Army Research Laboratory

Test of High Power Laser Diode Protection Circuitry Designed and Built by Science Research Laboratories

by Jeffrey O. White and Robert Dibiano

ARL-TR-4685 **December 2008**

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14. ABSTRACT
High power laser diodes have important military applications, particularly for material processing, and for pumping solid state lasers. The latter in turn can be used for neutralizing explosives, intercepting rockets, missiles, mortar shells, etc. The Joint High Power Solid State Laser program makes exclusive use of laser diode pumping. Science Research Laboratories, Inc. (SRL) has developed electronic circuitry to extend the lifetime and/or output power of high power laser diodes. Their results have reported enhancements ranging from a factor of three for continuous wave (cw) operation to ten for pulsed operation. Our primary objective was to independently verify their results. Our testing shows that the prototype device works, and that the claims are valid.

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High power laser diodes, electrical filaments, catastrophic optical damage

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Summary

As sources of light for optically pumping solid state lasers, high power laser diodes have surpassed arc lamps in most aspects of performance, e.g. efficiency, spectral purity, size, weight, robustness, and cost. Science Research Laboratories (SRL)[1], has developed circuitry designed to increase the power-lifetime product of laser diodes. They have measured typical increases of a factor of three for cw operation, and higher for pulsed operation. Their testing focused on microchannel-cooled bars, although conduction-cooled mounting was also used.

The Army Research Lab (ARL) High Energy Laser team was asked by the High Energy Laser - Joint Technology Office (HEL-JTO)[2] to provide an independent test of the circuit performance. We tested five conduction-cooled laser diode bars, all operating continuous wave (cw). Our results also show a significant improvement in lifetime for the lasers that are protected by the SRL circuitry.

While laser diode failure is of a statistical nature, and time constraints limited us to testing only five bars, we believe that our results substantiate the SRL claims. The authors recommend that the Army support, or at least monitor, the further development of this type of protection circuitry, for eventual incorporation into fielded systems. Systems that stand to benefit from this technology include several-kW lasers for mine neutralization, and much larger lasers for defense against rockets, artillery, mortars, and missiles.

[1]15 Ward St., Somerville, MA 02143, 617-547-1122. Our contacts were Jonah Jacob (Pres.), Rod Petr (engineer, P.O.C.), Jonathan Vignati (software and database), and Rob Pierce (electrical engineer).

[2]P.O.C. Don Seeley, don.seeley@JTO.HPC.MIL, (505) 248-8205.

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1. Introduction

As sources of light for optically pumping solid state lasers, high power laser diodes have surpassed arc lamps in most aspects of performance, e.g., efficiency, spectral purity, size, weight, robustness, and cost. At the nominal current, the output of a typical 1-cm bar lasing at 808 nm, producing 30 W, is ~10^4 hours. Science Research Laboratories (SRL) has developed circuitry designed to increase the power-lifetime product. They have measured typical increases of a factor of three for continuous wave (cw) operation, and a factor of 10 for pulsed operation. Their testing focused on microchannel-cooled bars, rather than conduction-cooled.

The ARL HEL team was asked by the JTO to provide an independent test of the circuit performance. We tested five conduction-cooled laser diode bars, all operating cw. Three bars were protected by SRL circuitry, and two were not. Our results also show a significant improvement in lifetime for the lasers that are protected by the SRL circuitry.

The SRL protection circuitry functions by stopping the current for ~0.5 ms whenever there is a sudden change in the resistivity of the diode. When driven by a constant current source, the resistivity is monitored by measuring the voltage drop across the diode. Sudden changes in resistivity, on the time scale of 1 µs, are believed to be due to the formation of an electrical filament in the active region, between cathode and anode. Filaments can form when the carrier density increases in a region where the bandgap is smaller, due to a fluctuation in temperature. The increased current flow gives rise to additional heating, which causes, in turn, a further increase in local carrier density. The process eventually results in melting and catastrophic optical damage. Interrupting the current is a way of stopping the process before it gets far enough that the damage is permanent. Data taken at SRL indicate that the lifetime of a diode can be extended from three to 10 times by their fault detecting scheme. Our main goal is to independently verify this claim. Elucidating the mechanism for the enhancement was mostly beyond the scope of our work, but SRL has gathered data on the subject.

The semiconductor active region in a laser diode has an electrical conductivity that increases with temperature. Normally the temperature throughout the lasing material is fairly uniform, but occasionally a small region becomes slightly hotter due to local variations in composition or heat dissipation, lowering its resistance. If the current intensity is very high, further increasing the number of electrons moving through the now unstable region can cause it to heat up more, further lowering its resistance and leading to a runaway effect. These thin regions of extremely high current density are called current filaments and are one of the main sources of damage to laser diodes during operation. SRL’s fault-detection circuit detects transient drops in the diode voltage that may indicate such a filament has formed. The modulator circuit cuts the power to the diode for 0.5 ms, halting any runaway and giving the temperature enough time to stabilize. The thermal time constant of the active region is on the order of 10 µs. For the Army applications mentioned above, which rely on heating a mine or projectile, a 0.5 ms interruption in the optical power is negligible.

2. Methods, Assumptions, Procedures

We tested gallium arsenide (GaAs) laser diode bars operating in cw mode, emitting at 808 nm. The LD40757 and LD41860 are Nuvonyx model TH-C1840-H. LD266158, 59 and LD266160 are Coherent model CCP-CW-30%x1.0-40W-805to811-F. All five bars have the same design; the company simply changed hands. Each bar contains 19 emitters and produces ~40 W when driven at its nominal current of 40 A. We operate at 50-60 A to accelerate the aging. Three diodes were tested with the protection, and two without. All bars were conduction-cooled at 20 °C.

The bar was housed in a sheet metal enclosure for eye safety, fitted with an air filter to prevent dust from burning onto the facets (figure 1). All signals were fed into a connector block[3] attached via shielded cable to an analog-to-digital converter,[4] which recorded fault signals, and measured the diode current, diode voltage, and optical power. The diode voltage measured here records long term variations that occur over the lifetime of the diode, not the short term variations that are indicative of the formation of a current filament. The short term, i.e. µs, variations are detected by the SRL circuitry, triggering the modulator, and they are recorded as faults by the data acquisition software.

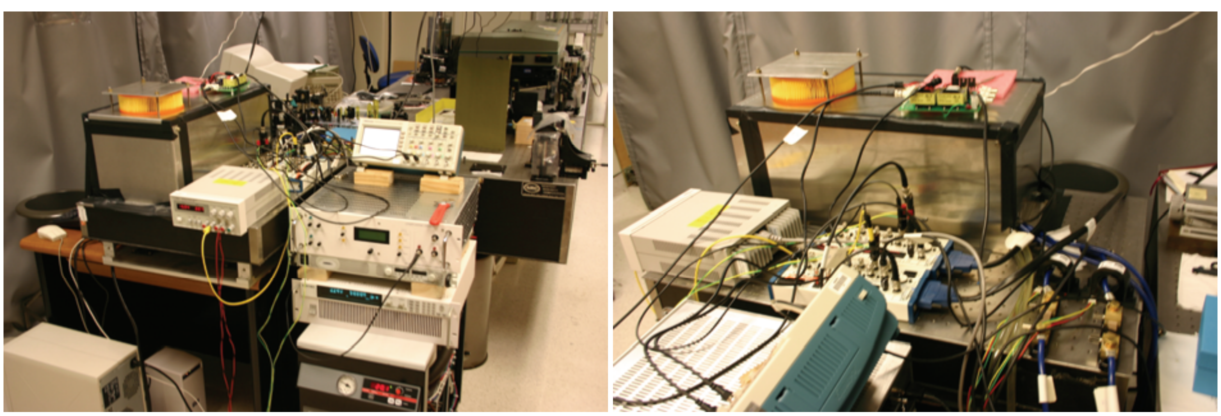

Figure 1. Testbed setup.

The diode current was initially measured via the voltage across a calibrated 1 mΩ shunt resistor in series with the diode. We later switched to a Hall effect sensor[5] which gave a larger signal.

[3] National Instruments BNC 2120.

[4] National Instruments PCI 6221 M-series Data Acquisition board.

[5] F.W. Bell RS-100A.

The optical power was initially determined by measuring the voltage across a ~1 kΩ resistor connecting to a silicon (Si) photodiode. This was adequate because the required bandwidth was very low, much less than 1 Hz. We later switched to an op-amp with a zero effective input resistance, which converted the current from the photodiode into a voltage, to increase the range over which the measurement was linear.

The unprotected laser diodes (LDs) were supplied at constant current by a Xantrex switching power supply.[6] The protected LDs were initially powered by an SRL unit that incorporated a fault-detection circuit, and a modulator circuit for switching (shunting) the current away from the LD in the event of a fault. Because the SRL power supply was designed for pulsed operation, with minimal capacitance, its noise level was higher, making an unbiased comparison between protected and unprotected diodes more difficult. Therefore, we switched to using the Xantrex with and without a stand-alone fault-detection circuit board and modulator. All of the results reported below were obtained with the Xantrex power supply, except the last bar, which was tested with a Sorensen power supply.

SRL supplied software that measures all the inputs every five minutes, and records the data in a Microsoft Structured Query Language (SQL) database. Data is also recorded a few ms after every fault is detected. The data is displayed in a strip chart fashion, and instantaneous readings are also provided in digital form (figure 2). Data is extracted from the SQL database via a query. The Microsoft SQL Server could run queries coincident with LD Logger.

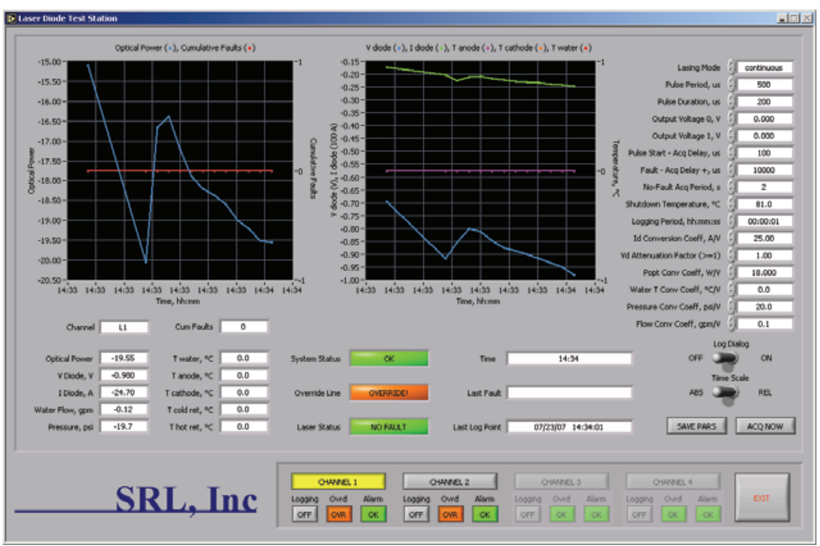

Figure 2. SRL's LD logger user interface.

It was of interest to know if the degradation resulted from all the emitters failing partly or from a few failing completely. For this purpose, we imaged the near field of the LD using a digital camera (figure 3).

[6] Xantrex XDC 80-75.

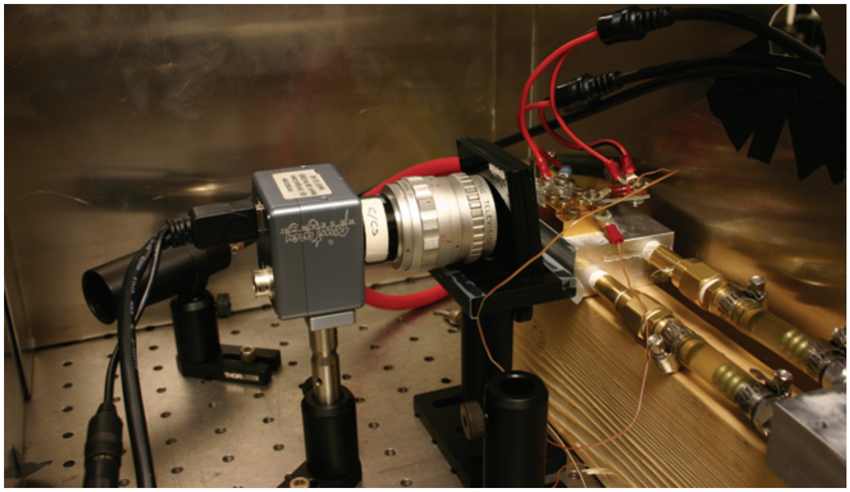

Figure 3. Beam intensity distribution measurement.

3. Results and Discussion

Five LD bars were tested. The results are given below in chronological order.

3.1 LD40757 (Protected)

In our initial run, the fault level was set too close to the power supply noise level, producing spurious faults at a rate of several Hz. To reduce the data from that particular run to a manageable size, the query averaged the readings over a one min period. Also during the initial run, the voltage-to-optical-power calibration was redone several times, and the experiment was also shut down intentionally, as bugs were being worked out of the data acquisition system. After accounting for recalibrations, outages, and downtime, it was possible to determine the rate of decline of the optical power (figure 4). The test ended when a building power outage shut down the cooling system, overheating the diode (figure 5).

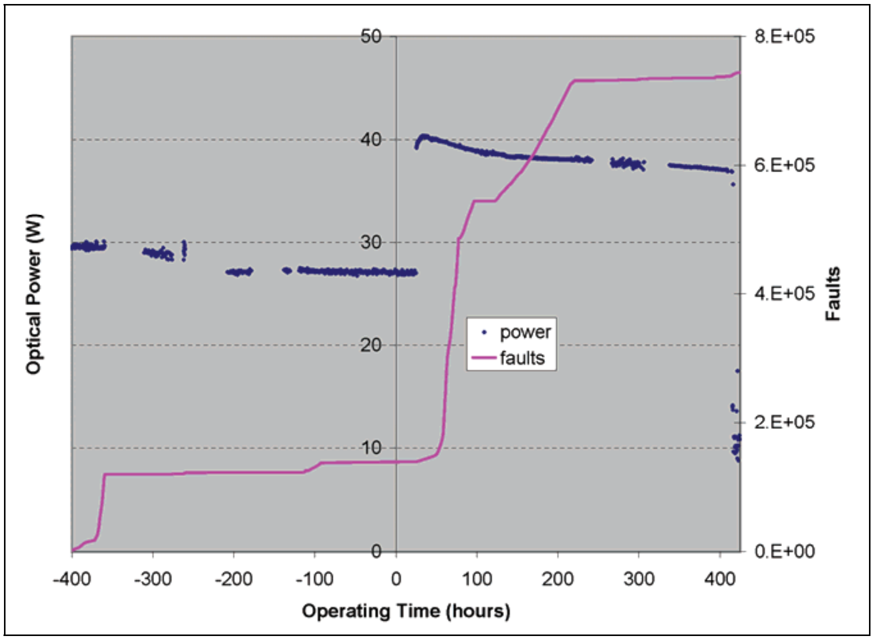

Figure 4. LD40757 (protected) output power and faults.

Although many spurious faults were produced, the total of six min of downtime represented only a 0.01% drop in average power. SRL recommends setting the fault level at 110-120% of the noise level because spurious faults, on the level of one per min, carry essentially no cost. The noise level from the Xantrex was not constant, however, so readjustment, or a more conservative setting, was necessary to avoid overloading the database with too many faults.

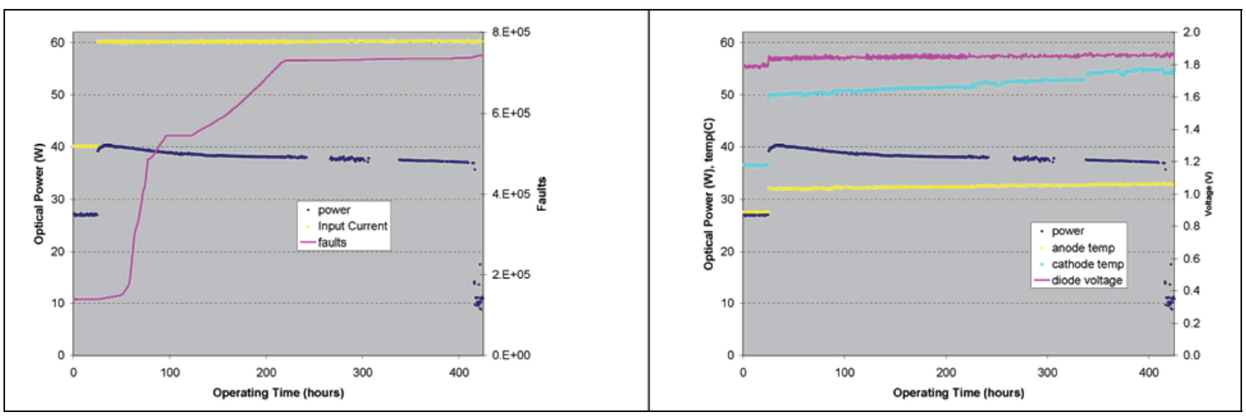

Figure 5. LD40757 (protected) current, voltage, anode temperature, cathode temperature.

3.2 LD41860 (Unprotected)

The next diode was still monitored by the fault-detection circuit, but the current was not modulated in response to the faults. The fault level was set to a larger value of –75 mV, so as to trigger less often. The test results clearly show that the SRL system works. The unprotected diode had occasional steep drops in optical power, each probably corresponding to the catastrophic failure of an emitter (figure 6). The final slope was about two to two and one-half times as steep without the protection, meaning the life was extended by at least a factor of two, but the unprotected diode also experienced regions of more rapid degradation at the beginning of its lifetime and after each sudden drop in optical power. Consequently, depending on how one calculates lifetime, the amount of improvement could be 2.3× or 35×. The unprotected diode fell below 90% power within about 11 hours, while the protected diode was still just above 90% after 390 hours, operating at the same 60 A current (figure 7). However their starting optical powers were different, so the results are hard to interpret. When LD41860 (unprotected) reaches the 40 W level, its decay is just as slow as that of LD40757 (protected), which began at the 40 W level.

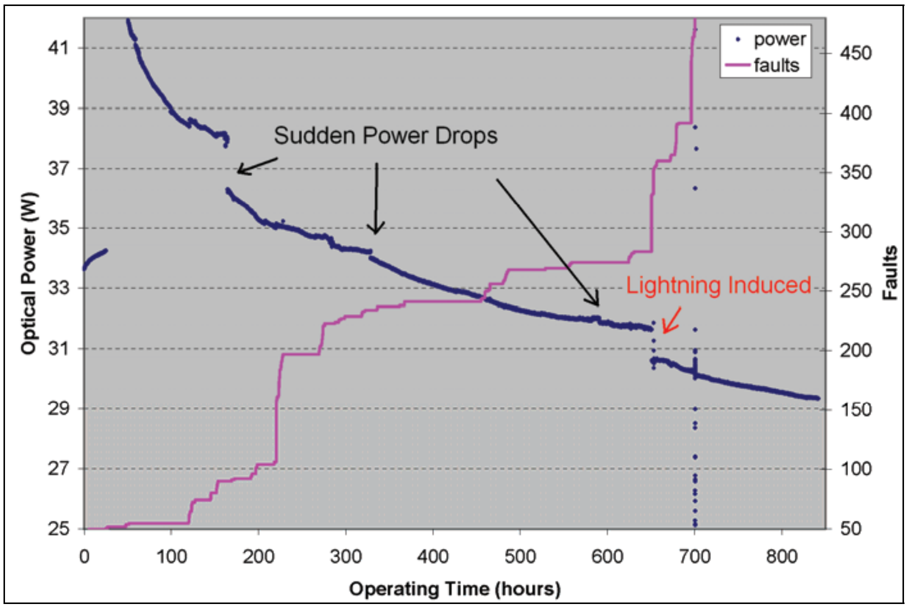

Figure 6. Expanded plot from LD41860 (unprotected).

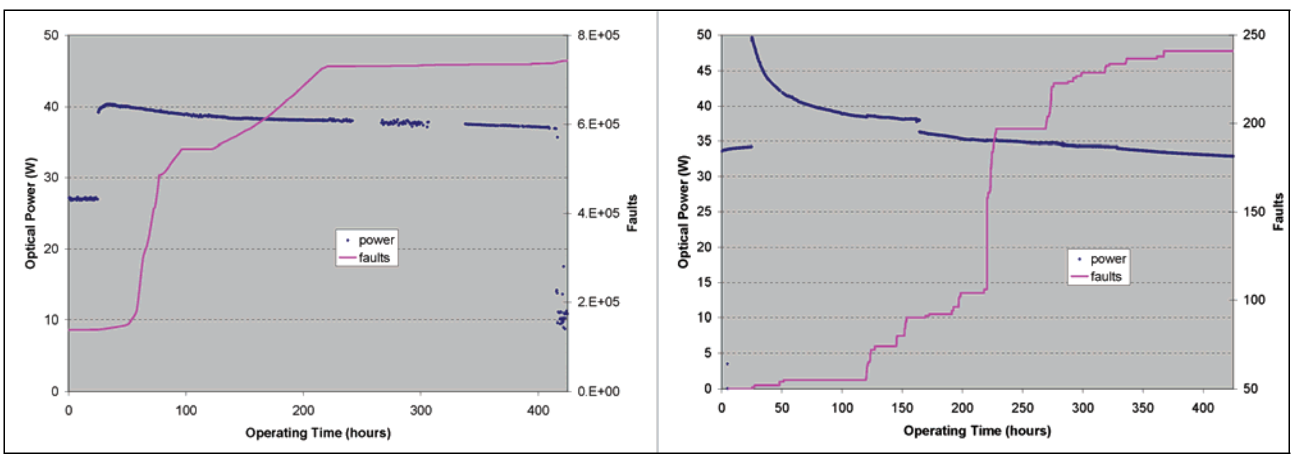

Figure 7. (a) LD40757 (protected) and (b) LD41860 (unprotected) optical power/faults, plotted with the same time scale.

The input current, diode voltage, and temperature readings for LD41860 are shown below (figure 8). As the diode degrades, the voltage increases slightly, if at all. At a constant current this indicates a slight increase in resistivity. As the optical power fell, diode temperature increased. This is a result of a larger portion of the input power being converted into heat instead of photons. LD41860 has an anomalous rise in cathode temperature at 600 hrs.

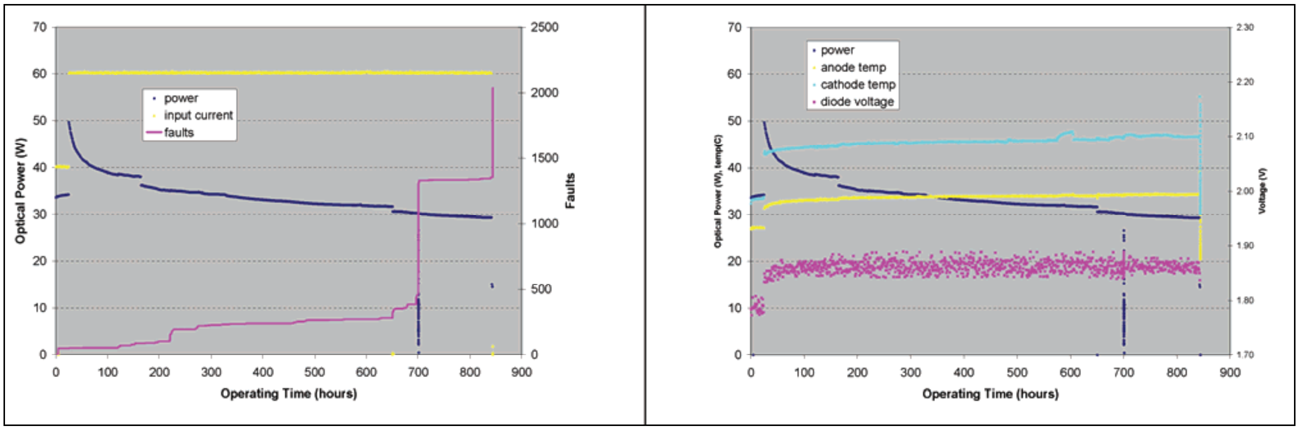

Figure 8. LD41860 (unprotected) current, voltage, anode temperature, cathode temperature.

Oddly, drops in optical power were not always coincident with faults. In order to capture the transient parts of the monitored signals, we used a digital oscilloscope[7], triggered with the fault signal, and programmed to store the diode voltage and optical power just before and after faults. Most of the faults seemed to be spurious fluctuations in the diode voltage due to external factors, e.g., other devices being plugged into the power strip. In one particular fault, the optical power oscillated, rather than simply dropping (figure 9).

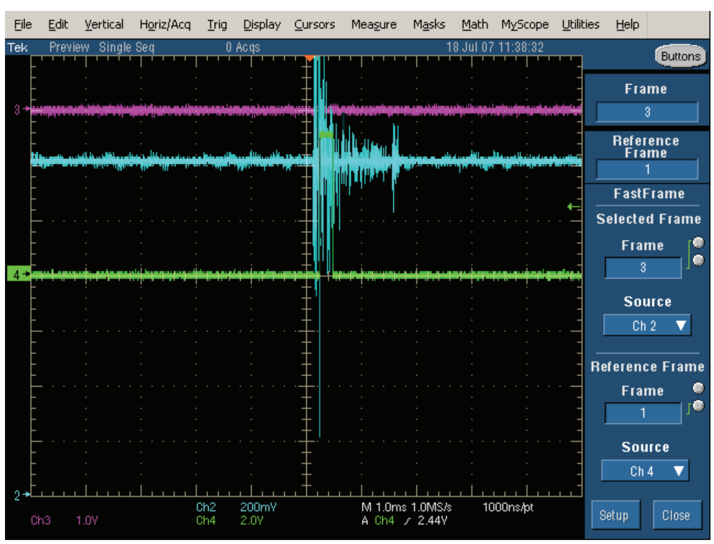

Figure 9. Digital fault pulse (green), diode voltage (red), and optical power (blue).

[7]Tektronix TDS 5100.

From post-test images of the output facet (figure 10), we calculated the power versus current of the bar as a whole (figure 11), the power per emitter (figure 12), and the power versus current of the individual emitters (figure 13). Note that all emitters were connected in parallel, so the current per emitter is unknown. One can say, at least, that the output varied widely from emitter to emitter. Some emitters were still just starting to lase as others were rolling over, and the slope efficiencies differed as well.

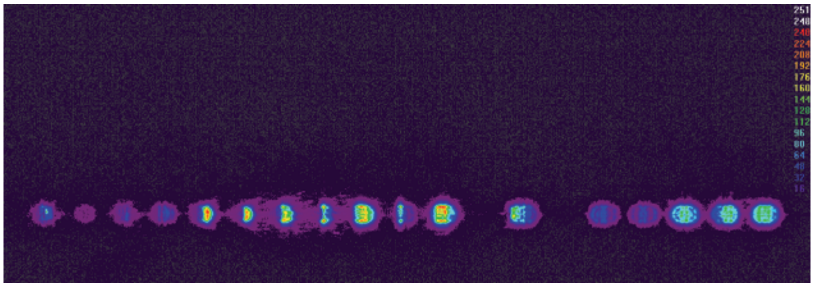

Figure 10. LD41860 beam profile at 18A.

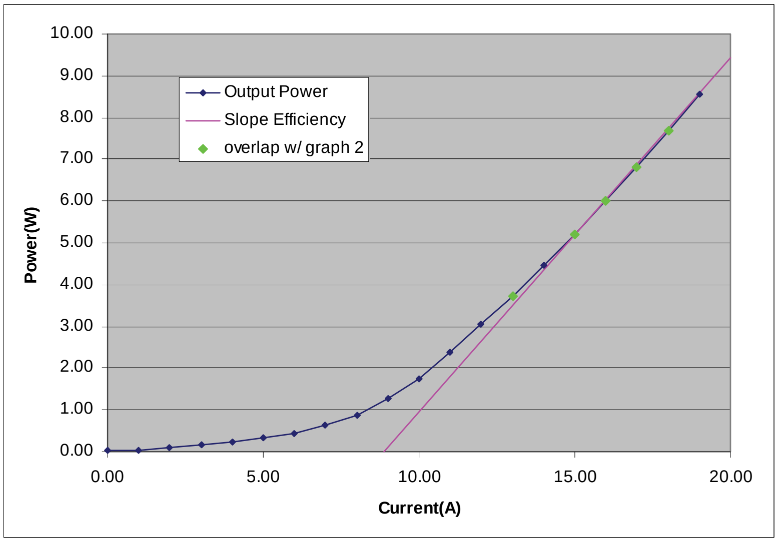

Figure 11. LD41860 lasing threshold and slope efficiency.

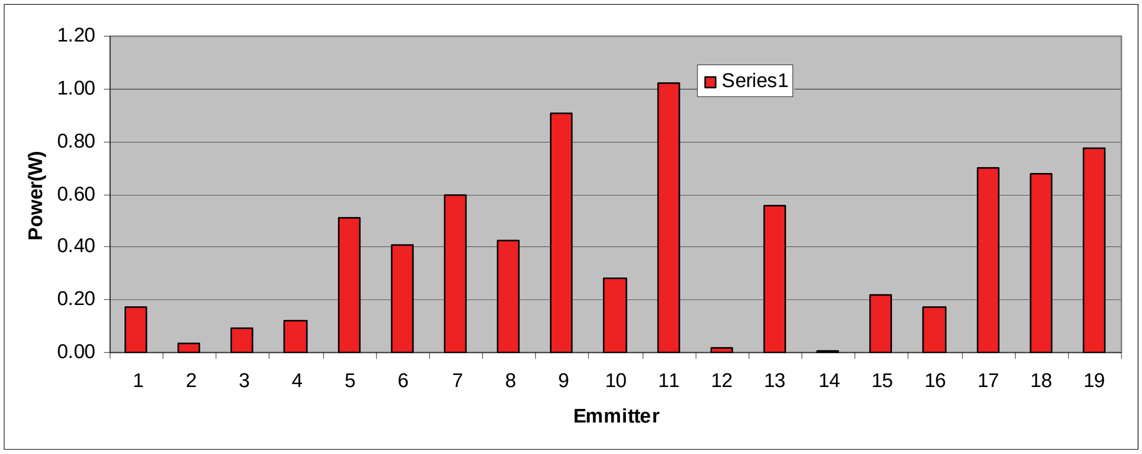

Figure 12. LD41860, post-test power per emitter at 18 A, calculated from figure 10.

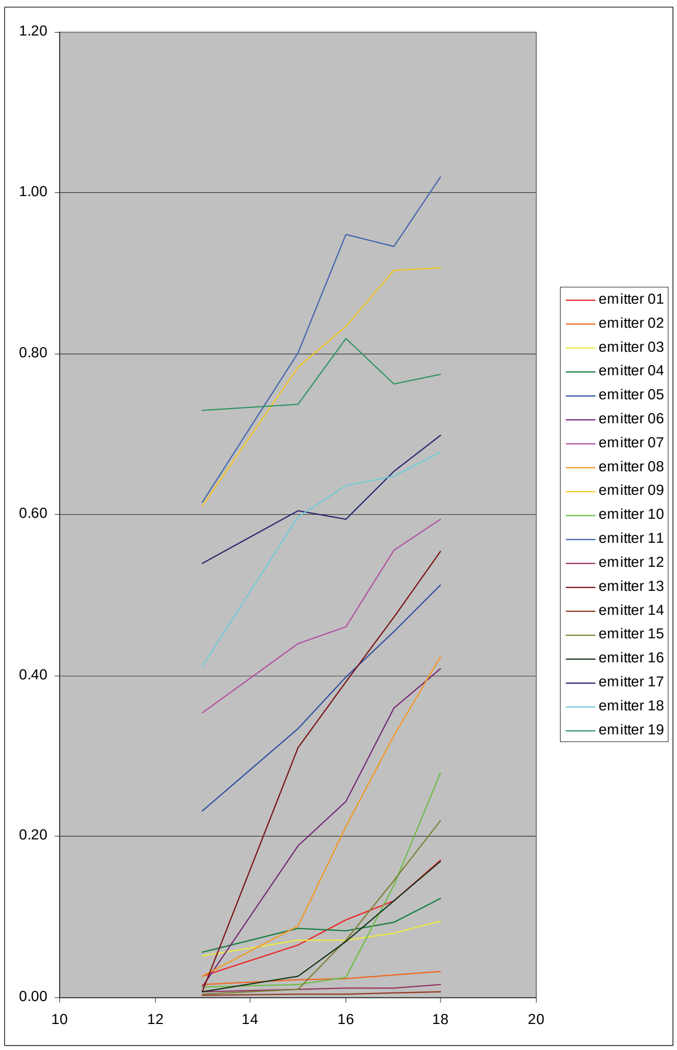

Figure 13. LD41860, optical power (arbitrary units) versus current (amps) of individual emitters, calculated from figure 10.

Three distinct failure modes were observable: slow failure on the order of the lifetime, rapid failure on the order of several days, and catastrophic failure of an element on a time scale short compared to the sampling period of 5 min (figure 6). We fit the data from the second diode to a simple curve. The catastrophic failures are pseudorandom to the extent that there is no point in trying to predict them with this method, and they were, therefore, removed from the data before fitting. The long term failure mode appears to have a constant rate of decay, or possibly an exponential with a very slow time constant. In this model it is approximated by a linear function. The short term failure mode is nearly exponential. The short term failure mode appears to recur after sudden power drops (figure 6). Fitting the first drop yields an exponential decay time constant of 39 hrs, and a linear decay slope of –0.0072 W/hr (figure 14).

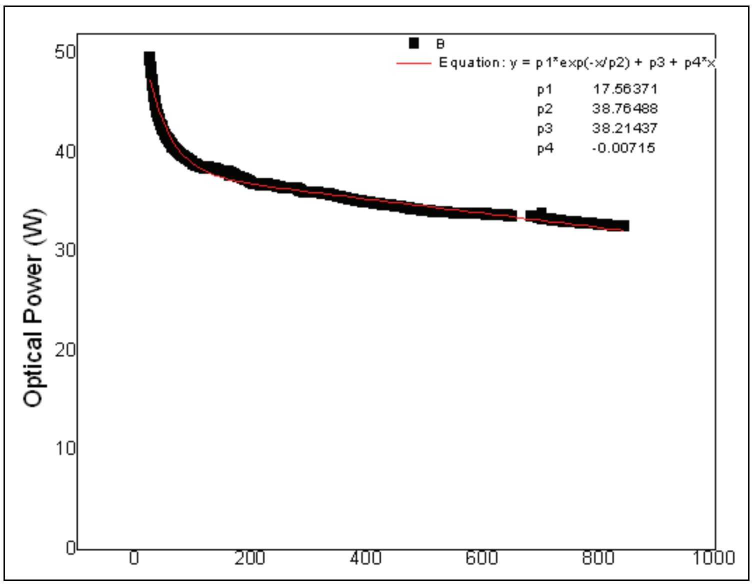

Figure 14. Results of curve fitting on the second diode.

3.3 LD266159 (Unprotected and Protected)

We continued the test, using an improved fault-detection board, with a quieter on-board power supply. The diodes were nominally the same as the previous ones, however, the initial rapid decay was not present. The initial reduction in optical power was approximately linear, with a slope of –0.035 W/hr (red line, figure 15). The improved sensitivity of the board was not realized because the 80 kHz switching transients of the Xantrex power supply masked the intrinsic, filament-related voltage transients across the diode. To reduce the switching transients, we added a 150 µH inductor[8] to the + and – Xantrex outputs at 600 hrs. The subsequent degradation rate improves by a factor of two to ~–0.017 W/hr (green line, figure 15).

[8] Coil Winding Specialists E70340-014 150.

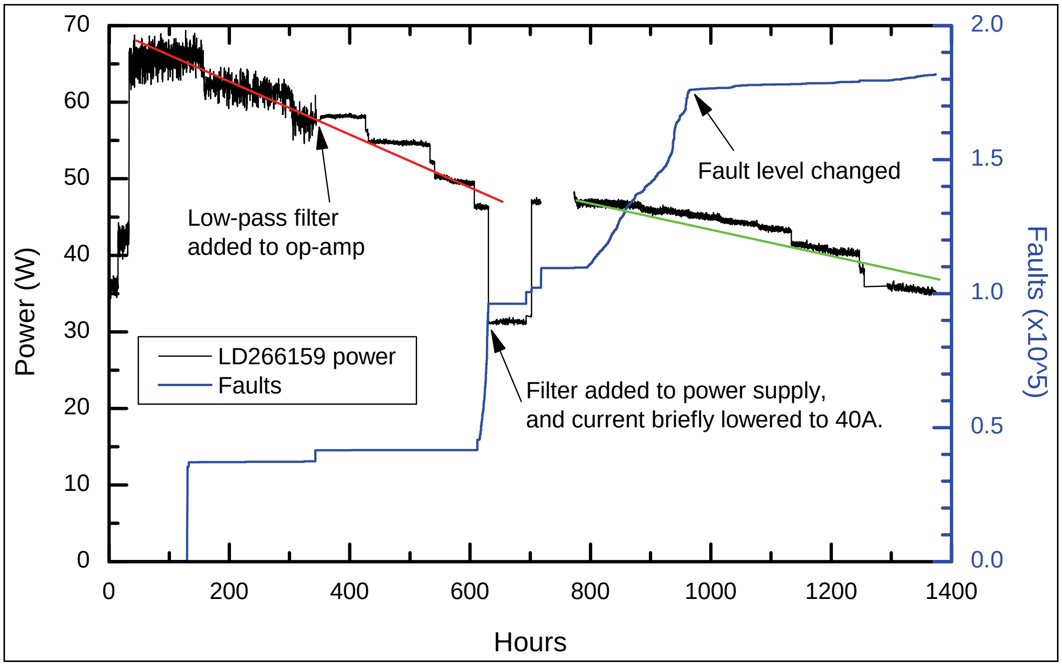

Figure 15. LD266159 output power and faults. The red line (unprotected) has a slope of –0.035 W/hr. The green line (protected) has a slope of –0.017 W/hr.

3.4 LD266160 (Unprotected)

As an additional control run, LD266160 was tested with the fault-detection circuit, but without the modulator. The degradation rate of –0.031 W/hr (red line, figure 16), matches the initial slope in figure 15.

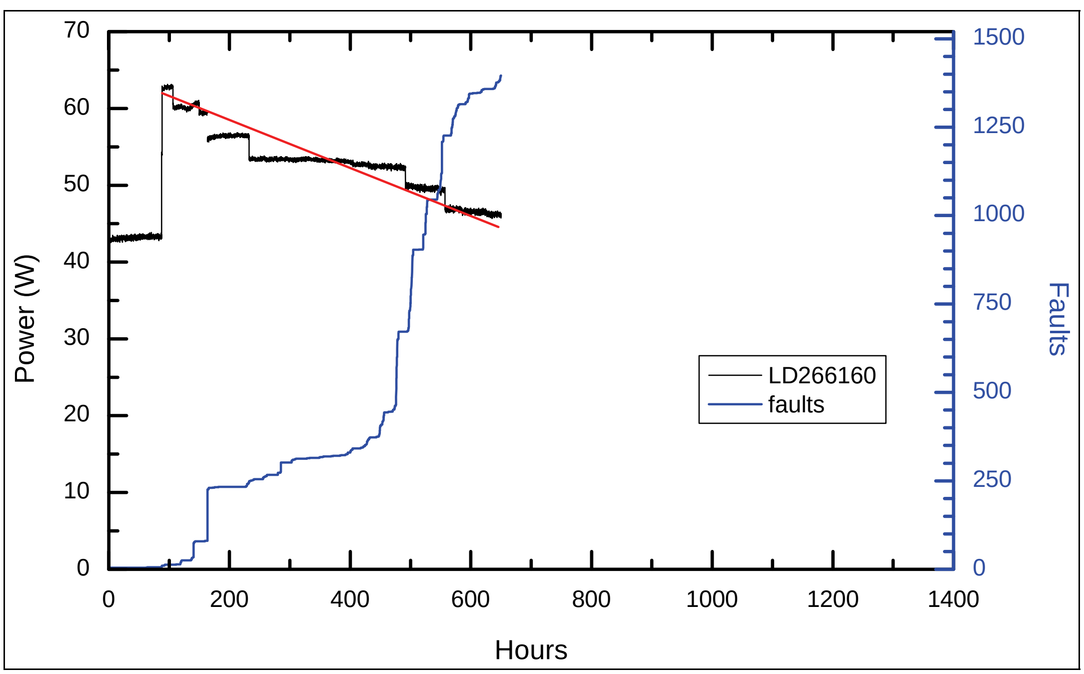

Figure 16. LD266160 (unprotected) output power and faults. The red line has a slope of –0.031 W/hr.

3.5 LD 266158 (Protected)

The last diode was tested with a Sorensen switching power supply[9], with the same inductors added to the output as before. The noise level being lower than with the Xantrex power supply, it was possible to set the fault reference level at –50 mV for the first 350 hrs of the test, increasing to –60 mV for the last part. This was the most sensitive level used in our testing. SRL routinely runs their tests with a reference level of –50 mV. Under these conditions, we can expect to see the best fault protection performance.

The output power was relatively constant for the first 150 hrs, and then had a steep drop with a slope of –0.14 W/hr (red line, figure 17). After losing 25% of its power, the decline slowed to a rate of –0.0086 W/hr for 300 hrs (green line, figure 17). Over the course of the test, most of the loss in power came from discrete jumps of ~3 W, or 5% of the initial power, presumably corresponding to the loss of one emitter from a total of 19.

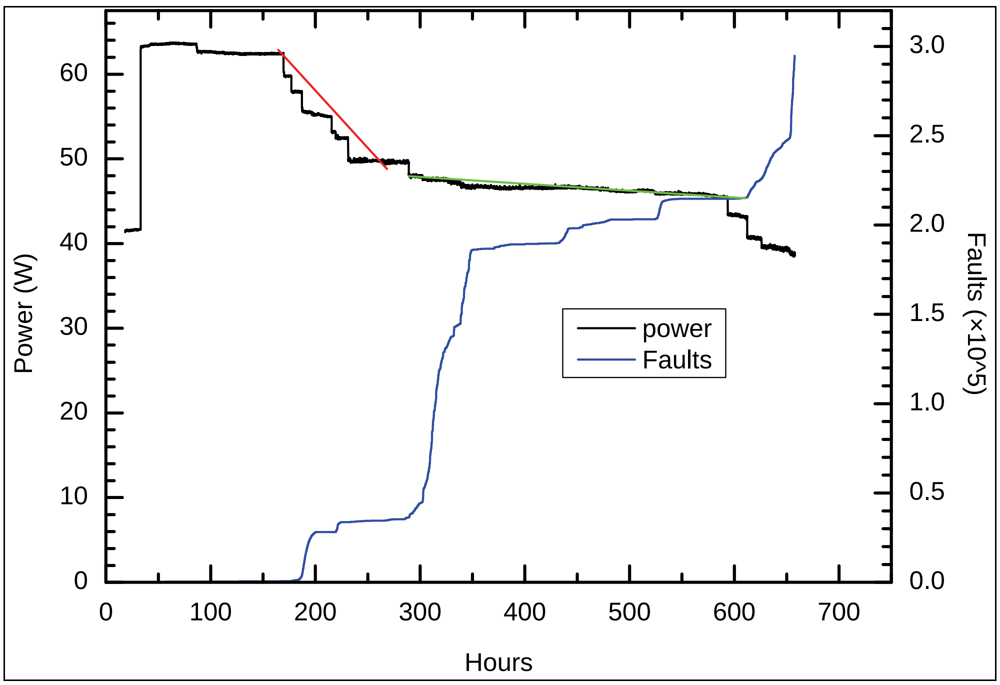

Figure 17. LD266148 (protected) output power and faults. The red line has a slope of –0.14 W/hr. The green line has a slope of –0.0086 W/hr.

It is tempting to ascribe the initial rapid decline, in this LD and others, to filaments that occur where the bandgap of the active region is smaller because of a “frozen in” variation in the local alloy. Such filaments will reoccur in the same place after the interruption in current. When those areas have all been “burned out”, i.e., converted to regions of high resistance, subsequent filamentation may occur predominantly at local, transient fluctuations in temperature. After current interruption, this kind of filament would be unlikely to reoccur in the same position. One

[9] Sorensen model SGA 80X125C.

can then expect interruptions of current to have a larger effect in slowing the degradation of the diode in this region of its life span. It may be that the effect of the protection circuitry will only be observed during the period subsequent to the intial rapid decline. This is purely speculation on our part. SRL has performed much more sophisticated characterization of the LDs, in realtime, and post mortem, and thus have a much better understanding of the microscopic mechanism involved in degradation.

On five occasions, the fault rate appeared to increase after a sudden drop in power, rather than before a drop in power, as was seen before. If the reference level is set too close to the noise level, a very large number of spurious faults will be generated, and one cannot expect to see a meaningful correlation between faults and drops in power. If the reference level is set too far above the noise, one can expect to see a correlation, at the risk of missing some bona fide faults due to filamentation. As the noise level of the power supply changes on a time scale of hours to days, we made small adjustments in the reference level from day to day, in an attempt to find the best compromise. Without characterizing the system in greater depth, it is hard to say whether any correlation we see is meaningful.

The diode voltage decreased over time (figure 18), which was unusual. We have no explanation for it. Normally, one expects filamentation to proceed to the point where it results in an “open” diode with high resistance. The same total current should continue to flow through the remaining diodes that are still conducting. One expects a slightly higher voltage across the bar as time progresses, due to the higher resistance.

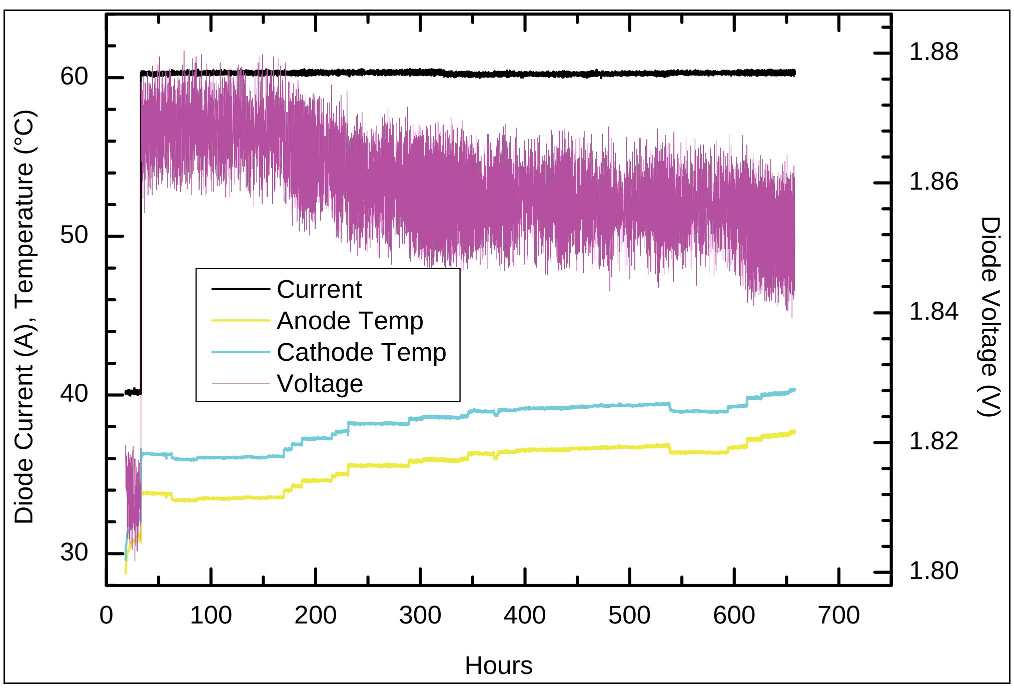

Figure 18. LD266158 (protected) current, anode temperature, cathode temperature, and voltage.

4. Summary and Conclusions

In conclusion, the device clearly improves diode lifetime by a factor of two or more. It is difficult to define the improvement factor, given the complexity of the output power vs time curve for a bar, and the diversity of behaviors for different bars. To determine the improvement factor more accurately would require testing many bars to accumulate better statistics, and is beyond the scope of this project.

How much SRL's protection scheme helps a diode under different circumstances (quasi cw versus cw, high power versus medium power) should be investigated. SRL has observed that filaments form most often at the leading edge of a current pulse. One, therefore, expects the improvement factor to be greater for quasi-cw operation, and this is what SRL observes.

The correlation between faults and power drops should also be investigated more thoroughly at some point. We have occasionally observed drops unaccompanied by faults, which is surprising, but not inconceivable. Successful operation of the device depends on having a quiet current source for the laser diode, and careful adjustment of the fault level. Automatic adjustment of the fault level, to give one fault per minute, for example, could be accomplished electronically, with a feedback circuit.

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1	US GOVERNMENT PRINT OFF DEPOSITORY RECEIVING SECTION ATTN MAIL STOP IDAD J TATE 732 NORTH CAPITOL ST NW WASHINGTON DC 20402
1	US ARMY RSRCH LAB ATTN AMSRD ARL CI OK TP TECHL LIB T LANDFRIED BLDG 4600 ABERDEEN PROVING GROUND MD 21005-5066
1	DIRECTOR US ARMY RSRCH LAB ATTN AMSRD ARL RO EV W D BACH PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709
1	SCIENCE RSRCH LABS ATTN J JACOB 15 WARD ST SOMERVILLE MA 02143
13	US ARMY RSRCH LAB ATTN AMSRD ARL CI OK PE TECHL PUB ATTN AMSRD ARL CI OK TL TECHL LIB ATTN AMSRD ARL SE EO J WHITE (5 COPIES) ATTN AMSRD ARL SE EO R DIBIANO (5 COPIES) ATTN IMNE ALC IMS MAIL & RECORDS MGMT ADELPHI MD 20783-1197

TOTAL: 24 (1 ELEC, 1 CD, 22 HCS)