LAWRENCE LIVERMORE NATIONAL LABORATORY

LLNL-TR-736975

# Water Treatment Using Advanced Ultraviolet Light Sources Final Report CRADA No. TC02089.0

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August 16, 2017

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

# Water Treatment Using Advanced Ultraviolet Light Sources

**Final Report**
**CRADA No. TC02089.0**
**Date Technical Work Ended: February 3, 2011**

Date: February 24, 2011 Revision: 1

## A. Parties

This project was a cooperative effort between Lawrence Livermore National Laboratory (LLNL) and Teknichal Services, LLC.


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## B. Project Scope

This was a collaborative effort between Lawrence Livermore National Security, LLC as manager and operator of Lawrence Livermore National Laboratory (LLNL) and Teknichal Services, LLC (TkS), to develop water treatment systems using advanced ultraviolet light sources. The Russian institutes involved with this project were The High Current Electronics Institute (HCEI) and Russian Institute of Technical Physics-Institute of Experimental Physics (VNIIEF). HCEI and VNIIEF developed and demonstrated the potential commercial viability of short-wavelength ultraviolet excimer lamps under a Thrust 1 Initiatives for Proliferation Prevention (IPP) Program.

The goals of this collaboration were to demonstrate both the commercial viability of excilamp-based water disinfection and achieve further substantial operational improvement in the lamps themselves; particularly in the area of energy efficiency. Specifically, this project was to design, fabricate, test, and demonstrate water disinfection reactors that utilize short-wavelength ultraviolet excimer lamps developed by the Russian HCEI under a Thrust 1 IPP Program. It was envisioned that the reactors would be configured for several different types of water treatment uses by changing reactor operating parameters and by using excimer lamps having different wavelengths or power. The fabrication of several prototype units would take advantage of the lessons learned from the previous model. Prototypes would be tested to determine if the stated design goals had been met. It was envisioned that some prototypes would be offered to external organizations for user testing.

The successful demonstration of this UV source would open the door for substantial improvements in existing UV applications. Demonstration of their use in water disinfection may well open up new applications in other fields.

Three (3) successive prototypes were envisioned.

1. *Exploratory:* This prototype would be built to understand issues in design, fabrication, and operating an excimer lamp-based reactor, and develop ideas for a proof of concept system.

2. *Proof-of-concept:* This prototype used the lessons learned from the exploratory unit. The goal was to develop a unit that will prove the potential of the excimer lamp based reactor in a commercial environment. If successful, this prototype would be offered to potential users for testing in the actual industrial environment. Lessons learned from user testing will be used to develop a prototype commercial unit.

3. *Commercial:* This prototype would demonstrate the commercial practicality of the excimer lamp based reactor. Testing in an industrial environment would characterize the performance and economic advantages as a basis for planning the commercialization of the technology.

This project consisted of 4 phases, 15 major tasks, and the following 29 major deliverables:

**Deliverables –all deliverables under this project have been completed.**

**<u>Funding Year 1 - Phase 1</u>**

1. Report outlining attractive lamp applications and the lamp characteristics thought to be needed for these applications. (TkS) (Task 1)
2. Obtain export license. (LLNL) (Task 2)
3. Obtain export license. (TkS) (Task 3)
4. Report describing important performance characteristics (e.g., power, wavelength, life), the range of characteristics achievable by HCEI and VNIIEF, and the estimate of how cost varies as a function of variation in key characteristics. (HCEI/VNIIEF) (Task 4)
5. Design water treatment and performance goals for the first prototype reactor. (TkS and LLNL) (Task 5)

Deliverables 6, 7, and 8 relate to Task 6.

6. Deliver specifications for the first experimental prototype lamps to HCEI. (LLNL)
7. Manufacture several experimental prototype lamps. (HCEI/VNIIEF)
8. Report describing effectiveness of the lamps for selected treatments, and the effect of variations of lamp critical characteristics upon treatment effectiveness. (HCEI/VNIIEF)

**Funding Year 1 - Phase 2**

Deliverables 9 through 12 relate to Task 7

9. Conceptual design of first prototype reactor. (TkS)
10. Prepare design of lamps required for first prototype reactor to LLNL. (TkS)
11. Deliver specification of required number of lamps and characteristics to HCEI/VNIIEF. (LLNL)
12. Deliver final design and fabrication documents to LLNL. (TkS)
13. Deliver overall test plan to TkS. (LLNL) (Task 8)
14. Deliver lamps for use in the first prototype reactor. (HCEI/VNIIEF) (Task 9)

**Funding Year 2 – Phase 2**

15. Deliver one or more exploratory reactor prototypes to LLNL. (TkS) (Task 10)
16. Deliver test setup and test report to TkS. (LLNL) (Task 11)

**Funding Year 2 – Phase 3**

Deliverables 17 through 20 relate to Task 12.

17. Deliver test setup and test report for second prototype to TkS. (LLNL)
18. Deliver one or more proof-of-concept prototypes to LLNL. (TkS)
19. Deliver test report to TkS. (LLNL)
20. Deliver revised requirements for commercial prototype. (TkS, HCEI/VNIIEF, LLNL)
21. Deliver summary of commercial test findings. (TkS) (Task 13)

**Funding Year 3 – Phase 4**

Deliverables 22 through 25 relate to Task 14.

22. Revised requirements for the commercial prototype (TkS)
23. Deliver one or more proof-of-concept prototypes. (TkS)
24. Deliver test report. (LLNL)
25. Revised requirements for commercial prototype (TkS, HCEI/VNIIEF, LLNL)

Deliverables 26 through 29 relate to Task 15.

26. Deliver summary of commercial test findings. (TkS)
27. Deliver revised requirements for production units. (TkS)
28. Final Report and Abstract due within thirty (30) days of completion or termination of the project, as required under Article XI of the CRADA. (LLNL, TkS)
29. Deliver commercialization plan (TkS)

This project was originally designated as a three (3) year project. Two no-cost time extension requests were executed for this project, each one extending the CRADA for an additional 12 months with a modified expiration date of February 3, 2011.

## C. Technical Accomplishments

The specific technical accomplishments were as follows:

1. Three UV excilamps emitting in the range of 200-350 nm were manufactured by HCEI SB RAN, installed in the first reactor prototype, and delivered to LLNL. Subsequently three KrCl, two XeBr-excilamps and four $Xe_2$-excilmaps, installed in reactors, with associated power supplies were manufactured and sent to LLNL

2. Lifetime tests of excilamps at 222 and 308 nm were completed.

3. Research regarding optimum range of excilamp working characteristics at wavelengths 222, 282 and 172 nm for was carried out.

4. Bench top tests were conducted with the KrBr, KrCl, XeBr and XeCl to test effectiveness of exposure times on a suspension of Escherichia coli to determine efficacy of each lamp type. The tests were conducted under the supervision of U.S. partner Steve Oster of TkS at Prima Environmental.

5. The results of efforts under this project were published in 17 reports and in proceedings of International Conferences and in 18 articles in a peer reviewed journals.

6. All final reports from HCEI SB RAS have been completed

7. Three RU patent applications have been submitted.

## D. Expected Economic Impact

The UV industry has experienced double-digit sales growth over the last 20 years, and combined annual sales of UV products will soon be in excess of $500 million. The vast majority of these sales are of traditional mercury arc system. Excimer technology has been around for over 20 years, but low efficiency and short lamp life limited their commercial application. The HCEI team increased output up to 100W in the short wavelengths at efficiencies that approached or exceeded that available in commercial UV lamps. UV oxidation and ozone generation are more effective by orders of magnitude with short wavelength UV (206nm) than with traditional 254nm Mercury arc lamps. Nearly all research that has been done on the effectiveness of UV in disinfection has been with 254nm arc lamps, preliminary data suggest that short wavelength (with higher energy) may be more effective. Industrial applications of high power excilamps have not been explored before. Excilamp based water disinfection that achieves improvement over existing processes will open up an existing commercial market as well as open applications in other fields. Potential specific applications include:

Wastewater disinfection
NDMA treatment in wastewater
Drinking water disinfection
Advanced oxidation treatment processes
Ozone generation
Groundwater remediation
Manufacturing processes

Under this effort, effectiveness of the Excilamps was tested against its ability to produce a 5 log reduction in e Coli, a common food pathogen. Based on the results of the testing done by TkS at Prima Environmental, excilamps proved equal in effectiveness and efficiency to standard mercury arc lamps. Based on the results of this project, potential additional commercial applications of this technology may reside in semiconductor manufacturing (UV removal of photo-resist from silicon wafers during processing).

### D.1 Specific Benefits

Benefits to DOE
DOE could benefits through more efficient disinfection and treatment technology that will reduce DOE operating costs. DOE facilities must maintain the quality of water released to local treatment systems. Additionally, some DOE facilities must remediate ground water affected by their sites.

Benefits to Industry
Industry would benefit through improved UV oxidation technology that could reduce the need for chemical additives to power plant and other industrial facility cooling water. Many energy production facilities chemically treat cooling water in order to decrease the concentration of organic and mineral solids in the system. The food processing and drinking water industry could benefit from more effective or efficient disinfection methods. The semi-conductor industry could benefit from more effective or efficient cleaning methods.

## E. Partner Contribution

TkS provided its patented "Coaxial Flow-Through" reactor for the UV oxidation and disinfection tests. Staff from TkS worked with Proxima Environmental Services to calibrate the lamp output, assembled the final Reactor/Lamp test apparatus and operated the apparatus during the tests. TkS staff reviewed the data and helped prepare the final results and reports on the tests. TkS staff met with LLNL project staff and with HCEI project team members during visits to the US.

## F. Documents/Reference List

*Indicates Protected CRADA Information

**Reports**

ISTC Project No. 3583p*
Water Treatment Using Advanced Ultra-Violet Light Sources Final Project Technical Report on the work performed from January 01, 2007 to June 30, 2010.

ISTC Project No. 3583p*
Water Treatment Using Advanced Ultra-Violet Light Sources Final Project Activity Report on the work performed from January 01, 2007 to June 30, 2010

Report of finding, preparation for evaluation of Photo-decontamination of wastewater using various lamp types. Prima Environmental. December 2008.*

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Lomaev M.I., Skakun V.S., Tarasenko V.F., Schitz D.V (2008). One and two–barrier excilamps on xenon dimers operating in the VUV range. Technical Physics (53) 244–248.

Avdeev S.M., Erofeev M.V., Sosnin E.A., Tarasenko V.F. (2008) Emission of Cl2* molecules in a barrier discharge. Quantum Electronics (38) 791–793.

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Avdeev S.M., Sosnin E.A., Velichevskaya K.Yu., Lavrent'eva L.V. (2008) Comparative study of UV radiation action of XeBr and conventional low-pressure mercury lamp on bacteria. Proc. XIII International conference on atomic and molecular pulsed lasers. Tomsk 6938-6952.

Avdeev S.M., Sosnin E.A., Skakun V.S., Tarasenko V.F., Schitz D.V. (2008) Two-band emission source based on a three-barrier KrCl-XeBr-excilamp Tech. Phys. Lett. (34) 725-727.

Victor F. Tarasenko, Mikhail V. Erofeev, Igor D. Kostyrja, Mikhail I. Lomaev, Dmitri V. Rybka. Pulsed UV and VUV excilamps (2008) Proceedings of SPIE. High-Power Laser Ablation VII, Claude R. Phipps, Editors.

D.V. Shitts, V.S. Skakun, and V.F. Tarasenko (2008) A system of excilamps on xenon dimers for a flow photoreactor. Instruments and Experimental Techniques (51) 759-761.

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Avdeev S.M., Erofeev M.V., Sosnin E.A., Tarasenko V.F. (2008) Planar exciplex lamp excited by barrier discharge. Atmos. Oceanic Opt. (21) 725-728.

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E.A. Sosnin, E.I. Lipatov, S.M. Avdeev, V.F. Tarasenko, Yu.N. Novoselov / Application of a KrCl-I (222nm) for identification of natural and synthetic diamonds (2009) Proc. SPIE. V.7201. - 720118-6.

D.V. Shitz, M.I. Lomaev, V.S. Skakun, V.F. Tarasenko / Large–aperture excilamps for microelectronic applications (2009) Proc. SPIE. - V.7201. - 720119-6.

Tarasenko V., Avdeev S., Erofeev M., Lomaev M., Sosnin E., Skakun V., and Shitz D. (2009) High power UV and VUV excilamps and their Applications. Acta Physica Polonica (116) 333 – 335.

Tchaikovskaya O.N., Sokolova I.V., Mayer G.V., Karetnikova E.A., Nechaev L.V., Tarasenko V.F., Sosnin E.A. (2009) The use of modern UV radiation sources for remediation of the persistent toxic substances. Atmos. Oceanic Opt. (22) 1042 – 1046.

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Tsvetkov V.M., Pikulev A.A., Sosnin E.A., Avdeev S.M. and Tarasenko V.F. (2010) Dynamic pressure jump in barrier-discharge excilamps. Technical Physics (55) 807-811.

Sosnin E.A., Avdeev S.M., Erofeev M.V., Tsvetkov V.M., Pikulev A.A., Tarasenko V.F. (2010) Study of energy characteristics of barrier discharge driven KrCl-excilamps. Bulletin of the Tomsk Polytechnic University (316) 109-112.

Project ISTC No 3583p. Technical Report on the work performed during quarter 1-15 (16 reports)

Lomaev M.I., Shitz D.V., Skakun V.S., Tarasenko V.F. VUV light sources based on a barrier discharge. Proc. of the XI Int. Symp. on the Science and Technology of Light Sources. Shanghai, China, May 20-24, 2007. - PP. 83-84.

Lomaev M.I., Tarasenko V.F, Shitz D.V. Barrier discharge excilamps steady state formation. Proc. XI. Int. Symp. on the Science and Technology of Light Sources. Shanghai, China, May 20-24, 2007. - PP. 311-312.

Lomaev M.I., Rybka D.V., Baksht E.Kh., Tarasenko V.F. High intensity VUV spontaneous light sources based on plasma emission of nanosecond high current inert gases discharge. Proc. XI. Int. Symp. on the Science and Technology of Light Sources. Shanghai, China, May 20-24, 2007. – PP. 595- 596.

Sosnin E.A., Avdeev S.M., Tarasenko V.F. OH molecular based barrier discharge lamp. Proc. of Int. Conf. ICPIG. Prague, Czech Republic, July 15 – 20, 2007. - PP. 1184-1186.

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Sosnin E.A., Tsvetkov V.M., Pikulev A.A., Avdeev S.M., Tarasenko V.F. Thermodynamics processes in DBD driven excilamps estimated by jump of pressure method: radiation intensity control. Proc. of the 12th Int. Symp. on the Science and Technology of Light Sources (Eindhoven, Netherlands, 11-16.07.2010). – 2010. - CP 150. - P. 441-442.

Tsvetkov V.M., Pikulev A.A., Sosnin E.A., Tarasenko V.F. Thermodynamics processes in DBD driven excilamps estimated by jump of pressure method: thermal power controls. Proc. of the 12th Int. Symp. on the Science and Technology of Light Sources (Eindhoven, Netherlands, 11-16.07.2010). – 2010. - CP 126. - P. 369-370.

Pikulev A.A., Tsvetkov V.M., Sosnin E.A., Tarasenko V.F. Thermodynamics processes in DBD driven excilamps estimated by jump of pressure method: investigation of acoustic waves and heat generation. Proc. of the 12th Int. Symp. on the Science and Technology of Light Sources (Eindhoven, Netherlands, 11-16.07.2010). – 2010. - CP 102. - P. 295-296.

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Tarasenko V., Avdeev S., Erofeev M., Lomaev M., Sosnin E., Skakun V., Shitz D. High- power UV and VUV excilamps and they application. Abstr. of Int. School and Conf. on Photonics (PHOTONICA 09), August 24-28, Belgrade, Serbia. - Institute of Physics, 2009. - P. 98.

**Copyright Activity**

Data from laboratory tests of the Excilamps is summarized in the two reports by Prima Environmental listed above.

Drawings and design information from this project are included in two reports.

ISTC Project No. 3583p
Water Treatment Using Advanced Ultra-Violet Light Sources Final Project Technical Report on the work performed from January 01, 2007 to June 30, 2010.

ISTC Project No. 3583p
Water Treatment Using Advanced Ultra-Violet Light Sources Final Project Activity Report on the work performed from January 01, 2007 to June 30, 2010

**Subject Inventions**

As part of this effort, the following Subject Inventions were produced by one of the Russian institutes involved with this project, The High Current Electronics Institute (HCEI):

Sosnin E.A., Tarasenko V.F., Avdeev S.M. Facility for treatment of liquids with ultraviolet radiation (Int. Cl. A61L 2/10, C02F 1/32) // RU Utility model patent No 94562, Institute of High Current Electronics SB RAS, priority date: 02.11.2008.

Sosnin E.A., Tarasenko V.F., Avdeev S.M. Gas discharge light source (Int. Cl. H01J 61/04, 61/10, 65/00) // RU invention patent, Institute of High Current Electronics SB RAS, data of filing: 02.03.2010, favorable decision: 07.04.2010.

Sosnin E.A., Schitz D.V., Tarasenko V.F. Barrier discharge lamp power supply (Int. Cl. H05B 41/282) // RU utility model patent, Institute of High Current Electronics SB RAS, data of filing: 02.03.2010, favorable decision: 22.04.2010.

**Background Intellectual Property**

No Background Intellectual Property was disclosed by either party for this project.

## G. Acknowledgement

Industrial Participant's signature of the final report indicates the following:

1) The Participant has reviewed the final report and concurs with the statements made therein.
2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures generated by his/her respective company and attributable to the project have been disclosed and included in Section E or are included on a list attached to this report.
4) The Participant certifies that if tangible personal property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.

Steve Oster, President
Teknichal Services, LLC
4/2/11
Date

William Hoppes, LLNL Principal Investigator
Lawrence Livermore National Laboratory
4/15/11
Date

for Veronica Lanier
Erik J. Stenehjem, Industrial Partnerships Director
Lawrence Livermore National Laboratory
4/20/11
Date

Attachment I – Final Abstract

# Water Treatment Using Advanced Ultraviolet Light Sources

**Final Abstract (Attachment I)**
**CRADA No. TC02089.0**
**Date Technical Work Ended: February 3, 2011**

Date: February 24, 2011 Revision: 1

## A. Parties

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## B. Purpose and Description

This was a collaborative effort between Lawrence Livermore National Security, LLC as manager and operator of Lawrence Livermore National Laboratory (LLNL) and Teknichal Services, LLC (TkS), to develop water treatment systems using advanced ultraviolet light sources. The Russian institutes involved with this project were The High Current Electronics Institute (HCEI) and Russian Institute of Technical Physics-Institute of Experimental Physics (VNIIEF). HCEI and VNIIEF developed and demonstrated the potential commercial viability of short-wavelength ultraviolet excimer lamps under a Thrust 1 Initiatives for Proliferation Prevention (IPP) Program.

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The successful demonstration of this UV source would open the door for substantial improvements in existing UV applications. Demonstration of their use in water disinfection may well open up new applications in other fields.

## C. Benefit to Industry

Industry will benefit through improved UV oxidation technology that could reduce the need for chemical additives to power plant and other industrial facility cooling water. Many energy production facilities chemically treat cooling water in order to decrease the concentration of organic and mineral solids in the system.

## D. Benefit to DOE/LLNL

DOE benefits through more efficient disinfection and treatment technology that will reduce DOE operating costs. DOE facilities must maintain the quality of water released to local treatment systems. Additionally, some DOE facilities must remediate ground water affected by their sites.

## E. Project Dates

February 3, 2006 to February 3, 2011.