Letter of Transmittal

Dear Sirs,


In this study, NST has performed a complete analysis of the solid state laser for ORION applications as per the attached SOW. The study is presented in two (2) parts. The first part analyzes the energy per pulse, allowed rep rate and the phase aberrations produced, as well as options available to the laser engineer to provide "work-arounds" and/or mitigation techniques for these problems as required by the SOW. The second part of the study calls attention to the efficiency levels for the various device options, and bounds these efficiency levels for system analysts.

NST believes this final report is in full compliance with all NASA requirements as delineated in the Order For Supplies or Services, attached.

Dr. J. P. Reilly
CEO, President
Northeast Science & Technology, Inc

Distribution:

GP54 - L
CN22D
LA10 / New Technology Representative
CCO1 / Intellectual Property Counsel
COTR (Code PS02)
NASA Attn: Accessioning Dept.

E/6/96
Statement of Work
For Research Entitled
"Advanced ORION Laser System Analysis"

Contractor shall perform a complete analysis of the potential of the solid state laser in the very long pulse mode (100 ns pulse width, 10-30 hz rep rate) and in the very short pulse mode (100 ps pulse width 10-30 hz rep rate) concentrating on the operation of the device in the “hot-rod” mode, where no active cooling the laser operation is attempted.

Contractor’s calculations shall be made of the phase aberrations which develop during the repped-pulse train, and the results shall feed into the adaptive optics analyses. The contractor shall devise solutions to work around ORION fine track issues.

A final report shall be furnished to the MSFC COTR including all calculations and analysis of estimates of bulk phase and intensity aberration distribution in the laser output beam as a function of time during the repped-pulse train for both wave forms (high-energy/long-pulse, as well as low-energy/short-pulse). Recommendations shall be made for mitigating the aberrations by laser re-design and/or changes in operating parameters of optical pump sources and/or designs.
**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

**ORDER FOR SUPPLIES OR SERVICES**

**DO RATING**
- Do C9

**DATE OF ORDER**
- Jul 25, 96

**REQUISITION NO./PURCHASE AUTHORITY**
- W-6-PP-02784 (1F)

**ISSUED BY**
- PROCUREMENT OFFICE, GP-64-L, Betty M. Canestrari
- GEORGE C. MARSHALL SPACE FLIGHT CENTER
- MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

**SHIP TO:**
- NASA, MSFC
- Attn: PS02/Les Johnson
- L/S Business: S
- Comp/Non Comp.: NC

**TO:**
- (Contractor name and address, including ZIP Code)
  - Northeast Science and Technology
  - 117 North Shore Blvd.
  - East Sandwich
  - Cape Cod, MA 02537

**TYPE OF ORDER**
- ☑ PURCHASE
- □ DELIVERY

**MAIL INVOICE (IN TRIPlicate) TO:**
- FINANCIAL MANAGEMENT OFFICE, BF82
- MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

**DELIVERY F.O.B.**
- DEST. OR OTHER
- Sept. 25, 1996

**DISCOUNT TERMS**
- Reference your quote dated July 9, 1995. Please furnish the following on the terms specified on both sides of this order and on the attached sheets, if any, including delivery as indicated.

**ACCOUNTING AND APPROPRIATION DATA**
- UNITED STATES OF AMERICA
- BY JOHN C. CATHER
- JUL 25, 1996

**SCHEDULE OF SUPPLIES OR SERVICES**

<table>
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<th>ITEM NO.</th>
<th>DESCRIPTION</th>
<th>QUANTITY (No. of Units)</th>
<th>UNIT</th>
<th>UNIT PRICE</th>
<th>AMOUNT</th>
<th>QUANTITY ACCEPTED</th>
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<td>ADVANCED ORION OPTIMIZED LASER SYSTEM ANALYSIS</td>
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<td>3,000.00</td>
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**RECEIVED AT**
- GP-64-L / Betty M. Canestrari / 206-644-7178

**SHIPIMENT**
- TYPE NO.
  - TOTAL 3,000.00

**DATE RECEIVED**
- GROSS WEIGHT
- TOTAL CONTAINERS
  - B/L NO.
- DIFFERENCES

**RECEIVED BY**
- CARRIER
  - VERIFIED CORRECT FOR (Amount)
  - INITIALS

**QUANTITIES IN "QUANTITY ACCEPTED" COLUMN HAVE BEEN:**
- ☑ INSPECTED
- □ ACCEPTED
- □ RECEIVED BY ME, AND
- CONFORM TO CONTRACT (Items listed below have been rejected for reasons shown)

**CERTIFY THAT THIS ACCOUNT IS CORRECT AND PROPER FOR PAYMENT**

**REJECTIONS**

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<th>UNIT</th>
<th>QUANTITY</th>
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*Certified for National Defense under DMS Reg. 1

The DMS rating shown must be placed on all purchases by your firm in support of this order.

MSFC-FORM 3988 (REV. SEPTEMBER 1985)
Repped Solid State Geometries

a) Radial temperature profile
    - Input beam collimated
    - Pump light
    - Cooling

b) Axial temperature profile
    - Input beam collimated
    - Pump light
    - Cooling

c) "Zig-zag" amplifier
    - kW

d) "Disk" amplifier, gas cooled
    - kW < Mw
All rep-rate damage appears to stem from Thermal Deposition and Inadequate Heat Removal

| Fracture                  | thermal profile buildup induces-- tension in outer (free ) edges  
|                          | -- compression in center (free) region                      |
| Photoelastic             | stress-induced changes in refractive index at laser wavelength |
| Thermal Lensing          | symmetrical thermal change in refractive index causes beam divergence |
| Stress Bi-Refringence    | stress-induced changes in refractive index over range of wavelengths |
| Beam Steering            | asymmetric thermal changes in refractive index causes beam steering |
| Differential Expansion   | between gain mat'l and transmission-face coatings as well as edge-band coatings |
| Inclusions / Interfaces  | surface and bulk sites show --higher linear absorption than bulk deposition,  
|                          | --higher electric field concentrations with local heating higher than bulk deposition |
Cylindrical Geometry Solid State Technology Does Not Scale to High Average Power
PULSE REP-RATE AND PULSE DURATION EFFECTS ON SOLID-STATE AMPLIFIER OUTPUT FREQUENCY SHIFT AND FREQUENCY SPREAD

Assumptions: 75% quantum efficiency
60% extraction efficiency at core
No extraction at edge
Typical Nd:YAG properties

Between Pulses in a Train

During Each Individual Pulse

- Typical upper state deactivation rates
- Shift ($\Delta f$) and Spread ($\sigma f$)
- $\lambda = 2 \mu m$
- $\lambda = 1 \mu m$
- Continuous pumping required
- 2 $\mu m$
- 1 $\mu m$
- Quasi-CW pumping required

Three-level system
- Ground-state relaxation
- Pump band transfer

Four-level System
- Ground-state relaxation
- Pump-band transfer
Key Scaling Issues in Cooling of Slab Laser Geometries

1- Allowable Thermal Limits on Laser Slabs Materials and Geometry

2- Allowable Thermal Limits on Transmissive Optics which contact Cooling Fluid

3- Flow Characteristics of cooling fluid (gas, liquid) and how it transfers heat from the hot laser slabs

4- Power Requirement to perform this cooling and how it affects overall efficiency

5- Beam Losses and distortions due to passage through turbulent flow in cooling passages

6- Beam Losses and distortions due to passage through turbulent flow in Drift Spaces
Average Power Output = $J_{lim}$ (joule/cm$^2$ per pulse) $\times A_{beam}$ (cm$^2$) $\times$ PRF (pulses/sec)

Limited by:
- Single Pulse Damage
- Distortion

Limited by:
- Manufacturing Processes
- Avg Power Cooling

Limited by:
- Thermal Recovery between pulses
- Avg Power Cooling
Limiting Single Pulse Fluence in ND:Glass Beamlet Train

LLNL Beamlet and Novette Lasers have Demonstrated 10-20 j/cm² Optics


\[
\frac{T_c - T(z)}{T_c - T_s} = \left(\frac{Z}{H}\right)^2
\]

- Uniform heat deposition and two-sided cooling

- Center region experiences more than surface, pulling them along, induces moment causing tensile stress in each extension surfaces & compression at center.

\[
\sigma = 2E \left[ -T(z) + \frac{1}{2H} \int_{-H}^{+H} T(z) \, dz + \frac{3}{2} \left(\frac{Z}{H}\right)^2 \int_{-H}^{+H} T(z) \, dz \right] = \frac{2E}{2H} \left( T_c - T_s \right) \left[ \frac{1}{3} - \left(\frac{Z}{H}\right)^2 \right]
\]

- If compressive load constant is imposed, a uniform compressive stress is superposed.

\[
\sigma_c \left( \frac{A}{Z} \right) = \frac{2E}{2H} \left( T_c - T_s \right) \frac{1}{3} = \frac{1}{6} \frac{2E}{2H} \left( T_c - T_s \right)
\]

\[
\text{Net stress at surface} \quad \frac{\sigma}{\alpha E (T_c - T_s)} = -\frac{3}{2} \text{ to } -\frac{1}{2} \approx -0.60
\]

\[
\text{At center} \quad \frac{\sigma}{\alpha E (T_c - T_s)} = +\frac{1}{3} \text{ to } +\frac{1}{2} \approx +0.40
\]
Required and Demonstrated Heat Transfer Rates

LLNL Demonstrated Cooling Rates and Energy Deposition Indicates 10 - 20 hz Appears Feasible
Gas Flow Cooling can Support Continuous Operation

\[ \dot{q} = S_T PU C_p (T_{wall} - T_{gas}) \]
\[ = S_T PM \frac{c_p}{R} \alpha \left( \frac{T_{wall} - T_{gas}}{T_{gas}} \right) \]

Helium: \( \frac{c_p}{R} = 2.5 \)
\( \alpha = 8.7 \times 10^4 \text{ cm/s} \)
at 300 K

\( S_T = 0.005 \) (turb)
\( T_{gas} = 300 \text{ K} \)
\( T_{wall} = 350 \text{ K} \)

Helium cooling flow on each slab face
- Heat transfer allows continuous op'n
- Pressures to 3 atm allow low scattering losses below M = 0.5
- Pumping power losses negligible below M = 0.3
Scaling of Rep-Pulse Solid-State Slab Lasers

Limited by 1) cross-slab ASE
2) 20% $\sigma_{\text{fracture}}$

Potential Operating Point ??

Ref: J.A.P. Vol 69 No 3, 1 Feb 1991
FIGURE 3. (a) Schematic drawing of the multipass NIF laser design. (b) Prototype Beamlet design.
FIGURE 5. Plan view of Beamlet as configured for the tests described in this article. (02-30-1091-3760F801)
"HOT ROD" CONCEPT FOR NEAR-TERM DEMO OF SOLID-STATE LASER
- REF: Battelle Columbus Proposal / Small-Scale Demo
- REF: LLNL Design Proposal to P.L. 8's ABL Program Office

Max total ΔT for 10% gain loss
3.3% Nd₂O₃ LHG-5 glass
T_max = 350 K (g₀ = 0.01/cm)
T_max = 400 K (g₀ = 0.05/cm)

Temperature rise per pulse
J_ads = °C ΔT₁ h

100 - 1000 pulse burst
Without cooling
Allows possible near-term demo
Conclusions from Repped-Pulse Laser Source Study

1- The closest tool at our disposal for the pusher laser application is a repped-pulse version of the Beamlet or Novette devices at LLNL.

- the demonstrated single-pulse energy is high enough to serve as a pusher, satisfy plasma ignition, “optimum” plasma impulse coupling and simple surface-vaporization-reaction impulse production, given our canonical 40 cm spot at range.

- the demonstrated single-pulse energy is high enough to serve as an illuminator, acting as a handover tool from a typical 100-200 meter dia microwave radar acquisition region so as to refine the target position sufficiently for the pusher function to be accomplished with the smaller (40 cm dia) spot at range.

- the required pulse repetition rates for the pusher function (10 - 50 hz range) appears to be achievable with the current Beamlet slab materials, the current slab heat loading and flashlamp pumping, and the current Helium-flow cooling technology to achieve safe operation of the laser and good (not perfect) beam quality—-the adaptive optic may have to compensate for some of the aberrations. The flashlamps, power supplies and beam aberrations need further examination.

- the required pulse repetition rates for the illuminator function (10 - 100 hz range) appears also to be consistent with these demonstration of cooling technologies, heat loading and beam quality levels. Aberrations are less important for the illuminator function (because of the large spot) than for the smaller-spot pusher function.

The only realistic option for Orion in the near term is with LLNL’s technology and personnel. Even so, funding would have to be provided from somewhere, perhaps as a “joint venture” with DOE’s National Ignition Facility effort.
AN ISSUE FOR THE COST ANALYSES AND TRADE STUDY:

EFFICIENCY OF SOLID STATE LASERS CAN BE VERY LOW
Fig. 6.78: Energy balance in an optically pumped solid-state laser system. (The percentages are fractions of electrical energy supplied to the lamp)
SOLID STATE SYSTEM EFFICIENCY

\[ \eta_{\text{tot}} = \frac{\text{laser power out}}{\text{total power in}} = \frac{P_L}{P_1 + P_2} = \frac{P_1 \times \eta_{PC} \eta_{coup} \eta_{pump} \eta_{ext} \eta_G}{P_1 + P_1(1 - \eta_{PC} \eta_{coup} \eta_{pump} \eta_{ext} \eta_G)} (1 + f_{HR}) \]

\[ f_{HR} = \frac{\text{additional power required into heat exchange}}{\text{power lost from rest of system}} \]

\[ f_{HR} = \frac{P_2}{P_1 - P_L} \]
DIODE-PUMPED SOLID-STATE LASER
SYSTEM EFFICIENCY AND TYPICAL VALUES

\[ \eta_{\text{total}} = \frac{\eta_{\text{PC}} \eta_{\text{conv}} \eta_{\text{coupl}} \eta_{\text{pump}} \eta_{\text{ext}} \eta_{\text{G}}}{1 + (1 - \eta_{\text{PC}} \eta_{\text{conv}} \eta_{\text{coupl}} \eta_{\text{pump}} \eta_{\text{ext}} \eta_{\text{G}})(1 + f_{\text{HR}})} \]

- Heat rejection: 50%-80% efficiency (0.1 ≤ f_{\text{HR}} ≤ 0.5)
- Harmonic generation: 40%-70%
- Extraction: 70%-90%
- Absorbed pump x quantum effici. x Stokes shift (70%-90%) x 90% x 76%
- Optical coupling: 70%-90%
- Conversion to diode output in pump band: 30%-50%
- Power conditioning and controls: 80%-90%

Diode conversion and heat rejection efficiency show biggest
tradeoff potential for system efficiency.
DIODE-PUMPED SOLID STATE LASER SYSTEM EFFICIENCY RANGES

Lower bounds on all other component efficiencies

Upper bounds on all other component efficiencies

With careful engineering, solid state systems can have 7%-15% system efficiencies.