Executive Summary

The fiscal year ending September 2013 (FY13) included the first six months of the fourth five-year renewal of Cooperative Agreement DE-NA0001944 with the U.S. Department of Energy (DOE). A portion of the year was funded as an extension of the prior Cooperative Agreement DE-FC52-08NA2832 with DOE. This annual report summarizes work carried out under the Cooperative Agreement at the Laboratory for Laser Energetics (LLE) during the past fiscal year including work on the inertial confinement fusion (ICF) campaign; laser, optical materials, and advanced technology development; operation of the Omega Facility for the ICF and high-energy-density (HED) campaigns, the National Laser Users' Facility (NLUF), the Laboratory Basic Science (LBS) Program, and other external users; and programs focusing on the education of high school, undergraduate, and graduate students during the year.

Inertial Confinement Fusion Research

One of LLE's principal missions is to conduct research in ICF with particular emphasis on supporting the goal of achieving ignition on the National Ignition Facility (NIF). This program uses the Omega Laser Facility and the full experimental, theoretical and engineering resources of the laboratory. During FY13, a total of 1984 target shots were taken at the Omega Laser Facility (comprised of the 60-beam OMEGA UV laser and the four-beam, high-energy petawatt OMEGA EP laser). More than 40% of the facility's target shots in FY13 were designated as ICF experiments or experiments in support of ICF. During the last five years of the current Cooperative Agreement, 8204 target shots were taken on the Omega Laser Facility in support of the National Nuclear Security Administration (NNSA) missions. The OMEGA and OMEGA EP lasers attained average experimental effectiveness of 96.6% and 93.7%, respectively, in FY13.

LLE plays a lead role in the validation of the performance of cryogenic target implosions, essential to all forms of ICF ignition. LLE is responsible for a number of critical elements within the Integrated Experimental Teams supporting the demonstration of indirect-drive ignition on the NIF and is the lead laboratory for the validation of the polar-drive (PD) approach to ignition on the NIF. LLE has also developed, tested, and constructed a number of diagnostics that are being used at both the Omega Facility and the NIF. During this past year, progress in the inertial fusion research program continued in three principal areas: ICF experiments and experiments in support of ICF; theoretical analysis and design efforts aimed at improving direct-drive–ignition capsule designs (including polar-drive–ignition designs) and advanced ignition concepts such as shock ignition and fast ignition; and development of diagnostics for experiments on the NIF, OMEGA, and OMEGA EP.

1. Inertial Confinement Fusion Experiments in FY13

Simulations of polar-drive–implosion experiments conducted on OMEGA are presented (p. 15). Good agreement is observed between the experimental measurements and *DRACO* simulations in terms of areal density and symmetry. The scaling of these experiments to the NIF and the role of laser–plasma interactions are discussed.

We report on a comparison of measured and simulated angular dependence of the unabsorbed light in OMEGA experiments (p. 27). The 3-D simulations show that cross-beam energy transfer explains the decreased laser absorption, which can be mitigated using smaller laser beams on target and tuning the wavelength of the laser beams organized in different rings.

We report (p. 33) on the measured hot-electron fraction generated by the two-plasmon–decay (TPD) instability in planar experiments using one to four linearly polarized beams, 18 beams with polarization smoothing, and, in spherical geometry, 60 beams with polarization smoothing. The overlapped intensity threshold for hot-electron generation is different for each experimental configuration. These measured thresholds are compared and shown to be consistent with convective gains calculated with a resonant common wave model.

The results from a series of cryogenic deuterium–tritium (DT) implosions are presented (p. 145). A flexible direct-drive target platform was used to implode cryogenic DT capsules on the OMEGA Laser System. The goal of these experiments was to demonstrate hydrodynamically equivalent ignition performance, where the laser-drive intensity, implosion velocity, fuel adiabat, and in-flight aspect ratio (IFAR) were the same as those for a 1.5-MJ target designed to ignite on the NIF. The implosions spanned a broad region of design space to study target performance as a function of shell stability (adiabat) and implosion velocity. High implosion velocities are achieved with the higher-adiabat target designs that stabilize the hydroinstability growth at the ablation surface. For targets driven with higher-adiabat (~4) conditions, the measured areal density and primary neutron yields are >80% to 90% and ≥25% of the 1-D code predictions, respectively. Comparable performance for targets with adiabats in the range of 2.0 to 2.5 is needed to demonstrate ignition hydrodynamic equivalence.

We report the results of polar-driven direct-drive experiments performed on the OMEGA Laser System (p. 156) using targets with a contoured shell thickness (shimmed). The objective of these experiments was to explore the efficacy of using a shimmed target to improve implosion symmetry. These experiments demonstrated that target shimming can improve the low-mode symmetry over beam pointing alone. Given the need to control the shape of PD implosions on the NIF, and the anticipated benefit of shimming to increase the ignition margin, these results indicate that further research into methods to shape the DT encapsulating shell, and possibly the DT layer itself, should be undertaken. The authors point out that even indirectly driven implosions may benefit from using shimmed capsules, emphasizing the importance of this method.

OMEGA experiments demonstrate that spectra and images near $\omega_0/2$ (where ω_0 is the laser frequency) provide a powerful direct-drive, coronal plasma diagnostic for ICF (p. 161). Spatially and temporally resolved half-harmonic spectra and images of laser-driven implosions show evidence of local, multibeam-driven TPD instability. This instability always starts with the multibeam absolute instability that rapidly evolves into the convective regime extending between $n_c/4 \le n_e \le n_c/5$. The lower density is determined by Landau damping. Judging from the $\omega_0/2$ spectra, this instability is never observed in its linear stage, consistent with expectations. When the target view included the target normal and the TPD threshold was exceeded, a sharp, red-shifted $\omega_0/2$ spectral feature was observed that can serve as a convenient local electron temperature diagnostic. Time-resolved electron temperatures revealed locally increased electron temperatures in areas of enhanced overlapped irradiation intensities. Corroborating information was obtained from spatial images taken in the blue portion of the $\omega_0/2$ spectrum.

We report on measurements of the divergence of fast electrons in laser-irradiated spherical targets (p. 167). In experiments using directly driven spherical targets on the OMEGA Laser System, the energy in fast electrons was found to reach ~1% of the laser energy at an irradiance of $\sim 1.1 \times 10^{15}$ W/cm^2. The fraction of the fast electrons absorbed in the compressed fuel shell depends on their angular divergence. This divergence is deduced from a series of shots where Mo-coated shells of increasing diameter D were embedded within an outer CH shell. The intensity of the Mo-K_α line and the hard x-ray radiation were found to increase as $\sim D^2$, indicating a wide divergence of the fast electrons. Alternative interpretations of these results (electron scattering, radiation excitation of K_α, and an electric field caused by the return current) are shown to be unimportant.

Published measurements and models of the cross section for electrons causing K_α emission from copper are reviewed to find a suitable expression for analyzing K_α emission measurements in laser–solid experiments at peak intensities above 10^{18} W/cm^2 (p. 173). There exist few measurements in the electron energy range currently of interest, 0.1 to 10 MeV, leaving a number of models that could be suitable. These models are summarized with a number of typographical errors corrected. Two different limiting forms for the cross section at relativistic energies are used, and existing measurements do not give a clear indication as to which is correct. Comparison with the limiting form of electron stopping power indicates (1) an alternative relativistic form and (2) that the density effect correction will be important in copper above 10 MeV. For data analysis relying on relative K_α emission caused by electrons with energy much greater than the K-shell binding energy, the existing uncertainty in cross sections is unimportant, but it will be a source of uncertainty when using absolute values and for electron energies up to about 6× the binding energy. K_α emission caused by photons and protons is also briefly reviewed.

The first experimental study of rocket efficiency where different ablators were used to vary the ratio of the atomic number over the atomic mass is presented (p. 199). Success of direct-drive implosions critically depends on the ability to create high ablation pressures (~100 Mbar) and to accelerate the imploding shell to ignition-relevant velocities ($>3.7 \times 10^7$ cm/s) by using direct laser illumination. It is demonstrated that the implosion velocity of Be shells is increased by 20% compared to C and CH shells in direct-drive implosions. These measurements are consistent with the predicted increase in the hydrodynamic efficiency of 18% for Be and 7% for C compared to a CH ablator.

2. Theoretical Design and Analysis

Beginning on p. 1, the performance of a shock-ignition (SI) polar-drive design is estimated using 1-D and 2-D simulations for implementation on the NIF. This design was developed within the NIF Laser System specifications. The target implosion velocity is higher than for standard SI designs to account for laser power limitations on the NIF. The proposed capsule ignites in 1-D simulations on the NIF with an $ITF_{1\text{-}D}$ (ignition threshold factor) of 4.1 using 700 kJ of input laser energy. The capsule is robust in 1-D to shock mistiming. Hot-electron energy coupling during the spike pulse is shown to have a positive effect on target margin at hot-electron temperatures up to 150 keV and hot-electron energy levels below 20% of the incident spike-pulse energy.

We review the physics and possible implementations of two-state optical zooming to mitigate cross-beam energy transfer on OMEGA (p. 43). Scattering of the incident laser energy is reduced using a smaller beam radius on target for the main drive pulse while maintaining the beam size for the picket pulses.

A generalization of the extended Zakharov model of TPD (p. 112) includes the evolution of the electron-distribution function in the quasi-linear approximation. This makes it possible to investigate anomalous absorption of laser light and hot-electron production caused by the TPD instability of multiple overlapping electromagnetic waves.

Particle-in-cell simulation results are reported (p. 127) pertaining to cone-in-shell integrated fast-ignition experiments at the Omega Laser Facility. These simulations provide further evidence of the detrimental effects of pre-plasma in the cone. Studies of hot-electron generation from laser/pre-plasma interactions and transport show that the generated hot electrons are dominated in number by low-energy electrons but in energy by multi-MeV electrons.

3. Diagnostics for ICF Experiments

We report on the reliability and accuracy improvement of streak-camera–based short-pulse measurements by homogenizing the slit illumination using an anamorphic diffuser and calibrating the space-charge broadening. These improvements apply to the measurement of OMEGA EP pulses with durations ranging from 8 to 250 ps (p. 58).

The characterization of a high-proton-energy x-ray imager is reported (p. 205). The Bragg angle, rocking curve, and reflection efficiency of a quartz crystal x-ray imager (Miller indices 234) were measured at a photon energy of 15.6909 keV, corresponding to the $K_{\alpha 2}$ line of Zr, using the X15A beamline at the National Synchrotron Light Source at Brookhaven National Laboratory. Using one of the curved crystals, the Zr $K_{\alpha 2}$ emission was imaged from a hot Zr plasma generated by LLE's 10-J Multi-Terawatt laser. Estimates of the reflectivity obtained by comparing the spatially integrated signal from the images to the direct x-ray emissivity of the source were, within experimental error, in agreement with values obtained at the X15A beamline.

Lasers, Optical Materials, and Advanced Technology

The design of a new solid-state, high-voltage pulse generator for driving large-aperture Pockels cells is discussed beginning on p. 64. These generators are reliable replacements for the obsolete thyratron-based drivers used in the large-aperture ring amplifiers of the OMEGA and OMEGA EP front ends.

The performance of OMEGA EP seeded by optical pulses with high-frequency phase modulations is described (p. 75). This demonstration of multiple-frequency modulation smoothing by spectral dispersion includes angular dispersion by a diffraction grating, propagation, and amplification in a NIF preamplifier module and one OMEGA EP beamline, frequency conversion, beam smoothing after a distributed phase plate, and focusing. Laser operation is characterized under conditions relevant to an implementation of multi-FM beam smoothing on the NIF to support polar drive.

Modeling and simulation results describing the propagation of spatially dispersed frequency-modulated optical pulses are presented (p. 85). A comprehensive CEA-provided laser design and simulation code (Miró) was used to set a peak-power limit for multi-FM pickets, taking into account nonlinear propagation in the optical components and conversion of frequency modulation into amplitude modulation because of diffraction.

We describe the fiber front end laser system built to support the demonstration of multi-FM beam smoothing on OMEGA EP (p. 98). High-bandwidth pulse shaping, multi-FM phase modulation, spectral-amplitude compensation, chromatic dispersion compensation, and fail-safe systems have been implemented to provide seed pulses that meet all operational requirements.

We report on research on the fracture mechanics of delamination defects in multilayer dielectric coatings (p. 187). During the fabrication of multilayer-dielectric (MLD) thin-film coated optics, such as the diffraction gratings used in OMEGA EP's pulse compressors, acid piranha cleaning can lead to the formation of chemically induced delamination defects. The causes of these defects are investigated, and a mechanism for the deformation and failure of the MLD coating in response to hydrogen peroxide in the cleaning solution is described. A fracture mechanics model was developed and used to calculate the crack path that maximizes the energy release rate, which was found to be consistent with the characteristic fracture pattern observed in MLD coating delamination defects.

A process is demonstrated for producing ultra-broadband coatings (for femtosecond pulse applications) with high reflectivity, high-laser-damage thresholds, and controlled dispersion (p. 212). Large-aperture deposition of high-laser-damage-threshold, low-dispersion optical coatings for 15-fs pulses was developed using plasma-ion–assisted electron-beam evaporation. Coatings are demonstrated over 10-in.-aperture substrates.

A study of the spectral and temporal properties of the optical signals generated by multiple sinusoidal temporal phase modulations (multi-FM) of a monochromatic source is presented (p. 222). Statistical analysis based on the central limit theorem shows that the signals' optical spectrum converges to a normal distribution as a number of modulations increases, making it possible to predict the frequency range containing a given fraction of the total energy with the associated cumulative density function. Analysis and simulation of frequency-modulation-to-amplitude-modulation conversion of arbitrary multi-FM signals are performed. These developments are of theoretical and practical importance for high-energy laser systems, where optical pulses are phase modulated in the front end to smooth out the on-target beam profile and prevent potentially catastrophic damage to optical components.

We present the results of experiments and models relating to dental calculus ablation in human teeth using 400-nm laser pulses (p. 136). This work was the result of a collaboration involving researchers from LLE, The Institute of Optics, the University of Toronto, and the University of California, San Francisco. Calculus-removal rates, microscopy, and spectroscopy after irradiation are consistent with tissue-specific ablation at 400 nm caused by absorption by bacterial porphyrins within calculus. A heuristic model for calculus ablation agrees well with observed data.

FY13 Omega Facility Report

During FY13, the Omega Facility conducted 1408 target shots on OMEGA and 576 target shots on OMEGA EP for a record total of 1984 target shots for the ICF, HED, NLUF, and LBS program and also provided several shot days for CEA and the University of Michigan's Center for Radiative Shock Hydrodynamics (CRASH) program (see Fig. 1).

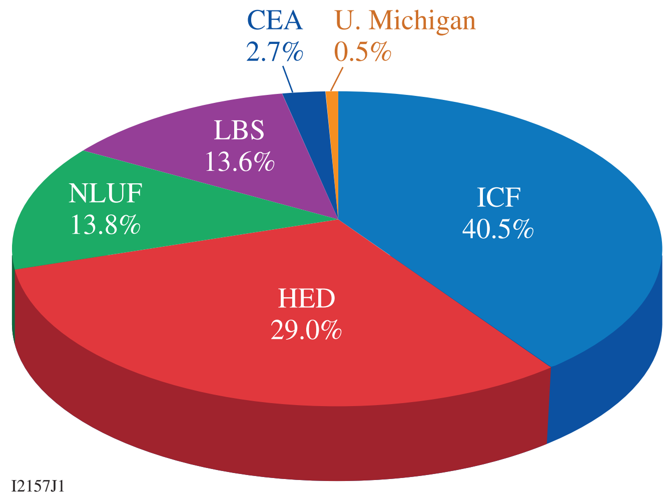

Figure 1
Pie chart showing the distribution of Omega Facility target shots by program in FY13.

Nearly 70% of the shots were taken for the ICF and HED programs.

OMEGA averaged 11.5 target shots per operating day with availability and experimental effectiveness averages for FY13 of 93.9% and 96.6%, respectively. OMEGA EP was operated extensively in FY13 for a variety of internal and external users. A total of 576 target shots were taken into the OMEGA EP target chamber including 69 joint shots into the OMEGA target chamber. OMEGA EP averaged 6.7 target shots per operating day with availability and experimental effectiveness averages for FY13 of 93.8% and 93.7%, respectively. Highlights of achievements in FY13 are detailed starting on p. 245 and include the following:

- Joint cryo backlighting
- 4ω probe diagnostics
- Replacement of neutron temporal diagnostics
- Tritium fill station cryo permeator
- Sydor framing camera
- Solid-state Pockels cell drivers

National Laser Users' Facility and External Users' Programs

Under the facility governance plan that was implemented in FY08 to formalize the scheduling of the Omega Laser Facility, Omega Facility shots are allocated by campaign. Nearly 70% of the FY13 target shots were conducted for the ICF and HED campaigns.

The fundamental science campaigns accounted for ~27% of the target shots taken by the facility in FY13. Half of these were taken for the National Laser Users' Facility (NLUF) program and the remainder for the Laboratory Basic Science (LBS) program.

The Omega Facility is also being used for several campaigns by teams from the Commissariat à l'énergie atomique (CEA) of France and the Atomic Weapons Establishment (AWE) of the United Kingdom. These programs are conducted at the facility on the basis of special agreements put in place by DOE/NNSA and the participating institutions.

The facility users during FY13 included 11 collaborative teams participating in the NLUF program; 16 teams led by Lawrence Livermore National Laboratory (LLNL) and LLE scientists participating in the LBS program; many collaborative teams from LLE and the national laboratories conducting ICF experiments; investigators from LLNL and Los Alamos National Laboratory (LANL) carrying out HED experiments; and scientists and engineers from CEA, AWE, and the University of Michigan's CRASH program. In total, ~62% of the Omega facility target shots were conducted by teams led by external users.

1. FY13 NLUF Programs

FY13 was the first of the two-year period of performance for the NLUF projects approved for FY13–FY14 funding and Omega facility shots. Eleven NLUF projects (see Table 136.VII, p. 248) were allotted Omega facility shot time and conducted a total of 274 target shots. The work of the NLUF projects in FY13 is summarized beginning on p. 247. Particularly noteworthy in FY13 was the awarding of the Edward Teller Medal to R. D. Petrasso at the 2013 Inertial Fusion and Science and Applications Conference in September 2013. Much of the work for which Prof. Petrasso and his MIT group were recognized was carried out under the auspices of the NLUF program at the Omega facility.

2. FY13 LBS Programs

Sixteen LBS projects were allotted Omega facility shot time and conducted a total of 269 target shot on the facility in FY13 (see Table 136.IX, p. 265). This work is summarized beginning on p. 263 of this report.

In FY13, LLE issued a solicitation for LBS proposals to be conducted in FY14. A total of 38 proposals were submitted. An independent review committee reviewed the proposals and recommended that 17 proposals receive 28 shot days at the Omega facility in FY14. Table 136.VIII (p. 264) lists the successful FY14 proposals.

3. FY13 LLNL Omega Facility Programs

In FY13, LLNL teams led over 600 target shots on the Omega Facility: 166 for the ICF campaigns, 303 for the HED campaigns, and more than half of the LBS target shots.

The ICF campaign experiments included the following:

- A new platform for absolute equation-of-state (EOS) measurements
- VISAR (velocity interferometer system for any reflector) measurements of the EOS of boron carbide
- Shock-release isentrope measurements of ICF-relevant materials
- Thomson-scattering measurements from Au spheres
- Measuring the adiabatic index of polystyrene using counter-propagating shocks and x-ray Thomson scattering
- Angularly resolved x-ray Thomson-scattering measurements of shock-compressed aluminum
- Enhanced bremsstrahlung backlighters
- Hohlraum-drive spectroscopy
- Ablator opacity measurements
- Hohlraum wall-plasma emissivity measurements
- D–D and D–^{3}He yield anomalies versus D:^{3}He fuel ratio in indirect-drive exploding pushers
- Platform development for measuring charged-particle stopping in warm dense plasmas

High-energy-density experiments included the following:

a. Material dynamics and strength:
  - Tantalum Rayleigh–Taylor experiments
  - Iron Rayleigh–Taylor experiments
  - Long-pulse silver backlighter development
  - Material recovery experiment
  - Diffraction studies on shocked tantalum
  - Classical Rayleigh–Taylor experiments

b. Materials equation of state:
  - Demonstration of single-shot EXAFS measurements on ramp-compressed Ta
  - Sn melting and recrystallization
  - Ta x-ray diffraction with ramp compression
  - Development of a Soller-slit diagnostic for dynamic diffraction studies
  - Radiographic EOS measurements of shocked foams
  - High-energy x-ray diffraction development
  - Lithium-hydride equation of state
  - Ta equation of state

c. Radiation transport and opacity:
  - Heated wall radiation transport

d. Hydrodynamics:
  - Radiographic development for NIF hydrodynamic experiments
  - Copper foam shock-breakout measurements
  - Short-pulse, UV backlighting development for the NIF
  - X-ray area backlighter development

e. Burn physics:
  - High-resolution measurements of velocity nonuniformities in boron carbide—an alternative ignition capsule ablator material
  - Ablator physics tests of beryllium capsules

f. X-ray source development:
  - Solar cell electrostatic discharge
  - X-ray source development with nanostructured materials

4. FY13 LANL Experimental Campaigns

In FY13, LANL executed 207 total target shots on the OMEGA laser. LANL experiments contributed to the ICF and HED campaigns.

The ICF campaigns included the following:

- Measurements of the x-ray ablative Richtmyer–Meshkov growth of isolated defects on beryllium ablators
- Studies of the branching ratios and species separation (plasma kinetic effects) in DT fusion plasmas
- Development of neutron imaging and gamma-ray scintillator for the NIF
- Studies of the suppression of hohlraum laser–plasma interaction (LPI) with magnetic fields

The HED campaigns included the following:

- Studies of shear in a counter-propagating flow geometry driving turbulent mixing
- Backlit defect implosion experiments to study polar-drive symmetry control
- Measurement of spatial distribution of mix in gas-filled capsules
- Imaging x-ray Thomson-scattering platform development for dense plasmas and the EOS of warm dense matter
- Measurement of a supersonic radiation wave and foam aerogel EOS

5. FY13 CEA Experiments at the Omega Laser Facility

In FY13 CEA teams conducted 53 target shots on the OMEGA laser. The CEA experiments included the following:

- CEA vulnerability diagnostic development on OMEGA
- Neutron spectrometer [DEMIN (detector Micromegas for neutrons)] development on OMEGA
- Convergent ablation measurements using a gas-filled rugby hohlraum on OMEGA
- Laser-imprint mitigation using underdense foams

OMEGA Laser Facility Users Group (OLUG)

The fifth Omega Users Group (OLUG) Workshop was conducted at LLE in April 2013. More than 100 researchers from 25 universities met at the 2.5-day workshop to facilitate communications and exchanges among individual Omega users and between users and the LLE management; to present ongoing and proposed research; to encourage research opportunities and collaborations that could be undertaken at the Omega facility and other high-energy-density-physics facilities; to provide an opportunity for students, postdoctoral fellows, and young researchers to present their research in an informal setting; and to provide feedback to the LLE management from the users about ways to improve the facility and future experimental campaigns.

OLUG comprises 310 members from 35 universities and many centers and national laboratories. The interactions were wide ranging and lively as illustrated in the workshop report (p. 237). The first two mornings of the workshop included seven science and facility presentations. Since the facility is constantly evolving and improving, the facility talks proved particularly useful even to experienced users. The overview talks given by leading world authorities described the breadth and excitement of HED science either being undertaken at the Omega facility or well within the capabilities of the facility with improvements or upgrades.

Fifty students and postdoctoral fellows participated in the workshop and 36 were supported by travel grants from NNSA. In total there were 68 contributed poster papers including eight presented by Omega facility operations staff.

An important function of the workshop was to develop a set of findings and recommendations to help set and define future priorities for development of the Omega Laser Facility. LLE uses these recommendations as a guide for making decisions about facility operations, priorities, and future directions. In addition, the status of these OLUG Findings and Recommendations were updated and reviewed at a satellite meeting during the 2013 APS-DPP Conference.

Education

As the only major university participant in the National ICF Program, education continues as an important mission for LLE. The Laboratory's education programs cover the range from high school (p. 243) to graduate education.

1. High School Program

During the summer of 2013, 15 students from Rochester-area high schools participated in the LLE Summer High School Research Program. The goal of this program is to excite a group of high school students about careers in the areas of science and technology by exposing them to research in a state-of-the-art environment. Too often students are exposed to research only through classroom laboratories, which have prescribed procedures and predictable results. In LLE's summer program, the students experience many of the trials, tribulations, and rewards of scientific research. By participating in research in this "real" environment, students often become more excited about careers in science and technology.

The students spent most of their time working on their individual research projects with members of the LLE's technical staff. The projects were related to current research activities at the Laboratory and covered a broad range of interests including laser physics, computational modeling of implosion physics, experimental diagnostics development, spectroscopy, cryogenic deuterium properties, liquid crystal devices, tritium detection and capture, ballistic deflection transistors, positioning systems, and 3-D visual modeling (see Table 136.IV, p. 244).

Since its inception in 1989, 312 high school students have now participated in the program. This past year's students were selected from nearly 80 applicants. At the culminating "High School Student Summer Research Symposium" on 28 August 2013, the students presented the results of their research to an audience including parents, teachers, and LLE staff. At the symposium LLE presented its 17th annual William D. Ryan Inspirational Teacher Award. This year's recipient of the award was Mrs. Eugenie Foster, a mathematics teacher from Brighton High School. Teachers are nominated by alumni of the summer program. Mrs. Foster was nominated by Mitch Perry, Julia Tucker, and Jack Valinsky, participants in the 2010 program. They credited Mrs. Foster with developing a discrete math course to showcase mathematical topics outside of the core curriculum for students who "have that extra thirst which only mathematics can quench." They also credit Mrs. Foster with developing an Intro to College Math course "to reach out to students who do not perceive themselves pursuing math-related fields in college or those to whom math does not come easily."

2. Undergraduate Student Program

Forty undergraduate students participated in work or research projects at LLE this past year. Student projects include operational maintenance of the Omega Laser Facility; work in laser development, materials, and optical thin-film coating laboratories; computer programming; image processing; and diagnostics development. This is a unique opportunity for students, many of whom will go on to pursue a higher degree in the area in which they gained experience at the Laboratory.

3. Graduate Student Programs

Graduate students are using the Omega Laser Facility as well as other LLE facilities for fusion and HED physics research and technology development activities. These students are making significant contributions to LLE's research program. Twenty-six faculty members from five University academic departments collaborate with LLE scientists and engineers. Presently, 60 graduate students are involved in research projects at LLE, and LLE directly sponsors 37 students pursuing Ph.D. degrees via the NNSA-supported Frank Horton Fellowship Program in Laser Energetics. Their research includes theoretical and experimental plasma physics, HED physics, x-ray and atomic physics, nuclear fusion, ultrafast optoelectronics, high-power-laser development and applications, nonlinear optics, optical materials and optical fabrication technology, and target fabrication. In addition, LLE directly funds research programs within the MIT Plasma Science and

Fusion Center, the State University of New York (SUNY) at Geneseo, and the University of Wisconsin. These programs involve a total of approximately 6 graduate students, 25 to 30 undergraduate students, and 10 faculty members.

Over 310 graduate students have now conducted their graduate research work at LLE since its graduate research program began. In addition, 120 graduate students and post-graduate fellows from other universities have conducted research at the LLE laser facilities as part of the NLUF program. Over 60 graduate students and undergraduate students were involved in research on the Omega Laser Facility as members of participating NLUF teams in FY13. Table 136.X (p. 308) lists the authors, dissertation titles, and originating university of the Ph.D. theses from LLE and NLUF research in FY13.

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Vice President, University of Rochester