dimensions are clearly much larger than the values given by the strength analysis, but do not take account of the taper, nor does it make any allowance for a safety factor.

For a tapered tube there is typically no closed-form analysis. An approximate Rayleigh analysis for the self-weight buckling load can be performed by assuming the shape of the buckling mode and equating the strain energy of flexure to the work done by the load. A commonly assumed buckling mode is to calculate the shape the tower would adopt if it were mounted *horizontally* and subjected to a gravity load [8]. By this approximation the Rayleigh analysis for a uniform section overestimates the critical length by only 0.1% so it is reasonable to use the same approximation for a tapered tower.

A Rayleigh analysis of the tapered steel tube tower, with R = 68 m at the base designed to resist the wind load in flexure, and with a mode predicted as above, would buckle if the gravitational acceleration g_{cr} were 0.166 m/s^2. Since the buckling load will vary as R^2, in order to make the tube buckle when g_{cr} is 9.81 m/s^2, the tube dimensions would have to be increased by a factor of about 7.6, giving a diameter at the base just over 1 km. It would contain over a billion tonnes of steel. A CFRP tube would be more "reasonable", with a diameter of about 500 m and a weight of 62 million tonnes. Figure 4 shows these towers in comparison with some well-known landmarks to give some sense of scale. Current world production of carbon fibre is of the order of 50,000 t p.a.; scaling-up production to the required level would be extremely expensive.

Significant savings could be achieved if the CFRP tower were founded on a 5 km plateau; the base diameter would reduce to 350 m, and both the material weight and its cost would reduce by 70%. Access infrastructure would have to be provided; as a guide, the 1000 km railway to Lhasa at 5000 m is reputed to have cost about $4 billion in 2006 [9]. Given the costs of a tower it would be worth constructing a road up Mt Everest and building a tower there!

A more extensive variational analysis to choose the optimal shape of the tower to resist both global buckling and flexural stresses could be carried out, which might reduce the total weight of the tower. However, allowance would have to be made for reductions in stability caused by wind-induced deflections (a full wind load on the CFRP tube gives a deflection at the top of about 0.35 km), as well as local buckling effects, distortions of the cross-section and vibration of the tower when subject to gusting winds, all of which have been ignored here. All would be likely to add weight to the tower. The foundations would need careful consideration, and the effect of the very high point weight on the Earth's crust would also need consideration, as would the tower's susceptibility to earthquake. A safety factor would also be useful!

Guyed Masts are conceivable but since these would require guys that were ~30 km long they will not be considered further.

4. Balloon-Supported High Pressure Pipes

Pumping precursors to aerosols such as H_2S or SO_2 via a pipe elevated by a balloon or aerostat has been suggested [10]. The concept is for a lifting device to be located at around 20 km altitude that would support its own weight, the weight of a fibre-reinforced pipe, the weight of the fluid being pumped through the pipe and equipment to disperse the particles at altitude (Fig. 5).

The design altitude is just within the stratosphere. It might be preferable to disperse the particles higher, to reduce losses to the troposphere, but above 20 km the density of air decreases rapidly with altitude so a far larger balloon would be required. The other great advantage of the 20 km altitude is that the maximum wind strengths at this altitude are at a minimum, typically being of the order of 20 m/s or less. However the balloon needs to tolerate peak windspeeds of perhaps 50 to 60 m/s at this altitude. The injection does not need to be continuous so that operation for no more than 200 days of the year should be sufficient, given that the particle residence time-constants of the upper atmosphere are of the order of 1-2 years. Jet streams occur at an altitude of around 10 km and the design accommodates a peak jet stream velocity of around 95 m/s with 55 m/s winds at 20 km in the same direction. The maximum pipe angle under these conditions is around 30º to the vertical so the tether length needs to be around 23 km.

The pipe also acts as a tether and has to withstand both very high longitudinal tensile stresses and very high hoop stresses induced by internal fluid pressure. At the top the internal pressure is low and the load in the tether is primarily axial, and it might be supposed that at the base the axial force is low and all the load is due to hydrostatic pressure. However, when the tether is inclined there will be three forces at the base; a force P due to the hydrostatic pressure that is inclined with the pipe together with horizontal and vertical reactions H and V. These forces must align with the axial force in the tether, and will vary with the angle of inclination. In the extreme, if the tether becomes horizontal, $V \to 0$ and $H \to P$, so the tether must be designed for a significant axial force everywhere.

What material should be used for the tether? The "free length" of a material ($\hat{L} = \sigma / \rho_m g$) is the length of itself that it will support; it is a concept that rarely has much application in structural engineering but it is relevant here. For prestressing steels the free length is only ~26 km so alternative high strength materials must be considered. Both carbon and aramid fibres have $\hat{L}$ of about 200 km, while the strongest fibre available in quantity (PBO) has a free length of about twice this value. Carbon nanotubes and graphene would have free lengths in excess of 4000 km, but are available only in tiny quantities and have not yet been fabricated into engineering components. Ultra high modulus polyethylenes are strong enough but there are issues with creep.

Carbon fibres are almost certainly too brittle for use in the tether; they cannot be used without resin and it is proving very difficult to make reliable anchorages for CFRP prestressing tendons[11], which is the nearest comparable usage. There would also be concerns about the desirability of placing a lightning conductor into the stratosphere, although some work suggests it might protect the balloon from a lightning strike[12].

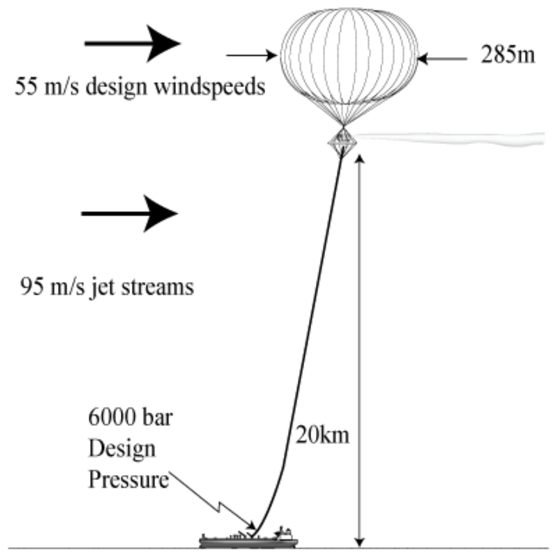

Figure 5: Tethered Balloon Concept.

For preliminary design therefore aramid fibres (Twaron or Kevlar) are being considered. They have a strength of about 2700 MPa, and a density of 1440 kg/m^3, but a design stress of 750 MPa has been assumed. However, they are susceptible to creep rupture, which is a thermally activated process [13] and allowance must be made for a 60% fill factor, the weight of the product being delivered, fibres to resist the high hydrostatic pressures in the pipe, possible temperature effects from the product and from the environment, the need to anchor the tether and a safety factor. Aramid fibres are suited to this application but their capabilities will be pushed to the limit. Less data is available for PBO but one of the objectives of the project is to determine its properties in more detail since the higher strength would allow a lighter tether, thus a smaller balloon, with less danger of "blow-over".

The design pressure of 6000 bar allows all pumping requirements to be satisfied at ground level. The pumping power is determined by the hydrostatic head (of the order of 3000 bar) and additional frictional pressure drop, which for a low capital cost design is comparable to but lower than the hydrostatic head. With a mean SO_2 density of around 1400 kg/m^3 and a maximum velocity inside the pipe of under 8 m/s, the frictional pressure drop is in the region of 2000 bar, leaving a total operating pressure at the pipe base of around 5000 Bar. Water-jet pumps at 5000 bar have a maximum capacity of around 5 litres/min compared to the required flow of the order of 3000 litres per minute, but a scale-up in flow-rate of the order of 10 to 100 seems entirely practical even if this requires a number of parallel pumps.

There are a number of issues that have to be resolved for the tether.

1. Should the tether have separate sets of fibres to resist bursting (which would be largely circumferential) and axial loads? For simplicity of anchorage, the current proposal is for the two sets of fibres to be separated.
2. Should the construction vary along the length?
3. Should the fibres be embedded in resin? Even though aramid fibres do not need resin, higher strengths can be achieved if resin is used because it can transmit loads across minor filament breaks. For this reason, typical strength for AFRP pultrusions is ~2600 MPa, whereas parallel-lay aramid ropes have strengths ~2000 MPa.
4. How should fibres be anchored? The normal anchorage system for a parallel-lay aramid or PBO ropes is a barrel and spike system, where the fibres pass around the outside of a central spike and are gripped by an external barrel; they can mobilise the full strength of the rope and are relatively easy to fit. When such ropes are used as carriers for optical fibres, or umbilicals, it is possible to make the spike with a central hole through which the untensioned element passes. Such a system is envisaged here, where the pressure pipe with its circumferential fibres would pass through the spike. For that reason, it is desirable to separate the axial and circumferential load-carrying elements, although a more sophisticated termination is under consideration.
5. What are the dynamic loads on the tether? The tether will not be static. Both the ship and the balloon will be subject to external loads and the tether itself will be subject to wind loads that vary in strength, and possibly direction, along its length. The tether will act primarily as a

stretched string excited not only by the high winds shown in Fig. 1 but also by geometric effects due to the variation in height of both ship and balloon. It is not yet clear whether standing waves will develop (as is the case for power transmission lines) or whether the distance between supports (20km) is sufficiently long that propagating waves will have decayed before reaching boundaries for reflection. The tether will be curved and tension will vary along its length so non-linear dynamic modelling is required. A detailed understanding of aerodynamic interactions will be crucial because there is potential for the balloon and tether to be brought down by excessive lateral loading in high winds. For this reason it may be advantageous to employ a non-circular tether but published literature [14] considers only tethers with a circular cross-section. Asymmetric cross sections can also arise as a result of ice build up. For these reasons the potential of flutter oscillations must be considered and these will couple torsional and translations motions of the tether, complicating enormously the nature of wave propagation and the determination of stability. It will be necessary to carry out scale model testing in order to validate analytical models.

6. What is the temperature of the fluid to be pumped? This has major implications for the tether design because of the temperature sensitivity of the materials. Simply because volcanoes throw out sulphur, which forms droplets of sulphuric acid that are naturally of almost the right size, there is no reason why a geoengineering system has to do the same. The scattering of light depends critically on the size of the particles (0.3 – 0.5 µm diameter is ideal) and their surface characteristics. The process industry can manufacture powders of controlled size and surface using a variety of mineral sources; SO_2 can be pumped as a gas, but other materials would require a carrier fluid; water would need to be heated to avoid freezing at height, and the dispersion equipment at altitude becomes much larger if anything other than a gas/solid dispersion is required. Furthermore, injecting water into the stratosphere may be counterproductive. Liquid nitrogen could be manufactured at low cost at the base of the delivery system and would be at a supercritical pressure in the tether. It would avoid any concerns about the injection of large quantities of water into the stratosphere and allows the particles to have a lower adsorption of Infra Red without the presence of significant hydroxyl group concentrations. The choice of particles and their delivery fluid is a separate part of the study but it clearly has implications for the tether design.

The design currently envisaged is for a tether of outer diameter 165 mm with an inside diameter of 50 mm that would weigh around 700 tonnes, including around 85 t of fluid. The balloon has to withstand gusts and is envisaged to be a pressurised balloon with an operating differential pressure of around 400 Pa across the balloon envelope. No credit is taken for operating with pumpkin balloons which have had launch issues, with large diameter balloons buckling at intermediate altitudes [15]. A 350 micron balloon fabric wall thickness has been assumed with a balloon weight of 125 t and a payload of 10 t (in addition to the weight of the tether).

This delivery method has several developmental issues:-

- the size of the balloon is much bigger than the largest balloon to date, (285 m vs. 120 m),
- the manufacture of a reliable high pressure tether,
- the need to ensure that no transient oscillations or dynamics compromise the integrity, and
- the need to scale up pumping technology.

It is believed, however, that all of these factors, although challenging, are at the edge of existing technology in one or more fields and can be overcome.

Since most of the technology required is simply a scale-up of existing technology, it is anticipated that in an extreme case a system could be deployed within 5 to 10 years, with minimal environmental impact once initial piloting had shown feasibility. It would be essential to carry out extremely careful tests on regional precipitation and atmospheric chemistry interactions.

5. Conclusion - Towers vs Tethers?

A detailed study of the costs of deliver options has been given elsewhere[4] and is summarised in Fig. 6. Although the design calculations carried out on the rigid towers above were necessarily very simplistic, the basic assumptions are valid, and it is clear that they are extremely expensive mainly because of their very high initial cost, although their running costs would be low and they could allow manned access to a permanent dispersal facility at high altitude. A balloon-supported tether system, on the other hand, would be several orders of magnitude cheaper, while other systems have intermediate costs. It is worth reflecting on why the tension system is so cheap:

1. The connection between the ground and the stratosphere, although permanent, is in tension and thus will tend to straighten whereas the tower is in compression and tends to buckle. The lift for the supporting structure comes free, from the natural buoyancy of Hydrogen or Helium.
2. Only the material to be dispensed at high altitude has to be lifted, and this is done by pumps at ground level. There are no artillery or rocket casings to be manufactured, lifted, or recovered.
3. The accelerations during launch, pumping and recovery are all small, which means that the system can be made from lightweight materials.
4. Because the system is mobile, it can be designed to avoid the worst effects of the jetstream.

There is an additional advantage in that the system would remain in place more or less continuously. Unlike systems that have to dispense their payload in a very short time, the dispensing system can operate semi-continuously, and would not get thrown away after every shot. This opens the way to improving both the effectiveness of the dispersion techniques and the choice of particles.

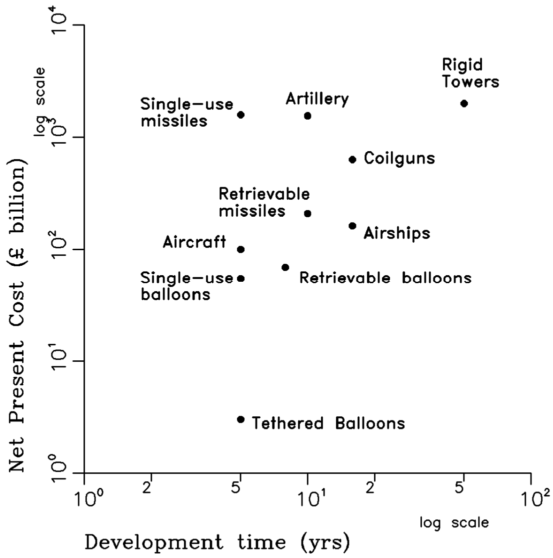

Figure 6. Cost and timescale of options

The conclusion from this analysis is a clear win for tethers in tension over towers in compression.

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