10
6-20-90 ①
38

UCID--21718

DE90 011760

Program and Applications for a Near-Term Laser Launch System

J. T. Kare

June 1989

Lawrence Livermore National Laboratory

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161

Price Code	Page Range
A01	Microfiche
Papercopy Prices	
A02	1- 10
A03	11- 50
A04	51- 75
A05	76-100
A06	101-125
A07	126-150
A08	151-175
A09	176-200
A10	201-225
A11	226-250
A12	251-275
A13	276-300
A14	301-325
A15	326-350
A16	351-375
A17	376-400
A18	401-425
A19	426-450
A20	451-475
A21	476-500
A22	501-525
A23	526-550
A24	551-575
A25	576-600
A99	601 & UP

Program and Applications for a Near-Term Laser Launch System

Jordin Kare

Lawrence Livermore National Laboratory
January 10, 1989

ABSTRACT

This note discusses possible applications of a minimum-size laser launch system capable of launching 20 kg payloads into orbit. Such a launcher could greatly reduce the cost, and increase the capability, of space-based system, particularly in connection with "Brilliant Pebbles" technology. The ongoing SDIO Laser Propulsion Program has experimentally demonstrated the basic properties of a laser propulsion thruster, and analyzed many of the physics and technology issues involved in building a launcher. This note also presents the outline of a 5 year program to build such a launcher, starting with a modest extension of the current SDIO Program.

Introduction

Laser propulsion uses a large ground-based laser to supply energy to a small rocket vehicle. The laser beam heats an inert propellant, which is exhausted to provide thrust. Because the propellant exhaust velocity is not limited by its chemical energy content, extremely simple laser propulsion thrusters can provide specific impulses of up to 1000 seconds. A ground-to-orbit laser launch system could launch very large numbers of small payloads into Earth orbit at a marginal cost of order $100/lb. Because the complex hardware of such a system remains on the ground, and thus easily accessible, both development and operating costs would be small compared to the costs of conventional aerospace hardware.

Over the past two years, the SDIO Laser Propulsion Program, managed through the Lawrence Livermore National Laboratory, has conducted research on a particular type of laser propulsion thruster, the double-pulse planar thruster [1]. This thruster uses a solid propellant block composed of one of several inert materials, such as plastic or water ice, seeded with additives to control its optical and chemical properties. An "evaporation" laser pulse ablates a few-micron-thick layer of propellant, forming a thin layer of gas which is allowed to expand to roughly atmospheric density. A second laser pulse then heats this gas layer to approximately 10,000 K. The hot gas layer expands rapidly, producing thrust. The entire process takes a few microseconds, and is repeated at 10^2–10^3 Hz rates.

Because the hot gas layer is only a few millimeters thick, while a typical vehicle is two meters across, no nozzle is needed to confine the expanding gas. The expansion generates thrust uniformly across the flat base of the vehicle (hence the "planar" thruster). In addition to making the vehicle design extremely simple, this scheme has two other advantages. First, the thrust direction is independent of the laser beam direction; the vehicle can fly at an angle to the laser beam. Second, the thrust can varied across the base of the vehicle by controlling the beam profile. The vehicle can therefore be steered from the ground, and does not need its own guidance system.

Properties of a Ground to Orbit Launcher

Figure 1 illustrates the components of a minimum-size ground-to-orbit launch system which could be constructed in the next four to five years. The laser is a 20 MW average power electric-discharge CO_2 laser, producing 500 kJ, 2 microsecond pulses at 40 Hz. This would be a very large laser, but the technology for such large CO_2 lasers was well developed in the 1970's. Because of the physics of the double-pulse thruster itself, the 10 μm wavelegth is preferred over shorter wavelengths, although a laser propulsion system could operate at wavelengths as short as 1 μm. A high-power free electron laser (FEL) would be even better, offering higher electrical efficiency (20-25% vs. 15%) and possibly greater reliability. FEL technology is still new, however, and may not be available at competitive prices for several years. The laser requires roughly 150 MW of electricity, which can be obtained from the national power grid or produced locally, e.g., by diesel generators.

The laser beam is focussed by a 10 meter diameter beam projector telescope onto a two meter diameter vehicle. This combination gives a useful range of approximately 1000 km. An adaptive optics system is needed to correct for atmospheric turbulence and thermal blooming, but the combination of long wavelength and a cooperative vehicle (which can even telemeter back information about the beam profile) keeps the complexity of this system well within the state of the art. However, a mountaintop (3 km altitude) launch site is needed to reduce absorption of the laser beam by atmospheric water vapor and CO_2.

The vehicle consists of 120-150 kg of propellant, and 20 kg of payload, with a few kg of structural support, primarily a stiff baseplate to support the thin propellant block. A throwaway air-breathing stage improves performance by lifting the vehicle subsonically to 20 km or higher. The vehicle then drops the air-breathing hardware and accelerates vertically to about 100 km, where it "turns over" and accelerates downrange to 400 - 500 km altitude and 1000 km range. At that point it runs out of propellant and enters a circular or elliptical orbit. The maximum acceleration is about 6 gees. The time from launch to entering orbit is 15 minutes or less.

Launcher Cost and Scaling

The cost of the 20 MW, 20 kg system described here is estimated at $450 million; this is roughly broken down in Table 1. The incremental cost of launching a single vehicle is simply the cost of the vehicle, propellant, and electricity; the electricity cost is some 30 to 40 thousand kWH or, at 4 cents/kWh, $1200 to $1600. The propellant cost and vehicle cost should be comparable to this; a total cost per launch of $5000 would give a cost to orbit of $250/kg or less than $120/lb.

The true cost to orbit requires amortizing the cost of the launcher itself, and its maintenance and manpower, and thus depends on how heavily the launcher is used. At one extreme, to reduce the true costs to $10,000/kg ($4500/lb, comparable to current expendable rockets) would require launching a minimum of 50,000 kg, or about 2500 launches, over the life of the system. At the other extreme, the launcher is capable of up to 100 launches per day, or more than 30,000 launches per year. That would put 600,000 kg, or more than 20 Space Shuttle loads, in orbit each year. This exceeds not only the capacity of the Shuttle fleet, but the total capacity of all existing US launch systems at current production rates [2]. Assuming a 5 year system life, and annual operating costs of 20% of the system cost, the total launch cost would be approximately $550/kg, or $200/lb.

The 20 MW, 20 kg system described here is probably near the smallest size that can be built cost-effectively. This results from tradeoffs among vehicle size and structural mass, beam projector size, and laser properties. There is, however, no obvious limit to increasing the system size, and larger systems gain at least linearly in payload size vs. laser power, and considerably better than linearly in payload size vs. system cost.

Table 1: Approximate system cost breakdown

Laser:	$185 M	(approx. $8/watt + $25 M design cost)
Telescope:	$100 M	(based on Keck 10 meter astronomical telescope cost)
Adaptive Optics:	$ 15 M	
Tracking:	$ 50 M	
Power plant:	$ 50 M	(Diesel generators)
Structure:	$ 50 M	(roads, buildings, etc.)
Total	$450 M	

Applications 1: Brilliant Pebbles

Laser Propulsion is an ideal match to current concepts for small space based kinetic kill vehicles (KKV's or "Brilliant Pebbles"). In its most basic use, a laser propulsion system can efficiently place Brilliant Pebbles in orbit at very low cost. Depending on the cost and weight of the KKV's, this could reduce the cost of initial deployment by half, and dramatically reduce the cost of maintaining a KKV constellation against normal attrition or deliberate attack. However, laser propulsion also offers at least two options not available with conventional launchers: massive decoys and refuelling.

With sufficiently low launch costs, essentially arbitrary numbers of decoys indistinguishable from real KKVs can be launched, thus protecting KKV's against many sorts of countermeasures. A brief analysis by Gregory Canavan [3] concludes that laser propulsion may even allow KKV's to remain cost effective against ground-based laser antisatellite weapons; essentially the cost to put a decoy in orbit becomes comparable to the cost of "killing" that decoy. This is an ideal use for the full capacity of a laser launcher.

Refuelling, a recent suggestion by this author, uses the laser to launch "small dumb boosters" consisting simply of a tank of solid or monopropellant liquid fuel and a nozzle, plus a very primitive stabilization system to keep the booster from tumbling while in free fall. The precision and timing flexibility of the laser launcher would allow such a booster to be launched into near-perfect rendezvous with any given KKV as it went overhead, typically once or twice a day. A Brilliant Pebble must be able to locate and "dock" with evasive targets at high velocities; only minimal additional hardware would be needed to allow one to recognize and dock with a cooperative booster at meter-per-second velocities. The boosters would be used only for straight-line thrust, not for final intercept maneuvering, and would thus not need a mechanically strong or electrically complex connection to the KKV.

A single booster, comparable in mass to a Brilliant Pebble, would provide a velocity increment of perhaps 2 km/s; one Brilliant Pebble could stack up two or more boosters for additional delta-V capability. Thus very capable, "long-legged" KKV's could be launched with a small laser system. This would keep the launch system cost low without sacrificing KKV performance. Indeed, the optimum KKV with laser propulsion might be more massive overall than with conventional launch.

Such one-time assembly in space, however, merely increases the cost advantage of laser propulsion, without offering any fundamental new capabilities. By contrast, the ability to refuel KKV's in space after a maneuver could greatly increase the flexibility of a space based interceptor system. KKV's could be redeployed into new orbits, either on a random basis to reduce their predictability, or en masse, then restored to full performance in a few days. Such redeployment would permit KKV's to be stockpiled in orbits that do not overfly the Soviet Union, placed in optimum orbits for the duration of a crisis, and put back into storage, safe from ground attack, as needed. KKV's could be "launched on warning" toward Soviet launch sites, then refuelled if the warning proved incorrect; this would make false alarms much less expensive and thus increase the usable warning time, possibly by a large margin. It would also make it impossible for one or a series of deliberate false alarms to deplete a KKV constellation for more than a matter of hours. This sort of refuelling is essentially impossible with conventional launchers, as each KKV is in a different orbit and each booster must be launched to a different rendezvous point.

Applications 2: Other Defense Uses

Laser propulsion can be used to launch anything that can be packaged in small pieces and that is needed either in large quantities or on short notice. Three major applications are for sensor satellites, reconnaissance missions, and communications satellites. Sensor satellites, for launch detection or other uses, and "packet switching" comsats, both represent uses for networks of many, perhaps hundreds, of small low orbit satellites, preferably with launch facilities capable of restoring the network quickly in case of attack.

Short-notice reconnaissance represents another unique laser propulsion capability which cannot be achieved with conventional launchers [4]. A laser launcher could place a small reconnaissance camera, or other sensor, at relatively low altitude (100 km) over any point on Earth within approximately 45 minutes of a request. It could launch additional cameras at 15 minute intervals for as long as desired. A conventional satellite, by comparison, offers at most two chances per day to observe a given point, generally not from an ideal angle. Dedicated launches have the additional advantage that the site being observed has very little warning of the satellite's approach; even if the launch is observed the warning time is 30 minutes or less.

The Soviet Union has used this frequent-launch approach to maintain hourly surveillance of past Middle East conflicts, but at tremendous expense; at current US costs of $10 million per launch for a Scout rocket, frequent launches are completely impractical. The unit cost of a laser launch, however, would be dominated by the camera cost, which could be made perhaps two orders of magnitude lower. A 30 cm telescope with a mass of less than 5 kg is already available [5]; that would give a diffraction-limited ground resolution of roughly 1 foot. It is even technically possible to have a camera re-enter over a point of interest, providing very high resolution indeed.

There are many possibilities for laser propulsion at higher power levels, or with improved technology. Some could have major effects on SDI or other areas of defense. One example is a laser powered air-breathing thruster -- a laser SCRAMjet -- working at orbital velocities. A KKV attached to a hypersonic glider could enter the upper atmosphere over a laser station and make a sharp turn, so as to approach the laser again on the next orbit; the laser would make up the velocity lost to drag in the process. With a suitable choice of laser location and orbit parameters, KKV's would follow an orbit fixed relative to the Earth's surface, rather than to inertial space, and thus drastically reduce the "absentee ratio" which currently plagues space based interceptors. However, the performance and reliability requirements for such a scheme would require much more extension of current technology than a simple launcher, which can be built very nearly "off the shelf".

Applications 3: Non-Defense Uses

A laser launcher would not be limited to defense uses, although in most other applications it would be competing solely on a cost basis against conventional launchers. Many rocket and Space Shuttle payloads are not amenable to subdivision into small pieces, and the aerospace industry has no experience designing small, very low cost payloads for space. Thus the size of the commercial and scientific markets that would be opened by a laser launcher is unknown. It is at least plausible that such uses could consume several hundred launches per year.

The number of applications grows enormously if some form of assembly in space is possible. It is currently impractical to assemble anything in space from 20 kg modules using either human or robotic labor; there is not even a practical way to collect such pieces and bring them together. Again, however, the technology of Brilliant Pebbles is applicable to building small autonomous spacecraft capable of rendezvous and docking maneuvers. A laser could launch such a guidance and command unit, which would over several days collect and join together independent modules (power, communications, scientific experiment, booster) to form, for example, an interplanetary probe.

A larger-scale application of this concept would be efficient resupply of the NASA Space Station. Supplies (food, water, tools, spare parts, and perhaps even fuels and oxygen) would be delivered to orbit perhaps 100 km from the Space Station (to keep the Station safe from both laser beams and packages at high relative velocity) A very small retriever vehicle would collect these supply packages and return them to a suitable airlock on the Station. Astronaut time would be needed only to unpack and store the supplies, and perhaps to monitor the final approach of the retriever to the Station.

The laser system cannot launch to a given non-equatorial orbit at any time; the laser is precisely in the orbital plane only twice a day. However, a combination of the laser's own range and a few hundred meter-per-second crossrange capability (on either the supply packages or the retriever) would allow at least eight payloads per day to reach the Space Station. Eight payloads per day would be over 50 tons -- two Shuttle loads -- per year. The limited size of each payload would be somewhat offset by the promptness of delivery; a tool or spare part could be delivered to the Station with, in many cases, less than a day's delay. As Federal Express has demonstrated, overnight delivery frequently commands a premium price, and is sometimes truly invaluable.

Applications 4: Uses for a Sub-Scale Laser Facility

Although a true launch-to-orbit system requires a 20 MW system, there are some propulsion applications for considerably smaller lasers. Perhaps the most important of these is orbital maneuvering propulsion. A laser as small as 1 to 2 MW can give considerable impulse to a satellite passing overhead. To keep the beam projector size and cost within reason, the satellite must deploy a crude reflector (essentially a beach umbrella of aluminized Mylar) to concentrate the laser beam. However, with such a concentrator, the satellite can get thrust with triple the specific impulse of solid rockets, or twice that of hydrogen/oxygen rockets, from a completely safe and stable block of inert propellant.

The laser can only "see" a given satellite in low orbit for a few minutes each day; exactly how much time depends on the details of the satellite's orbit and the laser range. (Orbiting mirrors would greatly increase this, but would cost much more than the laser system). That is sufficient to allow a 2 MW laser to maintain or raise the orbit an object as large as a Space Shuttle External Tank. It is also sufficient to push ton-sized satellites from low orbit to geosynchronous transfer orbit on time scales of weeks, while saving half to two thirds of the mass of a standard solid or liquid fuelled upper stage.

If a high enough laser flux can be achieved in orbit, the laser could also clear away space junk. Small bits of debris would be evaporated. The surface of larger pieces would ablate, producing enough thrust (at low specific impulse) to deflect the junk into orbits that re-enter the atmosphere.

A megawatt-scale laser facility is also a necessary step in developing a laser launcher. While not capable of putting anything in orbit, it could launch small "sounding rockets" to several hundred km altitudes, and provide detailed information on atmospheric absorption, turbulence, and blooming. It could also aid other space experiments, by providing very high levels of burst power to satellites passing overhead (although this function might be better served by a short wavelength laser whose light could be efficiently converted to electricity by ordinary solar cells).

Status of Laser Propulsion Research

The SDIO Laser Propulsion Program has been operating for nearly two years, with total expenditures to date of roughly $4 million. The Program has conducted experiments at several industry and Federal laboratories, and both industry and university groups have done theoretical analysis and computer modelling of the double-pulse planar thruster and related schemes.

We have demonstrated experimentally that the double pulse thruster concept works, producing higher thrust efficiency (exhaust kinetic energy/laser pulse energy) and higher specific impulse than can be achieved with single laser pulses under similar conditions. This was done with single pairs of CO_2 laser pulses, with pulse energies of a few Joules and pulse widths of 50 to 100 ns. Specific impulses of 700 to 800 seconds have been demonstrated using both single and double pulses.

The actual thrust efficiencies achieved with double pulses are only about 10%, while the launch system specifications cited above assume an efficiency of 40%. However, theory and computer modelling suggest that substantially higher efficiencies will be obtainable with longer pulses. Several energy loss mechanisms involve characteristic time or distance scales comparable to the scale of the current experiments, and will be much reduced at larger scales. We are currently preparing for experiments using a 2 kJ, 1 μs laser at Avco Research Laboratory, in which we hope to demonstrate efficiencies of 20% or more. Note that varying the efficiency changes only the size of the laser needed to lift a given payload; even at 20% efficiency all of the applications described above are practical, although the launch system cost would be somewhat higher.

We have identified several promising propellant candidates, including lithium hydride and other light hydrides, water ice, and certain C-H-O plastics, notably polyformaldehyde (trade names Delrin and Celcon). More important, we now understand many of the properties required of a good propellant, such as short optical absorption depth in the solid (for efficient evaporation during the first laser pulse) and at least one component with a low ionization potential (for efficient absorption of the second pulse, which is absorbed by electron-ion and electron-neutral interactions). We have demonstrated our ability to modify propellants to achieve desired properties, for exampe by mixing wavelength-sized metal flakes into a plastic propellant to serve as plasma ignition sites; these lower the flux needed to achieve efficient heating during the second laser pulse.

Finally, we have analyzed many of the critical systems-level problems involved in building an actual launcher. We have, for example, calculated the control-loop response involved in guiding a laser-driven vehicle from the ground, and demonstrated that such ground-based guidance is stable over a wide range of conditions.

If the planned tests with single pulse pairs at 2 kJ are successful, the Laser Propulsion Program will be ready to proceed to tests with a repetitively pulsed laser of significant average power. Unfortunately, few such lasers are available, and none provide our desired pulse format. The Program currently plans to modify the Humdinger CO_2 laser at Avco Research Laboratory, but we are still seeking other options. The Program will also begin work on tests using Nd:glass lasers at 1.06 μm, both to determine the wavelength scaling properties of the double-pulse thruster, and specifically to see how laser propulsion could be adapted to use the large 1.06 μm FEL's now under develoment by SDIO.

Program for Laser Propulsion

The following is an outline of a 5 year program leading to the construction of a 20 MW laser launch system in 1994. This is a fairly compressed schedule, although not a crash program; most of the technology needed for even very large CO_2 lasers has been available for a decade or more. The program could be initiated at low cost, simply by modestly expanding the current SDIO Laser Propulsion Program over the next two years; that would be enough time to confirm the performance of the double-pulse thruster and develop detailed plans and cost estimates for the entire system. Essentially all major aspects of the system (laser technology, optics, guidance) would be tested by late 1992, before construction of the large laser and telescope begins.

1989 (Current budget $1.7M; additional $500K needed)

- Laboratory tests with 2 kJ, 1 microsecond pulses; demonstrate >20% thruster efficiency
- Design 100 kW average power "rep-pulse" experiments
- Start modifications of Avco HUMDINGER laser

1990 ($5M)

- Do "rep pulse" experiments
  - Demonstrate sustained thruster operation
  - Fly 1 kg test vehicle at short ranges
- Design 2 MW laser module, 100 kW portable test laser, telescope, etc.
- Start construction of 100 kW 10 kJ laser

1991 ($20M)

- Construct and test 100 kW 10 kJ laser
  - Fly 1kg test vehicle at long range
  - Possible space propulsion experiment with a small satellite
- Complete design, begin construction of 2 MW laser module and 4 meter telescope
- Begin design of launch facility (20 MW laser, 10 m telescope)

1992 ($50M)

- Construct and test 2 MW laser facility at mountaintop site
- Sounding rocket and satellite maneuvering tests
- Complete design of launch facility

1993 ($150M)

- 2 MW facility operational; satellite maneuvering tests
- Begin construction of launch facility

1994 ($300M)

Complete construction of launch facility

First launch to orbit by mid 1994

Operational facility (10 launches/day) by end 1994

CONCLUSIONS

The United States could have a working ground-to-orbit laser launch system by the middle of the coming decade. Such a launcher would be capable of launching tens of thousands of small (20 kg) payloads into low Earth orbit every year, at an incremental cost approaching $100/lb. The capital cost of the system, including development costs, would be approximately a half-billion dollars -- comparable to the cost of a handful of Shuttle or expendable rocket launches, whose total payload the laser could launch in a few months.

Such a laser system could significantly lower the cost of many space operations, from Space Station resupply to launching of small communications satellites. It would be particularly valuable for the deployment of small space-based interceptors or "Brilliant Pebbles". It would also provide fundamentally new capabilities, not available with conventional launchers. These include the ability to refuel space-based interceptors in flight, greatly increasing their flexibility, and the ability to launch small reconnaissance satellites to any point on Earth on a few minutes notice. Even a sub-scale laser system, costing roughly 1/10 as much, could provide new capabilities, notably for maneuvering satellites using thrusters with two to three times the specific impulse of chemical rockets.

The basic operation of a laser propulsion thruster has been demonstrated in the laboratory; larger scale tests which should demonstrate realistic thruster efficiencies are planned for the next few months. Although there is considerable development work to be done, no major advances in physics or technology are needed to build a launch system using CO_2 lasers. A five year program to build a launcher is proposed; it requires only modest growth in the current SDIO program in the next year. The sub-scale laser system would be completed in 1992, and would be sufficient to answer essentially all questions about the performance of the full launcher. At that time, a commitment to build the launcher would lead, in two more years, to a true pipeline to space.

References

[1] Details of the double-pulse thruster, and additional background information on laser propulsion, are included in the *Proceedings of the 1986 SDIO/DARPA Workshop on Laser Propulsion*, Kare, J. T., ed., LLNL CONF-860778, (Lawrence Livermore National Laboratory, August 1987), volumes 1 and 2.

[2] U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyers Guide*, OTA-ISC-383 (U.S. Government Printing Office, July 1988), p. 20.

[3] Canavan, Gregory, "Decoy Deployment with Laser Propulsion", LA-UR-88-1246 (Los Alamos National Laboratory, April 1988).

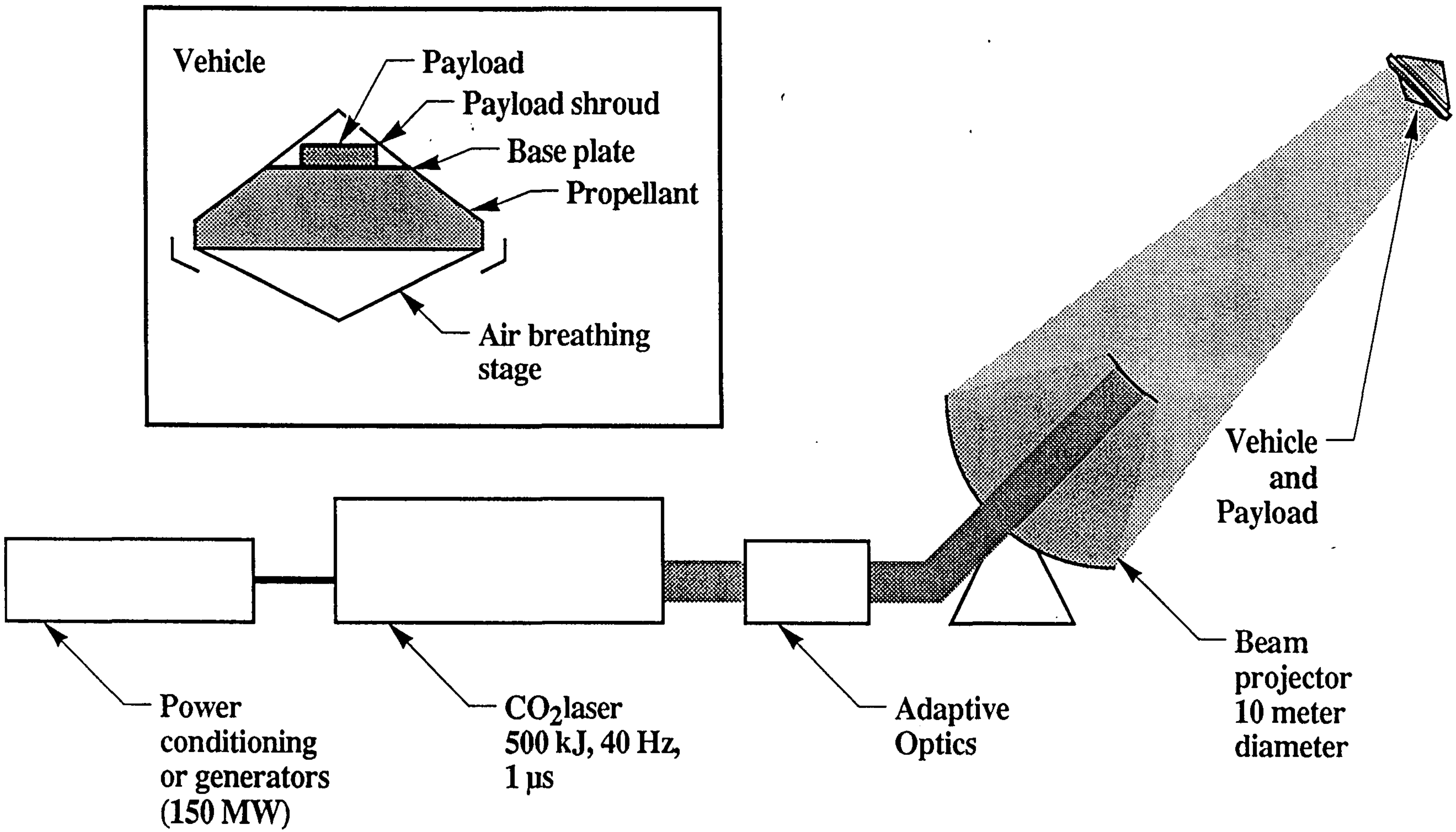
[4] This option has been examined in some detail by Dennis Reilly of Avco Research Laboratory, Everett, MA.

[5] Telescope developed by University of Arizona, as reported in Popular Mechanics, Nov. 1988, p. 95.

Figure 1:

Components of a 20 MW/20 kg Laser Launch System

SDIO Laser Propulsion Program



RC-003-U-3425-002