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Specification of optical components for a high average-power laser environment

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ABSTRACT

Optical component specifications for the high-average-power lasers and transport system used in the Atomic Vapor Laser Isotope Separation (AVLIS) plant must address demanding system performance requirements. The need for high performance optics has to be balanced against the practical desire to reduce the supply risks of cost and schedule. This is addressed in optical system design, careful planning with the optical industry, demonstration of plant quality parts, qualification of optical suppliers and processes, comprehensive procedures for evaluation and test, and a plan for corrective action.

Keywords: optical specifications, precision optics, subsurface damage, low absorption materials and coatings, microscopic surface and coating defects, laser damage threshold

INTRODUCTION

This paper will describe the specifications required for the optical components which will be used in an atomic vapor laser isotope separation (AVLIS) plant. This plant, as planned by the United States Enrichment Corporation, is described along with the optical requirements in a companion paper ¹ and is based on technology developed at the Lawrence Livermore National Laboratory (LLNL). The optical component specifications are based on laser system requirements developed in over 20 years of experience at LLNL. The optical component specifications have a major impact on the laser system performance. This impact is illustrated in several areas of performance. A general description of the optics needed for the plant are included along with key procurement issues and a proposed plan for procuring and testing these optics. Testing is described in a second companion paper. ²

The AVLIS laser system consists of dye chains pumped by copper lasers that produce high average-power laser light at precisely tuned wavelengths. The light from the dye laser is combined, transported to the separator and propagated through metal vapor as part of the photochemical process. ³ There are a variety of auxiliary alignment, adaptive optics, and laser diagnostic systems that monitor and actively control the laser system during operation. ⁴

1. OPTICAL REQUIREMENTS

The high average-power lasers and beam transport systems developed for AVLIS utilize thousands of efficient and reliable optical components. The basic elements of the optical system along with the quantities of optics required are illustrated in Figure 1. A significant effort has been made to optimize the design of these optical components for the specific AVLIS application. ⁵ Approximately 21,000 optical components are required for the high average-power laser which will generate the process light in the AVLIS plant. In addition, about 22,000 additional optics are required for the diagnostic systems used to maintain alignment, wavefront correction, and monitor power and profile of the process light. Although the optics in diagnostic systems are not used at high average-power, they often see significant power densities and demanding wavefront requirements. The 43,000 optics required for the plant compares with the approximately 44,000 optics which have been purchased for the AVLIS program over the past 13 years at an estimated cost of \$21M. In comparison, this similar level of procurement will be performed for plant activation in a planned 3 year period from 1999 - 2001.

Figure 1. Elements of the AVLIS plant laser system showing the quantity of optical components.

The laser and optical system plays a major part in determining the successful economic operation of the plant. A loss of power in the transport system, for example, has a direct impact in a loss of enriched product and can only be made up through additional lasers or improved optical component efficiency. The AVLIS plant optical system consists of demanding requirements:

- Optical efficiencies at process (visible) wavelengths
- Beam uniformity and wavefront quality (≤ 0.10 wave RMS)
- Beam pointing (microradian level) and position control (millimeter level)
- Images at specific locations
- High average laser power and power density ($> 10^4$ W/cm²)
- Reliability for maximum system availability over the following conditions:
 - the full range of laser power (alignment and operating)
 - the temperature and humidity environment (alignment and operating)
 - time

The primary requirements discussed here will be transport efficiency, wavefront quality of the delivered laser light to and through the enrichment area and reliability of the system. In order to increase optical system reliability, it is necessary to minimize (1) the risk of damage at high average-power, (2) changes that can occur with variations in power, temperature and humidity, and (3) changes over time. The optical system is designed using computer codes to perform ray tracing, diffraction, thermal effects, and enrichment performance. Part of this approach involves re-imaging the laser light at specific points through the laser chain and transport system to improve transport efficiency and beam quality. Although the system is designed to maximize passive stability, the system architecture and process requirements require that laser beam pointing and centering are monitored and corrected dynamically for long term operation. Similarly, transmissive optics required for beam combination and windows for interface to vacuum systems dictate that wavefront measurement and corrective systems be deployed to help maintain beam wavefront quality. Optical components must be large enough to avoid losses associated with diffraction losses.

Table 1 summarizes how the optical component relates to the optical system efficiency and wavefront quality. The high power density and long transport lengths impose specific requirements on the performance of optical components. The wavefront error contributed by optical components also results in efficiency losses over the long transport distances. Variations in the index of refraction for transmissive material and in shape of the optical surfaces are obvious causes of distortion of the wavefront quality of the laser light. It is also not surprising that component coating reflectance or transmittance (and related absorptance and roughness related scatter) would affect the overall system efficiency. The accumulated effects of optical component performance can be dramatic in a large optical system and in some cases even isolated components can cause major performance problems. Finding the defective components in a transport path consisting of over a hundred optics can be a time consuming challenge. The impact of these parameters on a large system like AVLIS will be discussed below.

Table 1 Impact of optical components on optical transport system performance

OPTICAL COMPONENT PERFORMANCE	OPTICAL SYSTEM	
	EFFICIENCY	WAVEFRONT QUALITY
Bulk index variation	✓	✓
Surface shape errors	✓	✓
Surface roughness / defects	✓	-
Reflectance / transmittance	✓	-
Absorptance	✓	✓

There are certain conditions where stability of the optical component performance can also be a factor in the overall system performance. These changes have been observed over various operating conditions and represent another level of control that must be imposed on the manufacture and quality of the optics. These conditions include:

- Spectral shift in the optical coating performance as a function of humidity (e.g., from air to vacuum)
- Change in the shape of the optical surface due to humidity changes in coating stress, (e.g., air to vacuum)
- Changes in coating absorption as a function of the power density in the laser beam
- Changes in absorption and stress over time
- Damage to coatings and bulk material due to high average-power density laser light

1.1 Efficiency The optical system transport efficiency can be related to reflectance (or transmittance) and roughness of the general component optical surfaces as shown in Figure 2. For a system with between 100 and 200 optical surfaces in the transport path, the efficiency is dramatically different due to only 1 part in a thousand difference in surface efficiency. To make up for a difference of 0.998 to 0.997 in surface efficiency, approximately 10% more pump laser power would be needed. This would be an expensive option. A similar loss is predicted due to surface roughness increasing from 10 Å RMS to 20 Å RMS.

Figure 2. Impact of component efficiency and surface roughness on optical system transport efficiency

An effort has been made to control coating efficiency through optimization of the design and coating process for AVLIS coatings. Specific test equipment have been developed to provide feedback to this development process and for production control. Roughness measurement and related scatter measurement are now possible as commercial equipment has become available. Achieving high efficiency and low roughness is part of the evaluation used to qualify AVLIS optics suppliers.

1.2 Surface quality Surface quality can be degraded by many causes from quality of the bulk material, grinding and polishing process, cleaning, coating, handling, and laser exposure. Cosmetic defects have traditionally been specified by the comparative size of scratches and digs. Pin holes in the coating and severe cases of crazing are easily recognized. In continuous or high-average power lasers, laser damage and scatter are undesirable results of more subtle forms of defects in the optical surface. The types of defects typically observed in the AVLIS inspection process are listed in Table 2. The performance impact on the optical system caused by these surface defects is

typically an increase in energy lost through scatter and in the likelihood of damaging in a high average-power laser environment. The test methods used to identify and characterize the defects are also listed in this table. Industry standards for specifying and controlling surface quality are inadequate for the AVLIS application. Close interaction with the manufacturers is a critical part of AVLIS optical supplier assurance and maintaining production quality.

Table 2. Surface quality defects which can increase scatter loss and lower the laser damage threshold

SURFACE QUALITY DEFECTS	TEST METHOD
Localized imperfections	Inspect with high intensity light; characterize by microscope
Scratches	
Pits (digs)	
Broken bubbles	
Sleeks (impact uncertain)	
Abrasions	
Stains	
Fixture marks	
Coating blemishes	
Pinholes	
Spatter	
Stains (impact uncertain)	
Crazing	
Global surface texture	
Surface roughness	
Micro-defects (gray)	Profilometer inspect with high intensity light; characterize by microscope ↓ TIRM or acid etch
Underpolish	
Haze	
Micro-structure	
Subsurface damage	

General surface degradation appears gray and this term is used to describe a variety of microscopic defects including underpolish (due to insufficient polishing time) or by material redeposited on the surface during polishing that is not removed during subsequent steps of polishing and cleaning (referred to here as "haze" and "micro-structure"). Haze is caused by discrete particulates of hydrated silica redeposited due to improper polishing conditions. Micro-structure is a continuous layer of redeposited material caused by improper polishing conditions and is the among hardest type of micro-defect to observe, often requiring high power magnification to identify. Subsurface damage consists of fractures propagating into the surface during grinding or polishing which is not completely removed during final polishing and is typically covered over by a layer of redeposited material which makes observation very difficult by conventional techniques. The importance of subsurface damage and its relationship to laser damage in the AVLIS application has been described.⁶ The usual approach to observe subsurface damage is by chemically etching the surface of the optic in hydrofluoric acid. This destructive method is typically not used by optic suppliers on a production basis. An alternate method, total internal reflection microscopy (TIRM), has been developed by others and applied to the AVLIS testing program as reported in the companion paper². An example of TIRM surface images are shown in Figure 3 compared to an etched and unetched surface. Light scattered by the subsurface fractures can clearly be seen under TIRM and is comparable to the microscopic view of the etched surface whereas it is not seen under a similar micrograph of the unetched surface.

Figure 3 Comparison of polished, etched, and TIRM inspection techniques of a well-polished surface. TIRM is able to detect subsurface defects that etching does not reveal.

Coating spatter consists of deposits of coating material on the optical surface in liquid form and typically increases the chance of damage in laser applications. This can be an effect of the coating materials chosen and the coating process itself. Coating chamber contamination and spatter in the early stages of coating deposition can result in "nodules" which have been observed to eject during high energy laser exposure and result in damage under certain conditions.⁷

Stains on the optical surface can be occasionally observed after polishing but more often is observed after coating. The stains result from improper processing during polishing and subsequent cleaning or in the cleaning and handling prior to coating. Stains appear as blotches on the surface and may be a form of contamination or variation in surface texture. Stains can be relatively easy to see but have not been confirmed to be related to laser damage. The possible damage mechanism in this case may be delamination of the coating from the substrate under the stress of high laser power or over time in isolated cases.

The optical surfaces are inspected under high intensity lights using an eye loop, with profilometers, and using TIRM. If discrete defects or grayness are observed, high quality microscopes are used to identify the cause as part the steps to correct the process problems.

1.3 Wavefront quality Wavefront errors stem from material inhomogeneity of the optical index, surface deviations from the ideal flat, spherical, or aspheric shape, or stresses imposed by the optical or mechanical mounting. Table 3 lists these causes of wavefront distortion and the specifications and methods of control used.

Table 3. Causes for wavefront distortion and methods of control

CAUSE OF WAVEFRONT DISTORTION	SPECIFICATION	CONTROL
• Variation in the bulk optical index	Typically <1 ppm (depends on size)	Interferometry using "oil-on" plates; interferometry after polished
• Thermally induced index changes	Bulk abs. <5 ppm/cm Coating abs. < 10 ppm	Design & cleanliness; see absorption below.
• Manufacturing deviation from the ideal optical surface	<0.05 wave p-v	Phase interferometry
• Stress in the optical coating	<0.05 wave p-v	Phase interferometry in operating environment (air or vacuum)
• Mechanical deformation in mounting	<0.025 wave p-v	Phase interferometry before installation

The combination of wavefront errors contributed by the optical components tend to be random in nature and the cumulative effect on the laser beam wavefront added in an RMS sense. An exception to that is the change in shape caused by coating stress. Conventional coatings produced by e-beam evaporation are deposited in vacuum at high temperature. When the components are cooled and exposed to the atmosphere, there is a differential dimensional change with temperature and the coatings absorb water vapor from the air, generally becoming convex. These stress-induced convex shapes typically are much larger than the error budget given in Table 3. Procedures have been developed for changing the stress balance imposed on the substrate through techniques such as optimizing the deposition parameters, backside coating (to balance the stress), and annealing. The measurement of coating stress on optical surface shape must be made in the same environment that the part is used in operation. This is necessary so that meaningful judgments can be made about the subsequent corrective action to be taken. Left uncorrected, the beam would see a systematic error on the order of 0.3 waves peak-to-valley for each of over a hundred optical surfaces which far exceeds the requirements for beam quality. The solution is corrective action by the coating suppliers to minimize distortion in each optical surface. Closed-loop adaptive-diagnostic systems are used in AVLIS to evaluate beam wavefront and change the shape of a thin mirror to reduce the observed wavefront error. The adaptive system corrects for a variety of errors in the beam and is most effective with low order aberrations such as the residual stress-induced curvature.

The other wavefront effects are more random in nature. Bulk fused silica is selected for its good homogeneity but until the surfaces are polished, final evaluation of the transmitted quality can not accurately be made. Some material is rejected after polishing because it does not meet the transmitted wavefront specification (0.05 waves p-v) and

these losses must be included in the procurement plan. Manufacturing errors in polishing the surface can be controlled by experienced suppliers with phase interferometry for feedback. Measurement accuracy is usually limited by the quality of the reference optics used in the interferometry for comparison. Similarly, interferometry has been found to be useful as a final evaluation of the mounted optics before installation in the system. Although the mounts are designed to be "stress free", problems still occur and are eliminated in the inspection process.

1.4 Absorption The optical transport system for a high average-power laser requires thermal management. Based on the size and complexity of the AVLIS system, a program decision was made in the early 1980's to manage heat absorbed in the optical components and the subsequent performance problems without active cooling. Active cooling methods had been deployed at that time in other high power application such as material processing and weapons applications at longer wavelengths. The AVLIS Laser Demonstration Facility which started operating in 1985 actually had a water cooled beamsplitter deployed at the end of each pump laser. Active cooling was not considered desirable in AVLIS because it introduces other lifetime and reliability issues, and becomes a liability in the extensive vacuum systems used for the process laser optical transport path.

System designs, optical coatings and substrate materials were selected and optimized to minimize the power density and influx of thermal energy into the optical component itself. When a substrate is heated by a laser beam, optical properties sensitive to temperature cause distortion of the laser beam and produce a lensing effect. The substrate material for transmissive optics must be selected for an optimum balance of absorption at the wavelengths involved, the thermal coefficient of expansion and the temperature dependence of the index of refraction against cost and availability. For the AVLIS wavelength range, fused silica is the material of choice. Early studies^{8,9} demonstrated that the alternate choices of fused silica were similar in absorption at these wavelengths. Mirror substrates which do not have to transmit high power, were chosen to be Zerodur or ULE in order to take advantage of their low thermal coefficient of expansion when heat is applied through the reflective coating.

Typical thin-film dielectric coatings at that time, which consisted of more than a few layers, demonstrated absorption in the range of 100-1000 parts per million (ppm). Besides being a significant part of the loss budget for each surface (total loss specified at <2000 ppm), the coating couples heat to the substrate material. In order to minimize the chance of coating delamination from the substrate (damage) at high temperatures and the beam effects due to thermally-induced changes in the substrate, the optical coatings also have to be optimized. Significant improvements in coating absorption within the first few years of this effort resulted in absorptions of <10 ppm for all antireflection, mirror, and most beamsplitter applications and <50 ppm for the more complex applications.¹⁰ Each coating manufacturer has optimized designs around their particular experience, processes, and equipment. With over 60 types of coating applications in the AVLIS plant, this effort is still continuing. Changes in wavelength, angle of incidence, reflectance and polarization characteristics for individual applications result in new requirements for the coating which has to be optimized. The AVLIS optical transport system is highly stable and reliable under changing thermal loads without any active cooling.

The ability to test for absorption was critical to the development of optimized optical coatings and also useful for evaluating the effects of surface contamination which may occur during handling and operation. This testing initially used the high power AVLIS laser itself as the energy source and has progressed to a low power method currently being developed as discussed in the companion paper.² Thermal analysis of the optical system is also critical. This is done with a computer code called TSO (for Thermal, Structural, Optical analysis).¹¹ Table 4 shows the results of a comparison of substrate material for a transmissive application (76 mm diameter, 12.6 mm thickness) using TSO. Compared to the fused silica, BK7 is approximately 32 times higher in absorption at the wavelength of interest, the thermal coefficient of expansion is 13 times higher, and the change in refractive index is only one-sixth as much. With a specific amount of distortion permitted, the fused silica will handle approximately 9 times more power than the BK7 substrate. Similar results have been confirmed in tests in the AVLIS system.

Table 4. Thermal modeling predicts the ability of fused silica to handle more laser power than BK7

PARAMETER	FUSED SILICA	BK7
Bulk absorption	5 ppm / cm	160 ppm / cm
Laser power (W)	645	69
Change in refractive index	18 ppm	1.5 ppm
Temperature variation (beam center to edge of part)	0.96°C	4.02°C
Wavefront distortion (waves p-v at 633 nm)	0.04	0.03

1.5 Survivability The optical transport system is designed to limit the power density on most of the components to relatively safe levels. Optics in the transport system image relay telescopes are subjected to the highest power levels along with optical components in the pump laser's fiber transport system and in the dye amplifier and interamplifier relay telescopes. The effort to reduce coating absorption lead to a dramatic improvement in the power densities at which the coatings could safely operate without damaging over years of laser exposure. An effort has also been made to find other relationships between coating survivability, coating designs, manufacturing defects and surface contamination. Most of the defects in Table 2 have been studied under high power laser light. The survivability testing is performed in the same area that the absorption measurements are performed using light from the AVLIS laser. Results of this testing has guided the coating design efforts and AVLIS coating suppliers, in setting the AVLIS laser and optical system specifications, and in planning for the levels of cleanliness needed for reliable operation. Examples of some of the survivability levels for AVLIS coatings are shown in Figure 4.¹² AVLIS coating designs have not been specifically optimized for the highest possible level of survivability, only to ensure reliable AVLIS operation. The term "survivability" is used in this case as opposed to more common terms such as the "laser damage threshold" to clarify that our studies and efforts have emphasized the exploration of safe operating limits rather than the onset and propagation of damage during laser exposure.

Figure 4. Survivability levels of AVLIS optical coatings

1.6 Reliability In addition to verifying optical component performance under static conditions, there are circumstances where changes in component performance has occurred which effects the optical system operation. All of these effects are associated with the thin-film coating applied to the optical surfaces. Catastrophic damage to the coating of an optical component, described in the previous paragraph, is the most disruptive event that can occur. Component failure can disrupt a section of the plant operation, causing loss of power and requiring immediate corrective action. The impact of this event warrants that an effective effort be made to ensure that all components installed meet a level of survivability which reliably ensures plant availability.

Other changes take place which complicate the acceptance of optical components and operation of the optical system. The spectral performance and stress in the coating depends on the amount of water vapor absorbed in the coating.¹³ These effects are illustrated in Figures 5 and 6. Coatings which depend on the critical placement of the

transmission curve such as dichroics and polarizers, have to be tested at the humidity level at which they will be used. Dry nitrogen or desiccants do not reach a level comparable to the AVLIS vacuum conditions (10^{-3} Torr) which means that spectral and interferometry have to be performed with the optics in vacuum chambers as described in the companion paper.² The time required for the optic to reach equilibrium in vacuum is often much longer than commonly believed. The time to reach equilibrium can be 48 hours. This causes long cycle times when coating suppliers are trying to control stress to meet the component wavefront requirements. This also has implications for the optical system when it is cycled from air to vacuum after maintenance. Critical angle adjustments have to be made in the transport system on sensitive optics to compensate for spectral shifts after sufficient time has been allowed for the components to stabilize in vacuum. This complicates the remote alignment requirements and extends the cycle time required for system maintenance. In order to avoid this problem, at least in the most critical applications, coating technologies which produce denser coatings have proven to offer advantages. Ion beam sputtered (IBS) coatings have been developed for at least six different types of coatings and demonstrate virtually no spectral shift or stress changes during air to vacuum cycling. This approach is utilized where the cost and capabilities permit.

Absorption of some coatings has been found to be dependent on power density.¹⁴ This has been dealt with by absorption testing at the maximum power density that the coatings will see in operation. Optics with strong nonlinearity characteristics are rejected during testing. This is a complication when attempting to use low power methods to test absorption which is a goal for providing absorption testing capability to the plant optical test capability and coating suppliers. Because some coatings are low absorbing when tested at a low power density and high absorbing at high power operation, the test approach must incorporate high power density which means very small beam sizes for commercial laser sources. This effort is described in the companion paper.²

The only unexpected aging effects observed in optical performance has been coating absorption. Over a period of six years, absorption of a set of optics was monitored. Changes were relatively small except for some of the coatings which utilized Ta_2O_5 as the high index material. An increase in absorption of almost 200 ppm was observed for some of these coatings. This effect was isolated to specific coating suppliers. Using this data, the manufacturers can modify the process parameters or select alternate materials.

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Figure 5. Spectral shift of broadband mirror coating showing the change in transmission between air and vacuum. The vacuum condition is 72 hours at 10^{-3} Torr.

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Figure 6. Change in reflected wavefront between test in air and vacuum (10^{-3} Torr).
The dense ion beam sputtered coating is relatively stable compared to conventional e-beam coatings.

2. OPTICAL COMPONENT DESCRIPTIONS

Of the 42,000 optics required for the AVLIS plant, approximately 25,000 are custom made with the balance available through commercial suppliers. The custom optics can be described by the quantity, size, materials, and coating types shown in Figures 7 and 8. The majority of the optics are on the order of 25 mm or less. Optical components for the process laser optical transport system are generally 150-200 mm in diameter. A relatively small number of large optics (670 mm in length) are required which present special manufacturing problems in order to meet the high performance specifications.

Figure 7. Description of the size (largest dimension) and materials used in the plant AVLIS custom optics

Figure 8. Description of the size (largest dimension) and coatings used in the plant AVLIS custom optics

Reflective optics are used wherever possible to avoid thermal distortion associated with transmission through bulk material. High quality fused silica is the only substrate material used when transmission is required for the high average-power laser light. Surface quality must meet demanding standards to ensure high levels of survivability (high assurance that damage will not occur due to laser exposure) and low transport losses. Optical coatings are optimized in each application for maximum efficiency, low absorption, high levels of survivability, and controlled stress. The specifications for the AVLIS optical components are summarized in Table 5.

Table 5. AVLIS plant optical component specifications

PARAMETER	REFLECTOR	TRANSMITTER	CONTROL OPTIC (Reflects & transmits)
Material	Zerodur (or ULE)	Fused silica	Fused silica
Homogeneity	Fine anneal	≤ 1 ppm	≤ 1 ppm
Bubble/inclusion	—	0.28 mm	0.28 mm
Bulk absorption (/cm)	—	≤ 50 ppm	≤ 50 ppm
Size	AVLIS standard	AVLIS standard	AVLIS standard
Surface parallelism	45 ± 15 arc sec.	45 ± 15 arc sec.	45 ± 15 arc sec.
Surface tilt angle	≤ 1 arc min.	≤ 1 arc min.	≤ 1 arc min.
Surface roughness	$\leq 10 \text{ \AA}$ rms	$\leq 10 \text{ \AA}$ rms	$\leq 10 \text{ \AA}$ rms
Subsurface damage	None	None	None
Microscopic defects	Minimize*	Minimize*	Minimize*
Radius tolerance	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$
Visual: scratch/dig	10:5	10:5	10:5
Wavefront distortion	≤ 0.05 waves p-v	≤ 0.05 waves p-v	≤ 0.05 waves p-v
Edge/chamfer	Inspection polish	Inspection polish	Inspection polish
Coating reflectance	≥ 0.998	< 0.003	≥ 0.99 (or ± 0.02)
Absorptance	≤ 10 ppm	≤ 10 ppm	≤ 50 ppm
Survivability (W/cm^2)	$> 10,000$	$> 10,000$	> 2000 to $> 10,000$
Wavelength range	510-950 nm	510-950 nm	510-950 nm
Uniformity	$> 99\%$	$> 99\%$	$> 99\%$
Environment	$35 \pm 15^\circ\text{C}$, vac/air	$35 \pm 15^\circ\text{C}$, vac/air	$35 \pm 15^\circ\text{C}$, vac/air

* Minimize through qualification and routine inspection.

3. APPROACH TO PROCUREMENT AND ASSURANCE

A well-planned procurement, test and quality assurance effort will be needed due to the large number of optics, the demanding specifications, and the importance of only installing acceptable optical components into the optical transport system. Based on current experience, obtaining the AVLIS plant optics will be a significant undertaking. There is a limited capacity for producing the high quality materials, substrates and coatings. In addition, there will be potential demands from other large markets such as the telecommunications and semiconductors, and large Projects like LIGO and the National Ignition Facility during this period of time. An outline of the experience and some of the areas of planning and assurance is given in Table 6. The cornerstones for assuring optical quality is qualification of suppliers, and maintaining the test capability to both qualify the suppliers and verify performance of the optical components during production acceptance testing. This testing emphasizes measurements of the actual optics (rather than witness samples) in the operational laser environment (particularly temperature, humidity, and power density), whenever possible. The optical industry capacity must be evaluated against the plant quantity requirements for both activation and continued plant operation. Qualifying suppliers of critical services and establishing long term relationships with optic suppliers are important parts of USEC's optical procurement plan.

Table 6. AVLIS plant optics procurement

<u>Current experience and assumptions:</u> <ul style="list-style-type: none">• Expensive materials and complex manufacturing processes• Large size of some parts requires specialized equipment• Long manufacturing times• Optical performance is difficult to verify• Industry capacity is limited for high quality optics• Other customers compete for limited capacity
<u>Plan and assurance:</u> <ul style="list-style-type: none">• Maintain USEC test capability• Plan the manufacturing cycle balancing plant volume against industry capacity - currently planning 3 years• Qualify suppliers in each area: material, fabrication and coating [Demonstrate supplier capability in manufacturing and test as well as corporate commitment]• Long term contracts: from plant activation to continuing operation• Supply unique manufacturing or test equipment• Verify actual part performance in operational conditions• Monitor production quality, cost and delivery

SUMMARY

The AVLIS optical components have demanding performance requirements dictated by the high average-power laser system, process requirements, long path lengths and economics of the AVLIS plant. To meet the plant requirements for delivered power and distribution of the laser light as well as reliability of the laser system, careful control must be exercised over the manufacture and testing to assure component performance. To meet the schedule and cost goals for plant startup, close coordination must be maintained with the optical industry to assure that specifications have been balanced against both manufacturing capabilities and plant economics and that qualified suppliers are available with the capacity to produce the large number of these high performance optics that will be needed. Because AVLIS optical specifications are not conventional performance and quality requirements, there are issues in manufacturing and testing which go beyond existing standards and general industry experience. The purpose of this paper was to review these AVLIS optical requirements with the optical industry. A major planning effort will be required to establish an effective relationship with key areas of the optical industry in order to have a adequate number of qualified suppliers of material, polishing, and coating. This effort must ensure sufficient production capability, testing facilities and a long term commitment to meet the needs for both the initial plant construction and the following plant support for replacement optics.

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REFERENCES

1. K. A. Primdahl, J. R. Taylor, and R. Chow, "Optical manufacturing requirements for an AVLIS Plant", *Proc. of SPIE on Optical Manufacturing and Testing II*, Vol. 3134, San Diego, 1997.
2. R. Chow, J. R. Taylor, W. K. Eickelberg, K. A. Primdahl, "Testing of optical components to assure performance in a high average power environment", *Proc. of SPIE on Optical Manufacturing and Testing II*, Vol. 3134, San Diego, 1997
3. R. P. Hackel, B. E. Warner, "The copper-pumped dye laser system at Lawrence Livermore National Laboratory," *Proc. of SPIE on Laser Isotope Separation*, Vol. 1859, pp.120-129, Los Angeles, 1993.
4. E. S. Bliss, R. L. Peterson, J. T. Salmon, R. A. Thomas, "Laser beam control and diagnostic systems for the copper-pumped dye laser system at Lawrence Livermore National Laboratory," *Proc. of SPIE on Laser Isotope Separation*, Vol. 1859, pp. 130-144, Los Angeles, 1993.
5. J. R. Taylor, C. J. Stolz, "High-efficiency high-reliability optical components for a large, high-average-power visible laser system", *Proc. of SPIE on Intracavity and Extracavity control of laser beam properties*, Vol. 1869, 104-114, Los Angeles, 1993
6. A. A. Tesar, N. J. Brown, J. R. Taylor, C. J. Stolz, "Subsurface polished damage of fused silica: Nature and effect on laser damage of coated surfaces," *Laser-Induced damage in Optical Materials: 1990*, editors H. Bennett, L. Chase, A. Guenther, B. Newnam, M. Soileau, Vol 1441, pp. 154-172, SPIE, Boulder, 1990
7. R. J. Tench, M. R. Kozlowski, R. Chow, "Investigation of the Microstructure of Coatings for High Power Lasers by Nonoptical Techniques", *Proc. of SPIE on Optical Interference Coatings*, Vol 2253, Part 1, pp. 596-602, Grenoble, France, 1994
8. R. Swimm and M Bass, private communication (June 1984)
9. R. Swimm, Y. Xiao, M. Bass, "Calorimetric Study of Optical Absorption of Suprasil W-1 Fused Quartz at Visible, Near IR and Near UV Wavelengths," *Applied Optics*, 24 322-323, 1985
10. J. R. Taylor, "Specification and testing facilities for optical components used in a high average power visible laser system," Vol 1047, pp. 250-265, SPIE, 1989
11. S. Cohen, R. E. English, C. Stolz, J. R. Taylor, "Thermal analysis of transmissive elements in high average power laser beam delivery systems", *Proc. of SPIE*, Vol. 1739-50, pp. 400-407, 1992
12. J. R. Taylor, C. J. Stolz, T. G. Sarginson, "Limits of survivability and damage for optical components used in a high repetition rate visible laser," *Laser-induced damage in optical materials: 1991*, editors H. Bennett, L. Chase, A. Guenther, B. Newnam, M. Soileau, Vol. 1624, pp. 411-422
13. C. J. Stolz, J. R. Taylor, "Damage threshold study of ion beam sputtered coatings for a visible high-repetition laser at LLNL," *Laser-induced damage in optical materials: 1992*, editors H. Bennett, L. Chase, A. Guenther, B. Newnam, M. Soileau, Vol. 1848, pp. 182-187, SPIE, Boulder, 1992
14. C. J. Stolz, T. G. Sarginson, J. R. Taylor, "Nonlinear absorption in high-reflector multilayers," *Laser-Induced Damage in Optical Materials: 1993*, editor H. Bennett, L. Chase, A. Guenther, B. Newnam, M. Soileau, Vol. 2114, pp. 433-442, SPIE, Boulder, 1993

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