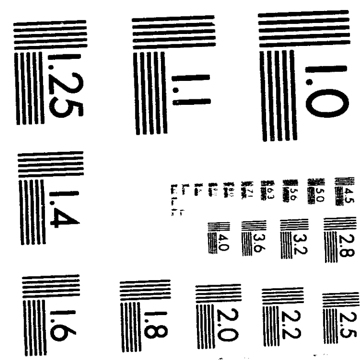

1 of 1

Reactor-pumped laser facility at DOE's Nevada Test Site*

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ABSTRACT

The Nevada Test Site (NTS) is one excellent possibility for a laser power beaming site. It is in the low latitudes of the U.S., is in an exceptionally cloud-free area of the southwest, is already an area of restricted access (which enhances safety considerations), and possesses a highly-skilled technical team with extensive engineering and research capabilities from underground testing of our nation's nuclear deterrence. The average availability of cloud-free clear line of site to a given point in space is about 84%. With a beaming angle of $\pm 60^\circ$ from the zenith, about 52 geostationary-orbit (GEO) satellites could be accessed continuously from NTS. In addition, the site would provide an average view factor of about 10% for orbital transfer from low earth orbit to GEO. One of the major candidates for a long-duration, high-power laser is a reactor-pumped laser being developed by DOE. The extensive nuclear expertise at NTS makes this site a prime candidate for utilizing the capabilities of a reactor pumped laser for power beaming. The site then could be used for many dual-use roles such as industrial material processing research, defense testing, and removing space debris.

1. INTRODUCTION

We must consider a number of issues in selecting a laser power beaming site. The major physical issues are latitude, weather, available water, power, roads, technical support base, and site altitude. In addition to these physical constraints, there are a number of sociological considerations such as air traffic corridors, environmental impact, and support from interested corporate or political entities. Consideration of the requirements of the various possible missions also affects the evaluation of the site. The primary potential missions as we see them today are replacing sunlight in GEO for satellites in the earth's shadow, orbit raising from low-earth orbit (LEO) to geostationary orbit (GEO), debris removal from LEO and high LEO, and beaming power to solar panels at a lunar base during the long lunar night.[1-6] The Nevada Test Site (NTS) in southern Nevada will be analyzed with respect to these constraints, considerations, and missions.

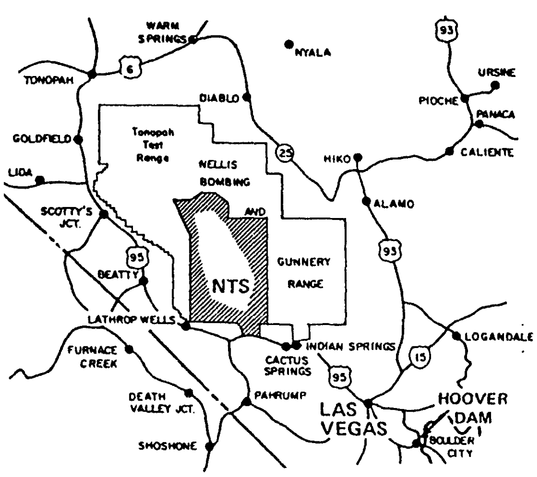

Figure 1. Overview of Nevada Test Site Region (adapted from reference 7).

Figures 1 and 2 show overview maps of NTS.[7,8] It is located 65 miles northwest of Las Vegas, is operated by the Department of Energy, and is the site for underground testing of nuclear weapons (presently suspended). Access to it is restricted. NTS includes 861,000 acres (3500 km^2) of federally owned land and is bounded at the west, north, and east by the Nellis Air Force Range, where access also is restricted. The airspace overlying NTS and the adjoining Nellis Range is restricted at all times and is controlled by Nellis Air Force Base in coordination with DOE at NTS. The area is a dry desert at 37° north latitude with broad flats at 3000 feet elevation and mountains up to 7000 feet in elevation. Land within NTS is used exclusively for national defense and energy-related purposes by DOE and is not open to public use for any purposes, such as agriculture, mining, homesteading, or recreation. Testing of nuclear explosives in the past has been conducted at Yucca Flat, Rainier Mesa, and Pahute Mesa. Testing of nuclear reactors, nuclear engines, and nuclear furnaces have been conducted at the Nevada Research and Development Area located in Jackass Flats.[8]

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2. LATITUDE

Most commercial satellites orbit above the equator, which suggests that the equator is the preferred location for power beaming. Unfortunately, the most southern extents of the continental U.S. is about 26° (Florida and Texas), and other considerations such as lack of land, cloudy climates, and lack of infrastructure make much of the equator non-optimal. So a quantitative assessment of the effect of higher latitudes is useful in deciding how far north (or south) of the equator is suitable for power beaming. Most commercial satellites are launched from Kourou in French Guiana at 5° north latitude or from Kennedy Space Center in the U.S. at 28.5° north latitude.[9] A satellite launched into LEO from 28.5° north latitude will have the center of its orbit at the earth's center and so will pass down to 28.5° south latitude on the opposite side of the earth. Once launched, the satellite remains in its inclined orbit while the earth turns under it. This means that, at times, the satellites in LEO will be as low as 28.5° south latitude when at the same longitude as a laser site north of the equator, making it difficult to access from the U.S. Fortunately, GEO satellites end up in a 0°-inclination orbit at 35,786 km altitude where they are much more accessible to sites away from the equator.

The fraction of time that a satellite is in view for a given pass is called the view factor and depends on its altitude, its latitude, the site latitude, and the allowable beaming angle off zenith. (See Figure 3.) The view factor averaged over all passes (as the earth rotates below the fixed orbit) is called the average view factor and is a function of orbital inclination as well. The angle from the laser site to the satellite, as measured from the zenith, is called the zenith angle (θ_z) and may be determined to be

$$\theta_z = \arccos\left(\frac{h^2 + s_{sl}^2 - s_{se}^2(1+h/r_e)^2}{2\, h\, s_{sl}}\right) \qquad (1)$$

where h is the altitude of the satellite, r_e is the earth's radius, s_{sl} is the slant range from the laser site to the satellite, and s_{se} is the separation between the laser site and the spot on earth directly below the satellite. Also,

$$s_{sl} = r_e \left[1 + (1+h/r_e)^2 - 2\,(1+h/r_e)\cos\gamma \right]^{1/2} \qquad (2)$$

and

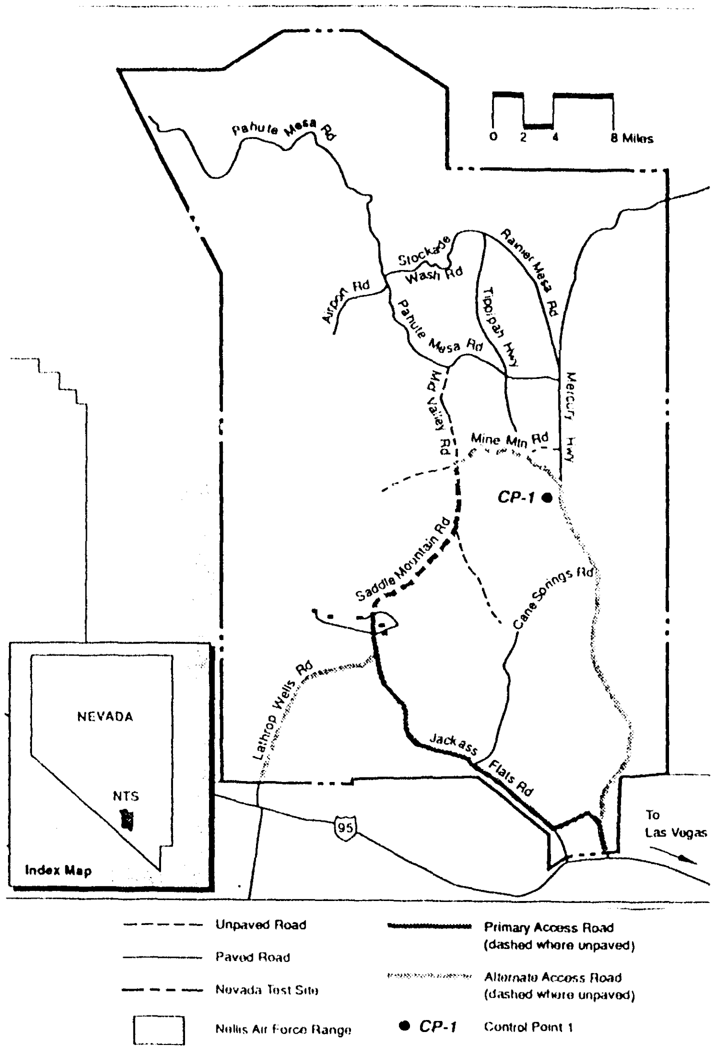

Figure 2. Map of Nevada Test Site (adapted from ref. 8)

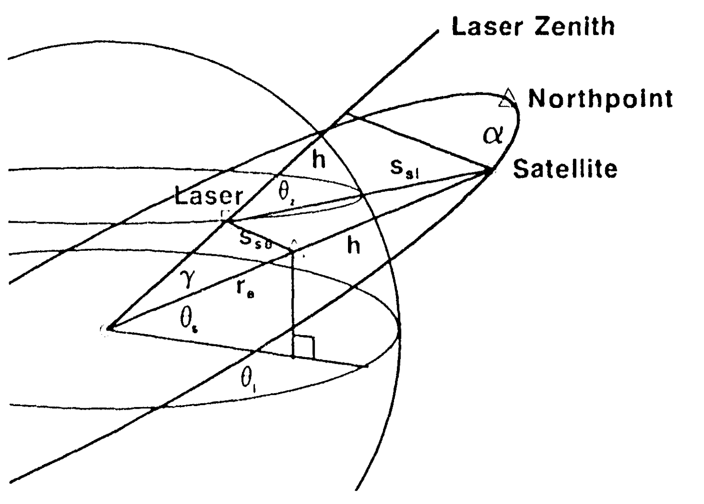

Figure 3. Geometry of satellite orbit and zenith angle.

$$s_{se} = r_e \left[2 - 2 \cos\theta_L \cos\theta_s \cos(\phi_s - \phi_L) - 2 \sin\theta_L \sin\theta_s \right]^{1/2} \quad (3)$$

γ is the angle between the laser site and the spot directly below the satellite on the earth's surface as measured from the center of the earth, θ_L and ϕ_L are the latitude and longitude of the laser site, and θ_s and ϕ_s are the latitude and longitude of the spot directly below the satellite on the earth's surface. In addition,

$$\gamma = 2 \arcsin\left(\frac{s_{se}}{2 r_e}\right) \quad (4)$$

$$\theta_s = \theta_i \cos\alpha \quad (5)$$

$$\phi_s = \phi_n + \alpha \quad (6)$$

where θ_i is the inclination of the orbit relative to the equator, ϕ_n is the longitude where the northernmost point of the satellite's orbit is, and α is the distance around the orbit (in degrees or radians) measured from that northpoint.

These equations may be used to determine how many GEO satellites can be accessed from a given site for a specified capability in zenith angle. Figure 4 shows the angular span in GEO ($\Delta\alpha$) accessible from different latitudes for several assumed limits in zenith angle. In order to access a decent number of GEO satellites from NTS (at 37° latitude), the beam director must be capable of atmospheric compensation down to 30° from the horizon (zenith angle of 60°). The atmosphere is effectively twice as thick at that angle relative vertical, so absorption and scattering will be about 40% instead of 20%.[4] In addition, twice as many actuators will be needed for the adaptive optics. But this is a small price to pay for the increase in access. And once the 60° capability is achieved, there is only a small difference in GEO access between the NTS site and a site on the equator. (The same is true for all the other potential sites in the southwest U.S.) The NTS site then could access a span of 80° in longitude in GEO from 76° to 156° west longitude. At present, this span encompasses 52 satellites.[9]

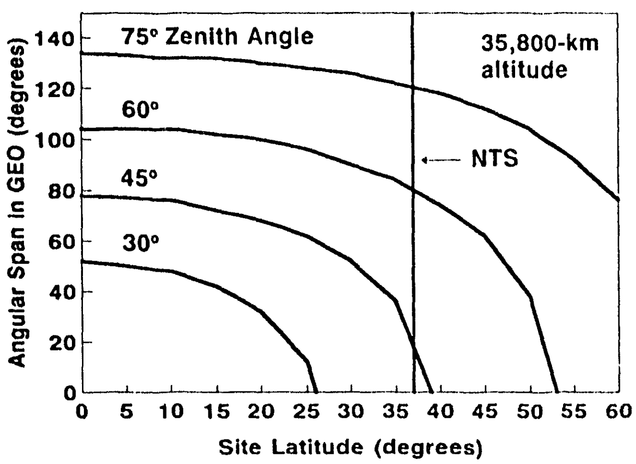

Figure 4. Angular span in GEO ($\Delta\alpha$) accessible from different latitudes.

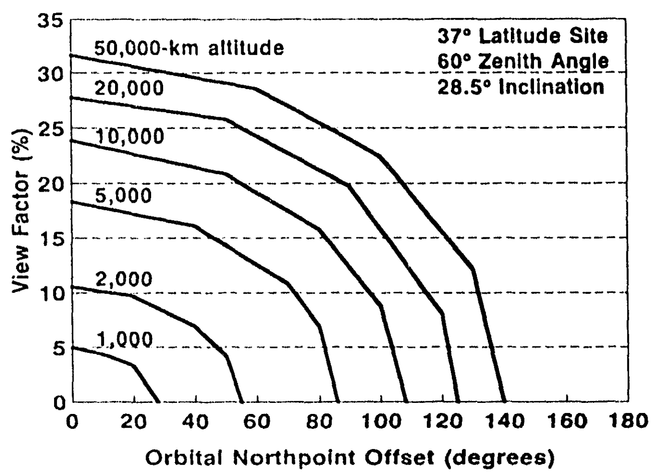

Figure 5. View factor from NTS for satellites in circular orbits.

Power-beaming missions for satellites in non-GEO orbits are more challenging because of the limited time they are in view from a given site. Figure 5 shows the view factor from NTS for satellites in circular orbits at various altitudes and 28.5° inclination. The view factor is plotted versus the longitudinal difference between the site and the furthest point north in the satellites orbit ("orbital northpoint offset"). This offset changes as the earth rotates below the fixed plane of the satellite's orbit. The largest view factor occurs when the offset is zero and the satellite altitude is high. When the offset is 180°, the satellite is below the equator as it passes the site's longitude and is not visible.

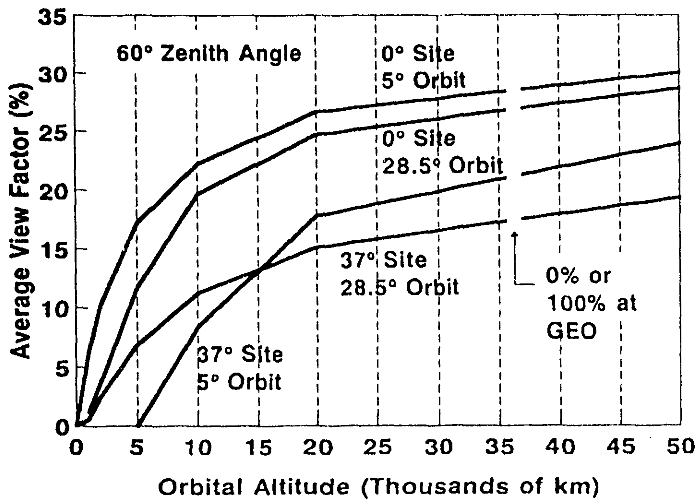

Figure 6. View factor from NTS averaged over many earth rotations.

Integrating below each curve in Figure 5 yields the view factor averaged over many days. This average view factor is plotted in Figure 6. Also shown are similar plots for orbits at 5° inclination (French Guiana launch) and for a site on the equator with each of the orbital inclinations. For LEO-to-GEO orbit-raising missions, the equatorial sites have an advantage, especially at the lower orbital altitudes. However, the NTS location can still do the job. For a trip from LEO to GEO, the flight-averaged and earth-rotation-averaged view factor is about 10% from NTS with 28.5°-inclined orbits. It is about twice that for the equatorial sites. This means that a laser for orbit raising would need to be twice as powerful (but operate for half as long per pass) at NTS as at an equatorial site. But other factors such as fraction of time without clouds or local infrastructure may subtract from this advantage for an equatorial site.

3. WEATHER

Even a steady-state megawatt-class laser can not burn through thick clouds, so weather is an important factor in selecting a power beaming site. Figure 7 shows a map of the world with contour lines of the total noon cloud cover, as determined by the Nimbus-7 satellite.[10] The best areas in the world for clear skies are the African/Mideast deserts, west South Africa, the Australian deserts, and the southwest U.S with an average total cloud cover of 4.3%, 14%, 16%, and 18% respectively at the best spots in each area. Almost all the equatorial sites have over 50% clouds. Figure 8 show a map of the U.S. with the annual percentage of possible sunshine. The best site appears to be Yuma, Arizona, but sites throughout southern California, Nevada, Arizona, and New Mexico are all fairly comparable.[11] Figure 9 shows a more detailed map of Nevada.[12] Nevada Test Site has a yearly average of about 82% of possible bright sunshine. Figure 10 shows the average cloud variation over one day, and indicates that the nights are a bit more clear than the days. There are also seasonal variations. In the spring GEO-eclipse season of March-April, NTS has about 77% of possible bright sunshine; in the fall eclipse season of September-October, NTS has about 90% of possible bright sunshine.[12] So for beaming at night during GEO eclipse, the average clear line of sight availability for NTS is about 87%. For total-year average (day and night) the availability is about 84%.

Winds also can affect seeing conditions and thus the ease of atmospheric compensation. High-altitude jet streams are especially harsh on seeing. The jet stream is usually far north of the U.S. southwest for most of the year. However, in December through February it often courses over all the prime power beaming sites. The effect of the jet stream is to decrease the effective size of a turbulent cell (Fried coherence length[13]) and increase the rate of fluctuation (Greenwood frequency[14]). These difficulties can be overcome by increasing the number of actuators in the adaptive optics (by a factor of 5 to 10) and increasing their frequency capability (by a factor of 5).[15] Note that this upgrade is not needed for the GEO-eclipse mission. However, even for the other missions it will not likely be a major problem since the added expense from this requirement should be small compared to the expected cost of the laser.

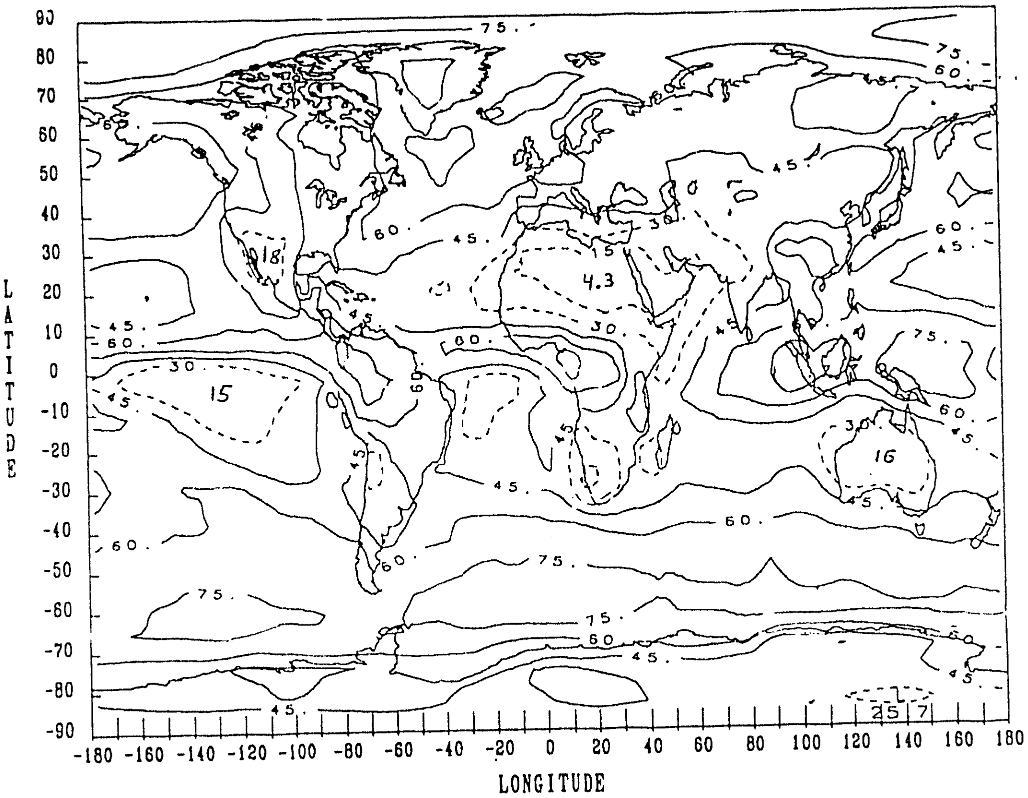

Figure 7. Map of the world with contour lines of the percentage of total noon cloud cover (from reference 10).

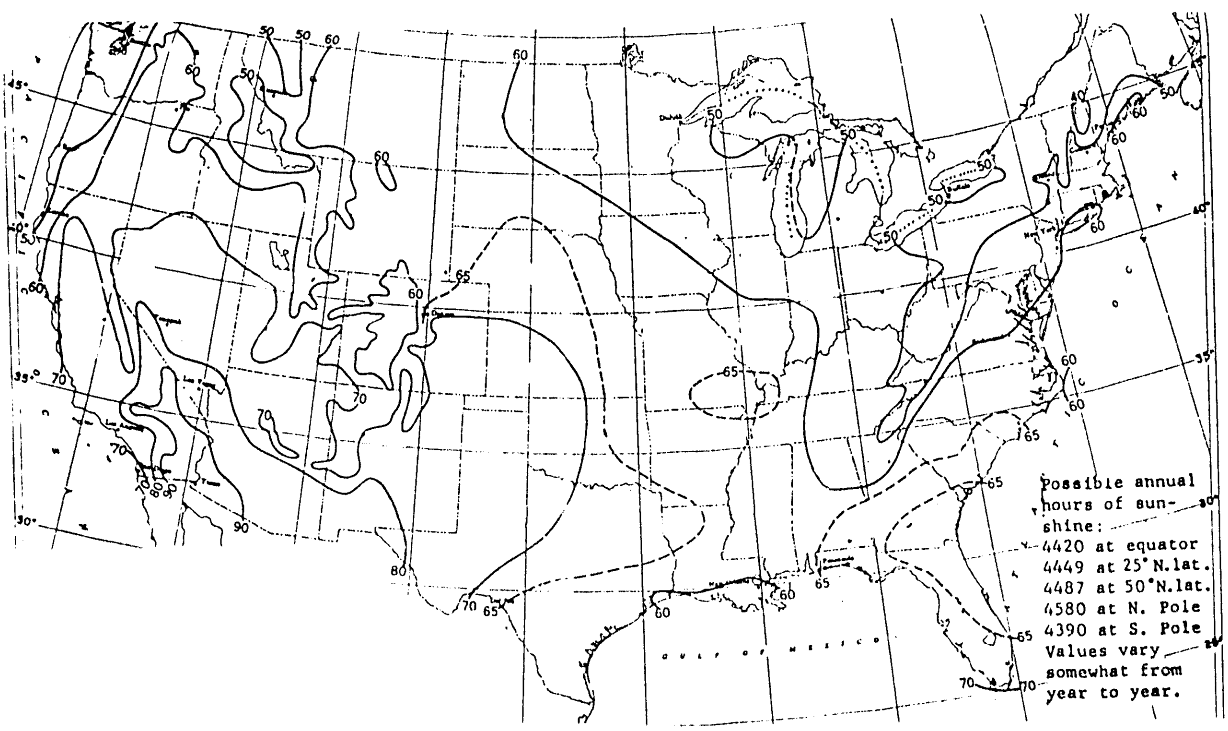

Figure 8. Map of the U.S. with the annual percentage of possible sunshine (from reference 11).

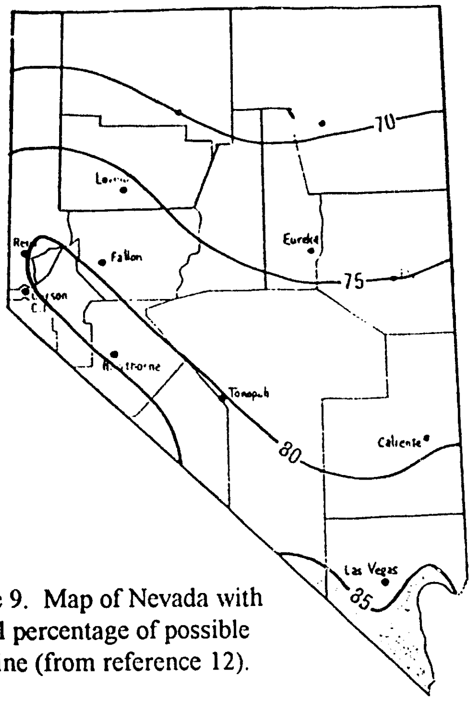

Figure 9. Map of Nevada with annual percentage of possible sunshine (from reference 12).

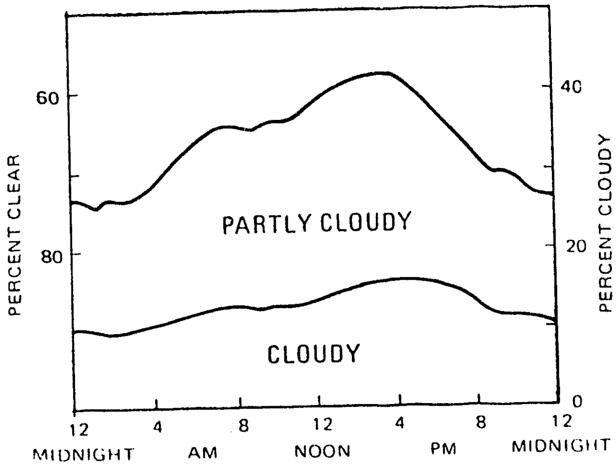

Figure 10. Average cloud variation over one day in Las Vegas, Nevada (from reference 12).

4. WATER

Megawatt-class lasers require cooling at the 10-1000 MW level. There are four underground aquifers on the site which are tapped by thirteen wells. The aquifer at Jackass Flats is 11 miles long, 3 miles wide, and contains about 40-190 billion gallons (150-720 billion kg). In 1967, the nuclear rocket program there consumed about 520,000 gallons (2.0 million kg) per day utilizing water from a single well.[16] That well, plus a standby well, have a total production capacity of 1.6 million gallons (6 million kg) per day. The present consumption rate for all of NTS today is 1.9 million gallons (7 million kg) per day.[8]

If we consider a mid-range requirement of 100 MW of cooling, and allow a temperature rise of 40° C, the water requirement is 600 kg/s (2.2 million kg/hour). For the GEO eclipse mission, or for orbit raising, 6 hours/day would be the maximum, requiring 13 million kg per day of water. This is about twice the 1967 capability from the two wells at Jackass Flats. Additional wells could be drilled at that location to make up the difference, or other locations may have better conditions. The water could be spread out in a cooling pond to allow heat transfer by evaporation to the atmosphere, thermal radiation to space, and conduction to the earth. Some salt build-up would occur from the evaporation, so an assessment of the environmental impact from this would need to be made before choosing this option.

Perhaps a better alternative to water cooling is air cooling. Assuming a 30° C increase in air temperature and a 20 m/s flow rate, the required area of heat exchangers is about 160 m^2. The heat exchangers are a simple and well-developed technology. (A very rough estimate of cost is about $10M). They may be more expensive than a cooling pond, but they would avoid the questions of water consumption and salt deposits.

5. SITE ALTITUDE

NTS consists of broad desert flats at an elevation of about 3000 feet (1000 m) and dry rounded mountains rising to as much as 7000 feet (2100 m) above sea level. These high altitudes allow beaming at larger zenith angles because of less air to penetrate and fewer aerosols. For example, a site at 5000 feet elevation is above 16% of the atmosphere. This allows an increase of about 7° in zenith angle for beaming (compared with a sea-level site). This in turn allows access to about 8 more GEO satellites (four on each side).

6. INFRASTRUCTURE, POWER AND ROADS

The NTS personnel have an extensive engineering, operational, and managerial capability stemming from 40 years of service to the nation in underground testing of our nuclear deterrent. The core capabilities at the site include architectural and engineering support for construction, geological services, engineering quality inspection, large-bore deep drilling, tunnel construction, radiation safety and monitoring, radioactive/mixed waste management, security, weather (history, monitoring, and predictions), seismic monitoring network, and a management team knowledgeable of the key requirements for hazardous, unique testing, such as design, safety operations, quality assurance, environmental safety and health, etc. The uniqueness of many of the capabilities at the NTS, coupled with an experienced, team-oriented, and knowledgeable infrastructure, is an unmatched national resource.

In addition to the personnel resources at NTS, there are also extensive facilities.[7,8] NTS uses commercial power provided by the Nevada Power Company over a 55-MW line rated at 138 kV. This is adequate for running a megawatt-class reactor pumped laser which is its own power supply, but is probably too low for electrically-driven lasers. For those, a power line could be run from Hoover Dam near Las Vegas 90 miles away. There is an extensive network of paved roads within NTS for a total length of about 175 miles, and additional supplemental unpaved gravel roads, as shown in Figure 1. Las Vegas is 75 miles away along U.S. 95. Area 5 at NTS contains a site for disposal of low-level waste generated by several DOE facilities.

7. REACTOR PUMPED LASER

Power beaming requires a laser which is 100-kW or greater for durations of several hours night after night. Chemical lasers in the 1.3 μm to 3.6 μm regime are near this power, but only operate for a minute or less. They consume and expel over a hundred tons of chemicals per MW-hr (chemicals such as chlorine, fluorine, and iodine). To operate for hours at a time, elaborate techniques would need to be developed to recover and recycle the chemicals (and still maintain the supersonic flow rates required). Free electron lasers (FELs) have a long way to go in power. Peak powers of 10 kW have been demonstrated over a brief period of 0.1 ms (and 100 MW over a very brief period of 10 ps), but for time scales greater than 1 second, the highest power demonstrated to date is 11 W at 2 to 10 μm.[17]

The DOE has been developing a reactor pumped laser which has excellent potential for long-duration lasing. (This laser is described in two other papers in this conference.)[18,19] The laser is driven directly by nuclear energy and is closed cycle for all gases. Lasing occurs in mixtures of inert gases such as xenon, argon, neon, and helium. Heat is removed by water heat exchangers in secondary loops. The system can be designed to run continuously (days or weeks) at the megawatt power level. The technology has achieved comparable levels of demonstration as FELs. Reactor-pumped lasing has been demonstrated in the lab at wavelengths of 0.585, 0.703, 0.725, 1.271, 1.733, 1.792, 2.032, 2.63, 2.65, and 3.37 μm with intrinsic efficiency as high as 2.5%. Powers of over 300 W have been achieved for 2 ms. Designs have been developed and demonstrated in experiments for modules which are predicted by detailed codes to be scalable to megawatt levels at continuous operation. Because of the nuclear expertise at the Nevada Test Site, it is in an excellent position to make use of a reactor pumped laser for power beaming.

Once constructed, a reactor-pumped laser could be used for a number of other dual-use applications. The continuous high power of an RPL opens many potential manufacturing applications such as deep-penetration welding and cutting of thick structures, wide-area hardening of metal surfaces by heat treatment or cladding application, wide-area vapor deposition of ceramics onto metal surfaces, production of sub-micron sized particles for manufacturing of ceramics, wide-area deposition of diamond-like coatings, and 3-D ceramic lithography. Defense-oriented development could be pursued, such as ship defense against anti-ship missiles and theater missile defense. The laser also could pursue long-duration projects such as removing space debris from LEO.[20]

8. SUMMARY

There are numerous considerations in choosing a site for laser power beaming. These include latitude, weather, water, infrastructure, altitude, and political or corporate support. Power beaming to GEO satellites from the continental U.S. requires the ability to access angles as low as 30° from the horizon because of the latitudes involved. Beaming during orbit-raising from LEO to GEO would be enhanced by using multiple sites because each site can view the satellite for only part of its orbit. The time-averaged view factor for LEO to GEO orbit transfer ranges from about 10% to 20% for latitudes ranging from 0° to 40° and orbital inclination angles ranging from 0° to 30°. These considerations give an advantage to equatorial sites. However, clouds obscure the equator for most land-base sites for about 50% of the time. In contrast, the availability of a clear line of site at the Nevada Test Site is about 84%, with potential sites more than a mile above sea level. In addition, there is a strong existing infrastructure for high-technology design, development, and construction. The present capability in handling nuclear materials also allows NTS to make use of a reactor pumped laser, which has the potential to supply a long-duration, high-power beam.

9. ACKNOWLEDGMENTS

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