COO-2007-97

ADVANCED METHODS FOR NUCLEAR REACTOR GAS LASER COUPLING

MASTER

FINAL REPORT
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DISCLAIMER

Abstract

Research is described that lead to the discovery of three nuclear-pumped lasers (NPLs) using mixtures of Ne-N_2, He-Hg, and He or Ne with CO or CO_2. The Ne-N_2 NPL was the first laser obtained with modest neutron fluxes from a TRIGA reactor (vs fast burst reactors used elsewhere in such work), the He-Hg NPL was the first visible nuclear-pumped laser, while the Ne-CO and He-CO_2 lasers are the first to provide energy storage on a millisecond time scale. Important potential applications of NPLs include coupling and power transmission from remote power stations such as nuclear plants in satellites and neutron-feedback operation of inertial confinement fusion plants.

Final Report

Approximately 100 technical reports and articles have resulted from this research. A listing is included in *Appendix A* and individual reports are referred to in the following discussion according to their report number, i.e., COO-2007-xx.

As a result of this work, three nuclear pumped lasers have been developed. This represents one-quarter of the NPLs discovered to date.

Research under this contract, initiated in January 1969, was concerned with the development of NPLs. When this work first began, the NPL was viewed as a technique to directly extract energy from a fission reactor. However, as the work progressed, it became apparent that other important applications might develop, e.g. neutron-feedback pumping for laser fusion reactors (see reports COO-2007-86 through 89).

This research was first designed at gaining a better understanding of radiation-induced plasmas. This was viewed as a prerequisite for ultimate development of an NPL. Highlights of this phase of the work include:

- Theoretical calculations of ionization-excitation rates and electron energy distributions in radiation-induced plasmas (COO-2007-3, 6, 17, 25, 26, 30, 36, and 51).
- Measurements of metastable densities in He-Ne mixtures during irradiation (COO-2007-4, 6, 11 and 14).
- Spectroscopy of radiation-induced plasmas (COO-2007-10, 19, 27, 37, 39, 41, 42, 52, and 53).

A second phase of the work concentrated on the effect of radiation superimposed on electrically operated lasers (COO-2007-7, 8, 9, 13, 44, 53, 54, 56, and 65). Also gain measurements were made in various mixtures including He-Ne, He-Ne-O_2, and He-Hg (COO-2007-20, 45, 58, 85, and 500).

Experience and understanding gained through this work ultimately resulted in the development of three NPLs. These are:

- Ne-N_2 (COO-2007-57, 66, 72P, 76P)
- He-Hg (COO-2007-78, 503)
- He or Ne with CO or CO_2 (COO-2007-506, 95, 91, 90)

The achievement of these lasers is considered to be an important accomplishment for several reasons. First this represents one-quarter of the dozen NPLs reported to date. The He-Hg laser was the first visible NPL, and even now the only other NPL in this wavelength range is He-Ne which appears quite restrictive in application. The mixtures with CO and CO_2, which lase on the same atomic carbon line, exhibit a time delay of orders of milliseconds, suggesting that they have an important energy storage capability.

Another aspect of this accomplishment is that, with one exception (He-Ne), all other NPLs have been developed using fast burst reactors (vs the TRIGA employed in the present work). The fast burst reactor gives other experimenters an order of magnitude advantage in flux and rise time. Still, for ultimate applications, the fluxes achieved with the TRIGA seem more realistic, although more demanding on the experimenter.

This work is put into perspective in a recent review paper on NPLs written by one of the principal investigators (GHM) and reproduced here as *Appendix B*. This appendix also indicates the present status and some potential applications of NPLs.

Several applications of NPLs have been considered in a very preliminary fashion (COO-2007-84). A very interesting and promising potential application involves neutron-feedback fusion, and some conceptual studies of this approach to inertial confinement have been explored (COO-2007-86, 87, 88, 89, 92)

Finally, it should be noted that this project, in addition to technical contributions, has provided research experience for over

30 graduate students. Ten received Ph.Ds in Nuclear or Electrical Engineering, two did MS theses, and the remainder either performed R/A duties or are still involved in Ph.D. research A complete listing of students who have, at various times, been associated with the project is included as *Appendix C*.

Appendix A

Listing of Reports Listed Under COO-2007 Series

LISTING OF COO-2007- REPORTS

COO-2007-1	"Advanced Methods for Nuclear Reactor Gas Laser Coupling" (J. Verdeyen and G. H. Miley, Progress Report, Jan. 1, 1969 - Dec. 31, 1969).
COO-2007-2	"On Gas Laser Pumping Via Nuclear Radiations" (G. Guyot, G. H. Miley, J. T. Verdeyen, and T. Ganley, *Res. on U. Plasmas,* pp. 359-368).
COO-2007-3	"Calculations of Ionization-Excitation Source Rates in Gaseous Media Irradiated by Fission Fragments and Alpha Particles" (P. Thiess, *Res. on U. Plasmas and Their Technological Applications,* NASA SP-236 (1971), pp. 369-96).
COO-2007-4	"Measurement of Atomic Metastable Densities in a Plasma Created by Nuclear Radiations" (J. Guyot, G. H. Miley, J. T. Verdeyen, and T. Ganley, *Trans. Am. Nuc. Soc., 13,* 77, July 1970).
COO-2007-5	"Advanced Methods for Nuclear Reactor-Gas Laser Coupling" (G. Miley and J. T. Verdeyen, Progress Report, Jan. 1, 1971 - Dec. 31, 1971).
COO-2007-6	"Calculated and Measured Atomic Metastable Densities in Noble-Gas Plasmas Induced by Nuclear Radiations" (J. Guyot, G. H. Miley, and J. T. Verdeyen, *Trans. Am. Nuc. Soc., 14,* 136, 1971).
COO-2007-7	"Enhancement of CO$_2$ Laser Power and Efficiency by Neutron Irradiation" (J. T. Verdeyen and G. Miley, Fundamental Nuclear Energy Res. Rept.)
COO-2007-8	"Effect of Nuclear Radiation on Operating Characteristics of a CO$_2$ Laser" (T. Ganley, J. T. Verdeyen, and G. H. Miley, *Trans. Am. Nucl. Soc., 14,* 133, 1971).
COO-2007-9	"The Effect of an Applied Electric Field of Optical Line Intensities in a Cylindrical Radiation Plasma Device" (P. Thiess and G. H. Miley, *Trans. Am. Nuc. Soc.,* (1971) not published).
COO-2007-10	"Optical Emission from Noble Gas Plasmas Created by Alpha Particles" (P. Thiess and G. H. Miley, *Trans. Am. Nucl. Soc., 11,* 171, 1971).

COO-2007-11	"Measurement of Atomic Metastable Densities in Noble Gas Plasmas Created by Nuclear Radiations" (J. Guyot, Ph.D. Thesis, Nucl. Eng., U. of Ill., 1971).
COO-2007-12	"Pumping of Lasers Via Heavy Ion Beams" (G. Miley, J. T. Verdeyen, T. Ganley, J. Guyot, and P. Thiess, Proceedings, 11th Symp. on Electron, Ion, and Laser Beam Tech., U. of Colorado, May 1971).
COO-2007-13	"Enhancement of CO_2 Laser Power Efficiency by Neutron Irradiation" (T. Ganley, J. T. Verdeyen, and G. Miley, *APL, 18,* 569, 1971).
COO-2007-14	"Metastable Densities in Noble-Gas Plasmas Created by Nuclear Radiations" (J. Guyot, G. H. Miley and J. T. Verdeyen, *J. Appl. Phys.,* Nov. 1971).
COO-2007-15	"Complete paper corresponding to abstract, COO-2007-12" (G. Miley, J. T. Verdeyen, T. Ganley, J. Guyot, and P. Thiess, Proceedings, 11th Symp. on Electron, Ion, and Laser Beam Tech., U. of Colorado, May 1971).
COO-2007-16	"Nuclear Radiation Effects on CO_2 Laser Output" (J. Verdeyen, J. T. Ganley, and G. H. Miley, *IEEE Device Res. Conf.,* 1971).
COO-2007-17	"Application of a Two-Region Heavy Charged Particle Model to Noble-Gas Plasmas Induced by Nuclear Radiations" (J. Guyot, G. H. Miley, and J. T. Verdeyen, *Nuc. Tech.*).
COO-2007-18	"The Effect of an Applied Electric Field on Optical Emission from a Radiation Plasma Device" (P. Thiess and G. H. Miley, *Trans. Am. Nuc. Soc., 14,* 430, Oct. 1971).
COO-2007-19	"Spectroscopic and Probe Measurements of Excited State and Electron Densities in Radiation-Induced Plasmas" (P. Thiess and G. H. Miley, *Proc. 2nd Symposium on Uranium Plasmas,* Georgia Tech. (Nov. 1971) pp 90-99.
COO-2007-20	"Pumping and Enhancement of Gas Lasers via Nuclear Radiation" (G. H. Miley, J. T. Verdeyen, J. C. Guyot and T. Ganley, *Proc. 2nd Symposium on Uranium Plasmas,* Georgia Tech. (Nov. 1971) pp. 39-44.

COO-2007-21	"Nuclear Radiation Effects on Gas Lasers" (G. H. Miley, *Laser Interaction and Related Plasma Phenomena,* Plenum Press, 1971).
COO-2007-22	"Progress Report - Jan. 1972 - Dec. 1972"
COO-2007-23	"Enhancement of Pulsed Low- and High-Pressure CO_2 Laser Operation Using Nuclear Radiation" (J. T. Verdeyen and G. H. Miley, HEC, *Fundamental Nuclear Energy Research,* 1972).
COO-2007-24	"Effects of a Heavy Particle External Ionization Source on Carbon Dioxide Laser Discharges" (J. T. Ganley, Ph.D. Thesis, Elec. Eng., U. of Ill., 1972).
COO-2007-25	"Monte Carlo Simulation of Nonlinear Radiation Induced Plasmas" (Benjamin Shaw Wang, Ph.D. Thesis, Computer Science, U. of Ill., 1972).
COO-2007-26	"Calculation of Electron Energy Flux Distributions in Noble Gases" (R. Lo and G. H. Miley, *Trans. Am. Nuc. Soc., 15,* 581, June 1972).
COO-2007-27	"Optical Spectra of High-Pressure Helium Irradiated by Alpha Particles" (P. E. Thiess and G. H. Miley, *Trans. Am. Nuc. Soc., 15,* 706, Nov. 1972).
COO-2007-28	"A High-Vacuum Pure-Gas Alpha Irradiation Facility" (G. H. Miley and P. Thiess, U. S. Atomic Energy Commission, 1972).
COO-2007-29	"A Digital Photometer for Studies of Spectra Produced by Ionizing Radiation" (P. E. Thiess, T. A. Visel, and P. A. Kwitkowski, *Trans. Am. Nuc. Soc., 15,* 707, Nov. 1972).
COO-2007-30	"Monte Carlo Simulation of Radiation-Induced Plasmas" (B. S. Wang and G. H. Miley, *Trans. Am. Nucl. Soc., 15,* 795, Nov. 1972).
COO-2007-31--34	Blank

COO-2007-35	"Excited Transfer from 2P Atomic States to Molecular States in High Pressure Helium" (P. E. Thiess and G. H. Miley, *APS*, 25th Annual Gaseous Electronics Conf., 1972).
COO-2007-36	"Monte Carlo Simulation of Radiation-Induced Plasma" (B. S. Wang and G. H. Miley, *Nucl. Sci. and Engr.* *52*, 130-141, 1973).
COO-2007-37	"Optical Spectra of High-Pressure Helium Mixtures Irradiated by Alpha Particles" (P. E. Thiess and G. H. Miley, *Trans. Am. Nuc. Soc.*, *16*, 56, June 1973).
COO-2007-38	"Technical Progress Report - Jan. 1973 - Aug. 1973" (J. T. Verdeyen and G. H. Miley)
COO-2007-39	"Production of Excited Molecular Ions by Rare Gas Molecular Metastables" (P. E. Thiess and G. H. Miley, *Bull. of Am. Phys. Soc.*, Series 11, Vol. 19, 152 (1974).
COO-2007-40	"Excited Kinetics in High Pressure Rare Gas Association Lasers" (P. E. Thiess and G. H. Miley, *Bull. of Am. Phys. Soc.*, Series 11, Vol. 19, 157 (1974).
COO-2007-41	"Ionization and Excitation Growth in High Pressure Rare Gases and Mixtures" (P. E. Thiess and G. H. Miley, *Bull. of Am. Phys. Soc.*, Series 11, Vol. 19, *163* (1974)).
COO-2007-42	"New Near-Infrared and Ultraviolet Gas Proportional Scintillation Counters" (P. E. Thiess and G. H. Miley, *IEEE Trans. on Nucl. Sci., NS-21, No. 1*, 125-146 (1974).
COO-2007-43	"An Integrated Circuit Analyzer-Counter-Ratemeter and Position Device for Nuclear Spectroscopy Studies" (P. E. Thiess, T. A. Visel, P. A. Kwitkowski, *IEEE Trans. on Nuc. Soc. NS-21,* No. 1, 826-837 (1974).
COO-2007-44	"Studies of Nuclear Radiation Enhancement and Pumping of Noble Gas Lasers" (R. DeYoung, E. Seckinger, W. E. Wells, and G. H. Miley, *Proc. IEEE Int. Conf. on Plasma Science* (1974)).

COO-2007-45	"Study of the Neon-Oxygen Laser Under Heavy Particle Bombardment" (E. L. Seckinger, M. S. Thesis, U of I, EE, (1974)).
COO-2007-46	"Studies of Excited States Formed in Neon And Argon by Ionizing Radiation" (P. E. Thiess and G. H. Miley, *Trans. Am. Nuc. Soc.*, (1974)).
COO-2007-47	Technical Progress Report - Aug. 31, 1973 - Aug. 31, 1974 (J. T. Verdeyen, G. H. Miley and W. E. Wells).
COO-2007-48	"Pumping and Enhancement of Noble Gas Lasers by Nuclear Radiation" (R. DeYoung, E. Seckinger, W. E. Wells, and G. H. Miley, *IEEE Conf. on Quantum Electronics* (1974)).
COO-2007-49	
COO-2007-50	"Lasing in a Ternary Mixture of He-Ne-O_2 at Pressures Up to 200 Torr" (R. DeYoung, S. Beckman, W. E. Wells, and G. H. Miley, *APS, 27th Annual Gaseous Electronics Conf.* (1974)).
COO-2007-51	"Non-Maxwellian Electron Excitation in Helium" (E. E. Maceda and G. H. Miley, *APS 27th Annual Gaseous Electronics Conf.* (1974)).
COO-2007-52	"Collisional Transfer of Excitation and Non-Metastable Penning Ionization of Nitrogen by Neon $2p_1$" (P. E. Thiess, G. H. Miley, J. L. Gorecki, and L. Zinkiewicz, *APS 27th Annual Gaseous Electronics Conf.* (1974)).
COO-2007-53	"Experimental Evidence for Two-Step Excitation/Ionization in High Pressure Rare Gas DC Townsend Discharges" (P. E. Thiess and G. H. Miley, *APS 27th Annual Gaseous Electronics Conf.* (1974)).
COO-2007-54	"Enhancement of He-Ne Lasers by Nuclear Radiation" (R. DeYoung, W. E. Wells, and G. H. Miley, *Trans. Am. Nuc. Soc.*, *19*, 66 (1974).

COO-2007-55	"Optical Spectra Produced in Neon and Argon Mixtures by Ionizing Radiation" (P. E. Thiess and G. H. Miley, *Trans. Am. Nuc. Soc.*, *19*, 64-66, (1974)).
COO-2007-56	"Enhanced Output from He-Ne Laser by Nuclear Preionization" (R. DeYoung, W. E. Wells, and G. H. Miley, 1974 Int. Electron Devices Mtg., Washington, D. C. (1974)).
COO-2007-57	"A Direct Nuclear Pumped Ne-N_2 Laser" (R. DeYoung, W. E. Wells, T. J. Verdeyen, and G. H. Miley, C.L.E.A., Washington, D.C. (1975)).
COO-2007-58	"Studies of Radiation-Induced Laser Plasmas" (R. DeYoung, M. A. Akerman, W. E. Wells, and G. H. Miley, *Proc. IEEE 2nd Int. Conf. on Plasma Sciences*, 75CH0987-8-NPS, IEEE, p. 79 (1975)).
COO-2007-59	"Laser-Pellet Fusion by Energy Feedback to a Direct Nuclear Pumped Auxiliary Laser" (W. E. Wells, *IEEE 2nd Int. Conf. on Plasma Sciences* (1975)).
COO-2007-60	"Continued Studies of UV-Visible-Neon IR Gas Proportional Scintillation Counters" (P. E. Thiess, *IEEE Nucl. Sci. Sym.*, Wash., D. C., Dec. 1975)
COO-2007-61	"Atomic and Molecular Spectra and Excited State Kinetics of Noble Gas Scintillation Counters" (P. E. Thiess and G. H. Miley, *IEEE Nucl. Sci. Sym.*, Wash., D. C., Dec. 1975)
COO-2007-62	"Gaseous and Quantum Electronics in Nuclear Engineering Education" (W. E. Wells, *Natl. Topical Mtg.-Nuclear Engr. Ed. Nuclear Technology* Vol. 27, Sept. 1975.)
COO-2007-63	Technical Progress Report - August 31, 1975 - May 20, 1976
COO-2007-64	"Direct Nuclear Pumped Lasers" (W. E. Wells, *APS Gaseous Electronics Conf.*, *16*, 1975)
COO-2007-65	"Nuclear Radiation Enhancement of a Helium-Mercury Laser" (M. A. Akerman, M. Konya, W. E. Wells, and G. H. Miley, *Trans. Am. Nuc. Soc.*, *22*, 133 (1975)).
COO-2007-66	"A Ne-N_2 Laser Excited Only by Neutron Reactions" (R. DeYoung, W. E. Wells, J. T. Verdeyen, and G. H. Miley, *Trans. Am. Nuc. Soc.*, *22*, 134 (1975)).

COO-2007-67	"Lasing in a Ternary Mixture of He-Ne-O_2 at Pressure up to 200 Torr" (R. DeYoung, W. E. Wells, and G. H. Miley, *J. of Applied Physics, 47,* 4 (1976))
COO-2007-68	(Same as COO-2007-65)
COO-2007-69	(Same as COO-2007-66)
COO-2007-70	(Same as COO-2007-64)
COO-2007-71P	"Direct Nuclear Pumped (DNP) Lasers" (G. H. Miley and W. E. Wells, 9th Int. Quantum Elec. Conf. Amsterdam, The Netherland (June 1976))
COO-2007-72P	"Direct Nuclear Pumping of a Ne-N_2 Laser" (R. DeYoung, W. E. Wells, G. H. Miley, J. T. Verdeyen, *Applied Physics Letters, 28,* 9, (1976))
COO-2007-73P	"Optical Emission and Kinetics of High Pressure Radiation Produced Noble Gas Plasmas" (P. E. Thiess, Ph.D. Thesis, Nuclear Eng., University of Illinois (1976))
COO-2007-74P	"Energy Distribution of Electrons in Electron Beam Produced Nitrogen Plasmas" (D. R. Suhre and J. T. Verdeyen, *Journal of Appl. Physics,* (1976))
COO-2007-75P	"Energy Distributions of Electrons in Electron Beam Produced Nitrogen Plasmas" (D. R. Suhre, Ph.D. Thesis, Elect. Engr., U. of Ill. (1976))
COO-2007-76P	"A Direct Nuclear Pumped Neaon-Nitrogen Laser" (R. DeYoung, Ph.D. Thesis, Nucl. Engr., U. of Ill. (1976))
COO-2007-77	"Recombination Pumped Atomic Nitrogen and Carbon Afterglow Lasers" (Gary W. Cooper, Ph.D. Thesis, Nucl. Engr., U. of Ill., (1976))
COO-2007-78	"Demonstration of the First Wavelength Direct Nuclear Pumped Laser" (M. A. Akerman, Ph.D. Thesis, Nuc. Engr., U. of Ill., (1976))

COO-2007-79	"Study of a Direct Nuclear Pumped, He-Hg Laser" (M. A. Akerman, APS-29th Annual)
COO-2007-80	"Recent Nuclear Pumped Laser Results" (G. H. Miley, W. E. Wells, M. A. Akerman, and J. Anderson, Proc. of the Princeton Univ. Conf. on Partially Ionized Plasmas, *102* (1976))
COO-2007-81	"The Pumping Mechanism for the Neon-Nitrogen Nuclear Excited Laser" (G. Cooper, J. T. Verdeyen, W. E. Wells, and G. H. Miley, *Proc. of the Conf. on Partially Ionized Plasmas, 91,* Princeton, (1976))
COO-2007-82	"A Laser-Fusion Concept Using D-D-T Pellets with DNP Laser Feedback System" (G. Miley, S. Sutherland, C. Choi, and J. Glowienka, *1977 IEEE/OSA Conf.*, Wash., D. C.)
COO-2007-83	1975-76 Progress Report - August 1975-August 1976
COO-2007-84	"Scale-Up and Potential Applications of Direct Nuclear Pumped Lasers" (G. H. Miley, *IEEE Intl. Conf. on Plasma Sciences,* RPI, Troy, NY (1977) No. 3D1-2 Invited, 96)
COO-2007-85	"Direct Nuclear Pumped Gain at 7945Å of HGII in a Helium-Mercury Mixture" (A. Akerman, F. Boody, and G. H. Miley, *IEEE Intl. Conf. on Plasma Sciences,* RPI, Troy, NY (1977) No. 3D3, 97)
COO-2007-86	"Energy Feedback by the DNP Laser for a Laser-Fusion Reactor" (G. Miley, S. Sutherland, C. Choi, and J. Glowienka, *IEEE Intl. Conf. on Plasma Sciences,* RPI, Troy, NY (1977) No. 3D11, 105)
COO-2007-87	"A Direct Nuclear Pumped Laser Approaching Feedback Laser Fusion Needs" (M. A. Prelas, J. H. Anderson, F. P. Boody, and G. H. Miley, *Trans. ANS, 27,* 63 (1977))
COO-2007-88	"D-D-T Pellet Laser-Fusion Feedback Concepts" (G. H. Miley, C. K. Choi, and S. Sutherland, *Trans. ANS,* San Francisco, CA (1977)) (Not published)

COO-2007-89	"A Self-Sustaining Nuclear Pumped Laser-Fusion Reactor" (F. P. Boody, C. K. Choi, and G. H. Miley, *Trans. ANS,* San Francisco, CA (1977)) (Not published)
COO-2007-90	"A Nuclear Pumped Laser Using Ne-CO and Ne-CO$_2$ Mixtures" (M. A. Prelas, J. H. Anderson, F. P. Boody, S. J. S. Nagalingam and G. H. Miley, *30th Annual Gaseous Electronics Conf. of the American Physical Society,* Palo Alto, CA, October 18-21, (1977) LA-Z, p. 118)
COO-2007-91	"A Direct Nuclear-Pumped Carbon Laser with Millisecond Time Delay" (M. A. Prelas, M. A. Akerman, F. P. Boody, and G. H. Miley, *30th Annual Gaseous Electronics Conf. of the American Physical Society,* Palo Alto, CA, October 18-21, 1977)
COO-2007-92	"NPL-NS - A "Next Step" Experiment for Inertial Confinement Fusion" (F. P. Boody, A. W. Kruger, D. Lee, C. K. Choi, and G. H. Miley, Topical Meeting on Inertial Confinement Fusion, February 7-9, 1978, San Diego, CA.)
COO-2007-93	"Progress in Nuclear Pumped Lasers" (F. P. Boody, M. A. Prelas, S. J. S. Nagalingam and G. H. Miley, submitted to *3rd NASA Conf. on Radiation Energy Conversion,* Jan 26-28, 1978, Moffet Field, CA.)
COO-2007-94	"Nuclear Pumping of a Neutral Carbon Laser" (M. A. Prelas, J. H. Anderson, F. P. Boody, S. J. S. Nagalingam and G. H. Miley, submitted to *3rd NASA Conf. on Radiation Energy Conversion,* Jan. 26-28, 1978, Moffet Field, CA)
COO-2007-95	"Nuclear Pumping of a Neutral Carbon Laser" (M. A. Prelas, J. H. Anderson, F. P. Boody, S. J. S. Nagalingam and G. H. Miley, Preprint: *3rd NASA Conf. on Radiation Energy Conversion,* Moffett Field, CA, January 26-28, 1978)
COO-2007-96	"Charge Exchange Phenomena in a Nuclear Radiation Produced He-Hg Plasma" (M. A. Akerman, W. E. Wells, G. H. Miley, *IEEE 1976 International Conference on Plasma Science*, Austin, TX, p. 86.
COO-2007-97	Final Report - 1 January 1969 - 5 January 1978

COO-2007-500	"Optical Gain in a Neutron-Induced ^{3}He-Ne-O_2 Plasma" (R. J. DeYoung, W. E. Wells, and G. H. Miley, *Appl. Phys. Letts.*, *28*, 194-197, February 15, 1976)
COO-2007-502	"Applications of Direct Nuclear Pumped Lasers and Gaseous Core Reactors" (George H. Miley, *Am. Nuc. Soc.*, *26*, 526, June 1977)
COO-2007-503	"A Helium Mercury Direct Nuclear Pumped Laser" (M. A. Akerman, G. H. Miley and D. A. McArthur, *Appl. Phys. Letts.*, Vol. 30, No. 8, 15 April 1977, p. 409)
COO-2007-504	"Direct Nuclear Pumped Lasers - Status and Potential Applications" (G. H. Miley, *Laser Interaction and Related Plasma Phenomena,* (H. Schwarz and H. Hora, eds.), Vol. 4A, Plenum Press, New York (1977) p. 181-229)
COO-2007-505	"Recombination-pumped Atomic Nitrogen and Carbon Afterglow Lasers" (G. W. Cooper and J. T. Verdeyen, Reprint: *Journal of Applied Physics*, Vol. *48*, No. 3, March 1977)
COO-2007-506	"A Direct Nuclear Pumped 1.45-m Atomic Carbon Laser in Mixtures of He-CO and He-CO_2" (M. A. Prelas, M. A. Akerman, F. P. Boody, and G. H. Miley, *Applied Physics Letters*, Vol. 31, No. 7, 1 October 1977)

Appendix B

Reprint of paper titled "Nuclear-Pumped Lasers" by George H. Miley

NUCLEAR-PUMPED LASERS*

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SUMMARY

Nuclear-Pumped Lasers (NPLs) directly convert the charged particle energy from nuclear reactions into coherent light energy. Since they avoid thermal processes and since excitation can come from throughout the volume of the laser, nuclear-pumped laser systems are intrinsically capable of greater efficiency and higher power than electrically pumped lasers. Twelve NPLs have been demonstrated and more are being actively pursued by several university and national lab teams. Applications studies have been performed on the design of a fast burst reactor based multi-MJ pulsed NPL, on a neutron-feedback nuclear-pumped laser fusion reactor.

INTRODUCTION

The MeV ions from nuclear reactions provide the excitation energy for nuclear pumped lasers. Because they short circuit the conversion of nuclear energy to heat, heat to electricity, and electricity to charged particles (the result of the nuclear reactions in the first place) NPLs offer the potential of greater efficiency from much more compact sources than conventional lasers.

Three key nuclear reactions have been utilized for nuclear pumping:

$^{3}\mathrm{He}(n,p)T$: $^{3}\mathrm{He} + n \rightarrow T + p + 0.76$ MeV,

$^{10}\mathrm{B}(n,\alpha)^{7}\mathrm{Li}$: $^{10}\mathrm{B} + n \rightarrow {}^{7}\mathrm{Li} + \alpha + 2.35$ MeV, and

$^{235}\mathrm{U}$ fission: $^{235}\mathrm{U} + n \rightarrow ff_{h} + ff_{\ell} + \nu n + 165$ MeV;

where the energies quoted are for charged particle release, ff indicates energetic fission fragments, ν is the number of neutrons/fission, and other symbols follow standard convention.

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*This review, compiled for the ANL-AUA Faculty Institute on Inertial Confinement, Argonne, Ill (June 1978) is largely extracted from recent articles by the author (Ref. 23) and by F. Boody, M. Prelas, J. Anderson, S. Nagalingam, and G. Miley, "Progress in Nuclear-Pumped Lasers," Proc. 3rd NASA Conf. Radiation Energy Conversion, Ames Res. Center, CA, Jan. 1978.

As illustrated in Fig. 1, two broad classes of NPLs are possible: lasers using boron or uranium coated tube walls or, alternately, designs using mixtures containing gases such as ^3He, UF_6, or BF_3, sometimes referred to as *volume sources*. The latter are best suited for large aperture and/or high-pressure operation since MeV ions are produced throughout the volume of the laser medium rather than having to start at outer walls. Neutrons to drive the reactions are presently obtained from high-flux pulsed fission reactors although other sources such as particle accelerators or fusion devices, such as a plasma focus, are possible.

Although the necessity of combining a neutron source with the laser may seem to be a hindrance, it in fact represents the major advantage of the NPL. Because they are uncharged, neutrons can penetrate great distances. This, of course, means a low reaction rate. However, because of the very large amount of energy released per neutron absorbed, a very slow neutron attenuation rate can result in a substantial energy release per unit volume.

MeV ions slow down in gases via both excitation and ionization collisions. High energy secondary electrons produced in ionization events carry off a major portion of the ion's energy, and, at the pressures of interest, *the subsequent ionization and excitation produced by these electrons provide the prime energy flow channel.* (Ref. 1-5) This is illustrated in Fig. 2 where the nascent (prime) electron energy distribution as well as the final steady-state distribution is shown for 1-MeV alpha irradiation of He. The high-energy "tail" on the distribution is a distinguishing feature that can lead to *non-equilibrium excitation.* In this sense, NPLs are similar to electron-beam-driven lasers. (Ref. 6) (One important exception, noted in connection with the molecular CO NPL, is that a significant portion of a fission fragment's energy can be transferred directly to vibrational states in molecular gases. (Ref. 7-8) Some important differences exist, however. The energy distribution associated with the secondary electrons in NPLs is not precisely reproduced by present electron-beam devices. Also, pulse rise times associated with neutron sources are slow compared to electron beams, requiring quasi steady-state inversions. The key difference, from a practical point of view, *is the possibility of pumping large volumes using the penetrating power of neutrons.*

While inversion via *direct excitation* due to electrons in the high-energy tail of the distribution is conceivable,* the characteristically slow rise time for NPLs makes this difficult. Consequently other means of selective excitation are typically sought. In fact, as seen from the next section, with the exception of the CO NPL, all experimental lasers achieved to date have employed a gas mixture to provide *selective transfer* from a majority (host) gas to the lasing gas.

Since electric fields are absent, the electron temperature in the NPL plasma is characteristically low, nearly in equilibrium with the gas

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*For example, inversion in pure helium has been predicted, based on both calculations and measured line intensity data. (Refs. 9,10) temperature. (Ref. 11) In this sense the NPL plasma resembles the "afterglow" regime in gaseous discharges and *recombination* provides another important mechanism for selective excitation. (Ref. 12)

Lasers Demonstrated

While the concept of an NPL laser virtually dates back to the discovery of the laser itself,[†] experimental verification was not achieved until 1974 when McArthur and Tollefsrud (Ref. 7) obtained lasing in CO using a uranium-coated tube with the Sandia SPR II fast-burst reactor. Closely thereafter, Helmick, et al. (Ref. 14) achieved direct pumping of a He-Xe mixture and DeYoung, et al. (Ref. 15-16) reported lasing with Ne-N$_2$. NPLs reported thus far are summarized in Table 1 and a more complete discussion is given in a later section.

With NPL research only in its infancy, many lasers beyond the twelve reported to date can safely be anticipated. However, the necessity to provide for nuclear reactions with volume pumping restricts the possible gases and mixtures.

Although the output powers obtained in experiments to date are small, typically in the milliwatt to watt range, the crucial question is whether these small experimental devices can be scaled up to large volumes and higher pressures. Perhaps the most attractive laser listed from a potential power/efficiency point of view is the molecular CO NPL where an efficiency (laser output/nuclear energy in) of well over 1% is predicted. (Ref. 42) This is attributed to an anomalously large transfer of energy to vibrational modes in CO via direct fission fragment encounters. (Ref. 8)

Lasing in the noble gases in the infrared range has been exploited for two reasons: 1) collisional transfer from host helium is efficient, and 2) these laser transitions offer relatively high gain. However, scale-up to higher energies, via higher total pressures does not seem likely.

He-Hg laser (Ref. 17-18) represents the first NPL with visible output. Gain, however, has been reported on the 8446-Å oxygen transition in a He-Ne-O$_2$ mixture and has been observed at 350 nm in Ar-Xe-NF. Among other uses, output in this range appears most attractive for laser-fusion coupling.

In the next section we will review NPL studies reported to date in more detail. Prior reviews of nuclear pumping are contained in References 19-23.

REVIEW OF NPL EXPERIMENTS

After evolving slowly during its first decade, nuclear-pumped laser (NPL) research has progressed rapidly during the last four years. In this section we review the results of this research.

[†] The first unclassified NPL study known to the authors is by L. Herwig in 1964. (Ref. 13)

Nuclear Reactors Employed

Experiments have used two types of pulsed reactors: the pulsed *TRIGA* and *fast burst* reactors developed from the original Godiva at LASL. For future reference, characteristics of these reactors are summarized in Table 2.

The fast burst reactors provide roughly an order of magnitude higher peak flux (10^{17} neutrons/cm^2-sec) than the TRIGA. Also, narrower neutron pulse widths on the order of 0.1 msec are possible, as opposed to ~10 msec with the TRIGA. On the other hand, for cases where TRIGA fluxes are adequate, faster data acquisition is possible since ~20 pulses per 8-hour working day are easily obtainable as compared to ~4 for a fast burst facility. (Ref. 24,25) In these facilities, the time between pulses is governed by the time to cool the reactor and run appropriate tests of controls. Future reactors designed as laser drivers could have forced convection cooling to minimize the time between pulses or permit steady-state operation at lower flux levels.[†]

In addition to providing a maximum neutron flux[†], pulsed operation has the advantage of minimizing activation of the laser and its accessories. However, even the fast burst reactor has a very slow rise time compared to typical laser-state lifetimes. Thus, in contrast to pulsed discharges or electron beams, neutron-driven nuclear reactions provide quasi-CW laser excitation. There seems little prospect for obtaining a shorter rise time with fission reactors; this restricts NPLs to gases suitable for quasi-CW operation.

Experimental Arrangement

A typical experimental arrangement used with the University of Illinois TRIGA is shown in Fig. 3. Basically the laser tube (or optical resonator in gain measurements) is placed in a beam port next to the reactor. The laser output is directed through a hole in the beam-port plug (radiation shield) and into the detection equipment.

Experiments at Sandia, Aberdeen (NASA-Langley), and LASL use a similar arrangement with several important differences. First these reactors, being "fast" neutron reactors as opposed to the "thermal" TRIGA, do not employ a water moderator with the associated concrete shield. Consequently the reactor is "bare" and the laser assembly can be placed on a stand next to the core (Fig. 4). This provides easy access between reactor pulses. A polyethylene sleeve, 5 to 10 cm thick, is placed around the laser tube to moderate the impinging neutrons so that they are more effective in causing nuclear reactions. Shielding, effectively provided by the reactor building (or Kiva), is still necessary to protect the output detectors from nuclear radiation.

[†] For perspective, the TRIGA can produce steady-state fluxes $\lesssim 10^{13}$ n/cm^2-sec while the Advanced Test Reactor in Idaho, a special high flux design, can produce fluxes two orders of magnitude higher.

Several differences between these reactor experiments and typical bench-type studies should be noted. First, as already mentioned, the data acquisition rate is slow due to the slow pulse rate. Second, parts of the laser and its carriage are activated during the experiment so that manual adjustments must be done quickly or delayed for a day or more. Third, with the complicated arrangement of shielding and with the background noise induced in instrumentation by stray radiation, the measurements can be quite complex. Consequently these studies are typically quite slow compared to R&D on conventional lasers. This is not an absolute necessity, however. Considerable improvement could be envisioned if a dedicated NPL reactor facility were built. Much of the problem comes from superimposing NPL research on facilities originally designed for other purposes.

Electrical-Nuclear Hybrid Lasers

By superimposing nuclear radiation on an electrically pumped laser, the laser output can be enhanced. This hybrid technique was first used to produce significant enhancement of a molecular CO_2 laser. The increase in CO_2 laser power output was found to be much greater than the power input of the nuclear radiation. The mechanism believed to have caused this effect is the added radiation-induced ionization allowing the electron distribution to shift toward lower energies, thereby increasing the electrons' pumping efficiency (Ref. 28). This effect appears, then, to be quite analogous to the improved output obtained with electron-beam sustainer techniques. Similar hybrid techniques have been applied to He-Ne at 1.15μ (Ref. 29) and He-Hg at 0.615μ, (Ref. 17) and in both cases enhancement was observed.

Gain Measurements

Important information about the characteristics of particular NPL's can be obtained from gain measurements. In principle this can be done using a single-pass technique where a reference laser beam of known intensity is directed through the center of a test cavity containing the active medium. The ratio of beam intensities exiting and entering the cavity provides a measure of the single-pass gain. To obtain greater sensitivity while maintaining simplicity, a related multipass technique was developed at the University of Illinois. This technique requires a small chopping fan, mounted so as to provide alternate blocking and unblocking of the back mirror in an otherwise conventional laser oscillator cavity. The chopped output (see Fig. 5) can then provide a measure of gain. The absolute value of the unblocked to blocked ratio, alternately termed the *stimulated emission ratio*, can also be used to infer the actual gain in the laser medium as indicated in Fig. 6. Furthermore, as illustrated in Fig. 7, the chopped output can provide a definitive demonstration of oscillation.

Gain has been observed using the multipass method in a neutron-induced He-Ne-O_2 plasma at 0.8446μ. (Ref. 30) The mixture in this case contained ^{3}He which was used as a volume excitation source. The multipass technique has also been used to measure gain in He-Hg at 0.6150μ. (Ref. 17, 18) Both measurements were made at the University of Illinois. The He-Hg laser eventually oscillated using the higher flux available with the Sandia fast-burst reactor. (Ref. 17, 18) An important point to make here is that the gain measurements allowed an optimization of gas pressures (partial and total) in the more accessible TRIGA prior to the attempts at lasing at the fast burst facility.[†]

The multipass method has also been used to measure gain in He-Hg at 0.7945μ, (Ref. 32) He-CO at 0.9605μ and 1.0691μ, and most significantly in the XeF* excimer at 0.351μ. (Ref. 33) Single pass CW gain was also recently reported in He-Ne at 0.6328μ. (Ref. 34) The most extensive NPL single-pass gain measurements to date were made on the molecular CO laser at Sandia. (Ref. 35)

Oscillation

In this section the existing NPLs which have demonstrated oscillation are divided into two categories: a) those limited to surface sources and b) those utilizing He buffer gas, thereby making possible use of ^{3}He for volume excitation. An expanded listing of the NPLs indicated earlier in Table I is included in Table 3.

The first NPL to oscillate, the molecular CO laser at 5.1-5.6μ, used a ^{235}U surface source (Ref. 7). This laser operated at 77°K and 300°K at efficiencies of $\lesssim$1% and $\lesssim$0.03% respectively. The Ne-N_2 NPL at 0.9393 and 0.8629μ utilized a ^{10}B surface source. (Ref. 16) A TRIGA research reactor was able to meet this laser's relatively low threshold flux requirement of ~10^{15} n/cm^2-sec. The efficiency of the Ne-N_2 NPL appears to be low, only ~10^{-4}%. The other NPL that has reached the threshold of oscillation at the relatively low flux supplied by the TRIGA reactor is the neutral carbon laser at 1.45μ in He-CO, He-CO_2, Ne-CO and Ne-CO_2. (Ref. 36,37) Here the ^{10}B surface source produced oscillation with delays between the laser output and neutron pulse of 1 ms. The delay is thought to be significant since the long energy storage times that are implied are compatible with Q switching. The delay occurs in mixtures of Ne-CO, Ne-CO_2, He-CO_2 and He-N_2-CO, but not He-CO; it is attributed to a long-lived intermediate state that enters the mechanism through excited molecular CO.

He-Hg at .615μ, the only visible NPL achieved to date, used a ^{10}B surface source. (Ref. 18) Inversion occurs through a charge-exchange mechanism, and while this is an efficient process, the existence of alternate energy channels appears to result in a lower efficiency (~10^{-6}%) than for the noble gas lasers.

The main advantage of He buffer NPLs is the possibility of a ^{3}He volume source excitation. The first laser system to oscillate using He as a buffer, the He-Xe NPL at 3.508μ, was originally excited by the ^{235}U

[†] Extension of the stimulated emission ratio technique to fast burst reactor experiments appears possible but, due to the narrow reactor pulse, requires changing from the simple mechanical chopper to an electro-vibrator such as a piezoelectric driven mirror. Even if this were done, the pulse rate per day, noted earlier, would limit data acquisition.

surface source (Ref. 14) and subsequently oscillated with ^{3}He volume excitation. (Ref. 38) However, as is characteristic of most of the noble gas NPLs, the measured efficiency was of the order of 0.1% or less. NASA-Langley's research group demonstrated the first ^{3}He volume source NPL with ^{3}He -Ar at 1.79μ and 1.27μ. (Ref. 39) Other ^{3}He excited NPLs obtained by NASA-Langley are ^{3}He-Xe at 2.026μ, ^{3}He-Kr at 2.52 and 2.19μ, and ^{3}He-Cl at 1.587μ. (Ref. 40, 41) These results are especially significant in that they demonstrate high pressure operation with a volume source. For example, several kW/cm^3 has been deposited in ^{3}He-Ar mixtures at ~4 atm, giving laser outputs of order of 4 watts at 0.1% efficiency (Ref. 41).

While the neutral carbon NPLs at 1.45μ in mixtures of He-CO and He-CO_2 (Ref. 37) used a ^{10}B surface source, it appears that they could equally well employ ^{3}He.

Pumping Mechanisms-Plasma Kinetics

There are no detailed experimental studies of the kinetics involved in the NPLs reported in Table 3. Any discussion of mechanisms must therefore be speculative; however, suggested mechanisms for the various lasers are summarized in Table 4.

Several points should be made. With the exception of molecular CO where there appears to be an anomalously large direct energy transfer to vibrational levels via fission-fragment collisions, the mechanisms involved are similar to those that occur in corresponding electrical-discharge lasers. In fact, all of the NPL transitions observed to date can also be obtained electrically. (Still, in the case of Ne-N_2, the NPL was discovered by workers who were not initially aware of its electrical counterpart.) This observation should not be taken to imply that there are no differences or that NPLs don't have unique features. The fact is, with nuclear pumping, it is possible to produce excitation in large volumes at high pressures -- something that cannot easily be duplicated electrically. Thus, while oscillation on the 0.615μ line in He-Hg was obtained both with nuclear pumping and with a hollow cathode discharge in the same laser tube, the NPL operated up to 1 atm whereas an electrical discharge could not be obtained above 100 Torr (Ref. 17, 18). While other types of discharges, e.g. a TEA or an electron-beam pumped design, could extend the electrical case to higher pressures, they appear to be limited ultimately to smaller volumes than are possible with nuclear pumping. In other words, nuclear pumping represents a means of obtaining large volume ionization-excitation with a characteristic low electron temperature (due to the lack of electron fields), leading to a recombination-dominated plasma. Situations where this can be exploited appear uniquely suited to nuclear pumping.

Theoretically, nuclear pumping can be divided into three key steps:

1. Interaction of high-energy ions with the laser medium
2. Secondary-electron energy-spectrum and interactions
3. Reaction kinetics

Studies of 1 and 2 (Ref. 25), noted earlier in the introduction, suggest that secondary-electron collisions (as opposed to direct ion excitation) play a dominant role at the pressures involved ($\gtrsim 10$ Torr) in all cases except molecular CO.† Thus, the excitation mechanisms in these NPLs *are essentially independent of the type of ions* (e.g. an alpha from ^{10}B vs. a triton from ^3He) *involved and their precise energy*. The key parameter is simply the energy deposition per unit volume. (This is discussed in the next section.)

Simplified studies of the kinetics for several NPLs have been reported, but the most thorough study appears to be for the ^3He-Ar NPL reported by NASA-Langley (Ref. 41). Since this appears to be representative of the noble gas lasers, it is constructive to consider the model that evolved from their study.

The model indicates that nuclear lasing in ^3He-Ar at 1.79 μm is achieved primarily as a result of Penning ionization by $He(2^3S)$ metastables and charge transfer from He_2^+, followed by collisional-radiative recombination of Ar^+ and radiative cascading into the upper laser level. For Ar concentrations greater than 10%, formation of Ar_2^+ and Ar_2^* becomes an important loss mechanism for Ar^+, thus quenching the laser action. Also, dissociative recombination of Ar_2^+ preferentially populates the lower laser level, further destroying the population inversion. The modeled laser output as a function of Ar concentration in ^3He gives good agreement with the experimental results, lending credence to its validity.

Finally, a unique aspect of the Ne-N_2 laser should be noted. Experiments show that under some conditions the laser output depends on absorbed nitrogen on the surface of the boron coated tube. (Ref. 15) This is thought to involve atomic nitrogen production at the surface as nuclear particles break through from the boron coating. The process appears to be unusually efficient and could conceivably be exploited in some unique laser designs.

ENERGY DEPOSITION CONSIDERATIONS

Compared to electron-beam-driven lasers, NPLs have far lower peak-power deposition rates. Their advantage comes through the ability to excite large volumes of gases more efficiently and, for some applications, the ability to achieve long term steady-state operation.

Typical Deposition Rates

An indication of the capability of nuclear pumping can be obtained from some typical examples of energy and/or peak power deposition (Table 5).

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† *The importance of anomalously high energy-transfer to vibrational states in CO via fission-fragment collisions* (Ref. 35) *cannot be underestimated.* If this hypothesis holds up under future examination, both efficient and unique vibrational-type NPLs should be possible.

The cases cited all assume coupling to a fast burst nuclear reactor that provides a peak fast neutron flux of $\sim 10^{17}$ n/cm^2-sec with a pulse FWHM $\sim 10^{-4}$ sec. It is seen that experiments have already achieved depositions of the order of kWs per cm^3. The ^{235}U-coated plate design of Sandia Laboratories (Ref. 47,43), based on a straightforward extrapolation of their experimental laser design, provides deposition rates as high as 20 kW/cm^3 whereas Lorents, et al. (Ref. 6) envision advanced designs with ~90 kW/cm^3.

If steady-state operation is desired, these results can be scaled according to the neutron flux available. Operation at thermal fluxes of the order of 5×10^{15} n/cm^2-sec is feasible; consequently, a power deposition on the order of 1 kW/cm^3 seems reasonable to anticipate in eventual designs. Thus, to produce a MW laser output with a 1% efficient laser, a 100m^3 active volume is required.

Volume Sources

As noted earlier, three key nuclear reactions have been utilized for nuclear pumping:

$$^{3}\text{He} + n \rightarrow T + p + 0.76\ \text{MeV},$$

$$^{10}\text{B} + n \rightarrow {}^{7}\text{Li} + \alpha + 2.35\ \text{MeV, and}$$

$$^{235}\text{U} + n \rightarrow ff_h + ff_\ell + 165\ \text{MeV};$$

where the energies (Q) quoted are for charged particle release. (When non-fission producing neutron absorption in ^{235}U is accounted for, the energy per neutron absorbed is ~141 MeV vs. 165 MeV per fission.)

On the basis of charged-particle energy released per neutron absorbed, ^{235}U fission is about sixty times better than ^{10}B(n,α)^{7}Li, which is in turn about three times better than ^{3}He(n,p) T. However, additional factors must be considered to account for the fraction of this energy available to the laser medium, i.e., the energy release per unit laser volume. This will depend on the form of the source, i.e. surface vs. volume source, and on the density of the source material in a given case.

The energy release rate, or power per unit volume P_ϕ, is given by:

$$P_\phi = n\sigma\phi Q$$

where n is the number of target (e.g. U^{235}) nuclei per unit volume, σ is that isotope's thermal neutron cross section, ϕ is the thermal neutron flux, and Q is the charged-particle energy released per reaction. For volume sources of interest here, the density n can be written as

$$n = f_s \frac{P_T}{kT}$$

where P_T is the total gas pressure and f_s is the atomic fraction of the mixture represented by "source" material (such as U^{235}) capable of neutron-induced reactions. Thus

$$P_\phi = \frac{P_1}{kT} \phi \, (f_s \sigma Q)$$

The product σQ is specific to the source and, as indicated in Table 6, is easily evaluated. The picture becomes clouded when considering the remaining factor, f_s, however. Two new characteristics must now be considered: the maximum pressure allowed for practical operation and the maximum source concentration possible before source atoms interfere with the laser kinetics. These parameters will vary for each laser, and currently specific values are known only on a limited basis or not at all.

When f_s is considered ^{3}He becomes more competitive with UF_6. For some systems such as ^{3}He-CO or ^{3}He-CO_2, f_s for ^{3}He approaches one. In contrast, fluorescence studies by Lorents, et al. (Ref. 6) indicate a maximum f_s for UF_6 in XeF* of ~10%. In other lasers, for example noble gas systems, UF_6 simply cannot be used (f_s~0) due to the disastrous effect of electron scavenging by fluorine.

To provide some insight into relative values, the factor $f_s \sigma Q$ is evaluated in Table 6 for the three key volume sources -- ^{3}He, BF_3 (giving ^{10}B reactions), and UF_6 (giving ^{235}U reactions). In doing this, a rough estimate for f_s for XeF* has been made. As anticipated UF_6 gives the highest factor, leading to deposition rates of ~20kW/cm^3 at 5 atm in the peak flux of a fast burst reactor. ^{3}He offers about half of this power density. This is higher than might have been expected based on Q values alone, because of the larger neutron cross section compared to ^{235}U and because larger concentrations of ^{3}He can be incorporated into a XeF* laser. The relative position of BF_3 is strongly dependent on the allowed concentration. No data is available on this in the present case so f_s was somewhat arbitrarily assumed to be ~10% as suggested for UF_6.

Clearly the deposition rates of Table 6 only apply to the specific case of XeF*. As stressed earlier, UF_6 simply may not be compatible with some laser mixtures, ^{3}He may not suit others, and so on. Consequently f_s is a crucial variable in any evaluation of volume sources.†

Finally, it should be noted that UF_6 offers the unique possibility of achieving a critical mass, i.e. a unified laser-nuclear reactor. This *gaseous core-laser* concept is discussed further in a later section. Compared to externally driven NPLs, this approach appears quite difficult. Still, even a sub-critical UF_6-type laser would have the unique advantage of internal neutron production, making excitation of even larger volumes conceivable.

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† Note that in cases where source gases are not compatible with the laser mixture, nuclear pumping can still be considered if a coated plate or surface source is used. As shown by the coated plate design of Table 5, good energy deposition is also possible this way and large volumes can be achieved using arrays of thin plates. This introduces more structural problems than the volume source approach, however.

NPL SYSTEM EFFICIENCY CONSIDERATIONS

At this early stage, it is difficult to extrapolate NPL efficiencies to full-scale systems. However, from a comparison of component efficiencies it appears that a self-contained (energy source plus laser) NPL system should be more efficient than an equivalent electrical system. This argument is presented in the first part of this section, followed by a discussion of some measured efficiencies from NPL experiments.

Self Contained Laser System

As illustrated in Fig. 8, the overall efficiency of a self-contained NPL system can be viewed as the product of three component efficiencies, i.e.

$$\eta \equiv \eta_S \cdot \eta_C \cdot \eta_L$$

where η_S is the energy efficiency of the nuclear source for production of coupling "particles," generally neutrons; η_C is the coupling efficiency, e.g. the efficiency for converting neutrons to charged-particle energy directed into the laser medium; and η_L is the laser efficiency, defined as the energy emitted as coherent radiation divided by the charged-particle energy deposited in the medium.

For comparison, consider the analogous efficiency chain for an electrically-driven laser. Following Fig. 8, we have

$$\eta_E \equiv \eta_{LS} \cdot \eta_{EG} \cdot \eta_{EC} \cdot \eta_{EL}$$

where the subscript E has been added to signify the electrical case. The new component included here is the electrical generator efficiency η_{EG}. Since many experimental lasers "buy" electricity, the energy source and electrical generation components, corresponding to a utility-owned power station, are often not considered in efficiency analyses. This would be comparable to assuming in the NPL case that the reactor used to produce radiation is primarily intended for other purposes such as power production so that the neutrons diverted to the laser are "free" of any efficiency penalty. To avoid this confusion, it is best to think in terms of *dedicated or self-contained laser systems*. Components in one type of electrical laser might then consist of: a diesel-generator set for the energy source and electrical generation, high-voltage equipment along with an electron-beam diode plus beam entrance "window" for coupling, and finally the laser medium itself.

A numerical evaluation of the η's is strongly dependent on the specific components selected. However, a rough comparison of the self-contained NPL and electrical laser systems can be made on the following basis: assume that they are both able to employ the *same* laser medium so that, to first order, $\eta_L \sim \eta_{EL}$.

The product $\eta_S\eta_C$ for NPLs can be quite high. Sandia's conceptual scale-up of a CO laser driven by a fast-burst reactor delivers ~20% of the total nuclear energy in the plate-type laser-driver section, while drivers employing UF_6 could, in principle, deliver up to ~70%.

For the electrical case, the corresponding efficiency product is $\eta_{ES}\eta_{EC}\eta_{EC}$. For present electrical generators, $\eta_{ES}\eta_{EC} \lesssim 40\%$, while the coupling efficiency η_{EC} ranges from ~10-50% depending on pulse length, gas pressure and other factors. The product of these three efficiencies will be of the order of 12%, roughly half of that for the NPL. While this estimate involves many approximations, it appears that *in general the NPL can have a factor of 2 or 3 advantage in overall efficiency* compared to an electrical laser.

While we have stressed efficiencies thus far, it should be added that the system efficiency has impact only in terms of its ultimate effect on parameters such as system cost, size, and weight per unit-output. While these parameters generally vary in proportion to efficiency, their relative importance depends on the specific application involved. For example, although specific weight is crucial in most space applications, it is not very important for land-based systems.

Experimental and Projected NPL Efficiencies

NPL studies to date have been more strongly directed at the achievement of new lasers than at the optimization of laser efficiency. It is thus premature to discuss efficiencies with great precision.

Available data from experiments reported thus far are summarized in Table 7. The achievement of 1% efficiency in the CO NPL is perhaps the most notable result. Sandia workers feel that achievement of 10% efficiency should eventually be feasible with this system.

The measured efficiencies for the various lasers employing helium or neon collisional transfer are all 0.1% or less. Optimized efficiencies above .1% are not expected in these mixtures where, compared to CO, the maximum quantum efficiency is lower and parasitic (non-lasing) energy flow channels more numerous. He-Hg in particular appears to suffer from the parasitic channel problem.

Missing from Table 7 are various obvious candidates for high efficiency such as CO_2 and excimers. Attempts to pump CO_2 have not yet been successful; the reasons for this are still unknown, and the prospects for achieving a CO_2 NPL remain unclear. As described elsewhere, preliminary results indicate a gain on the XeF* excimer line with nuclear pumping, but whether this will ultimately lead to oscillation remains to be seen.

Equally crucial to future developments is the ability to achieve lasing with a UF_6 volume source in order to maximize the source coupling efficiency (η_C). If possible, this would in principle allow even better overall system efficiencies than those predicted (Ref. 42,43) for Sandia's type source array. However, as noted earlier, the problem with UF_6 is that the electron "scavenger" action of the fluorine seemingly limits the laser choices to a few special mixtures.

WAVELENGTH AVAILABILITY

To cover a variety of applications, it is desirable that NPLs be developed to span a broad range of wavelengths. As seen from Table 7 however, existing NPLs are mostly in the near infrared (IR) region. Only one laser (He-Hg) has been reported with visible output although gain has been achieved on the 0.63μ He-Ne line. Oscillation has not yet been achieved in the ultraviolet (UV), but the prospect for a XeF* excimer laser seems good since gain was recently observed on the 0.35μ line.

In the present section we continue the review of NPLs but now focus on specific lasers within each wavelength region.

Visible and Near IR NPLs

Most of today's NPL technology is confined to lasers within the visible and near IR regions. Fortunately some good high-power NPL candidates exist within this group. For instance, as described in a later section, the conceptual design of a 2.1-MJ molecular CO NPL utilizing a SPR III reactor has been reported. This system is unique in that the laser-driver system occupies only 6 m^3. Another concept would use the CO NPL in a gas-dynamic configuration with a special reactor section to produce > 100 MJ pulses or multi-MW output.

Visible NPLs are the fewest in number of current NPL systems. The only visible oscillator yet achieved is the He-Hg laser at 0.6150μ (Ref. 17, 18). This laser required a relatively high flux of $\sim 10^{16}$ n/cm^2-sec. It is capable of CW oscillation and it has a theoretical quantum efficiency of ~8%. A ^{10}B surface source was used in the experiments although use of a ^3He buffer seems possible and attractive.

Gain has been demonstrated in He-Ne mixtures at 0.6328μ using quite low fluxes (Ref. 34). Although this system holds little possibility for a high power NPL, it may provide important insight into the kinetics involved in CW NPL operation.

The molecular CO NPL at 5.1 to 5.6μ represents, from the point of view of extrapolation to high power and efficiency, one of the most important NPLs (Ref. 7). The experimental laser used a ^{235}U surface source as a means of excitation, and substitution of volume source-gases does not appear practical. A serious problem associated with the molecular CO NPL is that the laser medium must be cooled (<77°K) in order to obtain ≥1% efficiencies, making high repetition rates difficult if not impossible.

Another NPL which has demonstrated good potential for high power operation is the ^3He-Ar laser at 1.79μ. (Ref. 39, 41) This laser has operated at pressures of 5 atm with 0.1% efficiency. This is an important result in that it demonstrates the potential for high-pressure operation with a volume source such as ^{3}He.

Other NPLs in the near IR range which have demonstrated operation with a volume source include: ^{3}He-Xe @ 2.027 (~1 atm), ^{3}He-Kr @ 2.5μ (~1 atm), ^{3}He-Cl @ 1.58μ (~0.5 atm), and ^{3}He-Xe @ 3.508μ (~0.5 atm). (Ref. 40, 41)

Energy storage has been observed in the He-neutral carbon and Ne-neutral carbon NPLs (Ref. 36,37) at thermal fluxes of $\lesssim 1\times10^{15}$ n/cm^2-sec. These lasers operated with a ^{10}B surface source at 1.2 atm. Since the centerline excitation density falls off at ~1 atm with this source, it is possible that operation at much higher pressures would be possible with the volume source ^{3}He. The energy storage phenomenon in these lasers appears to be very important for certain applications such as laser-fusion.

Ultraviolet NPLs

Extension into the UV range is an important goal for NPL research. If, for example, an excimer laser such as XeF* can be achieved, the potential for scale-up to a relatively efficient high-power laser seems good. One reason is that, as is discussed later, XeF* appears compatible with a UF_6 volume source which in turn promises good energy deposition rates.

While it is known that several groups have tried nuclear pumping of XeF*, no definitive results have yet been published. Recent gain measurements at the University of Illinois appear quite promising, however. These experiments employed the cavity chopping technique described earlier, and a ^{10}B-coated tube for pumping. Unblocked to blocked ratios of ~10 were observed in XeF* using mixtures of $Ar/Xe/NF_3$, $Ne/Xe/NF_3$ and Xe/NF_3. Maximum ratios were obtained in $Ar/Xe/NF_3$ mixtures in the ratio of 600:3:1 at a total pressure of 350 Torr. Neutron fluxes over 5×10^{13} n/cm^2-sec were necessary. High ratios were observed for periods up to 50 msec, corresponding to the longest neutron pulse available. This suggests that CW operation should be possible.

LARGE-SCALE SYSTEM DESIGN STUDIES

MeV ions from nuclear reactions provide the excitation for NPLs. One possible source is the natural α-decay of radioactive isotopes such as Po-210 (5-MeV alpha emitter). A Po-210-coated laser tube can be envisioned, but the low flux of α-particles possible is a drawback. One might be able to excite a low-threshold laser such as He-Ne, but such a design would be limited to low-power output.

Neutron-driven nuclear reactions offer a more attractive method of meeting the energy-density requirements for high power NPLs. The most obvious neutron sources are fission and fusion reactors. Other ways of obtaining neutrons include the natural decay of radioisotopes (e.g. californium), Be-Po reactions, or high-energy ion-photon bombardment of appropriate targets. These latter methods are complicated, expensive and yield only marginal fluxes. Thus, they are ruled out as practical NPL neutron sources.

Fusion reactors, once developed, could serve as attractive neutron sources. In fact, some existing experimental devices such as the plasma focus offer very intense pulses of neutrons. For *near-term* applications, however, *a fission reactor appears to be the most logical approach for high-power applications.*

While the added complication of building a reactor to pump a laser may appear to be a major complication, it must be remembered that any high-powered laser requires a high power and/or large energy source. Viewed in this way, the nuclear reactor is not too different from other alternative power supplies. The added complications of radioactivity and shielding must be weighed against the unique advantages of an NPL system for the specific application involved. For example, if a reliable self-contained power source is required, as in the case of remote power stations and space applications, a reactor-NPL system could be especially attractive. (Ref. 23,46,47) Another unique situation involves laser-induced fusion. There, because much of the fusion energy released is in the form of neutrons, neutron-driven nuclear reactions may be especially attractive for powering the laser in a feedback fashion. (Ref. 1,48-52)

Due to the newness of NPL research, the scale-up to high power has not yet been considered in great detail. However, some initial conceptual studies have been reported that can provide an indication of some of the unique capabilities of the NPL. It must be stressed, however, that such studies are very preliminary so that: a) questions about feasibility remain open and b) the designs are far from optimized.

Near-Term Fission Reactor Systems

Experimental lasers to date have simply used small, single laser cells. Consequently, they have only intercepted a small fraction of the total neutrons available from the reactor. It seems quite feasible, however, to design a relatively large-volume laser system that would efficiently utilize neutrons from a fast-burst reactor of the type noted earlier. These reactors (Ref. 25) typically consists of a uranium-alloy core in the form of a right cylinder of only 30-cm radius and height. They are capable of delivering 6 to 14 MJ in pulses lasting 100 to 200 μsec. Being pulsed, they do not require a steady-state cooling system. Thus, the laser medium can conveniently be placed around the entire core, providing a large volume filled with an intense flux of fast neutrons.

Sandia researchers (Ref. 42,43) have considered a possible NPL system, illustrated in Fig. 9, where the fast-burst reactor is used as a primary neutron source. Neutrons from the reactor enter a surrounding subcritical uranium region which, in turn, produces fission fragments that escape into and excite the laser gas. The subcritical (laser "driver") region consists of laminated plates having a thin (~3 micron thickness) coating of uranium metal on neutron-moderator slabs of ~0.2-cm thickness (Fig. 10). These

These slabs thermalize the neutrons to provide a better interaction with the uranium; they also serve as a heat sink and provide structural strength for the uranium. The thickness of the uranium coating is determined by the range of fission fragments (10 microns in uranium). With the design suggested, roughly 1/4 of the fission fragments escape from the surface. Half are born with velocities in the improper direction and thus are lost. Those emitted in the proper direction lose about half of their energy as they traverse the coating. Consequently, since about 80% of the fission energy goes into charged particles, about one fifth of the energy produced by fission in the uranium subcritical region is deposited in the laser medium.

The difference between the two designs in Fig. 9 involves the way that the subcritical excitation region is coupled to the laser cavity. If metastable states having sufficient lifetime are involved in the laser mechanism, it may be possible to pass gas through the subcritical region as indicated in Fig. 9a and then flow it into the laser cavity. This design has the advantages of removing the laser cavity from the radiation field and providing good cooling. However, excessive flow rates would be required except for only a few media that have quite long-lived metastable states.

To avoid the need for high flow rates, the design in Fig. 9b uses a cavity which is directly superimposed on the subcritical region. In this case, flow along the cavity axis is employed using tubes with a uranium coating and construction similar to the plate design. Performance estimates for four such systems are summarized in Table 9 where a molecular CO laser, similar to those used in experiments at Sandia is assumed. Based on coupling with Sandia's SPR-III fast burst reactor,* it is estimated that in one system 21 MJ could be deposited in the subcritical region, resulting in an ultimate 2.1 MJ laser. Due to the high efficiency for energy transfer to vibrational states in CO by direct fission fragment interaction, it is anticipated that over 50% of the energy deposited in the gas can be extracted as coherent light. Since ~20% of the energy released in the driver enters the gas, an efficiency of ~10% for the driver-laser is possible. (Since an additional 1 to 3 times the driver energy is produced in the SPR III core, the system efficiency is ~3.5%.) The relatively small size of this system is an important aspect of NPLs. Thus, the 2-MJ laser-driver system only occupies ~$6m^3$ while the overall unit (including the reactor) is approximately double this size.

The pulse repetition rate of such a system would be set by cooling requirements for the SPR-III core. Without forced-convection cooling, i.e. as shown in Fig. 9, approximately an hour is required between pulses. [Special designs might eventually reduce this time to minutes as illustrated by repetitive pulse experiments using a TRIGA reactor. (Ref. 44)] This should be adequate for near-term applications, and it offers the advantage that flow cooling of the laser would not be needed either. For the cases in Table 9, for example, the mean temperature rise of the driver section would only be 4-5°K although the peak (adiabatic) temperature in the uranium foil

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*This reactor will produce a burst of 13MJ, about twice that of the SPR II reactor described earlier.

itself could approach 800°K.

An important aspect of this concept is that near term development seems quite feasible. The basic reactor core uses existing technology. The subcritical driver system requires some new metallurgical techniques to assure good plating and proper moderator characteristics, but this seems relatively straightforward and similar uranium films have already been used in experimental laser studies. The CO laser-driver is based on earlier laser experiments at Sandia, and the tubular design of Fig. 9b is essentially a replica of the experimental device but with multiple tubes.

While these concepts employ uranium coated tubes, the same basic arrangement could easily be extended to a volume source. However, to take advantage of *existing* NPL laser technology, it would be necessary to use ^{3}He with the noble gas. As NPL research progresses, however, more attractive mixtures such as $Ar/Xe/F_2/UF_6$ can be envisioned.

Thus it appears that, using technology at hand, it should be possible to design and build a pulsed NPL capable of delivering $\gtrsim$ 1 MJ/pulse. Further, the system would be self-contained and sufficiently compact for use in satellites or remote sensing stations.

Advanced Fission-Driven NPLs

There are two possible routes to even higher energy NPLs, namely: 1) replace the SPR reactor used in previous examples with yet larger special-purpose reactors capable of driving larger NPL volumes, or 2) combine the reactor and laser-driver, i.e. design a critical NPL driver. Since the latter potentially offers the most unique performance, we will consider several examples here.

If plate-type driver units are to be employed at higher pulse repetition rates, or in a steady-state mode, cooling becomes a crucial problem. Consequently, a gas-dynamic laser represents an obvious approach; a conceptual design suggested by Sandia workers (Ref. 45) is shown in Fig. 11. The driver region, shown in more detail in Fig. 12, employs a laminate structure similar to that proposed for the SPR driver. However, sufficient plates are provided here to create a critical reactor which, depending on the design desired, could either be pulsed or operated in a steady-state mode. Also, the plates are shaped to provide proper flow and an expansion nozzle region. Except for the nuclear reactor, the system is identical to a conventional closed-cycle gas-dynamic laser, i.e. the reactor region simply replaces the conventional electric excitation region. Sandia investigators estimate that the operating conditions of Table 10 might be achievable with a CO laser. Quasi steady-state laser powers of ~60 MW are anticipated; thus with a 2.5 sec pulse ~150 MJ could be delivered.

Compared to the previous SPR design, this concept is much more speculative. A few of the difficulties to be faced are possible damage to the plate structure, due to temperature shocks combined with the high-speed flow; inhomogeneity effects in the laser cavity, due to turbulence; and the complication of fission product contamination throughout the flow system.

Perhaps the "ultimate" NPL system would be one in which the fission process takes place directly in the laser medium. With ~80% of the nuclear energy (~165 MeV/fission) carried by fission fragments, this would efficiently deposit large amounts of energy throughout the laser volume. Consider, for example, a UF_6-seeded laser driver coupled to a SPR-III reactor as assumed earlier in Fig. 9. For ambient temperature operation (UF_6 vapor pressure ~112 Torr), Fig. 13 (Ref. 6) indicates an energy deposition of ~7 kJ/liter. Then, assuming dimensions as in case 4 of Table 9, an energy deposition of 1 MJ per pulse could be achieved. Even larger energy depositions are possible with higher UF_6 pressures. Thus, with UF_6 at ~3 atm (at 350°K---see Fig. 14), a deposition equivalent to case 4 of Table 9 is obtained.

With UF_6 as the driver, it becomes feasible to consider a critical reactor. Indeed, NASA has had an active program aimed at the development of a UF_6-fueled gaseous-core reactor. (Ref. 46) The distinctive feature of such a reactor is that the fuel is contained in a "cavity" surrounded by a thick moderator-reflector (consequently, the name "cavity reactor" is sometimes used). 2-MeV fission neutrons easily traverse the low-pressure gaseous-core region, are thermalized in the surrounding moderator, and are efficiently returned to the core to cause thermal fission. This provides operation with a modest critical mass despite the relatively low density of the uranium core. The range of operating conditions projected for the NASA experiments (~0.5-m^3 cavity volume with 48-cm thick beryllium reflector) is indicated in Fig. 14. With a critical mass of ~14-kg ^{235}U, static gas experiments at ~400°K are planned with power levels up to 1 kW. (Such designs are most suitable for steady-state operation although a modified pulsed version is conceivable.) Then, by flowing the UF_6, the power level can be increased to 10 kW. Finally, by increasing temperatures to 1500°K, powers to 100 kW are envisioned. These experiments, planned over a 5-year period, are intended to prove the feasibility of UF_6 reactors. Once completed, yet larger volume UF_6 systems in the multi-MW range are envisioned, or alternately a transition to higher temperature (~5000°K) gaseous-uranium cores similar to those studied for nuclear rocket propulsion could be undertaken. If, in these examples, even a few percent of the output power could be converted to laser output, an important class of self-contained multi-kW lasers would be possible. The remainder of the reactor power could still be used for other purposes, e.g. electrical production.

The potential for using a gaseous reactor as an NPL has been recognized by NASA workers, (Ref. 46,47) and concurrent research on this is in progress. A key unanswered question at this time is whether UF_6 (or, alternately, pure U) itself will lase under nuclear pumping, or if a mixture with another lasing gas will work. No definitive information is available on UF_6 lasing, but some encouraging measurements of gain in XeF*, which is compatible with UF_6 were noted earlier.

A crucial consideration is the absorption cross section of UF_6. As shown in Fig. 15, lasing at wavelengths >400 nm is attractive since the absorption is small in this region out to the infrared. Also, as Lorents, et al. (Ref. 6) point out, the window at ~340 nm closely matches important I_2 and XeF* transitions.

To investigate the possibility of a XeF*-UF_6 laser, Lorents et al. (Ref. 6) measured e-beam induced fluorescence of XeF* from mixtures of Ar/Xe/F_2 with various amounts of UF_6 added. With 760 Torr Ar, 40 Torr Xe, and 4 Torr F_2, no change in XeF* intensity occurred with 4 Torr UF_6 added and the intensity only fell by one-third with 50 Torr added. Measurements at NASA-Langley (Ref. 41) with an electrical laser employing Xe-UF_6 confirm that laser action is unaffected by UF_6 concentrations up to 5%. Earlier measurements (Ref. 47) of emission intensities from N_2 (337 and 357 nm) and Ar (695 to 772 nm) in UF_6 mixtures show strong quenching of the N_2 lines while several Ar-lines (750 and 772 nm) are only quenched at >10% UF_6. Based on these various data, the possibility of finding a UF_6 mixture that lases seems quite promising. It is less certain, however, that sufficient UF_6 concentration (probably >10%) can be achieved to attain a high energy density during neutron bombardment, or to allow a critical mass of uranium for cavity reactor operation.

Laser-Fusion NPL

Neutrons from a laser-driven D-T pellet microexplosion can, in principle, be employed to pump an NPL. Output from the NPL could drive the next pellet implosion in a feedback fashion. Such an approach would avoid the inefficient external energy conversion and storage equipment required with a conventional electrically pumped laser. Consequently, an NPL-driven feedback fusion system could be quite attractive. However a number of fundamental problems must be tackled before the feasibility of this approach can be ascertained. Key problems include the development of adequate energy storage and pulse shaping techniques for the NPL.

Several preliminary concept design studies have been carried out to evaluate the attractiveness of NPL feedback fusion. (Ref. 48-52) A conceptual feedback fusion reactor is shown in Fig. 16. Most of this effort has been directed at the development of designs with optimum neutron economy. Requirements for tritium breeding and restrictions imposed by material damage combined with neutron threshold levels required for lasing, place severe strains on neutron economy. Results thus far seem encouraging.

CONCLUSION

Strong interest in nuclear-pumped lasers continues due to their two unique characteristics: 1) the energy from neutron-driven nuclear reactions is generated locally (i.e. volume source) rather than being transported from one electrode to another, making it possible to pump very large volumes; and 2) this nuclear energy is then directly converted to light energy, so that the system efficiency is the same as the laser efficiency. These characteristics result in three major potential advantages for NPLs: 1) direct scaling to the MJ level, 2) compactness of the total laser / power source system, and 3) high system efficiency.

Although NPL experiments are somewhat difficult, compared to measurements on electrically pumped lasers, significant progress has been made in recent years. While NPLs are far from optimized, they have reached the point where scaling to a 1 MJ laser is possible with *existing* technology.

The focus of NPL research has shifted from proof-of-principle experiments to the development of volume-source NPLs for applications. This development effort is being guided by the several large-scale systems studies recently performed.

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TABLE 1

Summary of NPL's Achieved to Date

Laser	Wavelength	Peak Laser Power[†]
He-Hg	0.615μ	~1 mW
CO	5.1-5.6μ	≈100 W
He-Ar; Kr; Xe; Cl	1.3μ to 3.5μ	≤4 W
Ne-N_2, CO; CO_2 He-CO; CO_2	0.8μ to 1.5μ	≲2 mW

[†] Powers indicated are for small experimental devices, typically of order of 0.1-liter volume. As indicated in the text, the scale-up to higher powers by employing larger volumes and a multiplicity of cells seems quite feasible.

TABLE 2

Characteristics of Reactors Used for NPL Studies

	TRIGA	Fast Burst
type reactor	thermal	fast
core materials	^{235}U, ZrH	^{235}U alloy
pulse FWHM	≲ 10 msec	≲100 μsec[†]
peak neutron flux	~5×10^{15} n/cm^2-sec	~10^{17} n/cm^2-sec[†]
energy/pulse	30 MW-sec	~3 MW-sec
pulse rate	~20 per 8 hour day	~4 per 8 hour day

[†] Effective thermal flux *after* thermalization in a typical moderator surrounding the laser tube. Unmoderated fast neutron fluxes are an order of magnitude higher and have a FWHM ~half of that indicated.

TABLE 3

Nuclear-Pumped Lasers

NPL	Pumping Reaction	Wavelength (μm)	Thermal threshold flux (n/cm^2-sec)	Estimated Efficiency (%)	Research Group	Ref.
CO	^{235}U(n,F)FF	5.1-5.6	$\sim 5 \times 10^{16}$	≥ 1	Sandia Labs	7
He-Xe	^{235}U(n,F)FF	3.5	$\sim 3 \times 10^{15}$	~.01	LASL & U of Fla	14,38
Ne-N_2	^{10}B(n,α)^{7}Li	.93936.8629	$\sim 1 \times 10^{15}$	$\sim 3 \times 10^{-5}$	U of Ill	16
Ne-CO, Ne-CO_2	^{10}B(n,α)^{7}Li	1.45	$\sim 1 \times 10^{15}$	$\sim 10^{-4}$	U of Ill	36
He-CO, He-CO_2	^{10}B(n,α)^{7}Li	1.45	$\sim 2 \times 10^{14}$	$\sim 10^{-4}$	U of Ill	37
^{3}He-Ar	^{3}He(n,p)T	1.79 & 1.27	$\sim 1 \times 10^{16}$	~0.1	NASA Langley	39,41
^{3}He-Xe	^{3}He(n,p)T	2.026	$\sim 4 \times 10^{15}$	$\gtrsim 0.1$	NASA Langley	40,41
He-Hg	^{10}B(n,α)^{7}Li	.615	$\sim 1 \times 10^{16}$	$\sim 10^{-6}$	U of Ill & Sandia	18
^{3}He-Kr	^{3}He(n,p)T	2.52 & 2.19	$\sim 5 \times 10^{16}$	$\gtrsim 0.1$	NASA Langley	40,41
^{3}He-Cl	^{3}He(n,p)T	1.587	$\sim 5 \times 10^{16}$	$\gtrsim 0.1$	NASA Langley	41

TABLE 4

Pumping Mechanisms in NPLs

Laser	Suggested Mechanism
CO	Energy transfer to vibrational states involving both secondary electron and fission fragment collisions.
He-Hg'	Charge-exchange starting with He^+
$Ne-N_2$	Recombination; surface formation of atomic nitrogen involved.
He-noble gases He-CO etc.	Recombination dominated with possible contribution from direct electron excitation. Intermediate vibrational states involved in the neutral carbon systems.

TABLE 5

Typical Peak Deposition Rates For ^{3}He and ^{235}U Sources Coupled to a Fast Burst Reactor

Situation	Peak Power Deposition, kW/cm^{3}	Ref.
^{3}He-Ar Laser Experiment at 4 atm Volume Source	~1 kW/cm^{3}	41
Conceptual reactor design, CO at $\lesssim$1 atm, U-coated plates Surface Source	~20 kW/cm^{3} (~2 kJ/ℓ per pulse)	42,43
Conceptual mixture with 350 Torr ^{235}U Volume Source	~90 kW/cm^{3} (~9 kJ/ℓ per pulse)	6

TABLE 6

Comparison of Three Major Volume Sources

	^{3}He	BF$_{3}$	UF$_{6}$
Charged Particle Energy Release, Q (MeV)	.76	2.35	165
Neutron cross section, σ(barns)	5330	3840	577
Max source gas fraction, f_s, for XeF* (%)	~99	~10*	$\gtrsim$10^{+}
Relative $f_s \sigma Q$	0.4	0.1	1.0
Power density, P_ϕ (kW/cm^{3}; 5 atm at 10^{17} n/cm^{2}-sec)	~8	~2	~20

*No data available for BF$_{3}$; assumed equivalent to UF$_{6}$.

+Estimate based on measurements in operating electrical lasers.

TABLE 7

NPL Efficiency Data

Laser	Laser Efficiency, η_L, %		Theoretical Quantum Efficiency, %
	Experimental	Projected	
CO	$\gtrsim 1$	~10	17-50[†]
He-Xe; Ar; Kr, Cl	$\gtrsim 0.1$	~1	3-4
Ne-N_2; CO; CO_2 He-CO; CO_2	~10^{-4}	~1	3-6
He-Hg	~10^{-6}	~0.1	8

[†] Efficiency over the 5.1μ-5.6μ wavelength band is 50%; efficiency in the 5.1μ line is 17%.

TABLE 8

Wavelengths of Available NPLs*

Wavelength Range	Oscillation Reported	Gain Reported
UV(<0.4μ)	—	Xe-NF_3; Ne-Xe-NF_3; Ar-Xe-NF_3 (0.35μ)
Visible (0.4μ to 0.7μ)	He-Hg (0.62μ)	^{3}He-Ne (0.63μ)
near IR (0.7μ to 3μ)	Ne-N_2 (0.86μ; 0.94μ) Ne/He-CO/CO_2 (1.45μ) ^{3}He-Ar/Cl/Xe/Kr (1.27μ-2.42μ)	He-Hg (0.79μ) He-Ne-O_2 (0.85μ) He-CO (0.94μ; 1.07μ)
(> 3μ)	He-Xe (3.5μ) CO (5.1 - 5.6μ)	CO (5.1-5.6μ)

*Further details and references given in Table 3.

TABLE 9

Typical CO-Laser, Driver Characteristics*
(From Ref, 42)

	DRIVER DIMENSIONS			REFLECTOR GRAPHITE	FUEL
Case	Inside Radius (cm)	Outside Radius (cm)	Height (cm)	Thickness (cm)	Concentration 10^{19} atoms/cm^3
1	30	85	150	--	5.36
2	30	85	150	40	1.34
3	30	85	150	40	5.36
4	30	130	150	40	5.36

Case	Laser Driver (LD) Volume (ℓ)	E_{LD} (MJ)	E_{GAS} (MJ)	E_{LASER} (MJ)	Gas Energy Density (kJ/ℓ)	Average Output Energy Density (J/cm^2)
1	2980	4.81	0.962	0.481	.82	40.0
2	2980	7.69	1.54	0.769	1.32	63.9
3	2980	11.75	2.35	1.17	2.01	97.2
4	6362	21.04	4.21	2.10	1.68	81.7

*Based on a reactor burst energy of 13 MJ with pulse duration ~100 μsec.

TABLE 10

Typical Operating Conditions CO Gas-Dynamic NPL (Ref. 45)

LASER POWER	~60 MW
E (GAS)	~600 J/LITER ATM
FLOW LENGTH	~1 METER
FLOW TIME	~23 MS
ΔT REACTOR	~360°K

TABLE II

Charged Particle Energy Release

As Fraction Of Total Energy Release

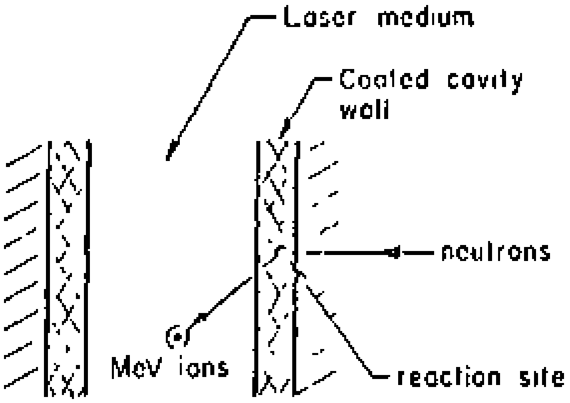
For Nuclear Pumped Laser/Reactor Combinations

Laser Excitation Source		Fraction of Total Energy Released as Charged Particles(1)
$^3He(n,p)T$	Volume	.004(2)
$^{10}B(n,\alpha)^7Li$	Surface	.003(2)
	Volume	.012(2)
^{235}U Fission	Surface	.17(3)
	Volume	.68(3)

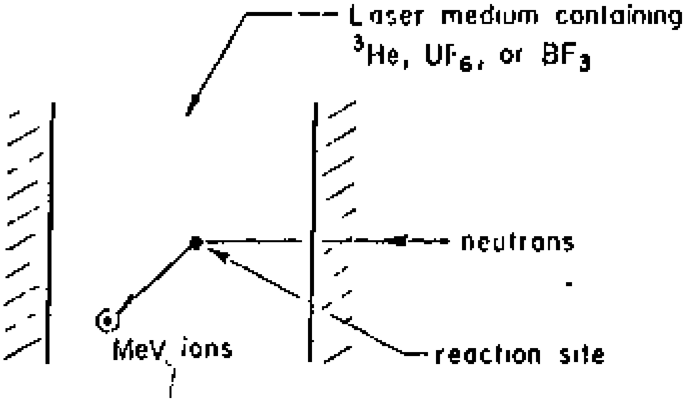
(1) Neutrino energy has been neglected in calculating total energy since it escapes the system and is not thermalized.

(2) One pumping reaction is assumed for each fission in the neutron source. This is equivalent to a breeding ratio of 1.0 in a fast breeder reactor.

(3) 80% of all fission reactions are assumed to occur within the sub-critical laser volume, with remaining fissions occurring in control regions.



A Coated tube design



B Volume source design

Figure 1. Illustration of types of NPLS.

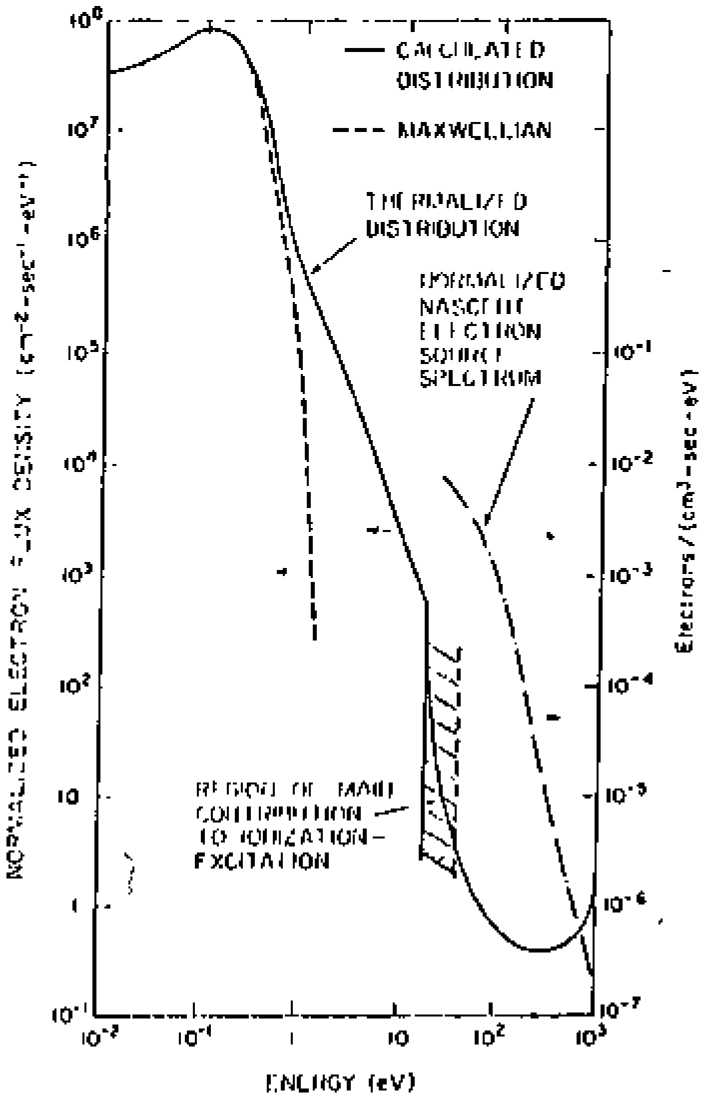


Figure 2. Nascent and asymptotic electron energy distributions for 1-MeV alpha-particle bombardment of helium (from Refs. 2 and 4).

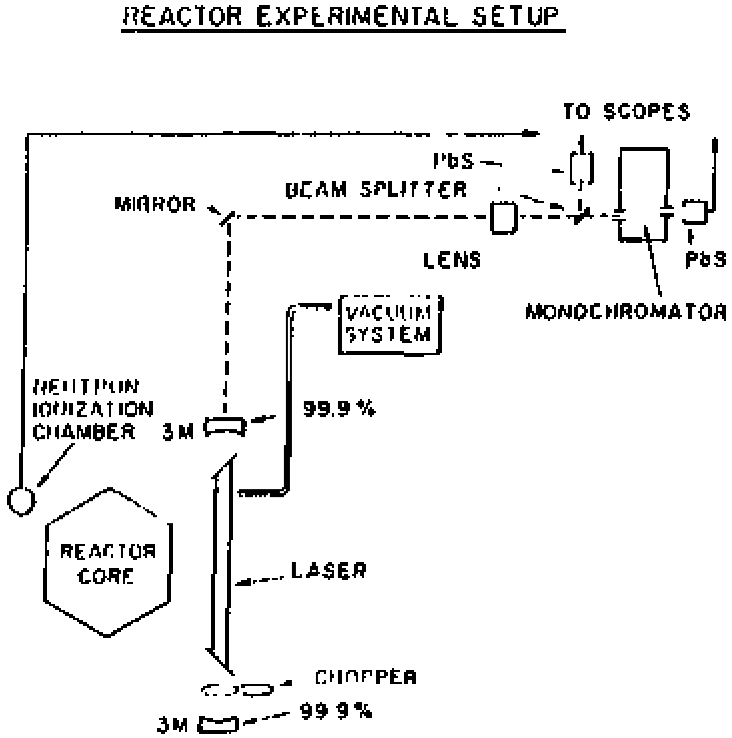


Figure 3. Experimental arrangement for the He-CO$_2$ NPL in the U. of Illinois TRIGA reactor.

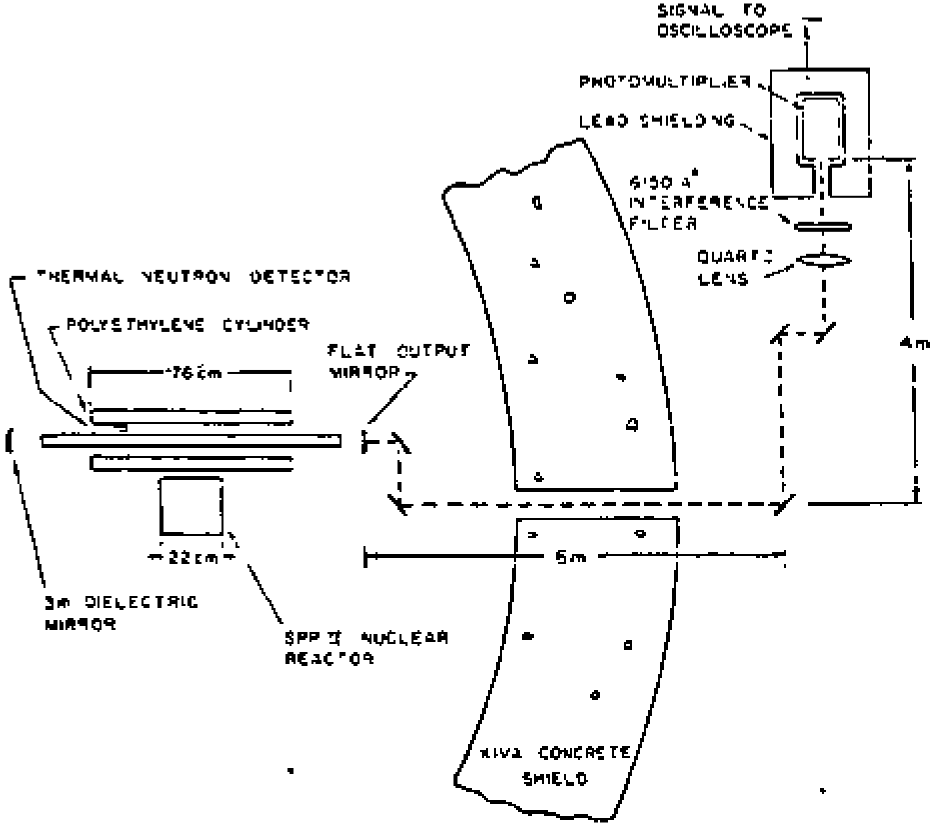


Figure 4. Typical experimental set-up at a fast burst reactor.

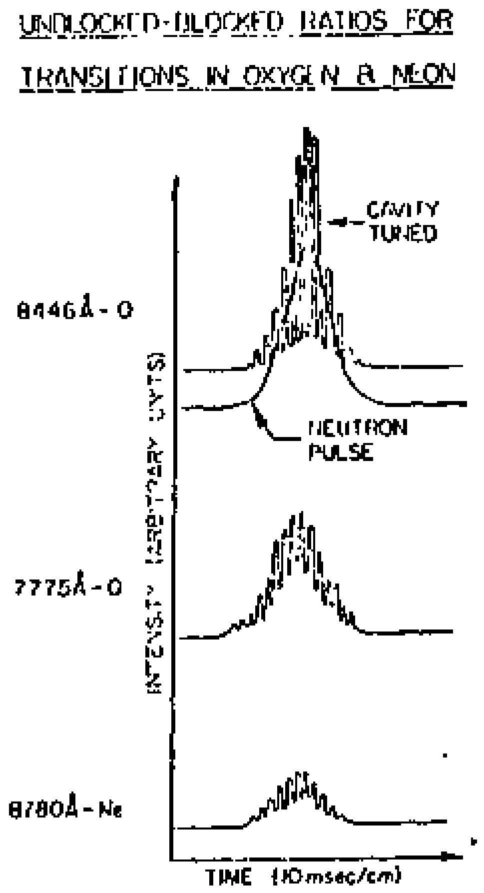


Figure 5. Stimulated emission ratio gain measurements for He-Ne-O_2. The large ratios recorded at 8445 Å indicates gain in atomic oxygen. As a check on the methods, ratios were measured for other lines lying within the reflectivity range of the cavity but not expected to be inverted. In these cases, ratios corresponding to background spontaneous emission were observed.

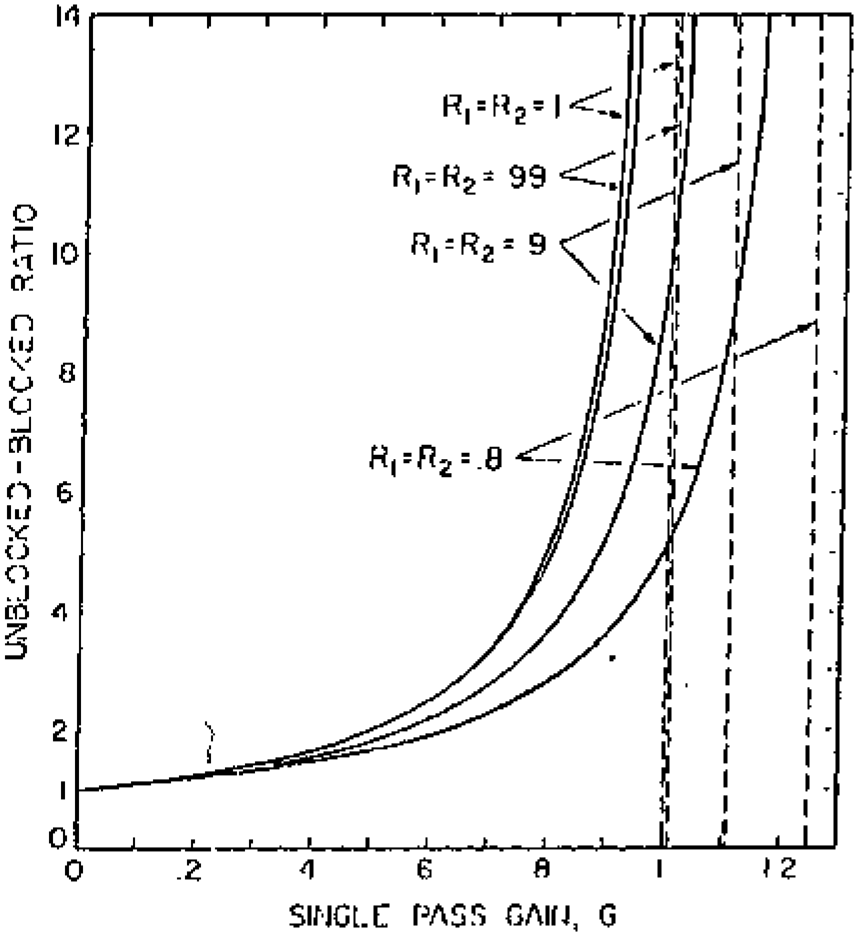


Figure 6. Unblocked-blocked ratio vs. single pass gain for various cavity-mirror reflectivities, R_1 and R_2. The curves shown are based on calculations employing a ray-tracing technique.

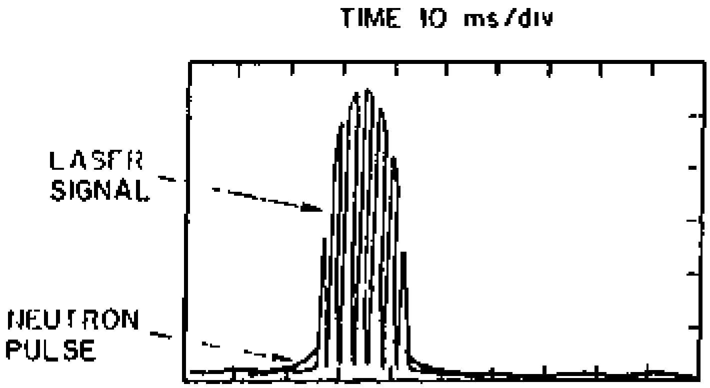
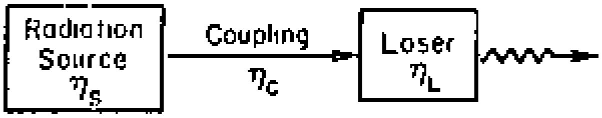
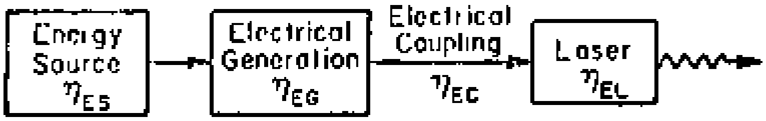


Figure 7. Typical oscilloscope traces for $He-CO_2$ NPL. The optical signals are interrupted by a chopping fan placed in the cavity.



A) Nuclear pumped laser efficiency components



B) Electrically-driven laser efficiency components

Figure 8. Energy flows in self-contained laser system.

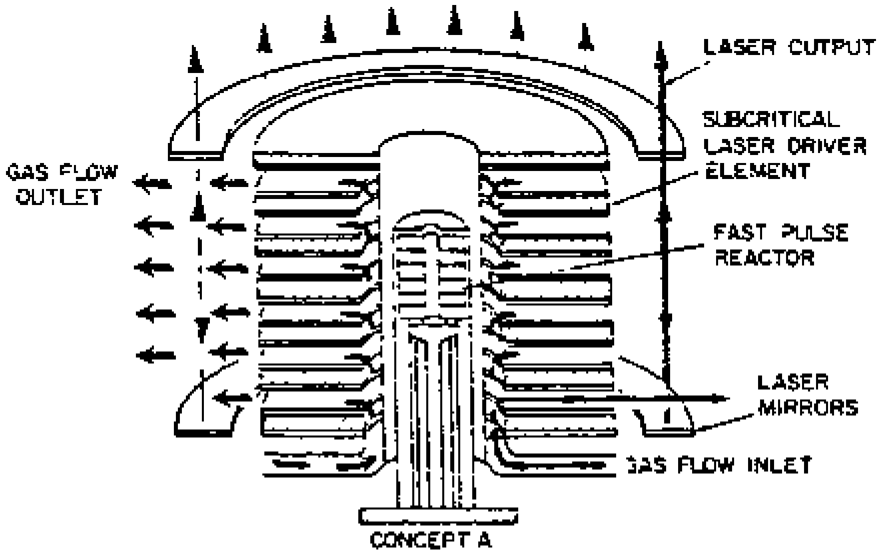


Figure 9a. Conceptual design where the excitation volume and laser cavity are separated, requiring long-lived laser states and high flow rates for coupling a NPL driver to Sandia's SPR-III reactor (after Schmidt and McArthur, Ref. 45).

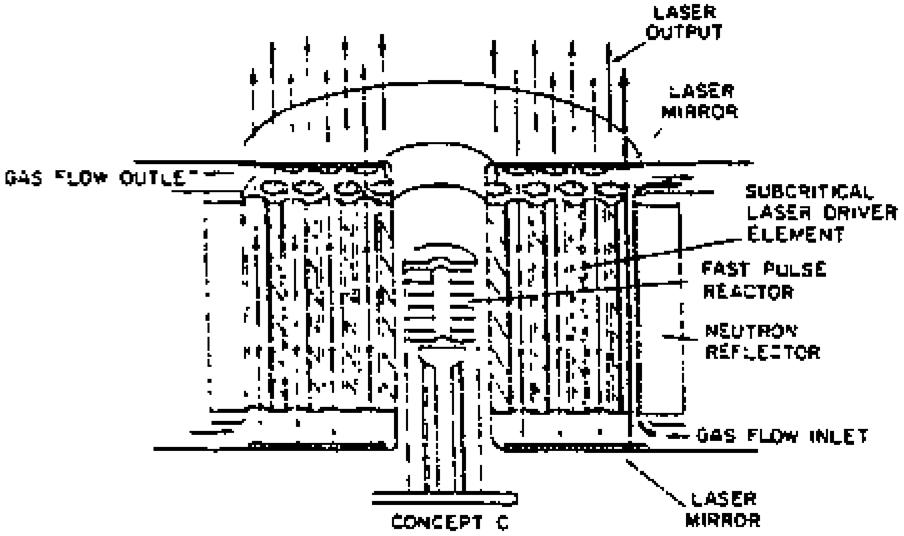


Figure 9b. Conceptual design for a combined excitation-laser region. Here gas-flow rates can be slow, depending only on cooling and gas renewal requirements for coupling a NPL driver to Sandia's SPR-III reactor (after Schmidt and McArthur, Ref. 43).

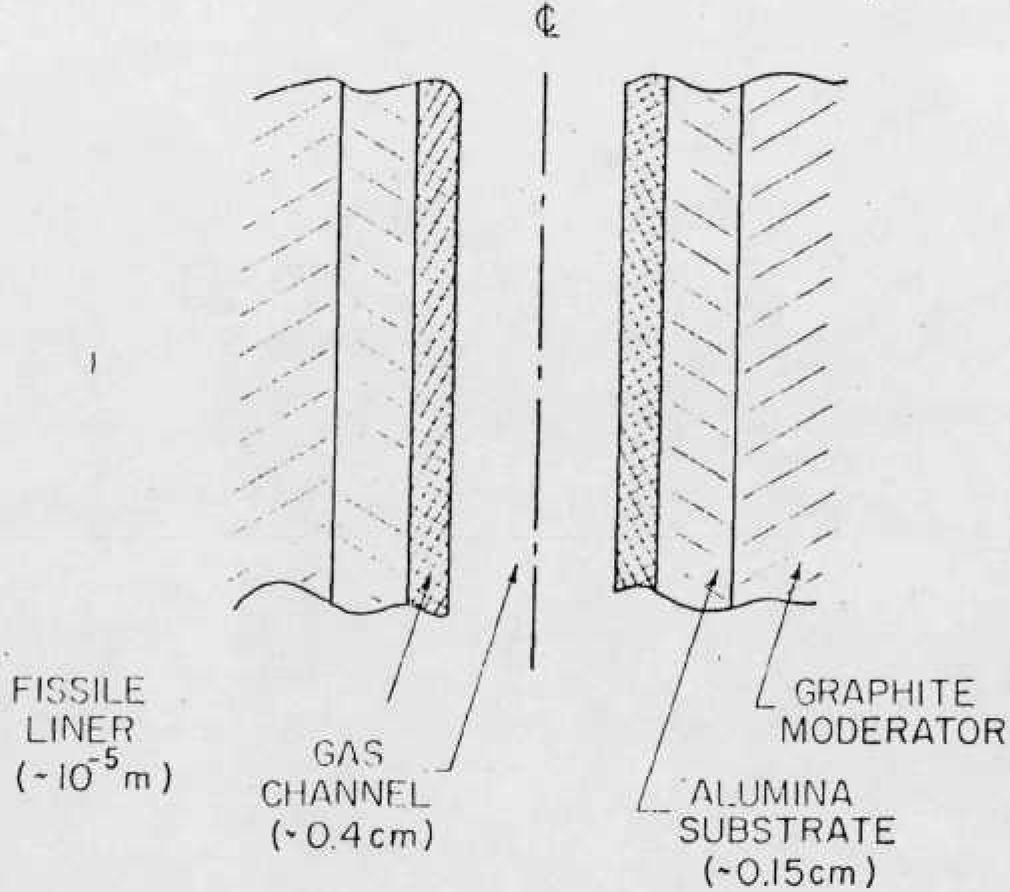


Figure 10. Schematic of laser-driven structure for concepts of Fig. 9. (Ref. 43)

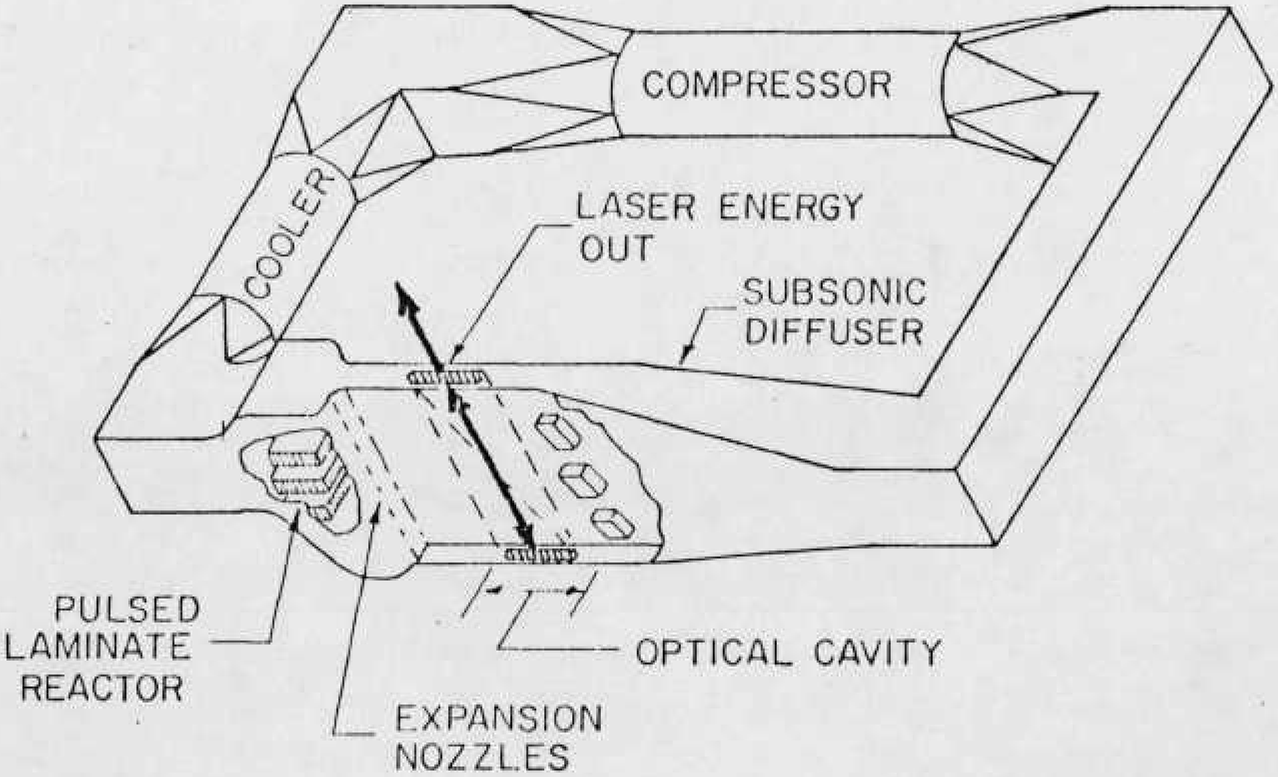


Figure 11. Gas-dynamic NPL concept. Overall system design. (Ref. 45)

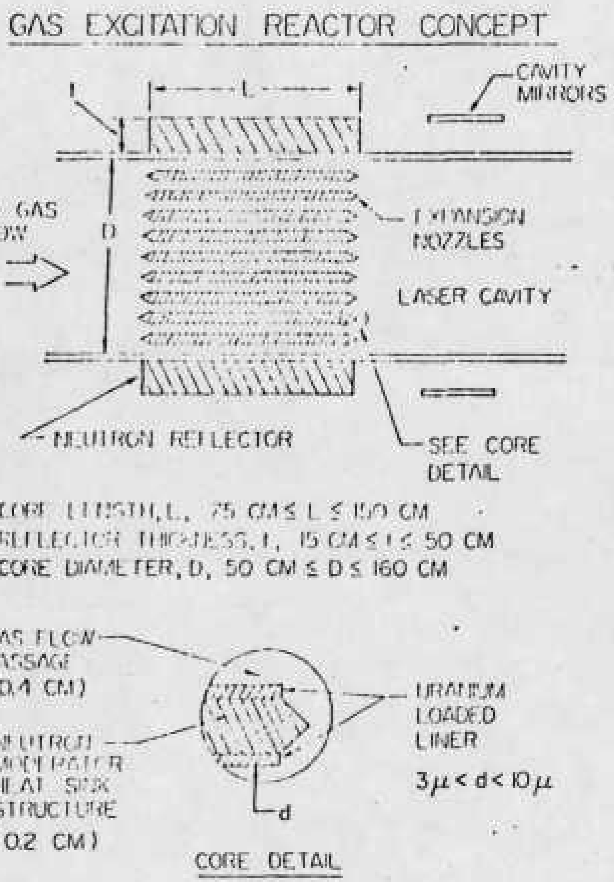


Figure 12. Gas-dynamic NPL concept. Structure in critical driver region. (Ref. 45)

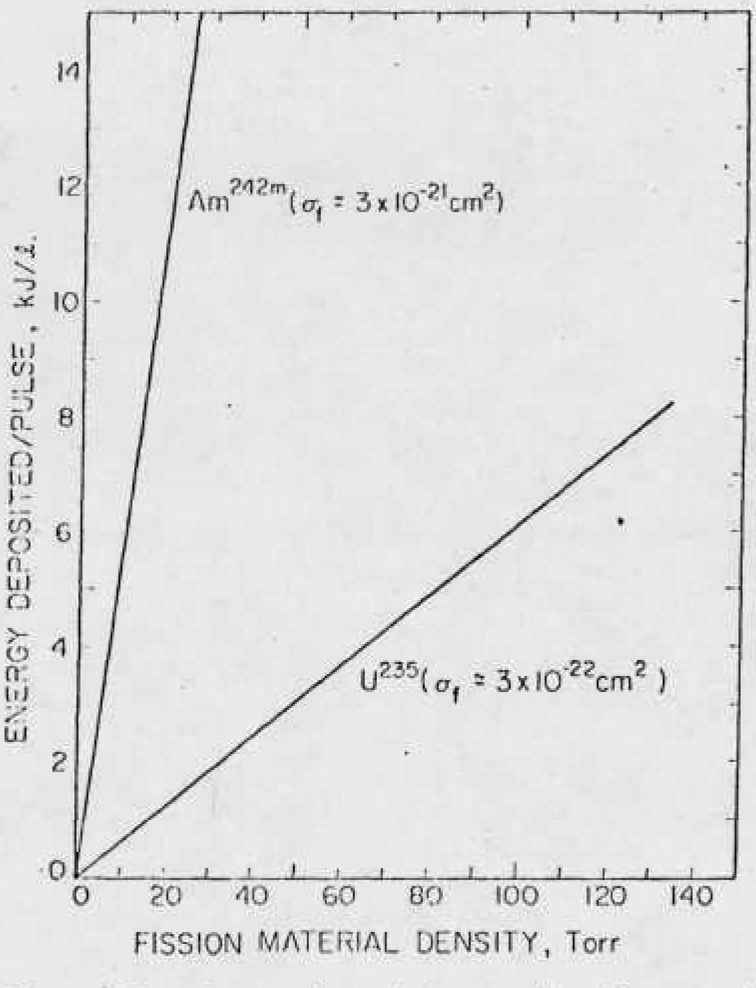


Figure 13. Energy deposition vs fissile material pressure for ^{235}U and ^{242}Am assuming coupling to the SPR III pulsed reactor (from Lorents, et al, Ref. 6).

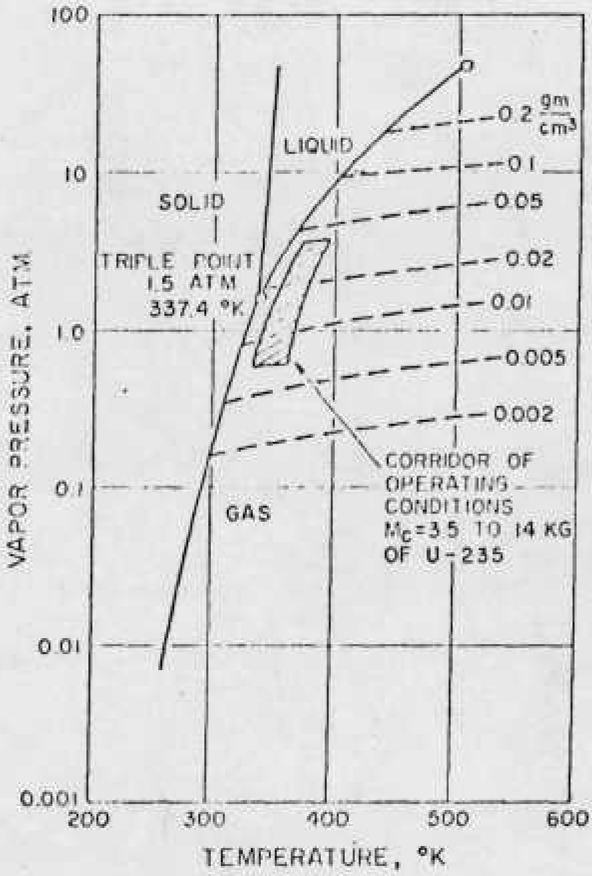


Figure 14. Vapor-pressure relation for UF_6 with operating region for near-term cavity-type UF_6-reactors indicated (from K. Thom, Ref. 6).

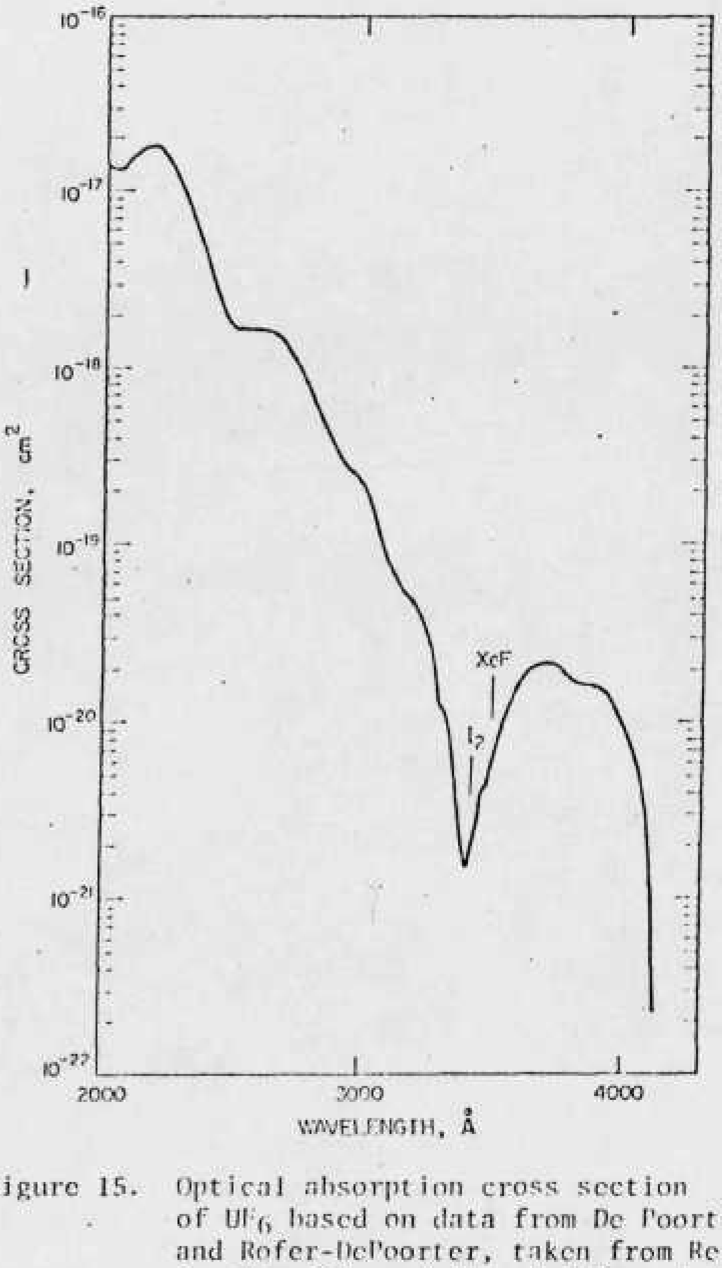


Figure 15. Optical absorption cross section of UF_6 based on data from De Poorter and Rofer-DePoorter, taken from Ref. 6. The 350-nm XeF^* and 342 nm I_2^* laser transitions fall in the absorption "window".

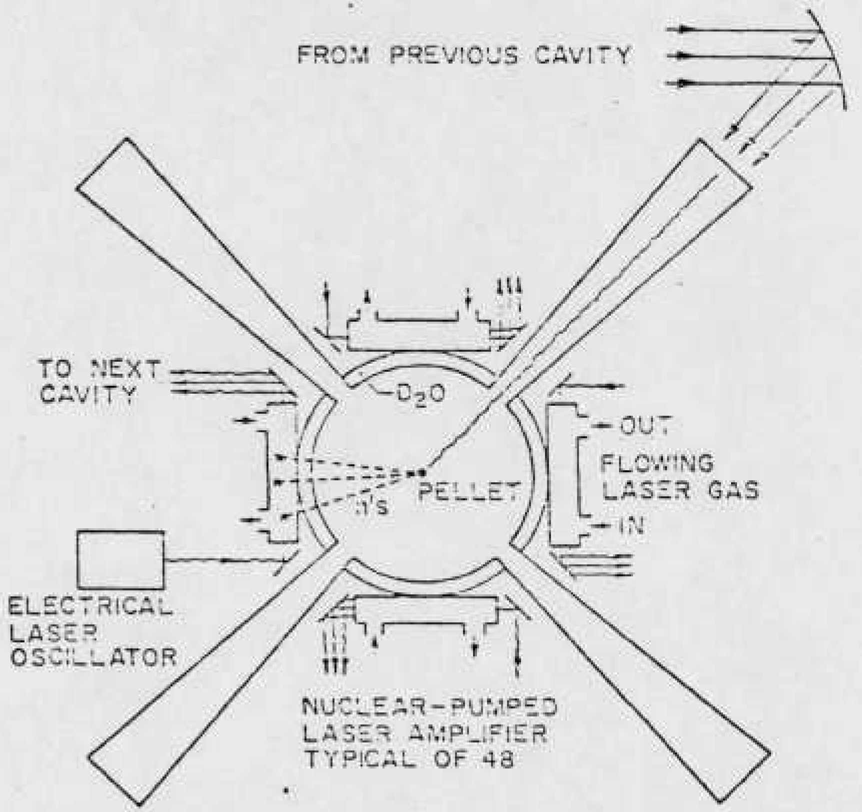


Figure 16. Conceptual feedback frusion reactor (Ref. 52).

Appendix C

Listing of Students Involved in NPL Research and Respective Thesis Titles.

NAME	DEGREE & DATE AWARDED	THESIS TITLE	PRESENT EMPLOYMENT
Guyot, Jean C.	PhD - Jan. 1971	"Measurement of Atomic Metastable Densities in Noble Gas Plasmas Created by Nuclear Radiations"	CGE Research Labs. Paris, France
Thiess, Paul	PhD - Oct. 1975	"Optimal Emission and Kinetics of High-Pressure Radiation Produced Noble Gas Plasmas"	Dept. of Mechanical Eng. Catholic U. of America
Weidenfeld, Danny		-	Graduate Student University of Illinois
Ibrahim, Khalid M.	PhD - Oct. 1973	"An Analysis of Non-Equilibrium Thermal Neutron Fields in the Fourier Frequency Plane"	Pakistan Atomic Energy Commission
Cook, John G.	MS - Aug. 1970	-	Illinois Power Company
Lo, Ronnie H-K	PhD - Oct. 1972	"Energy Distributions of Electrons in Radiation Induced-Helium Plasmas"	U.S. Nuclear Regulatory Commission
Orechwa, Yuri		-	Argonne National Lab
Ganley, James T.	MS - Aug. 1968	- (transferred to E.E. Dept.)	
Engelhardt, Ludwig	MS - Oct. 1972	-	Westinghouse Bettis Atomic Power Lab
Wang, Benjamin	PhD - 1972 (C.S.)	"Monte Carlo Simulation of Nonlinear Radiation Induced Plasma"	
Humphreys, Duane A.	MS - June 1973	-	Westinghouse Bettis Atomic Power Lab
DeYoung, Russell J.	PhD - Jan. 1976	"A Direct Nuclear Pumped Neon-Nitrogen Laser"	NASA - Langley Research Center
Miller, Ronald	MS - Feb. 1973	-	Graduate Student University of Illinois
Seckinger, Edward L.	MS - 1974 (E.E.)	"Study of the Neon-Oxygen Laser Under Heavy Particle Bombardment"	
Suhre, Dennis	PhD - 1976 (E.E.)	"Energy Distributions of Electrons in Electron Beam Produced Nitrogen Plasmas"	
Akerman, M. Alfred	PhD - Oct. 1976	"Demonstration of the First Visible Wavelength Direct Nuclear Pumped Laser"	Oak Ridge National Lab
Allen, Paul C.			

NAME	DEGREE & DATE AWARDED	THESIS TITLE	PRESENT EMPLOYMENT
Justiss, Stephen R.	MS - May 1974	-	U.S. Navy
Beckman, Stephen A.	MS - June 1976	-	Combustion Engineering
Cooper, Gary W.	PhD - Oct. 1976	"Recombination Pumped Atomic Nitrogen and Carbon Afterglow Lasers"	N.E. Department University of Wisconsin
Konya, Mark J.	MS - May 1976	-	Aerojet Nuclear Co.
Anderson, Jay H.			Graduate Student University of Illinois
Prelas, Mary A.	MS - May 1976	-	Graduate Student University of Illinois
Boody, Frederick			Graduate Student University of Illinois
Nagalingam, Samuel			Graduate Student University of Illinois
Sutherland, Stephen	MS - May 1977	-	Sandia Laboratory
Tsang, James	MS - May 1974	-	Graduate Student University of Illinois
Maceda, Edward L.	PhD - May 1977	"Optical Line Radiation from Uranium Plasmas"	Lynchburg Research Center
Lee, Daeshik		-	Graduate Student University of Illinois
Kruger, Anthony W.		-	Graduate Student University of Illinois
Anavim, Eshagh		-	Graduate Student University of Illinois