

INITIAL EXPERIMENTS WITH A LASER DRIVEN STIRLING ENGINE

Robert L. Byer

Stanford University

ABSTRACT

N 76 - 21524

During the spring and summer of 1974 three students,* taking my Quantum Electronics Laboratory Course, and I set out to build a laser driven engine. To our delight we succeeded for a brief time in driving a Beale free piston Stirling engine with a 40-W CO₂ laser. I have no doubt that our initial experimental success is but a first step in efficient energy conversion of laser radiation by engines.

INTRODUCTION

The ability to transform energy from one form to another has fascinated engineers for over a century. Although our preliminary experiments were motivated by the thought of transmitting energy over great distances by a beam of light and then efficiently converting the received energy to electricity, we are not the first with such a dream. Figure 1 shows an early solar driven steam engine exhibited at the Paris World's Fair by Mouchot, nearly 100 years ago (ref. 1).

We became interested in the possibility of demonstrating a laser-driven engine following the pioneering work of A. Herzberg et al (ref. 2). Unfortunately, the photon engine in the form described by Herzberg proved to be unrealizable in practice (ref. 3). Thus the problem of actually constructing a laser driven engine remained unresolved. As sometimes happens, a chance remark by Max Garbuny of his work on the problem (ref. 4) renewed our interest and led to ideas about new ways to overcome the experimental difficulties. Our experimental constraints of low available CO₂ power and a requirement for closed cycle operation led to consideration of a Stirling engine. Fortunately, Stirling engines have been extensively reviewed recently (ref. 5) and a number of design alternatives are possible. The elegantly simple free-piston Stirling engine invented by Professor W. T. Beale of the University of Ohio seemed to meet our needs. A call to Professor Beale** led to the purchase of a single piston, closed-volume demonstration engine with drive power requirements between 30 and 50 W. After modifying the engine by adding a window to transmit CO₂ laser radiation we arranged to borrow a 40 W CO₂ laser and begin our investigation.

*Chuck Hawley, David Moore, and James Phillips, graduate students, Applied Physics Department, Stanford University.

**Professor W. T. Beale of Sunpower Incorporated, Athens, Ohio.

BEALE FREE PISTON STIRLING ENGINE

Figure 2 shows a schematic of a small free-piston Stirling engine designed to produce useful work by pumping water through a simple check valve arrangement. The engine consists of a displacer piston and an engine piston which is coupled to an inertia mass load which drives the pump ram. The expansion space at the end of the displacer piston is heated and the compression space between the displacer and engine piston is cooled for operation. The engine is filled with air or helium to between 2 and 4 atm. For the laser experiments, a transmitting window was added at the end of the displacer cylinder to allow direct heating of the gas in the expansion space volume by the laser radiation.

The operating cycle of the Beale free piston Stirling engine is shown in figure 3. The illustrated cycle is representative of the engine's performance as determined in detailed studies by Agbi (ref. 6). Figure 4 shows the oscillating frequency, power output and operating efficiency (percent) of our particular engine operating under the conditions indicated with air as the working gas. The 2.5 percent thermal efficiency is quite good for such a small engine with relatively large losses due to mechanical resistance and thermal conduction (ref. 7). However, it is by no means a limit as Agbi has obtained efficiencies of up to 8 percent with air and 13 percent with helium as working gases in a similar engine.

The oscillating frequency of the engine is given by (ref. 6)

$$f = 0.7 \left(\frac{A^2 P_0 \gamma}{V M} \right)^{1/2} \quad (1)$$

where A and V are the piston area and working space volume, M is the oscillating mass, P_0 the charge pressure, and $\gamma = C_p/C_v$. Our engine operated at near 11 Hz but higher frequency operation is possible. Higher frequency oscillation would allow the use of a linear alternator in place of the water pump to efficiently couple power from the engine as direct electrical output.

The Beale engine operates with a sealed closed volume of gas. Furthermore, it is a simple mechanical device without gears, valves, or bearings and thus offers the possibility of lubrication-free long operating life. Finally, direct mechanical to electrical generation is possible with a simple linear alternator arrangement. These advantages make the Beale type engine ideal for conversion of small powers such as in solar power conversion or artificial heart pumps (ref. 6).

LASER EXPERIMENTS

Prior to operating the engine with a CO_2 laser source, we performed linear absorption measurements on helium - SF_6 gas mixtures. Our preliminary measurements showed that 100 torr of SF_6 in 1 atm of helium was adequate to absorb the CO_2 incident beam in less than a 1-cm path length. We arranged a gas manifold system that allowed introduction of SF_6 , He, and CO_2 to the engine at a total pressure up to 4 atm.

Our initial irradiation of the engine with a 40-W CW CO₂ beam immediately broke the salt input window. After replacing the window we began more cautiously by first electrically heating the engine to near its operating temperature and then applying the CO₂ laser beam. Under these conditions the engine operated for a few minutes before the salt window again cracked. However, inspection of the window showed that the inner surface next to the engine's heated gas had melted and then cracked from thermal stress. Unfortunately, the CO₂ laser was available for only a very short time and there was no alternative but to continue with the experiments using salt windows.

These early results raised some questions about the engine's operation that prompted further study. The questions included whether the cylinder walls had to be hot for engine operation or whether a hot gas was sufficient. Also, was the SF₆ - He gas mixture being directly heated by the CO₂ laser radiation or being heated indirectly from a hot window or displacer piston? Finally, was the gas mixture optimum?

Further testing and then a call to Professor Beale verified our suspicion that the cylinder wall did have to be heated to a temperature near 200°C for engine operation. A cold wall leads to gas quenching and non-ideal circulation by the displacer piston. We therefore arranged to heat the cylinder wall.

To check whether the gas was being heated directly by absorption, we attempted to operate the engine without the SF₆ dopant in the helium. The engine did not run and furthermore, the displacer piston did not even respond to a sudden turn-on of the CO₂ laser beam. These results indicate that gas absorption was responsible for the engine's operation.

The ideal gas mixture was more difficult to determine given the short operating times between window failure and a lack of a quantitative engine performance measurement. However, the engine did seem to perform better with SF₆ dopant, 1 atm of CO₂, and the balance of helium up to a total pressure of 4 atm. The engine would also run without SF₆ at 1 atm of CO₂ plus 3 atm of helium. However, the engine would not run on CO₂ alone presumably due to the incorrect viscosity for the 0.010-in displacer piston to cylinder clearance.

As a final experiment, we operated the engine with a chopped CO₂ laser beam. A variable speed chopper allowed operation at a 50 percent duty cycle at chopping frequencies from above to below the engine's resonant frequency near 11 Hz. The engine showed a definite resonance when pumped by radiation chopped near its resonance frequency and operated poorly when pumped only slightly off resonance. It ceased to run when pumped at a very high chopping frequency or at a very low chopping frequency. These observations indicate that higher efficiency operation may be possible by driving the engine with pulsed laser radiation at a pulse rate nearer the engine resonant frequency.

The lack of time and also of salt windows prevented further, more quantitative work with the laser driven engine. However, for demonstration purposes the engine will operate with a 35 W average power alcohol lamp which heats a brass plate in place of the salt window.

CONCLUSION

It is interesting to speculate about the future of laser energy conversion by engines. If the initial negative reaction to energy conversion using such a mundane device as an eighteenth century engine is overcome, then the approach is seen to offer a number of advantages. First, a laser driven engine should operate at greater than the 40 percent conversion efficiency which is now obtainable from 160 hp (0.122 MW) conventional Stirling engines (ref. 5). Secondly, closed cycle operation allows optimization of the gas mixture for both absorption of the laser radiation and engine operation. Thirdly, the engines can be very simple in construction, small in volume and lightweight per unit of output energy.

There are limitations, however, that arise due to the use of the laser as the energy source. These include window damage problems, gas absorption, saturation and dissociation, and mechanical vibration due to engine operation.

High power infrared window materials have been extensively investigated and their power and energy density limits are now known (ref. 9). With the exception of diamond and sapphire, infrared windows of salt or semiconductor materials withstand up to $1 - 10 \text{ kW/cm}^2$ of continuous power density. The small size of available diamond windows may limit their use, but diamond can withstand over 2 MW/cm^2 of continuous intensity at 10.6μ (ref. 10). Sapphire is nearly an ideal window material for wavelengths less than 5.5μ , because of its mechanical strength as well as optical quality.

If higher intensities could be handled by the window materials, such intensities would probably not be useful anyway because saturation and dissociation become important at intensities even less than 10 kW/cm^2 . For example, Karlov et al. (ref. 11), have shown that BCl_3 and SF_6 are more than 97 percent dissociated at an incident CO_2 laser intensity of 10 kW/cm^2 . In this regard CO may prove to be an optimum engine fluid due to its high dissociation energy. Finally, at high gas temperatures absorption bands begin to become transparent due to the reduced population. For example, CO_2 absorption coefficients for the 9.6μ and 10.6μ bands peak at 0.04 cm^{-1} at 900°K and fall to approximately 0.01 cm^{-1} by 1500°K (ref. 12).

In spite of these limitations the laser-driven engine does offer the possibility of efficiently converting absorbed laser energy to either mechanical or electrical energy. The efficient operation of a heat engine through laser heated gas is not accidental. Under most circumstances of interest, the heat engine cycle times are long enough to allow vibrational to translational energy conversion but short enough to prevent excessive heat losses due to thermal conduction to the walls.

With very high average power lasers now available, remote power transmission and conversion are indeed possible. Stirling, or perhaps Brayton cycle engines, offer an attractive alternative to efficient remote energy conversion. Closed-cycle operation, long life, inexpensive construction, and size scalability to 100 MW are significant potential advantages. Our preliminary experimental results show that nineteenth century heat engines may fulfill a twentieth century energy conversion need.

Acknowledgement — We wish to express our gratitude to Coherent Radiation Laboratory of Palo Alto, California, for providing the CO_2 laser.

REFERENCES

1. Wolf, Martin: Solar Energy Utilization by Physical Methods. Science, Vol. 184, 19 Apr. 1974, p. 382-386.
2. Hertzberg, Abraham; Christiansen, Walter H.; Johnston, Earl W.; and Ahlstrom, Harlow G.: Photon Generators and Engines for Laser Power Transmission. AIAA Journal, Vol. 10, no. 4, Apr. 1972, p. 394-400.
3. Begley, R. F.: A Thermodynamic Analysis of a Closed Cycle, Gas Dynamic CO₂ Laser. Department of Applied Physics, Ph.D qualifying orals, 8 Jan. 1973.
4. Garbuny, M.: Laser Engine Operating by Resonance Absorption. NASA Ames Research Center. Laser Energy Conversion Symposium, 18-19 Jan. 1973, NASA TM-X-62269, Jan. 1973.
5. Walker, Graham: Stirling Cycle Machines. Clarendon Press, Oxford 1973.
6. Agbi, Babatunde O: Theoretical and Experimental Performance of The Beale Free-Piston Stirling Engine, M. Sc. Thesis, University of Calgary, Canada, Faculty of Engineering, Dept. of Mechanical Engineering, 1971.
7. Scott, David: Flame Powered Push-Pull Generator. Popular Science, Vol. 206, no. 2, Feb. 1975, p. 82, 134.
8. Glass, Alexander J.; and Guenther, Arthur H.: Laser Induced Damage in Optical Materials. Washington, National Bureau of Standards, 1972. (NBS Special Publication, 372).
9. Douglas-Hamilton, D. H.; Hoag, E. D.; and Seitz, J. R. M.: Diamond as a High-Power-Laser Window. Journ. Opt. Soc. Am., Vol. 64, no. 1, Jan. 1974, p. 36-38.
10. Karlov, N. V.; Karpov, N. A.; Petrov, Yu. N.; and Stel'makh, O. M.: Dissociation and Bleaching of a Multilevel Molecular Gas by High Power CO₂ Laser Radiation, Soviet Physics: JETP, Vol. 37, no. 6, Dec. 1973, p. 1012.
11. Strilchuk, A. R.; and Offenberger, A. A.: High Temperature Absorption in CO₂ at 10.6 μ m, Applied Optics, Vol. 13, no. 11, Nov. 1974, p. 2643-2646.

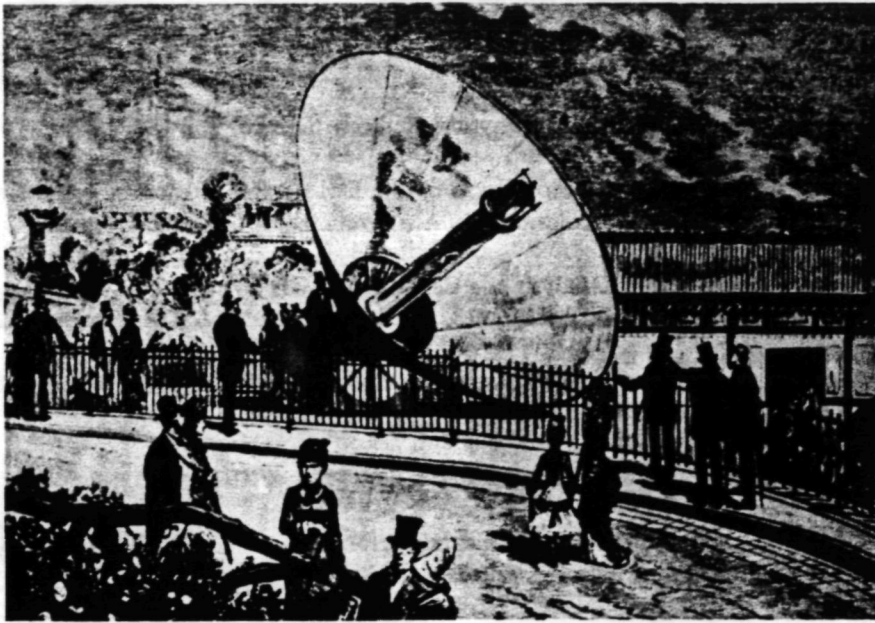


Figure 1.— A solar driven steam engine exhibited at the 1878 Paris World's Fair by Mouchot.

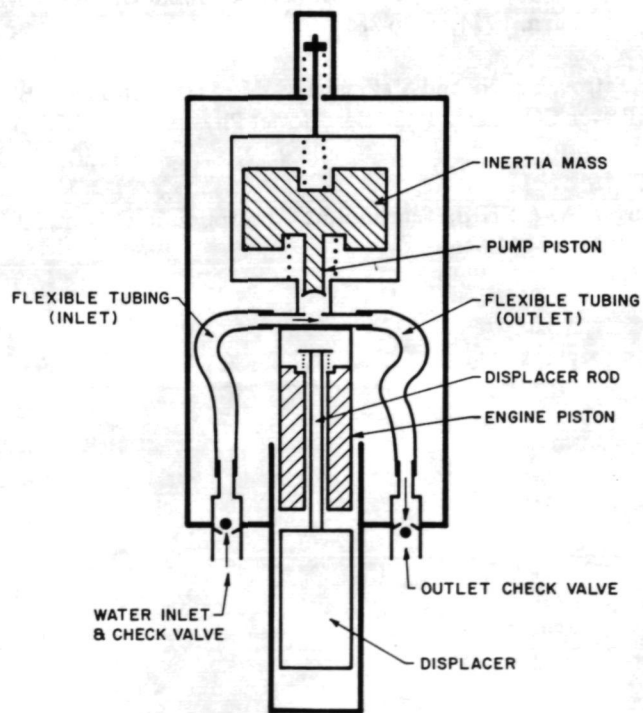


Figure 2.— A schematic of the Beale free piston Stirling engine.

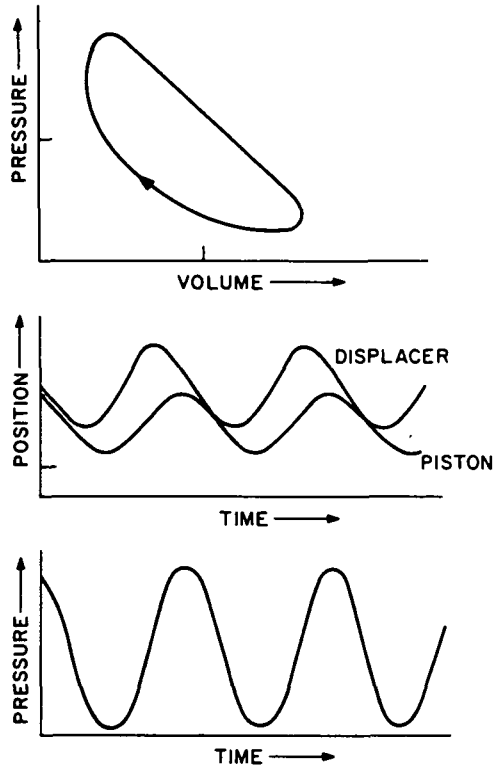


Figure 3.— Operating cycle, displacement of piston and pressure vs time for the Beale engine.

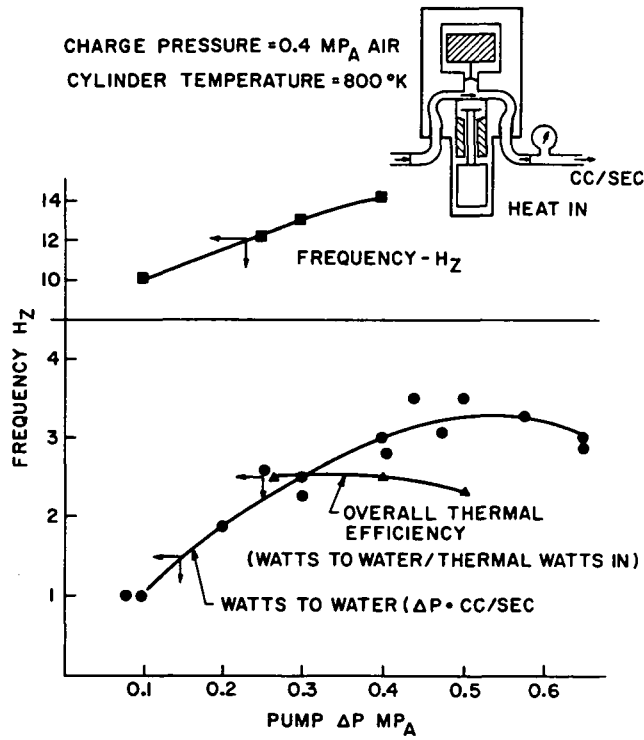


Figure 4.— Oscillating frequency, power output, and operating efficiency (percent) of our engine.

DISCUSSION

Ned Rasor, Rasor Associates – Are you familiar with the engine they worked on at McDonald-Douglas for the artificial heart program?

Answer: Yes, that is a closed cycle Stirling engine also. It differs a little from ours. The general schematic of this type of a Stirling engine has three volumes: a volume between your displacement piston and your heat source, which is your compressor volume, a volume between your working piston and your displacer piston, which is the cooled volume, and then you need the bounce space.

Ned Rasor, Rasor Associates – His engine puts out about 5 to 10 W and they are pushing 20 percent efficiency now.

Answer: Yes, that's about what the best of these run at. I should mention that 2 years ago, NASA, in conjunction with the Navy, did a very detailed study on engines to operate in closed environments, such as in submarines. They looked at 1 to 10 kW Stirling engines versus diesel engines versus other types of cycles. That is where I got the number of 40 percent loaded efficiency for the Stirling engine. And, indeed, engines have been built such as the work by the Phillips Company in the Netherlands, where 40 percent efficiency has been attained.

Don Nored, NASA Lewis Research Center – Just a comment on the thermodynamic diagram you showed where you said that sharp corners could not be attained in practice. We have worked on concepts, such as switching valves, which can help get rid of that.

Answer: Yes. The one thing I liked about the Beale engine is its utter simplicity but it does, therefore, suffer in efficiency. But for the type of device that you can consider sealing up in a stainless steel can and carrying it anywhere in the world you want, bouncing it in the Sahara, etc., and all you have to do is put helium in one end and it works – I think he has a lot of thought behind this type of construction.

Dick Pantell, Stanford University – You mentioned that Professor Beale designed this engine to work on solar energy. How does it operate in that mode? And does it have high efficiency?

Answer: Exactly like it's set up here. Right now, he has not yet produced an actual engine to fit that market. There is a capital cost problem. That is, a couple of square meters of collector are needed which together with an engine like this, to pump water in the desert, would cost approximately \$1000. For those in India or the Sahara, this is an enormous investment. So as of yet there is not a market for this device.

Gary Russell, J. P. L. – I think its a sobering thought that it has taken us 4 years to get 30 W of green light that your alcohol burner, which you used to demonstrate the operation of the Stirling engine for us, puts out!

SUMMARY PANEL DISCUSSION

Abe Hertzberg, University of Washington – Gentlemen, I would like to suggest that we members of the panel make brief statements and then see if we can start a dialogue with the floor.

Max Garbuny, Westinghouse – In looking through the proceedings, I had a few surprises. Many things have moved along beautifully. One thing, for example, that is of personal interest, is the possibility of remote laser chemistry. One idea might be, for example, a laser dissociation engine. I imagine that I have a gas such as $\text{Fe}(\text{CO})_5$ which dissociates with low energy IR photons. Thus by remote laser action we can increase the gas pressure by dissociation and we do not need high temperatures or conversion to translational molecular energy. I should point out, of course, the need for narrow bandwidth lasers for these laser chemistry processes. Perhaps on another occasion we should discuss this interesting field further! There were other interesting things on the agenda, such as the harmonic and sum frequency generation which may allow new converters to be used. I was particularly impressed by the laser-electron beam interaction work. Although it is not yet to the point of giving useful power, conceptionally it is a very interesting idea. I was also particularly impressed by the laser talks. Tunable IR lasers, such as proposed by Drs. Hess and Javan, where high pressure broadens the lines into bands, is of notable interest since it leads to tunable IR and at high powers. These things, and of course it goes without saying – the work on conversion to translational energy – were of great interest.

Ned Rasor, Rasor Associates – Being an engineering physicist I have an interest on both sides on all these interesting effects discussed. But my engineer side prompts me to say that perhaps someone is *really* going to need laser energy conversion someday! In fact, I think this feeling also hit Ken Billman when he wrote the letter of invitation to the authors saying that he wanted hard engineering data this time. If you look at the things that are ready for engineering – for example, if you would be on a wartime basis where, like the needs of the British in the radar area during World War II, and you had to use them very quickly – just how many things are like that at this conference? Of course there are conventional engines – you can get the Phillips Stirling engine or get a Brayton cycle engine from NASA Lewis, etc. But suppose those didn't do the job, for some reason, and you needed tomorrow's work today. What could you really push into use? Well, solar cells, if they could work at high temperatures and you used large arrays, are indeed a "bird in the hand", as are the conventional engines. I look over the rest of the things and, strangely, I find only the thermionic converter to really be in this category, if you really had to do it! Thermionic converters *are* producing power right now in a Russian reactor, as we would also be doing if the funding hadn't been lost when NASA dropped its nuclear energy program. But what are other alternatives. Fortunately, in the laser energy conversion program we have, as we have done in this meeting, the option of looking at all the possibilities. It seems that at each meeting people come up with a rediscovery of another old principle. Dr. Garbuny, Dr. Hertzberg, and I were talking about the fact that what you really want to do, if you cannot use a photon effect, that is, you are going to have to live with the Carnot theorem, is that you have to add the heat at high temperatures. In the thermionic case that's saying you are working with the electron gas rather than heating a metal.

At the conference 2 years ago, there was an interesting experiment explained in which a Russian scientist generated radiation to attract bugs by placing metal whiskers in a jar of silicon oil and applying an oscillating electric field. This aligned the whiskers and they radiated as simple diodes. Now the worry I have about printing up millions of optical diodes for laser energy

conversion is that it will be impossible on that scale and especially since they will have to be done in depth to achieve high cross section. But this whisker device might be worked in the inverse – using whiskers round on one end and pointed on the other, aligned by the electric field. When irradiated they will field emit for one direction of the optical field but not the other and thus you have a high voltage converter. I bring this up because the kinds of things I heard here stimulated me to think of such things. I hope everyone else here had the same thing happen to them. Furthermore, I hope the people who can affect the money will read the proceedings and similarly be stimulated.

Dick Stim, J.P.L. – Well, I would like to say that I was pleasantly surprised. We heard about adaptive optics and Abe showed us that he was adaptive also! I have to agree with Ned, that, compared with 2 years ago, we have generated some more ideas and, for Ken, there has been some hard engineering data. In fact, it is much more than I had expected to see in 2 years. I do think we are getting to the point where the Centers have to begin sharing this data and, for example, Don should tell us some of the parameters that are necessary to optimize certain applications. For example, what is the energy density we must operate with? This is important – photovoltaics may work in one region but other techniques are necessary for higher intensity. Are there applications that demand each of these? I think that the photovoltaics can work in the short term with a little more engineering. For latter applications, perhaps some of the more esoteric ideas will be useful. So the main point I would like to make is that we need to define more closely the operating parameters of the device. When the power density is defined, we can begin to engineer our devices to a potential mission.

Joe Lundholm, NASA Headquarters – I believe Dick's comment about now needing more coordination between the Centers is well taken. In the last 2 years the program has moved forward and now we have moved from the organization stage to an accomplishment stage. Carl Schwenk, incidentally, agrees and believes more meetings between the Centers would be very useful.

I believe the type program that Ken put together was a good one – covering the gamut from far out concepts to operating laser devices. Again, I would like to remind you to keep your eye on the timetable I showed yesterday. I should say that the philosophy of the Research Division at NASA Headquarters, which supports this work, is that we will work on research and technology and do everything possible to keep from getting bogged down in expensive systems development at this stage of the game. A lot of programs have been wrecked when they took off prematurely to get into systems. Fortunately, our philosophy appears to be followed by all of you.

Some new ideas have been introduced here. We look to the Centers to decide on which areas should continue to be funded or dropped and which should be added. Of course, they are operating on a pretty well fixed funding level. So they must make the hard decisions on what concepts are funded or deleted.

In the near future we are going to *consider* whether we should be making systems and applications studies. Again, the Centers will guide us on this.

Again, I would like to urge you to keep a sense of urgency in mind and keep our major objectives in mind; to develop the technology required to provide the knowledge that we hope we will be needing to make some major decisions around the 1980 time frame. Hopefully some NASA missions will be identified at that time; perhaps 10 years will then be necessary to develop a prototype system and then in 1990 the flyable system will begin construction. Thus, perhaps in 1990 we can actually begin the use of our high power laser systems.

Abe Hertzberg, University of Washington – How to sum all this up! First, in reviewing the progress made in the last 2 years, I can't really say that we are there! But our technology base, and our understanding of what we can and cannot do has increased significantly. For example, consider adaptive optics. In the early days, when we realized that laser beams were more akin to searchlights than diffraction limited beams, the suggestion that we put a phase correction plate in the beam was rejected as being too complicated. Now we have gone a step beyond that and are talking about the reality of actual adaptive optics that vastly will extend the capabilities. We are starting to narrow down what can and cannot be done. But let me play the devil's advocate. Suppose we had a perfectly good laser today, running at 75 percent efficiency, reasonably compact, and we had a good converter running at 75 percent efficiency. Would we use it? I'm not sure I can answer that question. I can only point to the future and say that it's probable, and perhaps inevitable, that we will use it. A historical analogy is the repeating rifle in the Civil War. The concept was there, the technology was there, but the frame of mind of the engineers and military were against it. One general argued that too much ammunition would be wasted with a repeating rifle! Here we are also dealing with the future and developing its technology, but we are going to have to build also a readiness and need to accept it. I would like the audience to help us think of a way to "slide" into application. Of course war is always a hot house for technology – witness the development and universal usage of the gas turbine for aircraft during the war. But, in the absence of that, we will have to "slide" this new technology into usage in some simple way so as not to encounter the attitude that this is too radical – too new. We could, of course, set up laser power transmission systems to transmit significant amounts of energy with not intolerable efficiency. But who is going to buy it?

Joe Lundholm, NASA Headquarters – I reviewed with Dick Stirn recently the progress in the solar cell area. If you are a program manager for a spacecraft you will probably stick with solar cells because you know you can get them without a cost overrun. Only when enough engineering is done will a program manager risk something new, since in these days of tight money any overrun usually means that the spacecraft will just not fly.

I should also mention that we are getting some requests at Headquarters on what these systems will be able to do. That's a two-edged sword. If we maintain a low profile, an overall budget cut could end up eliminating the laser program. If we take a high profile, then when funds get short they might ask what are the attainable efficiencies? If the current value is low then, of course, again the program could be dropped. So we have to take the middle path.

Bob Hess, NASA Langley Research Center – Isn't one possibility to combine the laser energy experiments with other experiments which NASA wants to do anyway? For example, the shuttle is looking for experiments. Both atmospheric absorption measurements and communications experiments could, for example, also be used to study power transmission. This would gradually bring power transmission to the public.

Fred Hansen, NASA Ames Research Center – I think I can give an answer to Abe. Even if we had a good system right now, 80 percent efficient laser, 80 percent efficient converter, the present climate is that it would just not be used.

Abe Hertzberg, University of Washington – Yes, that is just my point.

Fred Hansen, NASA Ames Research Center – But some of the things that interest me in the program are the spin-offs. Two years ago we heard the beginnings of optical diodes and frequency

conversion. Now we are making such progress in these areas that we can see that they will revolutionize some of the basic physics that we do. Two similar things which we heard about at this meeting, and we may hear more about in 2 years, are high voltage ceramics and the electron-laser interactions. Both of these are very exciting and offer great possibilities. Although neither of these may be directly applicable to laser energy conversion, a program like this allows such ideas to have a focus, to percolate for awhile, and to develop. I'm not sure how we can get this across to administrators, however.

Tom Karras, General Electric – I might just comment that the military will probably apply some of these concepts – this will get NASA going. This has always been the case.

Abe Hertzberg, University of Washington – Yes, history shows that to be the case. For example, the nitrogen fixation process was developed to make explosives for World War I. But the ultimate use was for peaceful fertilizer production.

Ned Rasor, Rasor Associates – Actually there is a very real, and almost wartime like requirement now if you want to latch on to it – the energy requirement. One of the best insurances of this program, when someone asks “What are we going to cut?” is that you have “energy” as your middle name! I've seen a lot of this happening here already. When people gave their talks they said “Incidentally, this device or process could use solar radiation”. An analogy is the semiconductor industry. Only one device coming out of Bell Labs. was able to guarantee the long-lived existence of the industry. Similarly, if one useful application in the area here were found, possibly in the energy area, it would quite likely guarantee the continued existence of the whole program.

Abe Hertzberg, University of Washington – I think you're right. Energy application is taking on a new importance. Ultimately we may use lasers for this purpose. For example, I don't see anything intrinsically wrong with the concept of a space borne nuclear reactor with a laser energy transmission system to the ground. But I just wonder about the mechanism of bringing into use a new technology – a technology that we are really not that far away from. Maybe sliding in through the military is the only way.

Don Nored, NASA Lewis Research Center – I think the propulsion area may offer a way to slide into it. The orbit to orbit application is one that could be done with foreseeable lasers. The military should be interested in another – the orbital drag make-up. As far as power transmission to satellites goes this faces a good competitor – solar cells. Most satellites want 1 to 2 kW and solar cells will do this. There is one thing, however, if you examine the NASA flights up through approximately 1990, there will be a total of about 419 flights. This will require about 1.8 billion dollars worth of solar cells – a very large amount of money just to build solar cells. So a low-cost converter could be attractive. There are all sorts of trade-offs – cost, weight, etc. We don't know all the answers yet.

Bob Hess, NASA Langley Research Center – Of course NASA is looking for Shuttle experiments. Wouldn't it just be possible to do a demonstration experiment? The efficiency would not have to be high – it would just demonstrate, with low profile – the possibilities in this approach.

Abe Hertzberg, University of Washington – I do agree, just because of NASA politics, we've got to tie it to the Shuttle.

Ned Rasor, Rasor Associates – Just so you are not riding on the anchor chain of the Titanic! Just remember what happened with thermionics. It was dropped because it was intuitively tied to the space nuclear program, which was dropped. So one has to show application in a number of areas.

Abe Hertzberg, University of Washington – Well, I have a high opinion of NASA management. They will attempt to keep the good parts of any program alive. But look, the first application of the laser will probably be in isotope separation. Its competition – diffusion separation – was a wartime emergency need which, if proposed today, would not be acceptable on energy considerations. So the laser will win this competition. It is an idea whose time has come. I think the laser power transmission will find that point in time. But I sure would like to know the way of edging it in. You must remember that a pure engineer is a very conservative fellow – ask him to change his viewpoint on anything he learned beyond his freshman year and you have an impasse. The aircraft industry is a classic example. Although the 747 was thought of as a tremendous advance, its swept wings, etc. are just scaled up from the 707.

Ned Rasor, Rasor Associates – Yes, remember the difficulty in getting commercial aircraft designers to accept the jet engine? They failed to see the advantages, such as extremely long, maintenance free, lifetimes of these devices. But your point is well taken, somebody has to take a risk.

Dick Stirn, J.P.L. – As Joe said, of course, project managers make conservative engineers look like liberals. Part of the problem is cost – you usually do not have ten backup vehicles. A trivial example is the case of solar cells. The first units were made p on n and they were flown in the early years. Then it was shown that n on p solar cells were a factor of 10 better in radiation resistance. But it took 3 years before these much superior cells were used on a flight.

Joe Lundholm, NASA Headquarters – Fred, you made the comment that NASA wouldn't use the system now, even if we had it. Of course NASA is spending much of its money now on Shuttle development. Assuming the budget remains at, say, 3.2 billion beyond this development, it will become available to *use* the Shuttle for experiments. And I believe that there will develop so many interesting Shuttle experiments that we will look back and say, "Weren't we naive and narrow in our predictions, back in 1975, on the uses of space?"

Fred Hansen, NASA Ames Research Center – I agree, Joe. I believe our best hope is to continue to have Headquarter managers that will keep programs like ours alive until the time comes. But in the meantime we must develop our technology so that when the moment arrives we are ready.

Joe Lundholm, NASA Headquarters – Yes, that is why I keep stressing 1980. Horizontal flights will take place at that time and then a great push for experiments should begin.

Fred Hansen, NASA Ames Research Center – As Ned said, however, we need some caution relative to Shuttle which has some rough periods ahead. If it goes, then one can imagine a large number of satellites being launched from it per year – but if it doesn't go we will probably only launch about five Apollo type units per year. This has to influence our applications thinking.

Ned Rasor, Rasor Associates – There is an extremely important point to be made here. What you want to do is to establish some kind of equilibrium situation so that it is not necessary to

continually need to dredge up new reasons to justify your existence. Has the Government, and in particular NASA, learned the value of maintaining a good research base independent of big programs? Do we always need some national emergency, like an astronaut about to die in orbit, to make research programs sell? You speak of the need of exciting the public – will a demonstration of laser energy transmission really get the attention of the public? Are we on the track of getting away from this continual justification need or do you detect no change in that attitude in NASA?

Joe Lundholm, NASA Headquarters – Well, the Shuttle is a big program, taking most of the money. There are significant other programs going on, however, such as Earth resources technology satellites, the Viking launches, etc.

Ned Rasor, Rasor Associates – But can there be an energy conversion category that exists regardless of all these missions?

Joe Lundholm, NASA Headquarters – Well, I think it's a sobering thought that we are funding about one-half of the country's total effort, with ERDA supplying the other half, on gas core reactor design and thermionic convertors. But NASA management has decided, and probably wisely so, that our main effort will be in space rather than in energy development.

Ned Rasor, Rasor Associates – I didn't mean to tie my question simply to energy. In other words, can there be, in NASA, an equilibrium situation where one can investigate, say, basic photon-plasma interactions without tying it to a mission? Does OAST have that kind of charter?

Joe Lundholm, NASA Headquarters – Yes, I think OAST has the tradition of having this.

Fred Hansen, NASA Ames Research Center – Of course there may be a change in NASA budgeting as a result of the energy research necessary. Maybe the situation will change.

Abe Hertzberg, University of Washington – We have been watching research budgets go down during the last decade. But they have bottomed during the last 2 years. There is a general realization by Congress that long-range research is an indispensable part of our economy. Even military thinkers are coming to this viewpoint. If you think about the green revolution, which makes our country the Saudi Arabia of food, you realize that this research has been a long one. But in terms of the effect on our country's economy, the return on the small research investment has been at least a thousandfold.

Max Garbuny, Westinghouse – Of course the military has had the relevance clause which has had a very depressing effect on individual creativity resulting in a depression of both quantity and quality of research. Now, there are some exceptions and one of them has been NASA. It has been willing to support non-mission relevance and this is good and important to national survival.

Ned Rasor, Rasor Associates – I hope they also realize that not only money is important, but that continuity is equally important. That is, one needs approximately 3 years for a good study and about 10 years for final results.

Kurt Wray, Physical Sciences, Inc. – Earlier a statement was made by Fred Hansen that we had better be ready or we may be passed over. It seems to me that when the time comes to be ready for

something, we are not going to be ready for it if we don't know what the something is. I don't know how many of these schemes we have discussed will be a good way to go or a bad way to go. But we're not going to find out until a mission is defined. In the meantime, all we can hope to do is continue these investigations on a very basic level, that is, keep bringing them along until a mission is defined and then scramble to design a system. I really haven't heard anyone define such a system yet, toward which we can design.

Abe Hertzberg, University of Washington — I essentially agree with you. But oftentimes you design the device that creates the mission, you take it to the people, who should be sensitized to it, but they don't know how to put it in. I think *that* is really our problem, that is, how to insert this into the system. Well, by clever timing, I have so arranged things that the time has run out, and I have had the last word on the subject!

Well, gentlemen, thank you. It has been a fascinating meeting and we owe sincere thanks to our hosts, NASA Ames, and especially to Ken Billman who single handedly put the meeting together, for providing us with a fabulous forum.