NASA Contractor Report 3774

Analysis of a 10 Megawatt Space-Based Solar-Pumped Liquid Neodymium Laser System

U. H. Kurzweg

GRANT NAG1-135
JANUARY 1984

NASA

NASA Contractor Report 3774

Analysis of a 10 Megawatt Space-Based Solar-Pumped Liquid Neodymium Laser System

U. H. Kurzweg
University of Florida
Gainesville, Florida

Prepared for
Langley Research Center
under Grant NAG1-135

National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1984

ABSTRACT

A ten megawatt solar-pumped continuous liquid laser system for space applications is examined. It is found that a single inflatable mirror of 434m diameter used in conjunction with a conical secondary concentrator is sufficient to side pump a liquid neodymium lasant in an annular tube of 6m length and 1m outer and 0.8m inner diameter. About one fourth of the intercepted radiation converging on the laser tube is absorbed and one fifth of this radiation is effective in populating the upper laser levels. The liquid lasant is flowed through the annular laser cavity at 1.9m/s and is cooled via a heat exchanger and a large radiator surface comparable in size to the concentrating mirror. The power density of incident light within the lasant of approximately 68 watt/cm^3 required for cw operation is exceeded in the present annular configuration. Total system weight corresponds to 2.05 x 10^4 kg and is thus capable of being transported to near earth orbit by a single shuttle flight.

INTRODUCTION

A new and potentially significant energy conversion technique suitable for space applications is the solar pumped laser which directly converts sunlight to laser radiation. Interest in this conversion method first developed during the early sixties [1,2,3] with most of the work involving high quality optical concentrators of small aperture used to pump neodymium doped yttrium aluminum garnet (YAG). Continuous and spike free laser outputs at 1.06 μm were observed at power levels up to one watt. Conversion efficiencies were generally quite low not exceeding one tenth of one percent. Typical pump radiation densities within the lasant required for threshold operation were about 100 w/cm^3 and thus needed concentrations of the incoming sunlight by better than one thousand at the cylindrical laser surface. This work was not pursued for nearly a decade until the middle seventies when NASA became interested in using very large solar pumped lasers for both space

communications and space power transmission. Several systems studies of 100 MW direct and indirect laser systems using gas as the lasant were undertaken[4,5]. From these studies it became clear that such solar pumped lasers would require very large concentrating mirrors up to 3000 m in diameter for a typical 100 MW gas laser system operating at one percent conversion efficiency. Concomitantly with these studies, NASA Langley undertook a series of small scale experimental studies using a solar simulator[6]. In these studies an iodine gas laser yielded pulsed outputs up to 3 watts at 1.315 μm when using a 4kw continuous light source. The conversion efficiency was approximately η=0.1 percent. This relatively low efficiency was in part due to the mismatch between the near ultraviolet pumping bands and the 6000 K black body spectrum of the solar simulator. Starting in 1981 we here at the University of Florida have been investigating an alternative solar pumped laser namely, the liquid neodymium system [7]. This NASA sponsored effort has as its objective not only to determine the characteristics of such a liquid laser system but also to construct an actual solar facility to pump these. The major advantages of a neodymium based solar pumped laser system over others are the excellent match of the neodymium absorption bands with the solar spectrum (Fig. 1), the expected 5 percent conversion efficiency and the ability to have much larger power densities than for gas lasers. A drawback of the neodymium liquid is the need to keep its temperature below 38°C if laser action is to be maintained. This requires very large radiator surfaces for cooling when dealing with space applications.

A large concentrator facility using eight by eight foot centrifugally spun epoxy mirrors has been built here at the University of Florida and we are now in the process of using the mirrors to lase a small neodynim fluid laser. We have succeeded in pumping a water cooled 5cm long YAG:Nd^{3+} laser rod using a single 8x8ft mirror and an axicon secondary concentrator. A

continuous laser output of approximately one watt for periods as long as ten seconds has been achieved.

As part of our research effort on liquid pumped lasers we have also been conducting a systems study on a 10 MW (1.4×10^4 HP) solar pumped liquid neodymium laser. It is our purpose here to discuss the characteristics of such a space based laser system including information on the concentrator size, the laser configuration and radiator requirements.

MIRROR CONFIGURATION FOR A 10 MW LIQUID LASER SYSTEM

We begin our investigation by first examining the size and configuration of the space mirror required to power a 10 MW liquid neodymium laser. Assuming a positioning of the laser system in near Earth orbit one has available 1.35 kw/m^2 of solar flux. This rather diffuse radiation can be concentrated via a parabolic mirror of diameter D and focal length F into a spot (blur circle) of diameter F/107, where 1/107 represents the angular width of the Sun as seen at 1 au. From this it follows that an ideal parabolic concentrator will produce a solar concentration of

$$C = 1.145 \times 10^4 \, (D/F)^2 \qquad (1)$$

suns and that the total intercepted power will be

$$P = 1060 \, D^2, \qquad (2)$$

where D is measured in meters and P in watts. The coherent laser output power possible using this concentrated radiation is equal to P multiplied by the overall conversion efficiency η. A plot of this output power as a function of mirror diameter and conversion efficiency is found in Fig. 2. From this figure one can see that a 10 MW neodymium space based laser operating at an efficiency of 5 percent will require a single parabolic mirror of D = 434 m. Note from Fig. 2 that such a mirror is smaller than that needed for the

proposed 100 MW gas laser system proposed by NASA[4] but very much larger than that used in existing ground based solar pumped lasers. Assuming a 600 m focal length, it follows from Eq. (1) that the flux density at the blur circle will be 809 w/cm^2 and the diameter of the focal spot will be δ=5.6 m. To achieve this concentration it is not necessary to use high quality diffraction limited optics and indeed mirror surface roughness elements of height Δ with slopes up to $\Delta/F = 0.01$ can be allowed without appreciably widening the blur circle. This also means that spherical mirrors can be used as the primary concentrator as long as the f number (F/D) does not become too small. It is clear from the 434 m diameter mirror required for the present 10 MW system, that even the relatively simple centrifugally spun mirror construction method used quite successfully by us for ground based studies[7] becomes of limited value for space applications because of weight considerations. We therefore propose a novel type of light weight inflatable mirror (see ref. 10 for some related work) constructed from two sheets of plastic as shown in Fig. 3. One of these 10 μm thick acrylic sheets would be transparent while the other would be coated with a thin aluminum layer of 0.2 μm thickness. The space between the sheets would be inflated with a gas so that the resultant lens like configuration with two spherical surfaces would be a self-supporting tension structure of about 6×10^3 kg mass. The materials used for the sheets would have to be resistant against ultraviolet radiation and an automated pressure control system would have to be provided to avoid changes in focal length due to heating or cooling of the gas between the plastic sheets. We are presently in the process of conducting some model tests of such inflatable mirrors as we believe their proper functioning will be a crucial requirement for any large space based solar pumped laser system.

We envision the concentrated radiation at the blur circle to be reconcentrated by means of a conical reflector (axicon) as shown in Fig. 4. The characteristics of such a concentrator have been discussed in detail elsewhere[8] and its function here is less to produce further flux concentration than to allow for an axisymmetric illumination of the cylindrical laser cavity for the purpose of side pumping. The dimension of this axicon concentrator must be such that its front opening just matches the focal spot size of the primary mirror while its length is determined by the required power density at threshold for cw lasing. This point will be considered next.

THRESHOLD CONDITION FOR CONTINUOUS LASING

In the present liquid laser system we are dealing with a 0.3 M ($3x10^{20}/cm^3$) solution of neodymium ions in phosphoric oxychloride. Because of the excellent overlap of the absorption spectrum of Nd^{3+} with the solar spectrum (Fig. 1) one can expect this lasant to yield an overall conversion efficiency of about 5 percent. The absorption coefficient for this fluid at the absorption lines is approximately 0.25 cm^{-1} with the addition of chromium (Fig. 1) providing an even higher value. It is at once clear that the estimated 26 percent of the solar spectrum overlaping the Nd^{3+} absorption bands will not propagate into the liquid lasant more than 10 cm. This suggests that for efficient side pumping the lasant be placed into an annular laser tube of 1 m outer and 0.8 m inner diameter. The inner tube would have a built in reflector for the radiation not absorbed so as to allow it to be rejected from the axicon system. With an assumed absorption of 26 percent of the total incoming 200MW and the conversion of 10 MW of this into laser radiation we would be left with some 42 MW which is converted to heat within the liquid lasant. This heat has to be removed from the cavity at a convective rate sufficient to keep the fluid from heating above its 38°C upper temperature limit for lasing. To determine the length of the laser cavity for

which this is possible we next calculate the minimum florescence power required for continuous output for this four level laser system. The florescence power per volume of lasant is[9]

$$\left(\frac{P}{V}\right)_f = \frac{N_t h\nu}{t_s}, \qquad (3)$$

where N_t is the threshold number density, t_s the lifetime of the upper laser level and $h\nu$ the transition energy. For the present neodymium system $t_s = 3 \times 10^{-4}$ sec. The threshold number density is given by

$$N_t = \frac{8\pi t_s \Delta\nu}{c t_c \lambda^2}, \qquad (4)$$

with $\Delta\nu$ the gain linewidth here equal to 6×10^{12} Hz, $t_c = \ell/Lc$ the decay lifetime of the cavity with ℓ the cavity length, c the speed of light in the n=1.5 medium, L the loss per path in the resonant cavity and $\lambda = 1.06\ \mu m/1.5$ the effective radiation wavelength. Assuming a 6m long cavity with a 10 percent loss per path yields $t_c = 3 \times 10^{-7}$ sec. Substituting this into Eq. (4) yields

$$N_t = 1.5 \times 10^{15} \text{ atoms/cm}^3 . \qquad (5)$$

This number density is consistent with the inversion density needed in smaller neodymium glass lasers[9]. Substituting Eq. (5) into Eq. (3) yields the flourescence power density of

$$\left(\frac{P}{V}\right)_f = 0.94 \text{ watts/cm}^3 \qquad (6)$$

required for continuous lasing. This in turn means that if 20 percent of the incoming 26 percent of the solar radiation absorbed is effective in populating the upper laser level and we have a 40 percent quantum efficiency with a 1.5 ratio of output to pump wavelength, that cw laser action will be maintained when the incoming solar radiation power per lasant volume equals

$$\left(\frac{P}{V}\right)_{pump} = 67.8 \text{ watts/cm}^3 . \qquad (7)$$

This result thus indicates that for solar pumped lasing in our liquid neodymium system the concentration of the pumping power must be of the order of 100 watts for every cubic centimeter of lasant. This condition is well satisfied in the present system where 200 MW of radiation power are available for 1.69×10^6 cm^3 of lasant within the annular cavity. Indeed we have an average power density of 118 w/cm^3 within the 6m long laser cavity. Lasing within the cavity will be made possible by two ring mirrors whose radii of curvature are large compared to the cavity length to insure mode stability. The mirrors will have to be cooled to prevent overheating and the resultant annular laser beam can be converted into a single cylindrical beam by an axicon mirror reflecting system located outside the resonant cavity.

FLUID COOLING AND RADIATOR DESIGN

The liquid lasant under consideration has an upper temperature limit of approximately 38°C. This together with the fluid freezing point allows a temperatue range of about 50°C. One is thus in a position of having to remove some 42 MW (10^7 calories/sec) of heat from the fluid. In space this is most easily accomplished by first passing the moving lasant through a heat exchanger where a volatile second fluid is vaporized and then passed via a secondary loop to a large radiator surface where it condenses. This heat pipe cooling is a well established technology and is capable of handling the large heat flow rates encountered in the present system. The velocity with which the lasant must flow through the laser cavity in order to stay within the above 50°C temperature range is readily calculated from the heat balance equation

$$\Delta T = \frac{P}{\rho C J Q} , \qquad (8)$$

where $\rho = 1.68$ gm/cm^3 is the lasant density, $C = 0.22$ cal/gm^0C the specific heat, Q the volume flow rate and P=42 MW the solar power converted to heat

within the fluid. J=4.18 joules per calorie is the mechanical equivalent of heat. Solving Eq. (8) for $\Delta T = 50°C$ yields a volume flow rate of $Q = 0.544 \times 10^6 cm^3/sec = 0.544\ m^3/sec$. From this it follows that the average axial velocity will be 1.92 m/sec. If this heat is to be dissipated via the radiator panels indicated in Fig. 3, one can show by balancing the heat added to the system with that radiated away that the total surface area (including both the front and back) of the four panels envisioned will be

$$A_r = P/\varepsilon\sigma T^4 \quad , \qquad (9)$$

where P=42 MW, ε the surface emmisivity and $\sigma = 5.67 \times 10^{-8}$ watt/m^2 $^oK^4$. Taking T=300°K as the mean radiator temperature yields a radiator surface area of $9.15 \times 10^4\ m^2$ for an ideal reflector with $\varepsilon=1$. That is, for four square panels oriented at right angles to each other and having their planes parallel to the incoming solar radiation, the fluid heat can be dissipated if each panel is 107m on a side. Note that the total radiator area is some 62 percent of the primary mirror area and hence quite large. The radiator surface could be constructed of thin parallel metal foils separated from each other by several millimeters to allow passage of the condensing vapor. A pump system for both the circulation of the lasant through the laser cavity and the circulation of the secondary cooling fluid in the radiator will be needed. We estimate a total of 20 kilowatt of electricity will be required to drive these pumps. The volume of secondary fluid in its liquid state will be comparable with the approximate 2.5 m^3 of lasant in the primary loop, with its volume in the gaseous state being a thousand times larger.

OVERALL SYSTEM WEIGHT FOR TRANSPORT TO ORBIT

We are now in a position to estimate the total mass of the proposed 10 MW laser system. The inflatable mirror as already discussed will have a mass of 6×10^3kg. The axicon secondary reflector constructed from aluminum and

coated with a highly reflective inner surface will have a mass of 0.6×10^3kg, the filled laser tube 3.4×10^3kg, the pumps and heat exchanger 2×10^3 kg. The metal foil radiator panels would have an approximate mass of 5×10^3kg and the volatile secondary loop fluid 3.5×10^3kg. Adding these masses yields a net effective mass of 20.5×10^3kg. This mass is about 68 percent of that capable of being transported to near Earth orbit by a single shuttle flight[5] and about 50 times less than the mass of the proposed 100 MW NASA gas laser operating at 1 percent efficiency.

CONCLUDING REMARKS

It has been shown that it is feasible to construct a 10 MW solar pumped liquid neodymium laser suitable for space operation. Such a laser system would require the development of a 434 m diameter inflatable mirror together with an axicon concentrator some five meters in diameter at its entrance and six meters long. The liquid lasant would be circulated through a 6 m long annular laser tube with a transparent outer glass wall through which some 200 MW of concentrated solar radiation would enter. The majority of the incoming radiation would be rejected from the system after multiple reflections with about 26 percent of the energy being absorbed by the neodymium lasant. The 42 MW of power converted into the heat within the lasant during the process is removed via a heat exchanger and a large radiator surface. The remaining 10 MW would be available for laser output at 1.06μm.

The above numbers are very much a function of overall laser efficiency. For example the reduction of the efficiency by an order of magnitude from the 5 percent value considered here would require not only a primary mirror ten times larger in area than the present one (Fig. 2) but also the radiator surface would need to be upscaled with the concomitant increase in overall system mass. At efficiencies below one percent the direct conversion of solar

energy to laser radiation would appear not to be competitive with indirect conversion schemes such collecting the sunlight via photovoltaic cells and then using the resultant stored electric energy to drive a high efficiency CO_2 gas discharge laser. The major drawback for the use of photovoltaic cells at the present time is their costs when the intention is to intercept large amounts of solar power as is required for large solar pumped laser systems.

REFERENCES

1) Kiess, Z. S.; Lewis, H. P.: and Duncan, R. C.: "Sun Pumped Continuous Optical Maser". Appl. Phys. 2, 93 (1963.
2) Reno, C. W.: "Solar Pumped Modulated Laser". RCA Review, vol. 27, no. 1, March 1966, pp. 149-157.
3) Young, C. G.: "A sun Pumped CW One Watt Laser". Appl. Optics, 5, 993 (1966).
4) Holloway, P. F. and Garrett, L. B.: "Utility of and Technology for a Space Central Power Station". AIAA-81-0449, Feb. 1981.
5) Schafer, W. J. Associates, Inc.: "Investigation of Possibilities for Solar Powered High Energy Lasers in Space". Space Laser Power Transmission Systems Studies. NASA CP-2214, Feb. 1982, pp. 45-56.
6) Lee, J. H. and Weaver, W. R.: "A Solar Simulator Pumped Iodine Laser". J. Appl., Physics, June 1981.
7) Schneider, R. T.; Kurzweg, U. H.; Cox, J. P.; and Weinstein, N.: "Research on Solar Pumped Liquid Lasers", Annual Progress Report. NASA CR-172121, March 1983.
8) Kurzweg, U. H.: "Characteristics of Axicon Concentrators for Use in Photovoltaic Energy Conversion". Solar Energy, 24, 441 (1980).
9) Yariv, A.: "Introduction to Optical Electronics. Holt, Rinehart and Winston Inc., New York, N.Y. (1971).
10) Etheridge, F. G.: "Solar Rocket System Concept Analysis". U.S. Air Force Rept. no. AFRPL-TR-79-79, Dec. 1979. (Available from DTIC as AD A079-117).

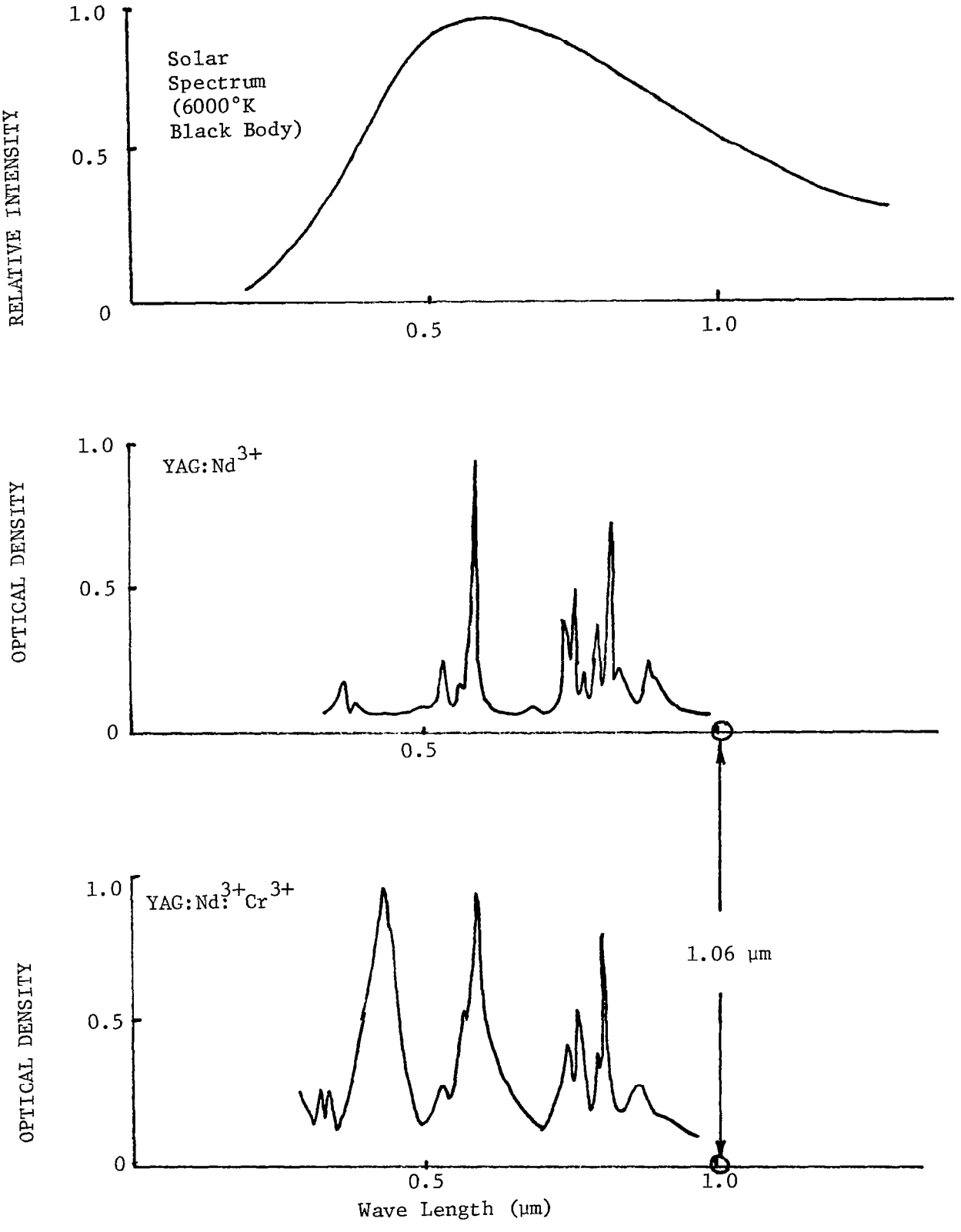
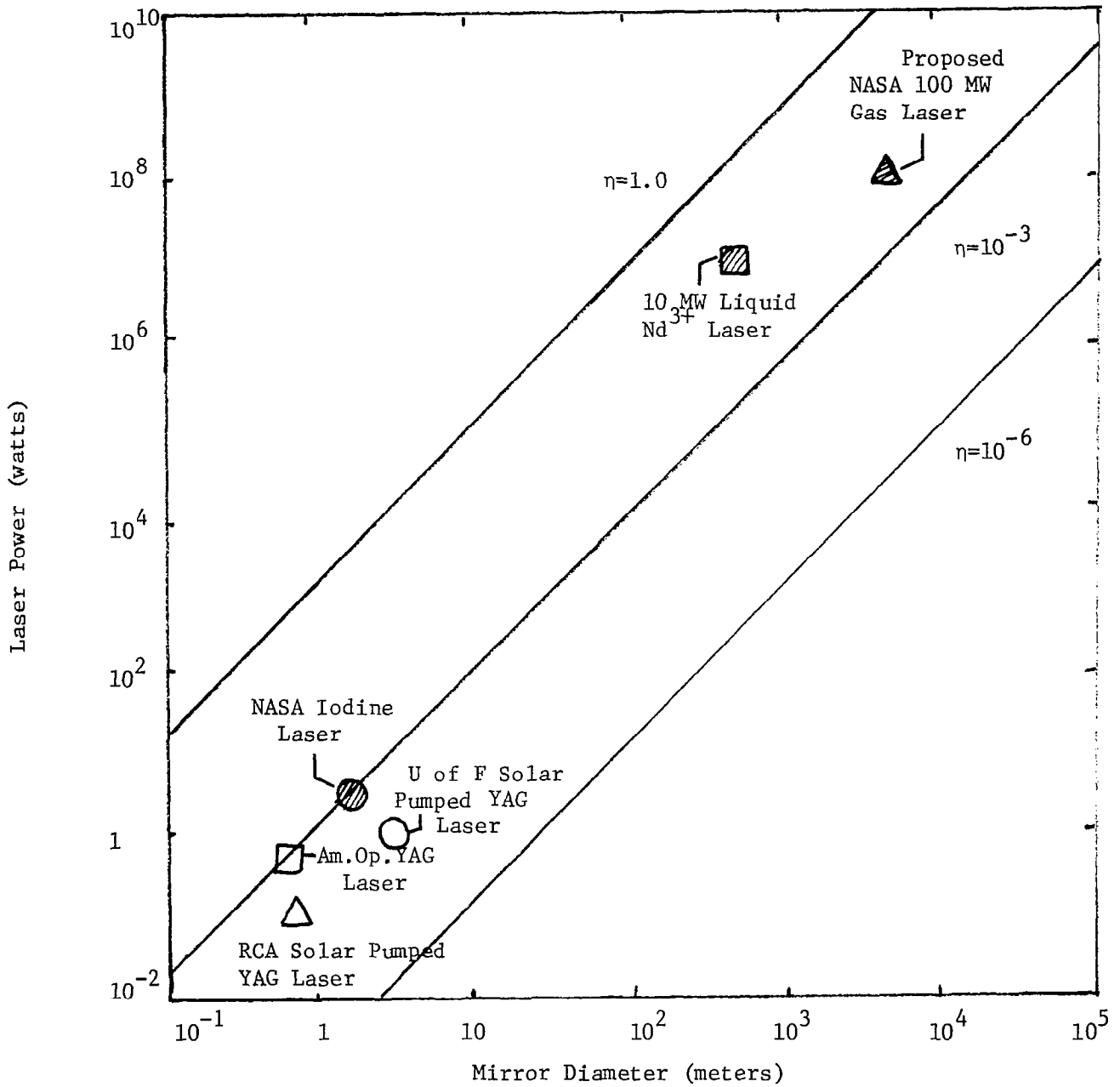


Fig. 1 - Compatibility of the Solar Spectrum with the Neodymium Absorption Spectrum.

Fig. 2 - Power of Solar Pumped Lasers as a Function of Mirror Diameter and Conversion Efficiency. The Points Indicate Existing or Proposed Solar Pumped Lasers.



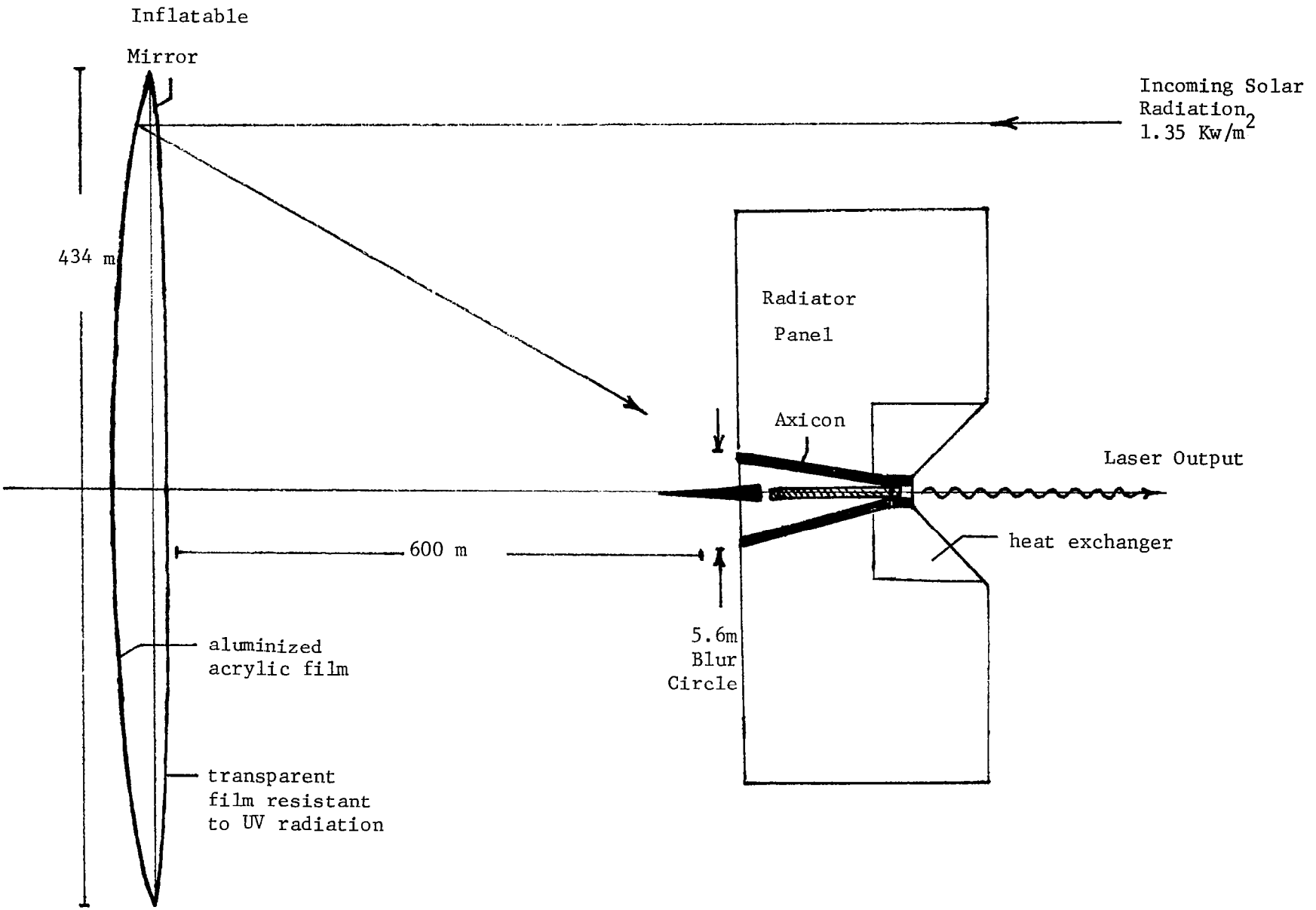
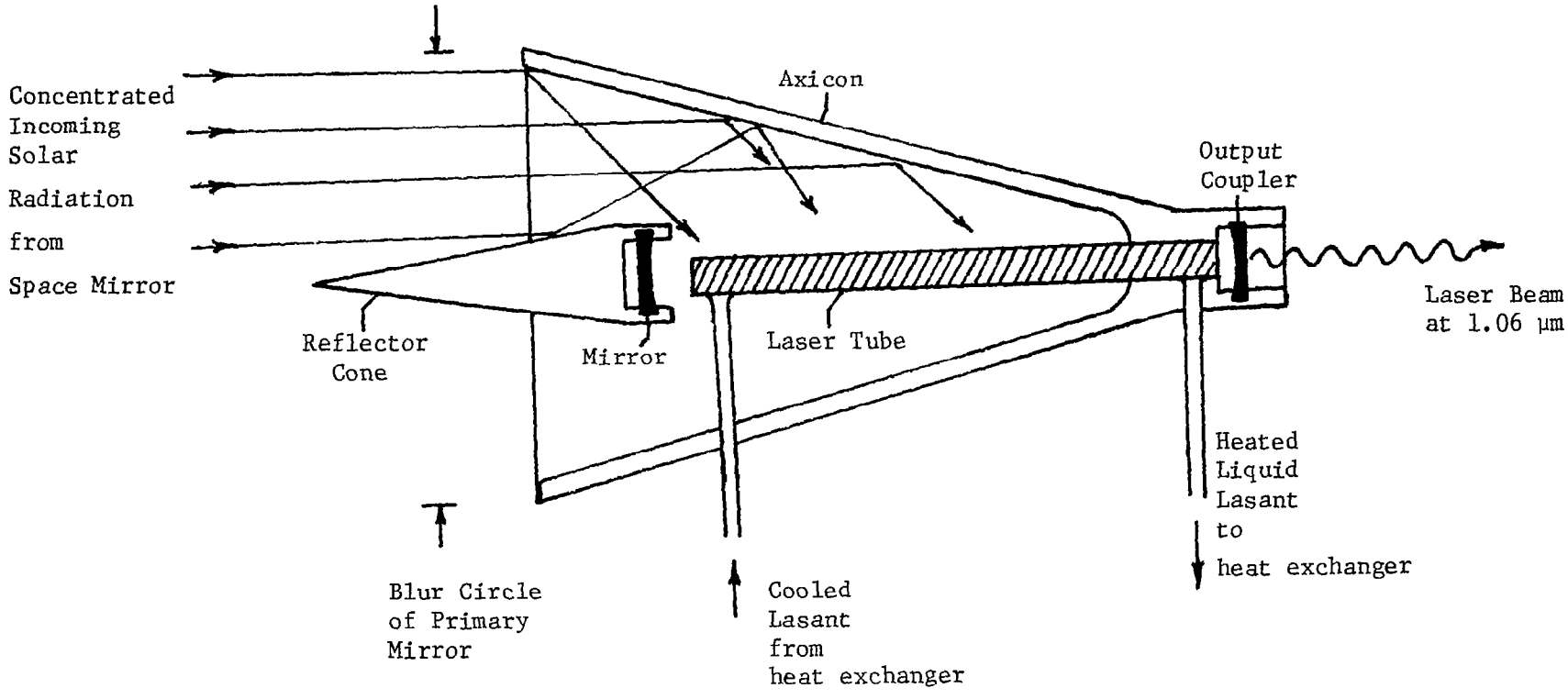


Fig. 3 - Schematic of a 10 Megawatt Solar Pumped Liquid Laser

Fig. 4 - Details of the Secondary Concentrator and Laser Configuration.



1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-3774		

4. Title and Subtitle	5. Report Date
ANALYSIS OF A 10 MEGAWATT SPACE-BASED SOLAR-PUMPED LIQUID NEODYMIUM LASER SYSTEM	January 1984
	6. Performing Organization Code
7. Author(s) U. H. Kurzweg	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address University of Florida Department of Aeronautical Engineering Gainesville, FL 32611	11. Contract or Grant No. NAG1-135
	13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Langley Technical Monitor: R. J. DeYoung

16. Abstract

A ten megawatt solar-pumped continuous liquid laser system for space applications is examined. It is found that a single inflatable mirror of 434m diameter used in conjunction with a conical secondary concentrator is sufficient to side pump a liquid neodymium lasant in an annular tube of 6m length and 1m outer and 0.8m inner diameter. About one fourth of intercepted radiation converging on the laser tube is absorbed and one fifth of this radiation is effective in populating the upper levels. The liquid lasant is flowed through the annular laser cavity at 1.9m/s and is cooled via a heat exchanger and a large radiator surface comparable in size to the concentrating mirror. The power density of incident light within the lasant of approximately 68 watt/cm^3 required for cw operation is exceeded in the present annular configuration. Total system weight corresponds to 2.05 x 10^4 kg and is thus capable of being transported to near earth orbit by a single shuttle flight.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Lasers Neodymium Laser Space Laser	Unclassified - Unlimited Subject Category 36

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	18	A02

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1984