TRADE STUDY: WHY SILVER

M.Lampton, UCB SSL,   April 2002; updated July 2002, August 2004, July 2007

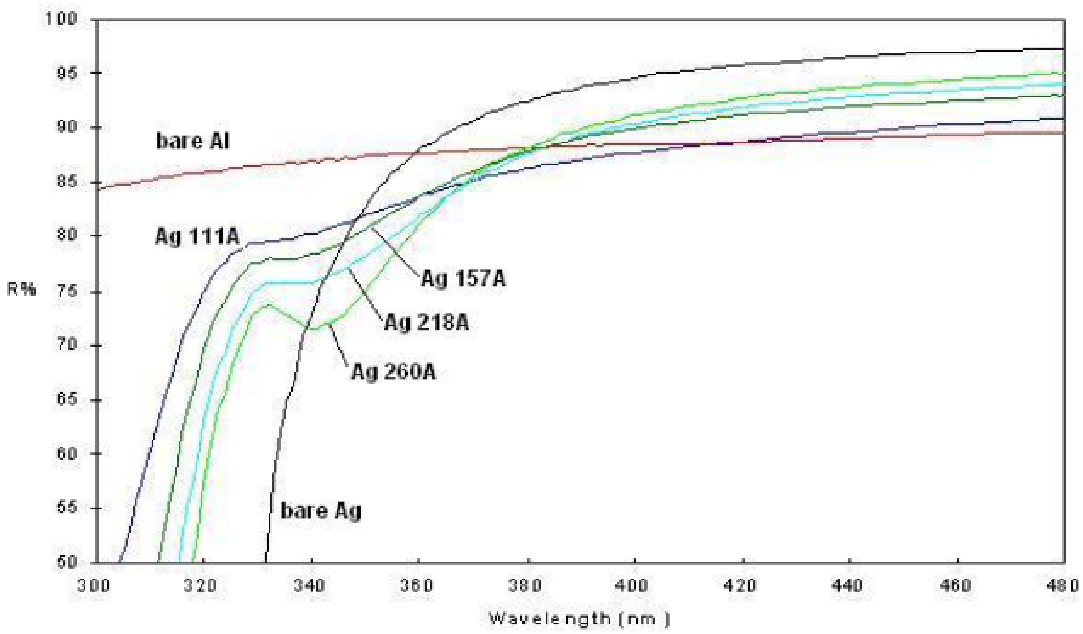

Figure 6: Initial Al-Ag coatings in comparison with Ag and Al only coating

from Sebag et al Proc.SPIE 6273 2006 exploring thin silver coatings atop aluminum.

J. Sebag et al, "LSST Reflective Coating Studies" Proc SPIE 6273 2006.

M. Boccas et al, "Coating the 8-m Gemini telescopes with protected silver" Proc. SPIE 5494, 239, 2004.

T. Vucina et al, "Gemini's Protected Silver Coatings: first two years in operation" Proc SPIE 6273 2006.

R. Wilson, Reflecting telescope optics II, chapter 6, 423-448, Springer-Verlag, Berlin, 1999.

D.Y. Song, R.W. Sprague, H.A. Macleod and M.R. Jacobson, “Progress in the development of a durable silver-based high-reflectance coating for astronomical telescopes”, Applied Optics, 24, 8, 1164-1170, 1985.

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Shimshock and D.C. Booth, "Development of silver coating options for the Gemini 8-m telescopes project", Proceedings of SPIE, 3352, 477-502, 1998.

N. Thomas, J. Wolfe and J. Farmer, "Protected silver coating for astronomical mirrors", Proceedings of SPIE, 3352, 580-586, 1998.

N. Thomas and J. Wolfe, "UV-shifted durable silver coating for astronomical mirrors", Proceedings of SPIE, 4003, 312-323, 2000.

D.K. Burge, H.E. Bennett and E.J. Ashley, "Effect of atmospheric exposure on the infrared reflectance of silvered mirrors with and without protective coatings", Applied Optics, 12, 1, 42-47, 1973.

P.D. Fuqua and J.D. Barrie, "Optical properties and corrosion resistance of durable silver coatings", in proceedings of Properties and processing of vapor-deposited coatings, Mater. Res. Soc. Proc., 555, 85-90, 1998.

C.T.Chu, P.D. Fuqua and J.D. Barrie, "An electrochemical impedance spectroscopy study of durable silver coatings", to be presented at the OSA/OIC, 2004.

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SUMMARY: In this trade study I present and summarize the findings of the SNAP optics and spacecraft teams during 1999-2001 concerning the issue of which reflective surface treatment our telescope mirrors should receive. The single highest priority desideratum bearing on the choice of mirror coating is the system throughput at the longest wavelengths where supernovae are the most distant and photons are the most precious. A secondary consideration is to establish a low thermal emissivity for the mirrors so that operating them at a reasonable temperature, approx 290K, will not seriously impair our astronomical sensitivity in our longest-wavelength near IR band, 1.3 to 1.7microns. A third concern is the mirror coating durability: during the years of telescope integration and launch preparation, the coating must not tarnish or otherwise degrade.

The most common coating for astronomical mirrors at visible wavelengths is SiO overcoated aluminum. It offers outstanding durability and unmatched reflectance throughout the visible band, 0.4 to 0.7 microns. A less common choice is protected silver, which is less efficient in the blue but more efficient in the red and near IR. Our SNAP optical system needs to operate over a wavelength range extending to 1.7 microns in the near IR, and has four reflections. The throughput therefore varies as the fourth power of the mirror coating reflectivity. We have baselined the use of protected silver rather than protected aluminum owing to its higher reflectance in the near infrared. We note that the Gemini 8 meter telescope at Mauna Kea (1) uses protected silver for essentially the same reasons. A comprehensive report on the Gemini work has been preprinted and published by Jacobson et al 1998 (2). Further examples of reflectance and throughput curves are included below.

(1) http://www.gemini.edu/
(2) http://www.gemini.edu/documentation/preprints/pre32.html

PROTECTED SILVER VS PROTECTED ALUMINUM

Bare metallic silver is poorly qualified as a reflective surface for two reasons: it adheres only weakly to glass, and its surface tarnishes badly when exposed to the atmosphere. For these reasons, silver requires extra care when used as a first surface reflective coating, as explained by Doug Miller of Northern Lights Optics (2000):

"Pure silver is not suitable as a coating as it has poor adhesion to most substrates and tarnishes quickly if left unprotected. Coating designers have addressed these limitations and many coating facilities have developed durable protected silver coatings that do not tarnish and maintain high reflectance and low polarisation. The details of the coating designs are typically not provided as they are considered proprietary by the vendors.

"Adhesion of the silver is improved by adding a binder coat between the substrate and silver layer. Tarnishing is prevented by adding a dielectric overcoat. An additional binder layer may be added between the silver and dielectric layer(s) to improve the adhesion between the silver and the dielectric overcoat. The choice of binder coats is dependent on the substrate and the choice of dielectrics is dependent on the required optical performance and environmental requirements.

"The Thin Films Group of the National Research Council were contacted regarding their capabilities with protected silver coatings. They described a successful coating process that has produced high reflectance pin-hole free coatings. The process involves placing a binder coat on the substrate and applying the silver layer. The silver is then overcoated with a very thin layer of silicon (Si) by sputtering. Oxygen is introduced to the chamber and a plasma is generated, completely oxidizing the Si to form a very dense, pinhole-free coating of SiO_2. Additional SiO_2 is then deposited to achieve the final required thickness.

"Some highly reflective protected silver coatings have flight heritage. The FSS-99 coating from Denton Vacuum has flown on a number of space missions. The FSS-99 coating is a proprietary front surface silver protected with multilayer overcoats with reflectance of 98% in the visible and 99% in the infrared. The coating meets a 24 hour humidity test along with the standard MIL-M-13508C requirements.

"There is some data that suggest that silver coatings are susceptible to UV degradation. Viswanathan presents data that show that reflectance can be degraded in the visible region with UV exposure. The choice of dielectric overcoat affects the severity of the degradation.

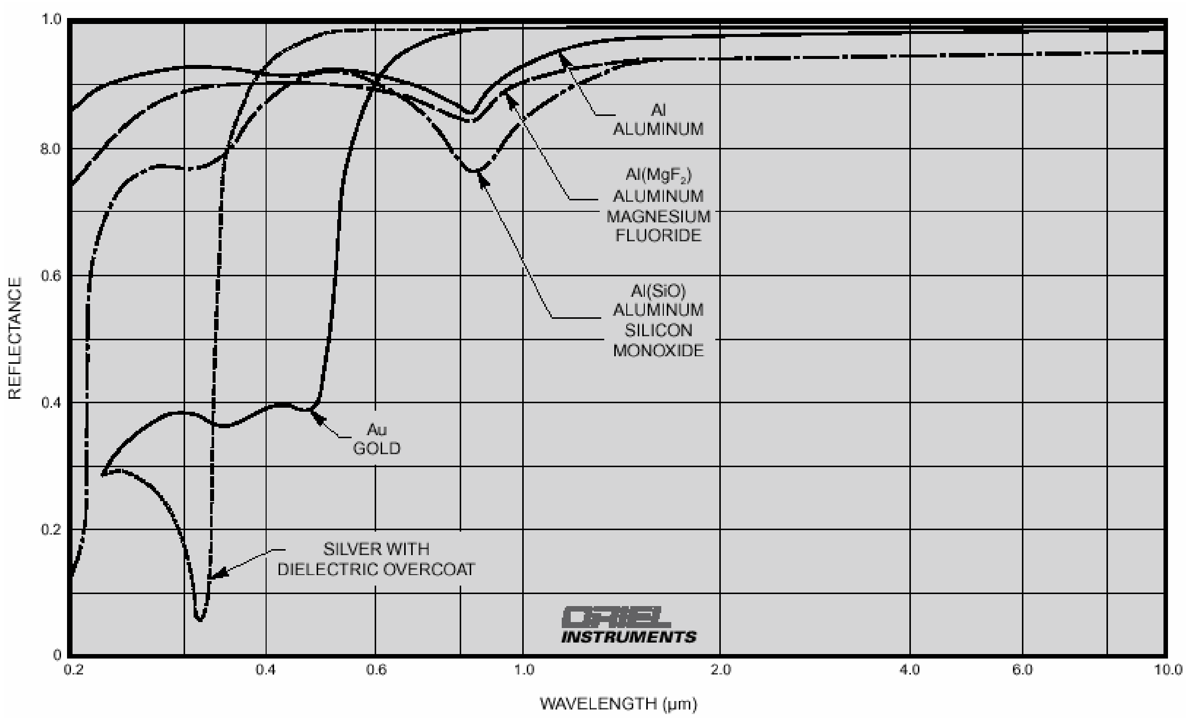
"Silver-based mirror coatings have also been developed for ground-based astronomy. Jacobsen described very high reflectance protected silver coatings developed for the Gemini telescopes (a joint project of the US, Canada, Great Britain, Argentina, Brazil and Chile).

These coatings have excellent reflectance over the vis-NIR spectral range and were designed to be deposited on ULE mirrors. "

-Doug Miller, 2000, Northern Lights Optics

Typical commercial protected silver mirror coating formulations are:

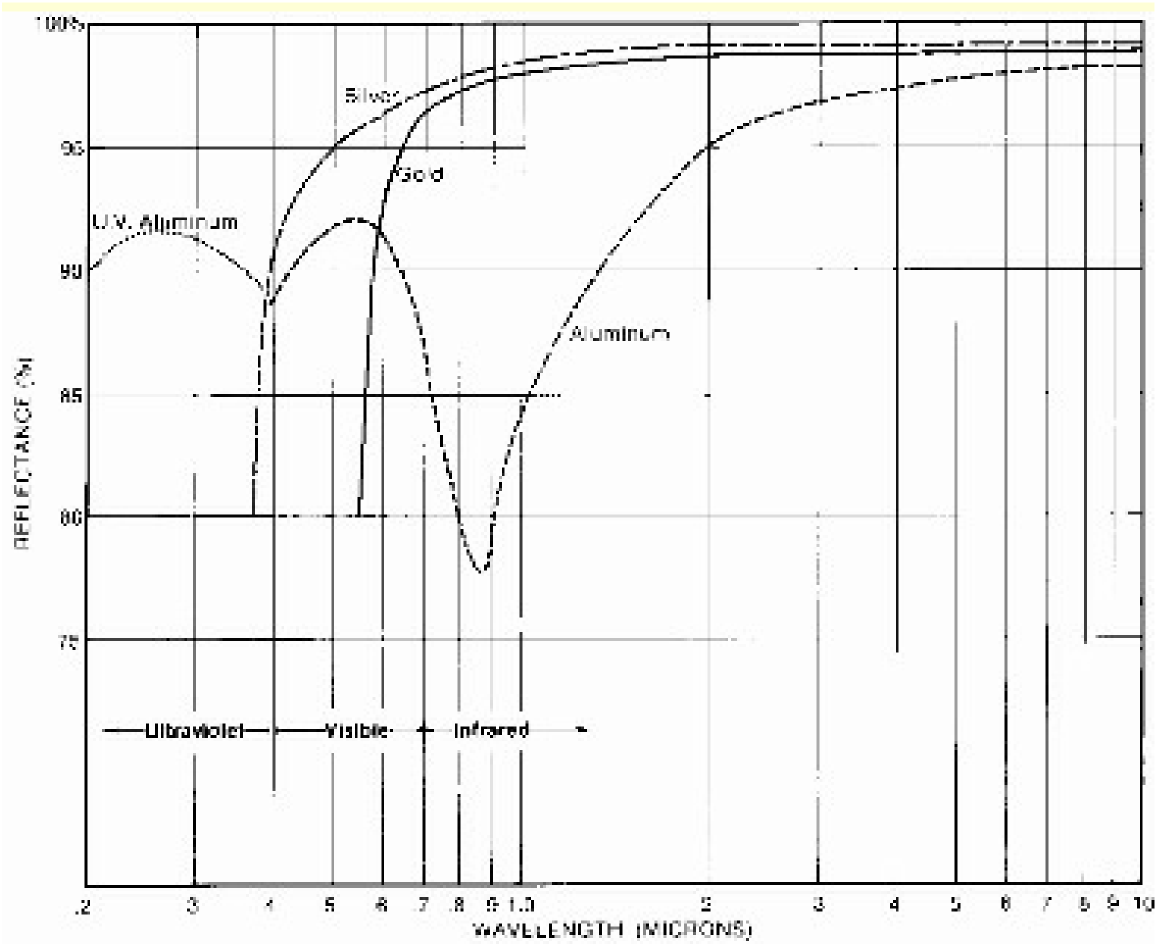
J.L.Wood Optical Systems type MPS-10
Opticorp Inc. Protected Silver
Denton Vacuum FSS-99
Oriel Instruments Protected Silver



Oriel Instruments (www.oriel.com/netcat/VolumeIII/pdfs/v36metct.pdf) presents the figure shown above for comparison between the normal incidence reflectivities of common mirror coatings. For the 0.35 to 1.7 micron SNAP band, silver with dielectric overcoat is the superior performer.

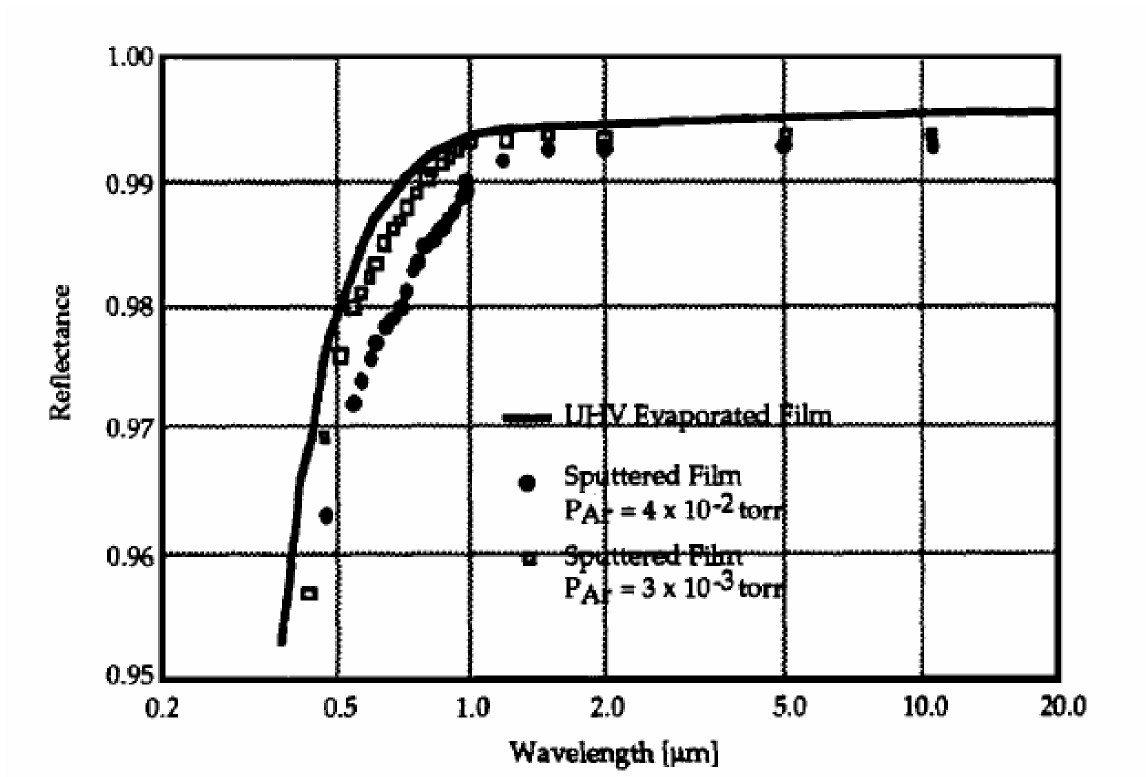
Denton Vacuum has extensive mirror coating experience for space mission telescopes and their website (http://www.dentonvacuum.com/coatings/FSS99.html) illustrates a variety of specialized protected silver coating applications.

Other manufacturers report similar curves for their proprietary protected silver mirror coatings. The following curves are from the Lambda/Ten website discussing the coating processes they offer (http://www.mcphersoninc.com/lambdaten/coatings.htm):

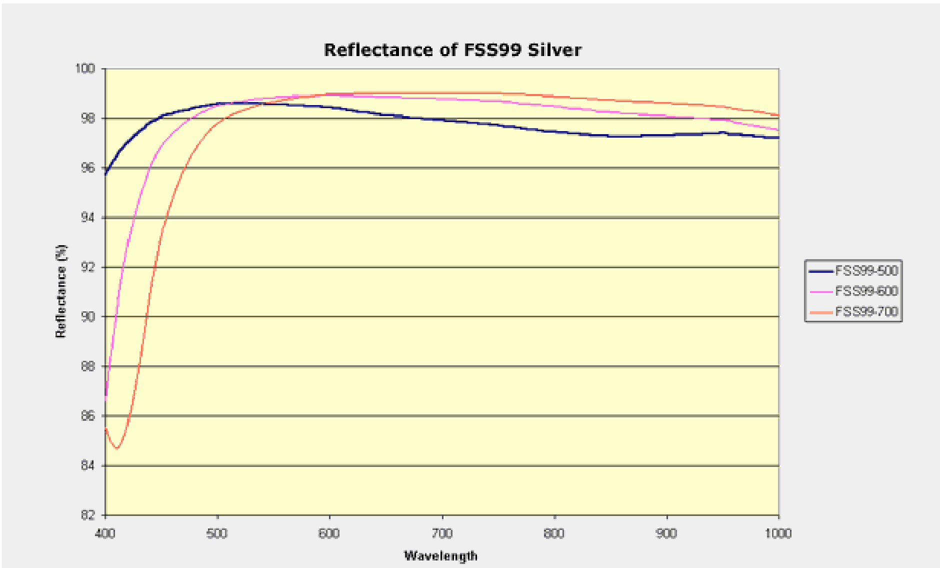


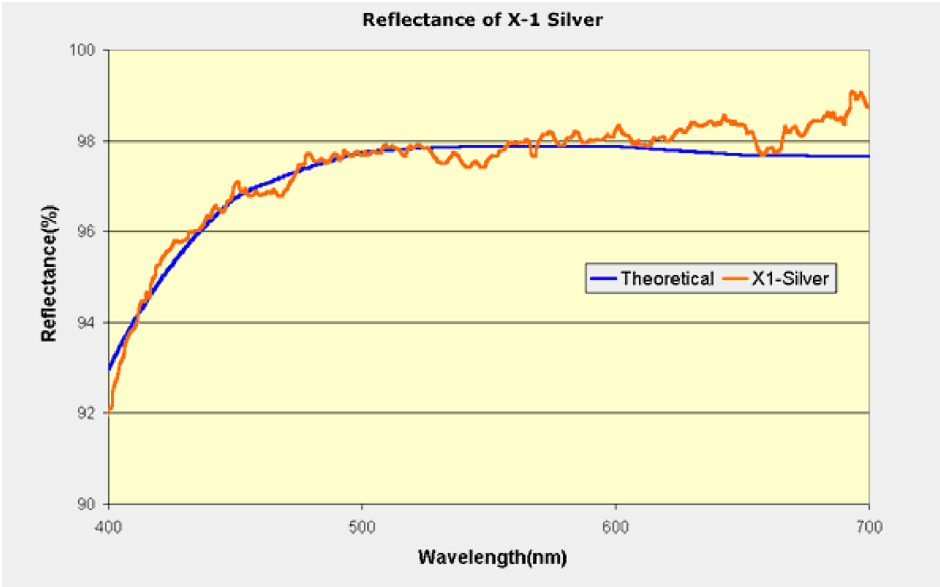
The chief problem with aluminum is the reflectance notch at 0.85 microns wavelength, at which the single reflection efficiency is about 80% at best. A four mirror telescope raises this loss to the fourth power, i.e. 40%, which is a serious hit in the NIR where signal to noise ratio is mission critical. We have concluded that our baseline choice of protected silver creates little or no mission risk while significantly improving our on-orbit signal to noise ratio.

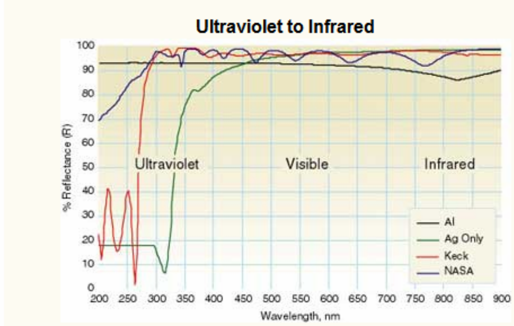
Test coatings of durable silver onto glass blanks have been measured in preparation for the GEMINI mirrors (http://www.gemini.edu/documentation/webdocs/rev/rev-te-g0007.pdf) and the reflectivity results are plotted in the figure below. These data suggest that a reflectivity of 99% or greater is achievable, and for SNAP we adopt a surface-average mirror reflectivity specification of 98.5% at one micron, and a mirror reflectivity goal of 99% at one micron.



FURTHER CURVES from Denton Vacuum added August 2004
http://www.dentonvacuum.com/coatings/metal.html#one







This graph compares the reflection bandwidth of bare aluminum and silver against the durable silver coatings designed for NASA and the Keck Telescope. Bare aluminum shows high UV reflection but has a reflection loss between 750 nm and 900 nm. Bare silver has the highest reflection of all but decreases dramatically below 400 nm. The NASA design, which emphasizes the extended ultraviolet, specifies greater than 70% R at 200 nm and greater than 95% average R from 300 nm to 2500 NM The Keck design, and that used for most terrestrial telescope applications, has greater than 95% R from 300 NM to 2500 NM.

CHARA Technical Report #91 Oct 2004, by S.T. Ridgway:
"Optical coatings for CHARA Reflective Optics"
http://www.chara.gsu.edu/CHARA/Reports/tr91.pdf

The GEMINI silver mirror coatings:

http://www.gemini.edu/files/docman/websplash/websplash2004-23/GN_silver_coating.pdf

COATING GEMINI'S MIRRORS WITH PROTECTED SILVER by Maxime Boccas

(sidebar) **Why Silver – A Scientific Perspective**

By Tom Geballe

The Gemini telescopes were designed to optimize performance at infrared wavelengths. One goal is to minimize infrared radiation from the telescope itself, which can cause the telescope to glow and make it more difficult to detect faint and distant objects in the cosmos. For example, the supports required to hold Gemini's secondary mirror are very thin as viewed from below, so that they block very little of the incoming radiation from a targeted astronomical object. More importantly, the amount of infrared radiation they emit into the telescope is minimized.

The telescope mirrors themselves are another source of background radiation. Although they look virtually spotless, dust particles, water droplets and other contaminants cause them to radiate more than pristine mirrors would. Thus the Gemini optics are cleaned frequently, and strict usage rules help protect the telescope from windblown dust, precipitation, and high humidity. In addition, the mirror coatings are a source of radiation, even when they are clean. Aluminum has long been the coating of choice because its reflectance is high (about 97% in the optical). It is relatively easy to apply, fairly resilient, and its infrared emissivity (how much heat it actually emits compared to the total amount a surface can theoretically emit) is only 3%. When coated with aluminum, Gemini's primary and secondary mirrors have a combined emissivity of about 6%. This seems like a low value, but at many infrared wavelengths where the atmosphere is highly transparent, the mirrors are the dominant source of extraneous and unwanted radiation.

Silver has an infrared reflectance of ~ 99% and an emissivity of only about one percent per mirror and in principle is a much better choice for an infrared-optimized telescope like Gemini. However, silver is much more difficult to apply and unless overcoated with a protective layer, is much more susceptible to damage from the environment. After lengthy and detailed tests, Gemini's engineers developed the techniques (described in the accompanying technical article) to coat the huge primary mirror and secondary mirror of each telescope with both silver and protective layers to assure a reasonable lifetime between re-coatings.

The scientific impact of this effort has already been felt. The effective increase in sensitivity at some near/mid-infrared wavelengths is equivalent to increasing our mirror's surface area by 13% when compared to an identical aluminum-coated mirror. This gives Gemini a significant advantage when exploring everything from the faint infrared glow of brown dwarf stars orbiting bright companions to distant galaxies exhibiting key spectral features that have been shifted into the infrared.

The Livermore Process: Jesse Wolfe and Dave Sanders
http://www.llnl.gov/IPandC/technology/profile/announcement/DurableSilverMirrorCoating.php

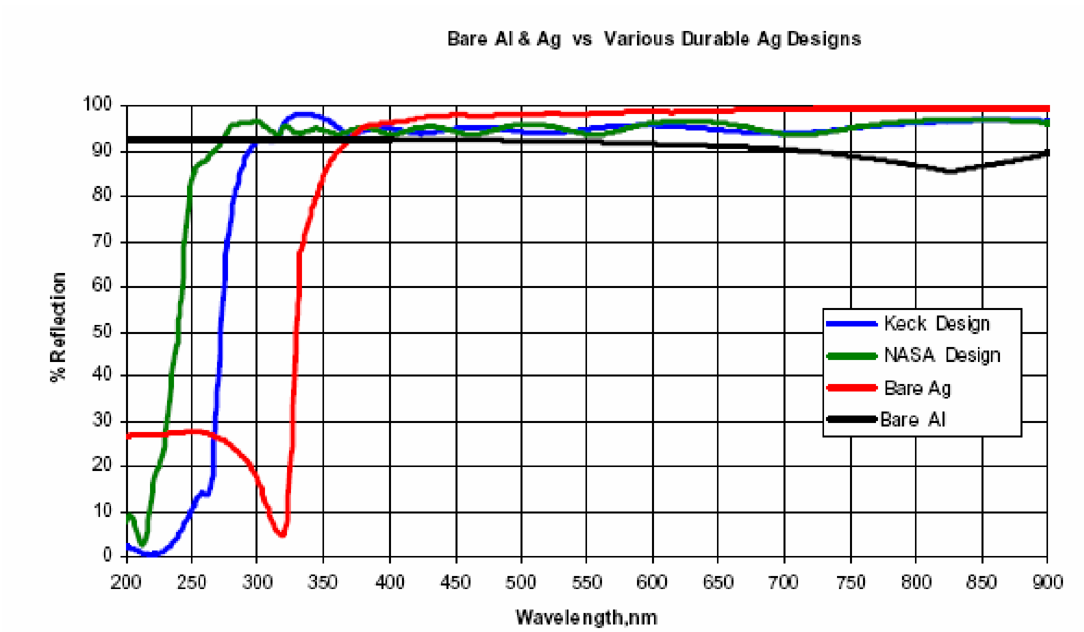
http://www.ucolick.org/~phillips/coatings/lit/fuqua_barrie.pdf

http://optics.nasa.gov/tech_days/tech_days_2004/docs/17%20Aug%202004/21%20LLNL%20Durability%20of%20Protected%20Silver%20Mirror%20Coating.pdf

Thomas and Wolfe (1998 SPIE 3352 580-586; 2000 SPIE 4003 pp.312-323) have described a process for creating a multilayer metallic reflective surface that combines the best features of silver and aluminum:

"UV-shifted durable silver coating for astronomical mirrors" -- abstract:

"Silver has the highest reflectance of all of the materials, but it tarnishes in the presence of sulfides, chlorides, and oxides in the atmosphere. Also, the silver reflectance is very low at wavelengths below 400 nm making aluminum more desirable mirror coating for the UV region. We have found a way to prevent silver tarnishing by sandwiching the silver layer between two thin layers of NiCrNx, and to extend the metal's high reflectance down to 200 nm by depositing the (thin) Ag layer on top of Al. Thus, the uv is transmitted through the thin Ag layer below 400 nm wavelength, and is reflected from the Al layer underneath. This UV-shifted durable coating provides a valuable alternative to the aluminum coating for telescope mirror coatings where high throughput and durability are important considerations. The throughput for a telescope with, say, six reflections from silver coatings is (0.97)6 equals 83% compared to (0.92)6 equals 60% for aluminum coatings, or 28% less. The use of silver coatings allows more photons to be collected by primary mirror. Aluminum also has a reflectance dip at 850 nm caused by inter-band transitions which is eliminated by placing the thin Ag layer on top. This paper describes a non-tarnishing silver coating having high reflectance down into the UV region. The average specular reflectance is 70% - 97% in the near-UV, 95% - 99% in the visible region, and >= 99% in the infrared region covering the total wavelength range 200 nm to 10,000 nm."



3% Thickness Uniformity Was Achieved With 2.5” Difference in Height Between Edge and Center