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DOE reactor-pumped laser program

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ABSTRACT

FALCON is a high-power, steady-state, nuclear reactor-pumped laser (RPL) concept that is being developed by the Department of Energy. The FALCON program has experimentally demonstrated reactor-pumped lasing in various mixtures of xenon, argon, neon, and helium at wavelengths of 585, 703, 725, 1271, 1733, 1792, 2032, 2630, 2650, and 3370 nm with intrinsic efficiency as high as 2.5%. The major strengths of a reactor-pumped laser are continuous high-power operation, modular construction, self-contained power, compact size, and a variety of wavelengths (from visible to infrared). These characteristics suggest numerous applications not easily accessible to other laser types. A ground-based RPL could beam its power to space for such activities as illuminating geosynchronous communication satellites in the earth's shadow to extend their lives, beaming power to orbital transfer vehicles, removing space debris, and providing power (from earth) to a lunar base during the long lunar night. The compact size and self-contained power also makes an RPL very suitable for ship basing so that power-beaming activities could be situated around the globe. 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.

1. INTRODUCTION

The concept of using nuclear energy to pump a laser has been pursued for almost two decades. both in the U.S. and in the former Soviet Union.[1-12] The motivation for these efforts has been the potential for developing very powerful, long-enduring lasers with compact and self-contained power sources. The Department of Energy (DOE) has been the principal supporter of reactor-pumped lasers (RPLs) in the U.S. for the past seven years. The present RPL program supported by DOE is called the FALCON (Fission-Activated Laser CONcept) project. Sandia National Laboratories serves as the lead laboratory with support from the Idaho National Engineering Laboratory and contributions from the Air Force Phillips Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Mission Research Corporation, Babcock & Wilcox, W. J. Schafer Associates, Lockheed, Kaman, Science Research Labs, University of New Mexico, University of Illinois, and Texas A&M University. This paper describes the accomplishments of the FALCON research program and some potential applications.

Nuclear fission is a simple and very concentrated source of energy. About 80% of the energy of fission is contained in the kinetic energy of the fission fragments. The rest of the energy is in gamma rays, neutrinos, neutrons, and radioisotope decay. FALCON utilizes the energy of the various products of fission to excite the laser medium. (See Figure 1). The highly energetic products produce copious secondary electrons which ionize and excite the laser gas mixture. The excited states so created are the source of energy for the lasing process. Different gases slow down the fragments at different rates, and also transfer energy to neighboring atoms at different rates. Lasing requires a balance between excitation of the source atoms and removal of the de-excited states. Because of this need, lasing efficiency is a sensitive function of fission pump rate, gas mixture, gas temperature, and gas pressure. Numerous experiments over the past several years have mapped out

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the regimes where reactor-pumped lasing occurs and determined the optimum conditions for lasing at various wavelengths[2,7-12]. The details of these results are described in a paper by Hebner and Hays in this conference.

Nearly all of the lasers investigated so far have been atomic lasers. That is, the lasing occurs between two states in an atom (typically a noble gas) rather than in a molecule or excimer. Gas mixtures of xenon, argon, neon, and helium have been explored. Table I summarizes the wavelengths that have been observed and peak intrinsic efficiencies that have been achieved. (Intrinsic efficiency is the ratio of laser light energy to total energy absorbed by the gas.)

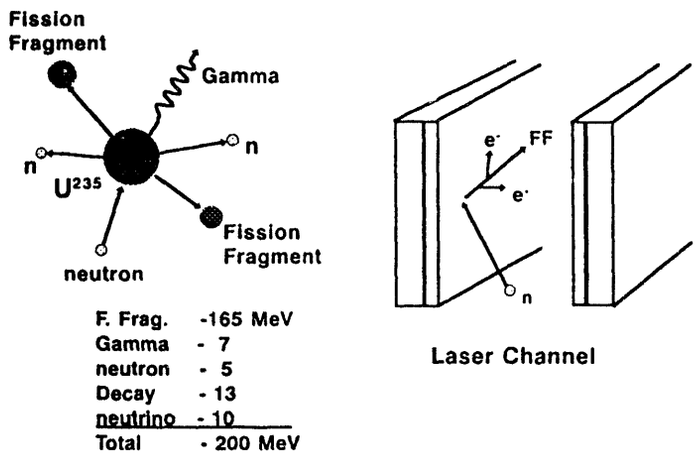

Figure 1. Basic concept for FALCON laser.

Table I. Demonstrated wavelengths and intrinsic efficiencies for reactor- pumped lasing.[7-12]

Lasing Atom	Wavelength (nm)	Intrinsic Efficiency
xenon	3370	>0.1%
xenon	2650	>0.1%
xenon	2630	>0.1%
xenon	2032	2.0%
xenon	1733	2.5%
argon	1792	1.4%
argon	1291	1.1%
neon	725	0.10%
neon	703	0.05%
neon	585	<0.1%

These small-cell physics experiments have mostly involved pulses lasting about 2 ms. The peak power reported has been about 300 W. The parameters involved with the 1792, 1733, and 1291 nm lines were varied fairly widely, so the efficiencies listed are probably close to maximum. Conditions for the other lasing lines were not extensively varied, so their efficiencies could be increased. Russian researchers report considerably higher efficiencies for the 585-nm line.[6]

The design of a reactor-pumped laser involves the proper choice of lasing medium, buffer gases, temperature, pressure, flow rate, fuel geometry, heat-removal structures, materials compatible with nuclear operation, critical mass of fuel, reactor moderator, other reactor and neutronics issues. In addition, one must consider the distorting effect of heat deposited in the gas, and the difficulty of scaling up from small experiments to high total power lasers. RPLs in general have an advantage over other lasers in that the energy source is self-contained within the laser and does not have to be brought in from the outside. However, care must be taken to maintain beam quality. We have developed designs for maintaining good beam quality and have tested these designs in sub-scale experiments in Sandia's reactors. Extrapolations with very detailed computer codes predict that the beam-quality will remain good for full-scale MW-class systems. These predictions need to be verified with larger-scale experiments, and such experiments are scheduled for the next year and a half.

If the planned scale-up experiments are successful, the next logical step may be a demonstration facility to prototype full-scale hardware. The facility would also be used to develop and, in some cases, to implement laser applications. One option is to advance to a multi-megawatt (laser output) facility with a self-critical reactor core. A less risky option is to construct a water-cooled pool reactor which is used to drive laser modules adjacent to it. This option allows changes in the laser module and development of different laser designs. A driven system might yield about 500 kW of laser light. To minimize cost, the system could be limited to run times of only a few minutes at a time. This would greatly reduce the requirements for a forced coolant system since the thermal inertia of the core and pool could be used. This also would reduce the levels of decay heat after the reactor is turned off, and minimize the radionuclide inventory. Potential locations for power beaming (utilizing an RPL or other laser systems) include DOE's Nevada Test Site, the Navy Air Warfare Center at China Lake (California), the Army's White Sands Missile Range (New Mexico), the Air Force's Edwards Air Force Base (California),

DOE's Idaho National Engineering Laboratory (Idaho), and the Army's Yuma Proving Ground (Arizona). Two of these potential sites are described in papers in this conference.[13,14]

A design code which accounts for the effects of all the phenomena mentioned above has been developed and utilized in a conceptual design for a multi-megawatt laser. The reactor, gas flow systems, and heat-removal systems are straightforward and based on existing technology. The optics involve state-of-the art techniques, but essentially all of the required technologies have been demonstrated. We have used this code to develop a conceptual design for a multi-MW facility (see Figure 2). The laser consists of the reactor core, a flow loop for the lasant, heat exchangers, and extraction optics. The flow loop is closed cycle and contains the noble gas used as the lasant. A primary coolant loop of recirculating D_2O and an open secondary water-cooled loop are used to remove waste heat. The gas flow rate within the lasing region is only about 10 m/s which results in little distortion of the laser beam. The reactor is smaller than that in a commercial nuclear power plant, contains considerably less fuel, and operates at near atmospheric pressure. These features yield a very benign reactor-driven system that is inherently safe.

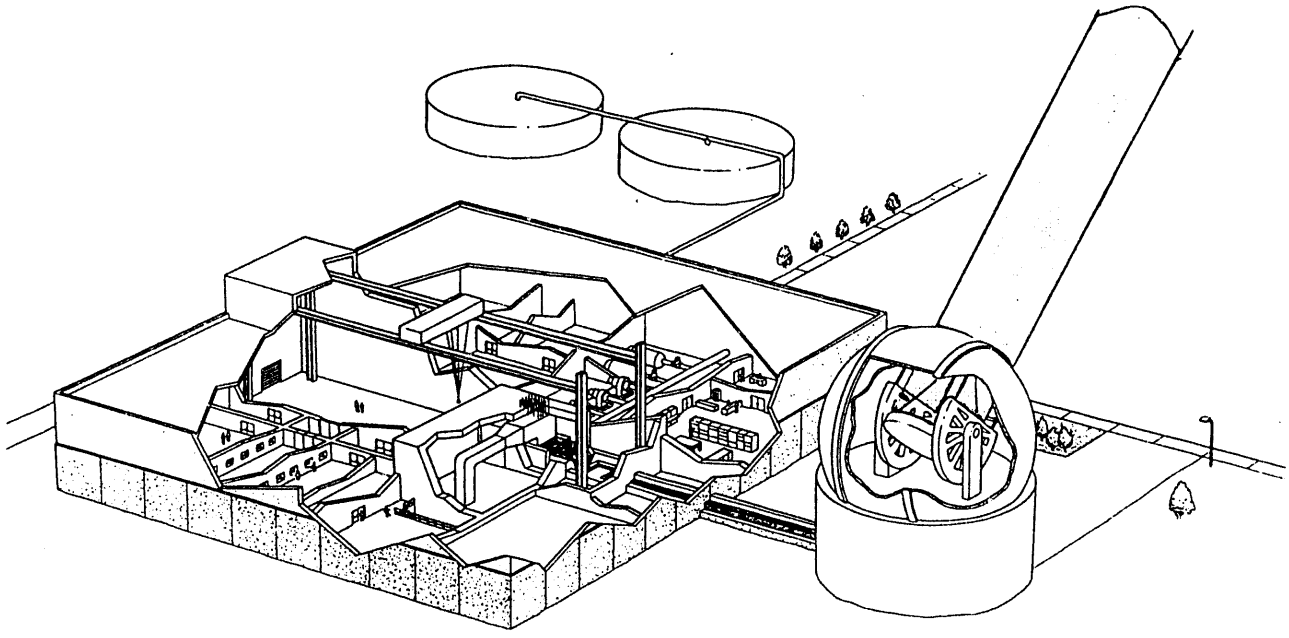

Figure 2. Multi-megawatt FALCON laser facility conceptual design.

We also have considered basing an RPL on a ship where having a self-contained, compact, and very long-enduring power source is of paramount importance. Preliminary analysis indicates that a multi-megawatt laser would fit comfortably on a ship comparable in size to a Navy guided-missile cruiser. Beam-director technology is advanced to the point where the large-scale low-frequency motion of the ship caused by waves could be accommodated. The small-scale high-frequency motions from ship vibrations and the atmosphere also can be compensated for, as they would be even on a land-based system.

The attributes of an RPL make it well-suited for applications that require long-duration operation such as power beaming to space or material processing for industry. In addition, once constructed for long-duration applications, an RPL also can serve for short-duration applications such as research and various military missions. The wavelengths already demonstrated for FALCON have been discussed, and more wavelengths are being demonstrated each year. In addition, the FALCON beam is projected to be of high enough quality that its frequency can be doubled with good efficiency. This would yield additional wavelengths at 353, 363, 636, 867, 896, 1016, 1315, 1325, and 1685 nm. Researchers at other laboratories have

demonstrated doubling in the infrared at over 50% efficiency in pulsed mode; to achieve high efficiencies at steady state would require focusing the beam and using numerous thin, cooled doubling crystals. A CW doubling efficiency of 20-30% would seem reasonably achievable in the near future. Most of the direct and doubled wavelengths mentioned above propagate well through the atmosphere.

2. POWER-BEAMING APPLICATIONS

An exciting and new possibility for high-power lasers is power beaming to photovoltaic cells on space hardware. This application is enabled by the recently developed ability to compensate for atmospheric distortion and keep the beam divergence very low as it passes through the atmosphere.[15] Another key requirement for a power-beaming application is that the photovoltaic (VP) array operate efficiently at the wavelength of interest. The monochromatic light of a laser leads to high efficiencies in collection arrays.[16] The efficiency for existing silicon arrays (including the dead space between the solar cells) peaks at around 20% for wavelengths of 700- 900 nm (compared to 9% for solar). Future arrays made of GaAs are projected to peak at around 40-50% for similar wavelengths. This suggests that 867 nm (doubled 1733 nm) may be the best wavelength for FALCON power beaming applications.

One opportunity for laser power beaming is to extend the life of geosynchronous satellites by beaming power to them when they are eclipsed by the earth's shadow (see Figure 3). This application has been proposed by Landis and Westerlund[16], and is further assessed in a paper by Monroe in this conference.[17] GEO satellites are eclipsed by the earth's shadow about 90 times per year for durations up to 70 minutes. Batteries normally provide power during these times, but the heavy charge-discharge cycle during eclipses decreases their life expectancy. Battery life, and thus satellite life, could be extended by providing power during eclipses via laser illumination of the photovoltaic array. An advantage of this laser application is that it can tolerate occasional cloud cover or laser outages--the batteries can be relied upon for those instances and the laser beaming will still increase the battery life on the average.

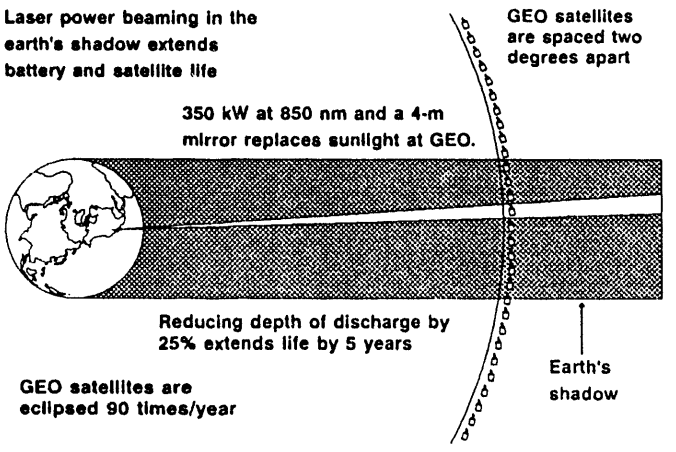

Figure 3. Concept for beaming power to geosynchronous satellites in the earth's shadow.

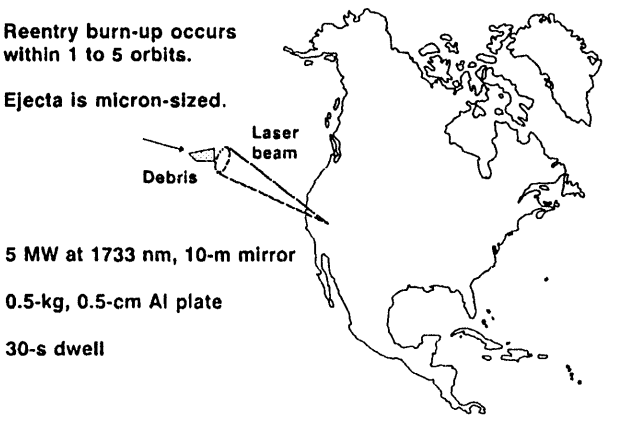

Figure 4. Concept for removing space debris with a ground-based laser.

Large mirrors, adaptive optics, and reasonably powerful lasers are needed for this application. There is a tradeoff between mirror diameter and laser power. For example, a 350-kW laser at 867 nm and 1.2 times diffraction-limited divergence, 20% beam loss in the optical train of the beam director, a final mirror 4-m in diameter, a beaming angle 45° off vertical, a compensation of atmospheric turbulence of 50% (Strehl=0.5), and negligible jitter, would yield the same electrical power as sunlight from a silicon photovoltaic array at GEO. With an 8-m transmission mirror, only 88 kW would be needed. Since satellites are spaced at about 2° separation, one site could access up to 50 satellites if the beam could be directed over a range of $\pm 50^{o}$. The commercial payoff for this application is that each satellite could continue earning up to about $25M/year in revenues in the extended-life mode.[16] A drawback to this potential application is that, so far, the batteries on

existing GEO satellites have exceeded their expected lifetimes by several years. In addition, future satellites will use longer-lasting batteries (NiH_2, rather than NiCd).

An extension of the concept described above is to supply power during eclipses to future satellites which are designed and launched without batteries. This would reduce their weight and launch costs. In this case, the laser would need to be available with greater reliability, but since eclipses only occur about 1% of the time (and during the local night), perhaps only two or three sites would be needed to assure adequate availability of the beaming service.

Laser illumination also could augment solar power to increase the power available to new satellites designed for power beaming. Increased power could boost the signal strength or allow more channels on the satellite. In addition, high-frequency channels (which require higher power to penetrate the atmosphere) could be used. Removal of waste heat from the satellite limits the amount of power that can be transmitted. But even with this limitation, a spin-stabilized satellite with power beaming could generate 0.9 kW/m^2 of electrical power, which is six times that of an equivalent conventional satellite using the same size solar panel.[18] A 3-axis stabilized satellite could generate 0.6 kW/m^2 (four times conventional). Because the satellite is dependent on the laser power in this mode, laser downtime must be minimized by having multiple sites, or applications which can tolerate outages must be found.

Another application for power beaming is to orbital transfer vehicles (OTVs) that deliver a satellite from low earth orbit (LEO) to geosynchronous orbit (GEO). The payload for an OTV can be increased by a factor of four if a plasma-thruster is used with power-beaming to the thruster.[19] A higher power reduces the time the satellite is exposed to intense radiation as it passes through the Van Allen belts. It also reduces the delay until the satellite starts producing revenues. The laser power needed is a few hundred kW and it need not be continuous. The high orbit of an OTV would allow it to be seen for about 25% of the time during the orbit, so a single site may be able to do the job. Occasional outages due to weather could be tolerated. The power beaming in this case need not be to photovoltaic cells. Instead one could beam to a light-weight solar collector (nominally 7 m in diameter) that focuses the energy to a thermal rocket. (This concept is an extension of solar thermal propulsion.) This approach has two advantages. The laser light could be infrared, which is easier to produce, transmits through the atmosphere more easily, and is much more eye-safe above 1500 nm. In addition, the process can tolerate much higher levels of laser light than photovoltaic conversion.

A ship-based laser could provide the option for basing power-beaming sites around the world (without being subject to control by foreign nations). This feature enables power beaming to GEO satellites over Europe, Asia, and the Pacific rim. It also enables an OTV to deliver its payload to high orbit in much less time. An additional advantage is that the ship could move away from cloud-filled weather patterns and increase the time available for beaming.

Power beaming to the moon also is an attractive option with the moon accessible about 25% of the time from a single site. The advantage of power beaming over lunar solar power is in the savings in energy storage systems for the 354-hour lunar night. The mass of such storage systems is over 10 times that of the photovoltaic system.[20] The cost of transporting and implementing just the power storage system alone for the full lunar night would cost several billion dollars. Power beaming could greatly reduce the need for energy storage. For example, a 2-MW laser beam of 867 nm at 1.2 times diffraction-limited divergence, 20% beam loss in the optical train of the beam director, a final mirror 10-m in diameter, a beaming angle 45° off vertical, a compensation of atmospheric turbulence of 50% (Strehl=0.5), negligible jitter, a lunar photovoltaic array 60 m in diameter, and 40% conversion efficiency in the array (GaAs), would yield 80 kW of electrical power on the moon. Energy storage systems would still be needed to allow for interruptions in the beaming (a few days), but those systems would weigh considerably less than those needed for a full lunar night (14 days), especially if the base could revert to a very low-power "survival mode" if a long-duration outage occurred. Power beaming may be the enabling technology for a lunar base, especially if safety and space-testing concerns delay the approval of a lunar nuclear power plant.

Space debris is becoming more of a concern for space assets, especially for the space station where human life is involved. A ground-based laser could remove the debris by ablating the surface and causing a retarding thrust (see Figure 4). The debris would then re-enter the atmosphere and burn up in half an orbit. The beam intensity must be high enough to overcome thermal radiation and reach vaporization temperature. This technique is probably the most effective available in terms of cost or energy usage, but it would require a 10-m diameter mirror that could track the debris for about 30 seconds.[21] A 5-MW laser could remove debris from the orbital altitude of our planned space station. Monroe addresses this subject in detail in another paper in this conference.[22]

Launching of small payloads into LEO via laser heating of the fuel is technically feasible, but may not be economically justifiable as a stand-alone system. But once a facility is built for other purposes, laser launching may become a very attractive means for launching small packages. One possible payload category is a constellation of LEO communication satellites. Another application is as an "overnight express" service to our future space station (or the Russian station Mir). It is estimated to require about 1 MW of laser power for each kg of payload delivered to LEO. (See paper by Monroe on this subject in this conference[23]).

3. MATERIAL PROCESSING APPLICATIONS

Lasers provide improved capabilities for welding, cutting, surface treatments, and vapor deposition. Many conferences have been held on these topics.[24,25,26] The primary industrial lasers today are CO_2 (10 μm, 45 kW maximum) and NdYAG (1.06 μm, 3 kW maximum). World-wide sales are about $350M per year for these lasers.[27] The purchase price and operational costs per installed watt for a reactor pumped laser are estimated to be comparable to those for CO_2 and NdYAG (about $100/W). So the true value of the RPL is not so much its cost advantage as its unique combination of very high power and excellent beam quality. Because of these, the RPL light can be focused to achieve new regimes of power density and temperature which should enable material processing that would otherwise be unachievable. Chemical lasers also could reach high power densities, but for continuous industrial operation, they would consume an excessive amount of fuel (100 tons per MW-hr of light) and expel tons of halogens (chlorine, iodine) that would need to be neutralized. In contrast, a reactor pumped laser would produce a few kg of spent fuel per MW-hr of light, with 99% of it being the supporting backing for the UO_2.

Potential applications for a high-power RPL include (1) single-pass deep-penetration welding and cutting of thick structures (especially aluminum) such as aircraft structures, deep-sea drilling structures, or reactor pressure vessels, (2) wide-area, uniform application of tungsten carbide and other claddings to metal by melting powders onto the surface, (3) wide-area hardening of metal surfaces by heating and cooling a thin surface layer, (4) clean, controllable vapor deposition of ceramics onto metal surfaces for high-temperature insulation or surface hardening (avoiding impurities associated with traditional plasma sources), (5) production of sub-micron sized particles for manufacturing of ceramics, (6) production of diamond-like coatings over wide areas for scratch protection, and (7) ceramic lithography, in which complex 3-D structures are built up by sintering layers of ceramic powders using the beam to sinter the contour at each level.

An enabling feature for utilizing an RPL for material processing is the fact that light between 500 and 1900 nm can be transported fairly efficiently in fiber optics. For example, a 2.4-kW 1060-nm beam has been transported 150 m in a 1-mm diameter fiber with only 10% loss.[28] So one could envision an industrial park established a few miles from the RPL. The laser light would be directed through a vacuum conduit with negligible loss to the industrial park. Once at the park, the light would be multiplexed through a network of fiber optics to the various work stations.

Most industrial lasers today are used for welding or cutting metals.[27] Both of these processes require more power to achieve greater depths.[29,30] We estimate that to weld or cut steel that is 2 inches thick at 1/4 inch/second requires 100 kW. The market for thick welds or cuts includes ships (commercial and Navy, construction and disassembly), off-shore oil-well drilling platforms, aluminum aircraft frames, and bridges. Many of these markets could be reached by a laser on a ship with a fiber-optic delivery system several hundred meters long.

Lasers can be used to apply cladding to the surface of metals to increase their hardness and wear resistance.[31] A powder of tungsten carbide, N60 (Ni, Cr, B, Si, C), Stellit (Co, Cr, Si, C, W), or other material is laid down on the surface, and the beam melts the surface of the metal. The melt entrains the powder and refreezes. This is presently done with 1/4-inch diameter beams that paint their way across surfaces in narrow strips. This is slow and often results in residual stresses that reduce the wear-resistance of the cladding. A 100-kW beam would allow a broad swath of about 2 inches (at 1 inch/second travel). The market for cladding includes cams on automotive camshafts, the wheel-bearing portions of axles, railway wheels, steam turbine blades, ship propellers, large valve seats, and catapult tracks on aircraft carriers.

Ceramics can provide good high-temperature insulation when they are applied to the surface of metal structures by vapor deposition.[32] However, impurities in the layer and surface cracks can lead to brittleness and flaking. Vaporization of a host

material using a laser beam inside a vacuum chamber can avoid these impurities, and the same beam can be used to melt and smooth the resulting layer. The potential market for ceramic deposition includes high-temperature turbine blades and internal combustion engine parts that would increase overall efficiency.

Lasers also can be used to produce particles which are less than a μm in diameter.[33,34] Such particles can be used as starting materials for sintered ceramics and result in stronger structures with less shrinkage. They also allow the production of composites with a very precisely controlled stoichiometry. Production rates of about 100 g/hr with a 1-kW beam have been demonstrated. Higher power lasers would yield proportionately higher production rates.

Deposition of diamond-like coatings requires vaporization of a carbon source at high intensity to avoid formation of graphite. This involves typically 10^{11} W/cm^2 at 1000 nm, or 10^8 W/cm^2 at 250 nm. Typically this has been achieved by tightly focusing a very short pulse NdYAG laser.[35] An RPL may be able to achieve similar results with high-power focusing, only moderate pulse compression, and possibly frequency doubling to reduce power requirements and minimize the production of contaminant forms of carbon. Markets include coating eyeglasses and aircraft windows to prevent scratching.

Three-dimensional stereo lithography is an existing technology in which a laser creates complex structures in plastic. A thin beam is scanned across the surface of a special liquid polymer in a specified pattern causing it to solidify where it is irradiated. Another thin layer of liquid is added, and the scanning beam solidifies another layer on top of the first in a slightly different shape. Contour levels are built up this way until a finished product results and the remaining liquid is drained away. This same process could be used to sinter ceramic powders into shapes which could not be machined. The enabling technology here is a laser powerful enough to overcome the radiative heat loss at the sintering temperature. The market for this area needs to be developed, but could include all-ceramic automotive, jet, and rocket engine parts for higher-temperature operation.

4. SUMMARY

Steady progress in nuclear reactor pumped laser technology by the DOE over the past decade has advanced the technology to the point where a large-scale RPL with good beam quality appears to be feasible. This preliminary conclusion needs to be verified with additional tests using larger prototypic modules, but if it holds true, then many new processes in the areas of manufacturing, commercial space, and defense may be enabled. (The current research program calls for a demonstration of a reactor-pumped module designed to deliver a high-quality laser beam at multi-kW levels by the end of 1995.) The unique high-power, long-duration capabilities of an RPL open a new regime of clean, high-temperature manufacturing to American industry. Potential material processes include: deep-penetration welding and cutting, wide-area surface cladding and hardening, wide-area deposition of ceramics and diamond-like coatings, and advanced processing of ceramic parts. Potential space applications for a ground-based RPL include power beaming to geosynchronous communication satellites, orbital transfer vehicles, and a lunar base. Space debris removal is also possible. Navy missions for a ship-based RPL include ship defense, troop support, coastal surveillance, disabling enemy satellites, and boost-phase intercept for theater missile defense.

5. ACKNOWLEDGMENTS

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