LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-TR-821049

Development of Gyrosole and Solar Thermal HVAC Technology for 20-60kW Applications, CRADA No. TC02164.0

C. L. Bennett, C. Hardt

March 31, 2021

Disclaimer

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

Development of Gyrosole™ and Solar Thermal HVAC Technology for 20-60KW Applications

Final Report
CRADA No. TC02164.0
Date Technical Work Ended: June 28, 2013

Date: August 15, 2013 Revision: 1

A. Parties

This project was a relationship between Lawrence Livermore National Laboratory (LLNL) and Sol Xorce LLC.

Lawrence Livermore National Security, LLC
Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550
Charles L. Bennett
Tel: (925) 423-6131
Fax: (925) 423-8988

Sol Xorce LLC
636 Anthony Trail
Northbrook, IL 60062
Chip Hardt
Tel: (312) 515-3548
Fax: (312) 235-1110

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 Sol Xorce LLC to develop LLNL's Gyrosole™ solar thermal energy system.

The original scope of the CRADA project was to develop LLNL's Gyrosole™ thermal-powered motor technology for solar thermal energy system use, and was originally entitled, "Development of Gyrosole™ Solar Thermal Technology for 20-60 kW Applications". The scope and title of the project were later modified under Amendment One to the CRADA.

The technical objective of this CRADA project was to develop Gyrosole™ motor technology so that it is marketplace-ready, and to produce a motor prototype that:

- ✓ Produces 50kW power at >22% efficiency
- ✓ Operates oil-free

- ✓ Has sufficient reliability and lifetime to be suitable for both commercial and residential applications
- ✓ Costs less than $100 per kW installed to produce at scale
- ✓ Can be combined cost-effectively to produce 200kW

The motor prototype would be integrated into model systems that provide electricity generation in combination with air/water heating, heat-pump driven cooling, desiccant dehumidification, and light industrial heat supply.

This CRADA was originally designated as an eighteen (18) month project and consisted of eight major tasks and the following deliverables.

Bold = LLNL to SolXorce deliverable
All others: SolXorce to LLNL deliverable

Not listed, but stipulated throughout:
1. Monthly checkpoint meetings for the team, date TBD
2. The achievement of economic and technical viability goals, TBD, based on the economic model and assessment of technical risk (i.e., if they cannot be achieved with reasonable certainty, the project will stop)

Task No.	End product	Responsible party	Date Due (assumes 10/4 start)
1.1	List of 3-4 scenarios to develop and test	SX	10/15/10
1.2	Efficiency estimates and design parameters for each scenario	LLNL	**10/29/10**
1.3	Refined economic model for each scenario	SX	10/29/10
1.4	Risk management plan	SX	10/15/10
1.5	Engine designs (on paper)	SX	11/30/10
2.1	Information on relevant technologies	LLNL	**8/13/10**
2.2	List of technologies desired for further study	SX	9/3/10
2.3	*Amended* CRADA	LLNL	10/29/10
2.4	Workplans and stood-up teams	SX	**11/12/10**
2.5	Developed, tested, and integrated prototypes	SX	7/22/11
3.1	Completed receiver prototype	SX	9/10/10
3.2	Test results for prototype receiver	SX	1/14/11
3.3	Draft manufacturing plan for receiver	SX	12/23/10
4.1	List of 5-6 potential projects	SX	8/27/10
4.2	Agreed-to list of projects	SX	9/24/10
4.3.1	Signed agreement with partner 1	SX	10/29/10
4.3.2	Agreed-to workplan	SX	11/25/10
4.3.3	Required materials to complete project	SX	1/7/11
4.3.4	Installed system	SX	10/28/11
4.3.5	Tested system	SX	5/11/12

Task No.	End product	Responsible party	Date Due (assumes 10/4 start)
4.4.1	Signed agreement with partner 2	SX	10/29/10
4.4.2	Agreed-to workplan	SX	11/25/10
4.4.3	Required materials to complete project	SX	1/7/11
4.4.4	Installed system	SX	10/28/11
4.5.5	Tested system	SX	5/11/12
5.1	1-2 design candidates	SX	12/17/10
5.2	1-2 detailed designs	SX	2/25/11
5.3	For each required element or subsystem: a component	SX	2/11/11
5.4	Completed prototype(s)	SX	3/25/11
6.1	3-4 system setups	SX	4/1/11
6.2	Formal testing regime agreed to	SX	3/18/11
6.3	Instruments	SX	3/21/11
6.4	Test results (functional)	SX	6/24/11
6.5	**Agreement with testing location**	SX/LLNL	3/15/11
6.6	**Completed test system**	SX	4/15/11
6.7	Deliver system to Agreed-to location	SX	4/21/11
6.8	Performance testing data	**LLNL**	**5/27/11**
6.9	Refined prototype	SX	8/5/11
6.10	Refined model	SX	7/8/11
7.1	List of required grid testing needs	SX	4/5/11
7.2	Grid testing regimen	SX	5/4/11
7.3	Testing location under contract	SX	5/10/11
7.4	Systems set up at testing location	SX	8/19/11
7.5	Test results/qualified systems	SX	9/30/11
8.1	Materials choice and source agreed	SX	4/15/11
8.2	Manufacturing process or source	SX	6/17/11
8.3	System component acquisition	SX	6/17/11
8.4	Finalized strategy	SX	7/29/11
8.5	Manufacturing set up and ready for execution	SX	12/2/11
9.0	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/SX	6/1/12

Amendment One, executed on September 29, 2011, changed the timeline for the CRADA project and added a new scope so as to develop another of LLNL's innovations -- the Solar Thermal HVAC system -- prior to the Gyrosole™ system. In addition, the title of project was revised to reflect this change. Amendment One modified the scope and deliverables, the term of the SOW, the associated funding levels, and modified Appendix C (Intellectual Property Agreement) to change the field of use, and Appendix D (Background Intellectual Property (BIP)) to add the HVAC intellectual property and update the current filing status of the BIP. The term was

extended by nine (9) months from the original expiration date of the CRADA. All other terms and conditions remained the same.

In Amendment One, the deliverables and due dates were modified as follows:

Task No.	End Product	Responsible Party	Date Due
1.1	List of 3-4 scenarios to develop and test	SX	10/15/10
1.2	Efficiency estimates and design parameters for each scenario	LLNL	**10/29/10**
1.3	Refined economic model for each scenario	SX	10/29/10
1.4	Risk management plan	SX	1/15/12
1.5	Engine designs (on paper)	SX	2/30/12
2.1	Information on relevant technologies	LLNL	**8/13/10**
2.2	List of technologies desired for further study	SX	9/3/10
2.3	*Amended* CRADA	LLNL	09/03/11
2.4	Workplans and stood-up teams	SX	**11/12/12**
2.5	Developed, tested, and integrated prototypes	SX	7/22/12
3.1	Completed receiver prototype	SX	9/10/11
3.2	Test results for prototype receiver	SX	1/14/12
3.3	Draft manufacturing plan for receiver	SX	12/23/11
4.1	List of 5-6 potential projects	SX	11/11/11
4.2	Agreed-to list of projects	SX	12/12/11
4.3.1	Signed agreement with partner 1	SX	10/29/12
4.3.2	Agreed-to workplan	SX	11/25/12
4.3.3	Required materials to complete project	SX	1/7/13
4.3.4	Installed system	SX	10/28/12
4.3.5	Tested system	SX	5/11/13
4.4.1	Signed agreement with partner 2	SX	10/29/12
4.4.2	Agreed-to workplan	SX	11/25/12
4.4.3	Required materials to complete project	SX	1/7/13
4.4.4	Installed system	SX	10/28/13
4.5.5	Tested system	SX	5/11/14
5.1	1-2 design candidates	SX	12/17/2011
5.2	1-2 detailed designs	SX	2/25/2012
5.3	For each required element or subsystem: a component	SX	2/11/2012
5.4	Completed prototype(s)	SX	3/25/2012
6.1	3-4 system setups	SX	4/1/2012
6.2	Formal testing regime agreed to	SX	3/18/2012
6.3	Instruments	SX	3/21/2012
6.4	Test results (functional)	SX	6/24/2012
6.5	**Agreement with testing location**	SX/LLNL	3/15/2012
6.6	**Completed test system**	SX	4/15/2012
6.7	Deliver system to Agreed-to location	SX	4/21/2012
6.8	Performance testing data	**LLNL**	**5/27/2012**
6.9	Refined prototype	SX	8/5/2012
6.10	Refined model	SX	7/8/2012

7.1	List of required grid testing needs	SX	4/5/2012
7.2	Grid testing regimen	SX	5/4/2012
7.3	Testing location under contract	SX	5/10/2012
7.4	Systems set up at testing location	SX	8/19/2012
7.5	Test results/qualified systems	SX	9/30/2012
8.1	Materials choice and source agreed	SX	4/15/2012
8.2	Manufacturing process or source	SX	6/17/2012
8.3	System component acquisition	SX	6/17/2012
8.4	Finalized strategy	SX	7/29/2012
8.5	Manufacturing set up and ready for execution	SX	12/2/2012
9.0	Agreement on metrics and proof of principle specs	SX/LLNL	9/15/11
9.1	**Design for proof of principle solar HVAC system**	**LLNL**	**9/30/11**
9.2	Create Drawings and Fabricate parts	SX	6/30/12
9.3	Assemble and Test Proof of Principle HVAC system	SX	9/30/12
10.0	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/SX	1/31/13

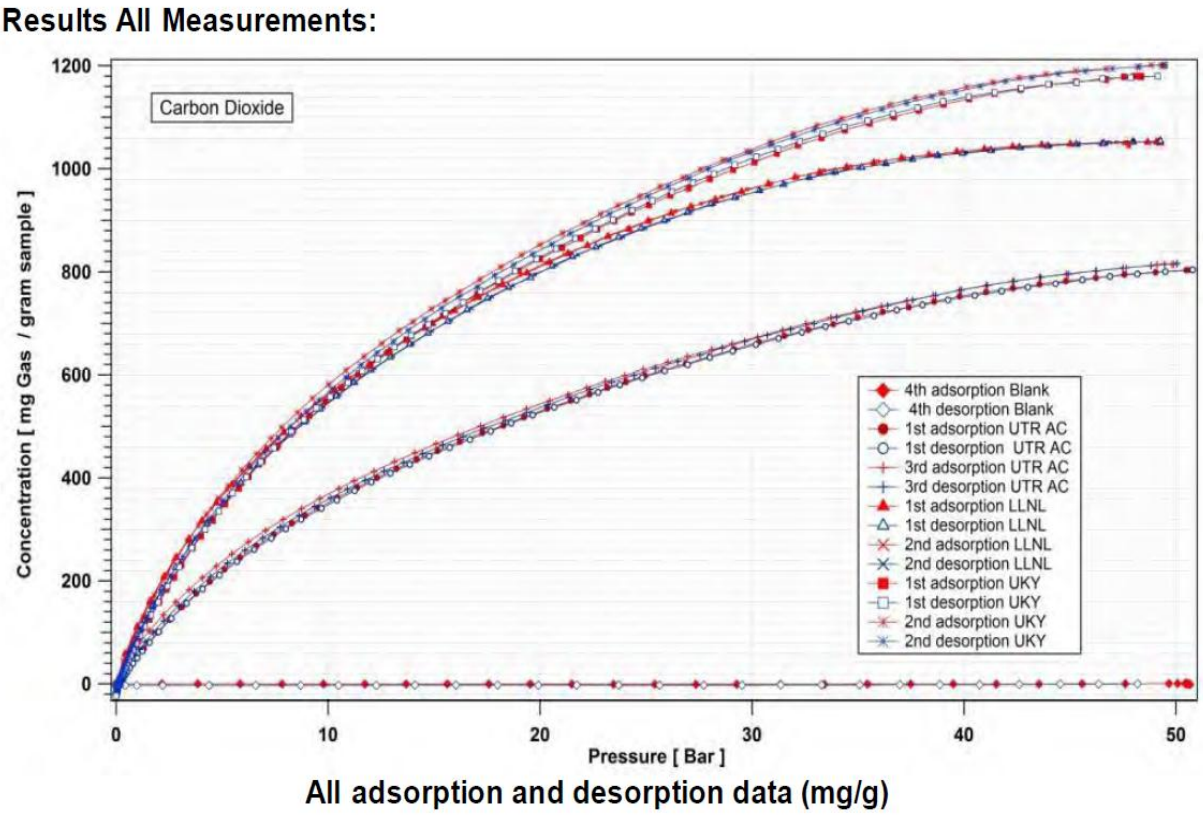
A no-cost time extension request was executed on January 17, 2013 extending the CRADA for an additional six (6) months to allow enough time to prepare and execute Amendment Two to the CRADA. Amendment Two was never executed.

Due to a change in SolXorce's direction and consequent interest in amending the CRADA, the current set of tasks were not fully funded. Only tasks 1.1 through 2.3 were successfully completed.

C. Technical Accomplishments

Charlie Bennett presented LLNL GyroSole solar thermal engine technology to SolXorce. Technical drawings and test data acquired prior to the current CRADA were shared with SolXorce. SolXorce assessed the feasibility of incorporating the technology as a "bottom end" solar thermal power generation system to its own high temperature and pressure solar thermal power generation technology. SolXorce determined that it could wait on external developments of the LLNL solar thermal technology, and under Task 2.1, reviewed other relevant technology, ultimately finding interest in LLNL's solar thermal HVAC technology. The combination of the SolXorce technology and the HVAC technology two was seen as a faster route to lower cost and low carbon footprint power and heating/cooling. The partners decided to delay the planned co-development of GyroSole in favor of the HVAC technology and amended the CRADA accordingly. The CRADA was not amended before the termination date. However, under tasks 2.1 and 2.2, LLNL supplied SolXorce with some "off the shelf" test materials. These materials were not optimized for the purpose of the HVAC materials, but served to give a very rough estimate of the minimum performance of the LLNL materials. SolXorce proceeded to obtain adsorption/desorption data for the LLNL material and other materials (Figure 1).

Figure 1. Adsorption/Desorption data for three materials, including starting material from LLNL.



Of the materials that SolXorce tested, the University of Kentucky material seemed to perform best. However, LLNL noted that experience has shown that several parameters could be modified to improve the performance of the LLNL material. SolXorce wished to understand costs which was difficult for LLNL to ascertain, even in a general sense, without taking several more steps to tailor its material to the HVAC requirements. Time had passed during these discussions and the CRADA had expired without further technical advancement.

Given the large change in scope of work, the partners had decided that should SolXorce wish to continue to collaborate with LLNL, it is appropriate to initiate a new CRADA.

D. Expected Economic Impact

SolXorce and LLNL wished to collaborate on the development of distributed solar thermal energy generation with solar thermal HVAC. SolXorce has high temperature and pressure solar thermal power generation technology and also a technology for a new generation of solar collectors. LLNL has technology for a “bottom end” solar thermal power generation system and solar thermal HVAC technology. The combination of the two was seen by the partners as a technologically feasible route to lower cost and low carbon footprint power and heating/cooling.

D.1 Specific Benefits

Benefits to DOE
This CRADA benefits DOE through the development of solar thermal power generation and solar thermal HVAC technology that can reduce energy usage.

Benefits to Industry
This CRADA benefits industry through the development of a commercially viable solar thermal technology that can reduce energy usage for American industry.

E. Participant Contribution

SolXorce and LLNL discussed the development of a system wherein the SolXorce "top end" solar thermal power generation technology could be coupled with the "low end" solar thermal power generation technology. SolXorce contracted adsorption experiments using several different candidate materials, including LLNL's tailorable carbon foam material. LLNL and SolXorce discussed next steps regarding what was needed to ameliorate results measured for the various materials. SolXorce wished to understand costs of manufacture. LLNL could provide only ballpark estimates of these costs since several developmental steps (under discussion as a possible amendment) needed to make the material useful for the purpose of solar thermal HVAC, had not yet been taken.

F. Documents/Reference List

Reports

None

Copyright Activity

None

Subject Inventions

None

Background Intellectual Property

LLNL disclosed the following Background Intellectual Property (BIP) for this project:

IL12190A, U.S. Patent pending

IL12205A, U.S. Patent pending

IL12206A, U.S. Patent pending

U.S. Patent No. 7,270,295 – *Solar Thermal Aircraft*; Inventor: Charles L. Bennett; Issue Date: 9/18/07 (IL11130A)

U.S. Patent No. 7,810,325 – *Self-Pressurizing Stirling Engine*; Inventor: Charles L. Bennett; Issue Date: 10/12/10 (IL11130B)

U.S. Patent No. 7,603,858 – *Harmonic Engine*; Inventor: Charles L. Bennett; Issue Date: 10/20/09 (IL11606A)

U.S. Patent No. 7,735,323 – *Solar Thermal Power System*; Inventor: Charles L. Bennett; Issue Date: 6/15/10 (IL11742A)

U.S. Patent No. 7,637,457 – *Rankine-Brayton Engine for Solar Thermal Aircraft*; Inventor: Charles L. Bennett; Issue Date: 12/29/09 (IL11805A)

Trademark:
Serial No. 77/286158 – Solar Thermal Power MARK: GYROSOLÈ™, Filing Date: 9/21/07 (IL11912A)

Sol Xorce has not expressed an interest in licensing the above LLNL BIP.

Sol Xorce did not disclose any BIP 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.

8/24/13

Chip Hardt, Chief Operating Officer — Date
Sol Xorce LLC

9/12/2013

Charles L. Bennett, LLNL Principal Investigator — Date
Lawrence Livermore National Laboratory

9/12/2013

Annemarie Meike, LLNL Project Manager — Date
Lawrence Livermore National Laboratory

10/1/2013

Richard Rankin, Director, Industrial Partnerships — Date
Lawrence Livermore National Laboratory

Attachment I – Final Abstract

Development of Gyrosole™ and Solar Thermal HVAC Technology for 20-60KW Applications

Final Abstract (Attachment I)
CRADA No. TC02164.0
Date Technical Work Ended: June 28, 2013

Date: August 15, 2013 Revision: 1

A. Parties

This project was a relationship between Lawrence Livermore National Laboratory (LLNL) and Sol Xorce LLC.

Lawrence Livermore National Security, LLC
Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550
Charles L. Bennett
Tel: (925) 423-6131
Fax: (925) 423-8988

Sol Xorce LLC
636 Anthony Trail
Northbrook, IL 60062
Chip Hardt
Tel: (312) 515-3548
Fax: (312) 235-1110

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 Sol Xorce LLC to develop LLNL's Gyrosole™ solar thermal energy system.

The original scope of the CRADA project was to develop LLNL's Gyrosole™ thermal-powered motor technology for solar thermal energy system use, and was originally entitled, "Development of Gyrosole™ Solar Thermal Technology for 20-60 kW Applications." The scope and title of the project were later modified under Amendment One to the CRADA.

The technical objective of this CRADA project was to develop Gyrosole™ motor technology so that it is marketplace-ready, and to produce a motor prototype that:

- ✓ Produces 50kW power at >22% efficiency
- ✓ Operates oil-free

- ✓ Has sufficient reliability and lifetime to be suitable for both commercial and residential applications
- ✓ Costs less than $100 per kW installed to produce at scale
- ✓ Can be combined cost-effectively to produce 200kW

The motor prototype would be integrated into model systems that provide electricity generation in combination with air/water heating, heat-pump driven cooling, desiccant dehumidification, and light industrial heat supply.

This CRADA was originally designated as an eighteen (18) month project and consisted of eight major tasks with subtasks and nine major deliverables.

Amendment One, executed on September 29, 2011, changed the timeline for the CRADA project and added a new scope so as to develop another of LLNL's innovations -- the Solar Thermal HVAC system -- prior to the Gyrosole™ system. In addition, the title of project was revised to reflect this change.

Due to a change in SolXorce's direction and consequent interest in amending the CRADA, the current set of tasks were not fully funded. Only tasks 1.1 through 2.3 were successfully completed. Time has passed during these discussions and the CRADA has expired without further technical advancement. Given the large change in scope of work, the partners have decided that should SolXorce wish to continue to collaborate with LLNL, it is appropriate to initiate a new CRADA.

C. Benefit to Industry

This CRADA benefits industry through the development of a commercially viable solar thermal technology that can reduce energy usage for American industry.

D. Benefit to DOE/LLNL

This CRADA benefits DOE through the development of solar thermal power generation and solar thermal HVAC technology that can reduce energy usage.

E. Project Dates

September 29, 2010 through June 29, 2013