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This paper was prepared for and presented at
SPIE Optical Manufacturing and Testing II
San Diego, California
July 27-August 1, 1997

July 14, 1997

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Optical manufacturing requirements for an AVLIS Plant

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ABSTRACT

A uranium enrichment plant utilizing Atomic Vapor Laser Isotope Separation (AVLIS) technology is currently being planned. Deployment of the Plant will require tens of thousands of commercial and custom optical components and subsystems. The Plant optical system will be expected to perform at a high level of optical efficiency and reliability in a high-average-power-laser production environment. During construction, demand for this large number of optics must be coordinated with the manufacturing capacity of the optical industry. The general requirements and approach to ensure supply of optical components is described. Dynamic planning and a closely coupled relationship with the optics industry will be required to control cost, schedule, and quality.

Keywords: enrichment, optical coating, optical fabrication, optical materials, optical metrology, supplier qualification.

INTRODUCTION

This paper will introduce the United States Enrichment Corporation (USEC), its Atomic Vapor Laser Isotope Separation (AVLIS) commercialization and pre-deployment efforts currently underway at Lawrence Livermore National Laboratory (LLNL), and the optical manufacturing requirements planning for AVLIS Plant deployment. AVLIS optical component specifications are based on laser system performance requirements developed—with industry participation—over the past twenty years. Details of the specifications are described in a companion paper. [1]

The AVLIS system consists of high-average-power, pulsed, dye-laser chains pumped by copper-vapor lasers. The dye lasers are tuned to provide precise wavelengths which are combined, multiplexed, and propagated to uranium-vapor deposition chambers. A variety of alignment, wavefront correction, and diagnostic systems will actively control the dye-laser beams during operation. Successful production of AVLIS optics requires verification of optical performance via state-of-the-art metrology. Details of the testing requirements are described in a second companion paper. [2]

1. UNITED STATES ENRICHMENT CORPORATION

The United States Enrichment Corporation (USEC) is a government corporation which produces and markets uranium enrichment services to more than sixty utilities that own and operate commercial nuclear power plants in the United States and eleven foreign countries. The Corporation is headquartered in Bethesda, Maryland, and it operates plants in Paducah, Kentucky and Portsmouth, Ohio. With annual revenues of approximately \$1.4 billion, USEC paid a \$120 million, February 1997 dividend to its sole shareholder, the U.S. Treasury. USEC serves approximately ninety percent of the domestic market and close to forty percent of the world market. Uranium enrichment accounts for about six percent of US energy exports.

Congress created USEC under the Energy Policy Act of 1992 (Public Law 102-486), to restructure the US Department of Energy's (DOE) uranium enrichment program. It was established as a government corporation to compete more aggressively in the world marketplace, to ensure a continued, reliable domestic source of uranium enrichment services, and to transition into a fully privatized commercial business. Thus, Congress turned the

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nation's uranium enrichment enterprise into a government corporation, as a step toward eventual privatization. On July 1, 1993, USEC opened its doors and began to produce and sell uranium enrichment services in a more efficient and profitable manner.

Nuclear energy, which provides 22 percent of the nation's electricity, requires enriched uranium to fuel nuclear reactors. Following mining, uranium ore is sent to a mill where it is chemically treated to extract uranium oxide (U_3O_8), more commonly known as "yellow cake." Uranium oxide contains two primary isotopes: ^{235}U and ^{238}U . The process of increasing the concentration of ^{235}U and decreasing ^{238}U is called enrichment, which is the service performed in USEC's gaseous diffusion plants. Uranium enrichment is an essential step in transforming natural uranium into nuclear fuel to produce electric power. In enriching uranium, the level of ^{235}U is raised from the less than one percent, as found in natural uranium, to between three and five percent, making it usable as a fuel in power plants. Customers typically deliver natural uranium to USEC and specify a desired level of enrichment. To prepare for this step, the yellow cake is put through a number of chemical processes to produce uranium hexafluoride (UF_6). The gaseous diffusion process enriches UF_6 in gaseous form via differential diffusion through a semi-porous membrane. After enrichment, the UF_6 is further processed into a sinterable uranium oxide (UO_2) and converted into reactor fuel by commercial fuel fabricators.

In July 1994, the USEC Board of Directors approved a recommendation by USEC management to begin taking steps necessary to commercialize the AVLIS process for uranium enrichment. This decision was based on two conclusions: (1) the AVLIS process was ready for deployment having reached an advanced state of development during the previous twenty years of DOE sponsorship at a total investment of approximately \$1.5 billion dollars, and (2) the AVLIS process was projected to have sufficiently low projected capital and operating costs, which would allow USEC to become the world's lowest cost supplier of enrichment services, and thereby strengthen USEC's world leadership position in uranium enrichment. Rather than performing enrichment by diffusion on UF_6 , the AVLIS process enriches vaporized uranium metal via a photoionization and an electric-field separation method.

On June 30, 1995, USEC presented to President Clinton and Congress its landmark plan for privatization. The plan calls for the complete transfer of ownership of the Corporation to private investors. It defines responsibilities, and outlines the approach to privatization that will be pursued after approval by the President. The objectives of USEC privatization are much like those of more than 7,000 successful privatizations of government-owned enterprises that have occurred worldwide since 1980; specifically, improved efficiency, competitiveness, business-based decision making, and financial gains. In forwarding the plan to the President, the USEC Board of Directors indicated that they believed it was consistent with the four general statutory requirements specified in the Act. These are: (1) maximize the long-term value of the government's uranium enrichment enterprise to the U.S. taxpayers, (2) ensure a continuing source of domestic uranium enrichment services, (3) create a viable private corporation without any need for future government support, and (4) support the nation's national security objectives.

2. ATOMIC VAPOR LASER ISOTOPE SEPARATION

Atomic Vapor Laser Isotope Separation (AVLIS) is a laser-based materials process for converting a single material feed stream into separate streams in which a desired set of isotopes has been enriched and depleted. The process utilizes the selective multi-step photoionization of an atomic (i.e., not molecular) vapor stream. The components of a generic AVLIS process are shown in Figure 1. The process hardware is divided into a separator system and a laser system that are, to a great degree, mechanically independent. Atomic vapor is produced as in a vapor-deposition system, expanding upwards in the vacuum. Laser light for photo-ionization is provided by a dye laser system that has a pump laser system as its energy input. Dye lasers are readily tunable to specific frequencies which can be matched to the isotope(s) of interest. Laser light illuminates the atomic vapor near the surface of an ion extractor, providing the energy necessary to release an electron from the selected isotope(s). The electric field of the ion extractor serves to draw the ionized particles to its surface for collection (and neutralization). The remaining, non-ionized vapor continues past the ion extractor for collection on the roof of the device. [3]

The dominant application of AVLIS, and USEC's mission, is the enrichment of uranium (as an alternative to the gaseous diffusion process described earlier). In such an enrichment mission, the material from the extractor is enriched product; the material from the roof is depleted tails. Copper-vapor lasers serve as the pump lasers in

USEC's uranium enrichment demonstration system at LLNL. Both the pump lasers and tunable lasers are configured in master-oscillator/power-amplifier (MOPA) chains.

Figure 1. The Basic AVLIS Process

The AVLIS Plant dye-laser chains consist of three or four amplifiers in series. The first two units serve as high-gain stages so as to saturate the subsequent amplifiers. Copper-vapor laser light, transmitted by fiber optics, is formatted by a mechanical-optical assembly to define the interaction region of the dye amplifier. Similarly, for the dye-laser beam, an image of a slit is magnified and relayed to the center of the first and each subsequent amplifier by the associated mechanical-optical assemblies. Beyond the dye amplifier chain, dye laser beams are propagated within a vacuum to eliminate the turbulence/distortion of air. Within the associated vacuum chambers, beams are combined and multiplexed, with pilot lasers incorporated to enable diagnostics and feedback to pointing-and-centering mirrors. Wavefront corrections are provided by a system of deformable mirrors, with their associated Hartman-sensor diagnostic and feedback systems. The associated optics include plano, cylindrical, aspherics, dichroics, achromats, splitters/combiners, polarizers, deformable mirrors, etc.

AVLIS Systems Conceptual Design

Figure 2. AVLIS Plant Architecture

3. OPTICAL MANUFACTURING REQUIREMENTS

As presently envisioned, the full-scale AVLIS Plant will require approximately 42,000 optics. Of these, approximately 25,000 will be custom while the balance are believed to be available from the "catalog optics" industry. Sizes range from 1" diameter to 8" diameter with a small number of larger optics. AVLIS will require significant quantities of high-purity fused silica and Zerodur,² along with smaller quantities of ultra-low expansion (ULE³) glass and other optical materials. The custom optics are nearly equally divided between plano and curved surface figures. Approximately 15% of these optics are expected to be replaced annually once the Plant is fully operational.

Laser beams propagated via AVLIS optics must be of high quality: high power (low losses), uniform wavefront, properly aligned, and stable. Optical specifications are therefore derived from and driven by the laser beam requirements. Hence, AVLIS specifications include limits on homogeneity ($< 1 \times 10^{-6}$), surface shape errors (aberrations $< 1/20$ th wavelength), thermal absorptance, efficiency (reflectance and/or transmittance > 0.998), and scatter. Metrology equipment used to assure adherence to specifications includes laser reflectometers, spectrometers, profilometers, microscopes, phase interferometers, and absorption measurement systems. Many optics for the AVLIS diagnostics systems have important, but less demanding specifications; hence, might be obtained as catalog items. Nevertheless, a limited level of performance verification is expected to be necessary as the "out-of-spec" impact of even catalog optics can be severe.

Figure 3. Quantity of Optics by Size

² Registered trademark of Schott Glass Technologies, Inc.

³ Registered trademark of Corning, Inc.

Figure 4. Substrate material and shape

Approximately sixty custom thin-film coatings are required for the Plant. Of these, several require development for spectral and mechanical stability (e.g., low stress, as a function of absorbing/desorbing moisture, thermal loading, etc.). In addition, the number of required optics in each propagation path demands high efficiency (high reflectance or transmittance; low scatter and absorption) which is specified at 0.998, with a goal of 0.999. Finally, survivability in our high-power laser environment is essential. In general, AVLIS requirements, whether for process laser wavelengths or several diagnostic laser wavelengths, are considered challenging by the optical coating industry.

For presently-developed coatings, industry capacity and yield are concerns—scaling for production may require further development. In particular, determining optimum chamber size is not straight forward. Experience has shown that (although some coatings have only been successful in large chambers) increasing chamber size does not always lead to improved throughput or yield. Coating process parameters, such as evaporated-plume profile and wall effects, are partly “art;” hence, must be determined empirically. Parameters for coating include material(s) selection, layer thickness, preparation steps, temperature, chamber pressure, oxygen partial pressure, chamber size, evaporation rate/profile, e-beam sweep pattern, amount and thermal characteristics of source material present, etc. Successful coating processes often do not transfer between chambers within a single supplier. Naturally, proprietary information of suppliers is held in strict confidence.

Traditionally, coating has been done by reactive e-beam evaporation/deposition. Unfortunately, the technique is not as exacting as would be ideal. Wobble of the evaporate plume (partly due to e-beam sweep pattern, partly due to uncontrolled causes) leads to layer thickness errors and inhomogeneities. Furthermore, the evaporated low-energy atoms and molecules tend to deposit in a columnar structure with void space between columns. Water vapor is easily absorbed in the space between columns, changing the refractive index and leading to substrate/coating stress and shifting of the spectral performance. Accordingly, energetic coating techniques (e.g., ion beam sputtering) are being developed by suppliers for the most critical AVLIS coatings. In sputtering, the evaporated atoms and molecules are increased in energy with the assistance of electric and/or magnetic fields, thereby leading to a more dense coating—the space between columns is “packed” with additional molecules. These dense coatings are less susceptible to the effects of moisture, because less moisture can be absorbed. Sputtering introduces the additional parameters of current and voltage; however, these are easily controlled and automated, leading to a more repeatable process (i.e., less “art”).

In general, the inspection and testing capability required for AVLIS optics is not yet widely available throughout the optics industry. Traditionally, LLNL provided the necessary and unique inspection; assisting qualified suppliers in

setting up subsets of the required metrology systems (in some cases with AVLIS-owned equipment). Development of suppliers' technical capabilities (skills in using optics-metrology equipment) will be required; while we will continue the existing AVLIS inspection/test/acceptance quality program (admittedly, with limited throughput). This area might benefit from a creative business arrangement, possibly including outsourcing of optical refurbishment for Plant operations as well. Damage-threshold testing can be expected to always be performed at an AVLIS facility, due to the need for testing with actual high-power lasers.

Some AVLIS coating development work requires one or more DOE-security-cleared individuals at each supplier's facility. Fortunately, production work can be done by uncleared individuals, in uncleared facilities. Maintenance of Foreign-Ownership, Control of Influence (FOCI) determinations (performed by DOE) is necessary for continued development work. This requirement is expected to continue beyond the privatization of USEC. For those suppliers who have qualified on one or more coatings, we intend to establish long-term FOCI determinations, well in advance of relevant activities.

4. QUALIFICATION OF SUPPLIERS

This AVLIS optical manufacturing qualification program provides assurance that optical components for critical applications in the Project will be supplied by manufacturers who have demonstrated that they are technically capable and are employing sound business/quality practices. The qualification program allows candidate suppliers to demonstrate that they can meet AVLIS performance and test requirements while providing a high level of confidence in qualified manufacturers. Under the program, candidate vendors of optical materials supply sample blanks of a defined geometry and specification (e.g., virtually no defects or contaminants), which the AVLIS Project evaluates against the defined criteria. Similarly, candidate suppliers of substrates provide samples which meet defined fabrication drawings and specifications (e.g., tight criteria for pits, digs, contamination, and other defects; polished to eliminate subsurface damage with low surface roughness), which are then evaluated by the AVLIS Project. Candidate optical coating suppliers provide samples of each coating for which they desire to be qualified. Again, the AVLIS Project's optical metrology laboratory performs an evaluation against the defined performance specification (e.g., optimum efficiency and low absorption, with minimum defects and stress). The qualification program is engaged wherever AVLIS performance and/or production volume warrant. The program's objectives include:

- Define and communicate specific criteria by which manufacturers are to be judged as qualified;
- Ensure selected AVLIS suppliers are technically capable, with sound business and quality practices;
- Assure fairness in competition and contracting;
- Identify and maintain a list of qualified vendors capable of providing products/services which meet AVLIS Project needs;
- Provide critical information necessary to supply planning; and ultimately,
- Ensure AVLIS optics contracts will be successful, as perceived by both USEC and its participating suppliers.

It is USEC's intention that qualification opportunities be provided to all who indicate interest and possess a reasonable chance of success. We are presently seeking new candidate firms for qualification; however, because extensive testing is required and in most cases AVLIS-supplied material is involved, time is required to prepare and conduct the qualification process. Individual requests for an opportunity to qualify may be held for up to a year so that several candidate vendors can be included at one time. In areas where procurements are not anticipated in the near future, requests may be held longer. The qualification effort will be driven by the anticipated need for AVLIS Plant procurements.

The cost of qualification is generally expected to be absorbed by the candidate vendor except for AVLIS-supplied material and AVLIS testing. Specifications and criteria for performance evaluation will be provided to candidate suppliers who wish to attempt qualification. All performance criteria must be met. AVLIS will test all parts submitted for compliance and comparison to vendor test data. Ability to predict performance and meet delivery schedules during the qualification process will be included as part of the evaluation. Results of qualification evaluations will be provided to each participating vendor.

5. PLANNED APPROACH TO OPTICAL ACQUISITION

Recognizing the unique requirements of AVLIS optics, the need for facilitization, and the significant efforts necessary to qualify as an AVLIS optics supplier, we are interested in working towards long-term relationships with participating suppliers. Emphasizing long-term value over adversarial approaches will allow for shared assurance efforts, planning for facilitization, development of technical capability, and cost-effective supply—most importantly, will allow for supplier continuity beginning with near-term development efforts, moving towards Plant production and finally to refurbishment activities. While USEC procurement is already moving towards commercial procurement practices (e.g., Uniform Commercial Code), privatization will allow the process to continue with greater urgency. Nevertheless, AVLIS Plant purchases will initially, by definition, be “project-like;” moreover, managing acquisitions may require maintaining an element of [fair] competition. In addition, qualifying an optimum number of suppliers for each area will reduce supply risk (cost & schedule), while minimizing Project costs (survey, development efforts, qualification, etc.). Wherever possible, long-term Plant orders will be split among two or more suppliers. While the most cost-effective (i.e., lowest total cost of ownership) supplier will be awarded a larger share, second sources will be meaningfully engaged. Finally, we will carefully ensure that less challenging requirements are not “skimmed” away from our valued suppliers who have qualified for the more difficult efforts. In general, our development efforts will be realized via many small contracts, while Plant deployment will be executed via fewer, large contracts.

While the AVLIS Project’s general approach (i.e., throughout Plant process equipment) is to seek the highest level of integrated supply readily available from industry, we expect to separately purchase optical materials, fabrication, and coating. Nevertheless, a creative contracting arrangement for integrated supply may be possible. The Project presently envisions a strategy of awarding long-term Plant-scale contracts for supply of optical materials with sufficient lead-time for identified suppliers. We expect interaction with industry will be required to determine sufficient lead-time; also, we plan to monitor other demands on the market for optical materials, fabrication, and coatings. While AVLIS has historically performed optical metrology on purchased materials before allowing fabricators to begin production, recent improvements in the optical-material industry’s ability to reliably perform such metrology may allow us to, with confidence, have material shipped directly to the selected fabricators.

The AVLIS project has a limited number of presently-qualified optical-fabrication suppliers. If current overall industry demand continues, we expect some facilitization will be required; (believed to be possible, given sufficient lead-time). In general, we expect to award large, long-lead contracts, letting suppliers work out their own facilitization. Nevertheless, early industry interaction is anticipated to ensure that planning for equipment and staff is closely linked to the Plant deployment schedule. Areas where AVLIS optical fabrication requirements are unique will receive early, individual attention. Similar to optical materials supply, we would benefit from engagement of optical fabricators who have, or are interested in developing, the required metrology capability—thereby allow shipment, with confidence, directly to selected coating suppliers. In any event, sample inspection (e.g., AVLIS optical metrology laboratory or otherwise contracted) will be planned. Many of the AVLIS optical designs, and associated drawings/specifications, are considered USEC Proprietary Information. Suppliers will be expected to handle such information accordingly; specifically, will be expected to decline any fabrication inquiries of AVLIS parts for delivery to others. Similarly, each supplier’s identified proprietary information will be held in strict confidence.

Our strategy is to requalify past coating suppliers for each previously-qualified coating; moreover, to engage in further supplier development as part of our ongoing thin-film coatings acquisition efforts. Summaries of suppliers’ capabilities, facilities, business interests, perceived commitment, etc. will be prepared, then compared to requirements and schedule necessary for production of Plant quantities. Individual plans of sequenced coating-development efforts, at specific suppliers will be generated (many coatings are incremental increases of requirements from other coatings). These mid-term efforts will serve to build supplier confidence in AVLIS, help to create confidence in our long-term requirements, and identify suppliers who are “Best-in-Class.”

While performance of optical coatings is critical to the AVLIS Plant, orchestration of the optical coating production plans is similarly crucial to the Plant’s deployment schedule. Plans will include reduction of technical risk via development and qualification of energetic coating methods and designs, while reducing supply risk by identifying

and qualifying a family of optical coating vendors. Our plans are anticipated to evolve such that each supplier will be expected to become both a primary supplier of many coatings, and a secondary supplier of others. Whereas development work will generally be on a task basis (with rates established as part of a blanket order, and non-recurring charges for equipment linked to specific deliverables), long-term Plant orders are expected to be fixed-price. The Project expects certain facilitization requirements can be handled by suppliers as part of long-lead contracts. In a limited number of cases, we may consider providing USEC-owned equipment, possibly for dedicated use, possibly with transfer of ownership as part of successful completion of contract—with “first rights” retained, of course. Should suppliers be interested, shared ownership, with a suitable “right to use” agreement may be possible. Since the industry appears to be presently operating at capacity (actually expanding), we plan to down-select early (if down-selection is warranted), thereby focus our facilitization investments, and minimize redundancy in the area of optical metrology. Many of the AVLIS coating specifications are considered USEC Proprietary Information. Suppliers will be expected to handle such information accordingly; specifically, will be expected to decline any inquiries of AVLIS coatings for delivery to others. As mentioned earlier, each supplier’s identified proprietary information will be held in strict confidence.

The AVLIS project expects to assist suppliers with development of measurement capabilities. Where equipment necessary for AVLIS will enhance their business, AVLIS may share in the cost, linking our expenditures to successful performance of contracts. Where AVLIS measurement requirements are unique (e.g., ratio reflectometers), we will provide the necessary equipment, but retain ownership. Installation and use of the sensitive instruments is expected to require sharing of AVLIS experience and knowledge. Our goal will be to develop each supplier’s optical metrology capabilities to the point where only random, independent inspection/testing is necessary for acceptance at Plant (i.e., statistically ensuring a high level of confidence in supplied optical components).

6. SCHEDULE

An overview of major optics supply activities is presented in figure 5. Demonstration and planning activities are presently underway. Qualification activities associated with AVLIS demonstration have also been ongoing; these will lead to similar; albeit, expanded qualification efforts with regard to Plant deployment and operations.

Figure 5. AVLIS Plant optics supply schedule overview

ACKNOWLEDGMENT

The work of B. Chow and J. Taylor was performed under the auspices of the U.S. Department of Energy of Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48; and was sponsored by the United States Enrichment Corporation.

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