

# Consultant Report on Onsite Molten Gallium Metal and Water Bath Calorimetry

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# Report on Onsite Molten Gallium Metal and Water Bath Calorimetry

## Statement of Assignment

I, Prof. Stephen Tse, was hired to observe tests and protocols of power-producing devices, known as SunCell®, involving molten gallium metal and water bath calorimetry of heat produced with inputs of electrical power and flowing gases into the devices. I was later given data (e.g., temperature, input voltage and current, mass flow rate of gases) acquired during testing that corresponded directly to what I observed to be taken during the tests. Based on my observations of the tests and analyses of the provided data, I was asked to deliver a Validation Report addressing the energy balances related to the power-producing cells.

## Abstract

On December 16-17, 2019, I visited Brilliant Light Power (BLP) of Cranbury, New Jersey, and observed the successful running of 3 cases involving different versions of the SunCell® reactor, on which the present report is based. Specifically, the Cases were:

1. Molten-metal-based calorimetry of a 4" cubical tungsten-liner cell with energy input from a capacitor bank. This experiment was run by Mr. Rahul Gandhi on the morning of Dec. 17; and data along with enthalpy calculations were provided.
2. Molten-metal-based calorimetry of a 4" cubical tungsten-liner cell with energy input from a capacitor bank. This experiment was run by Mr. Swapnil Mhatre on the afternoon of Dec. 17; and data were provided.
3. Water-bath-based calorimetry of an immersed 4" cubical cell without inside liner, involving a cantilever system that measures the water mass loss from evaporation. This experiment was run by Dr. Pawan Sharma on the afternoon of Dec. 17; and data were provided.

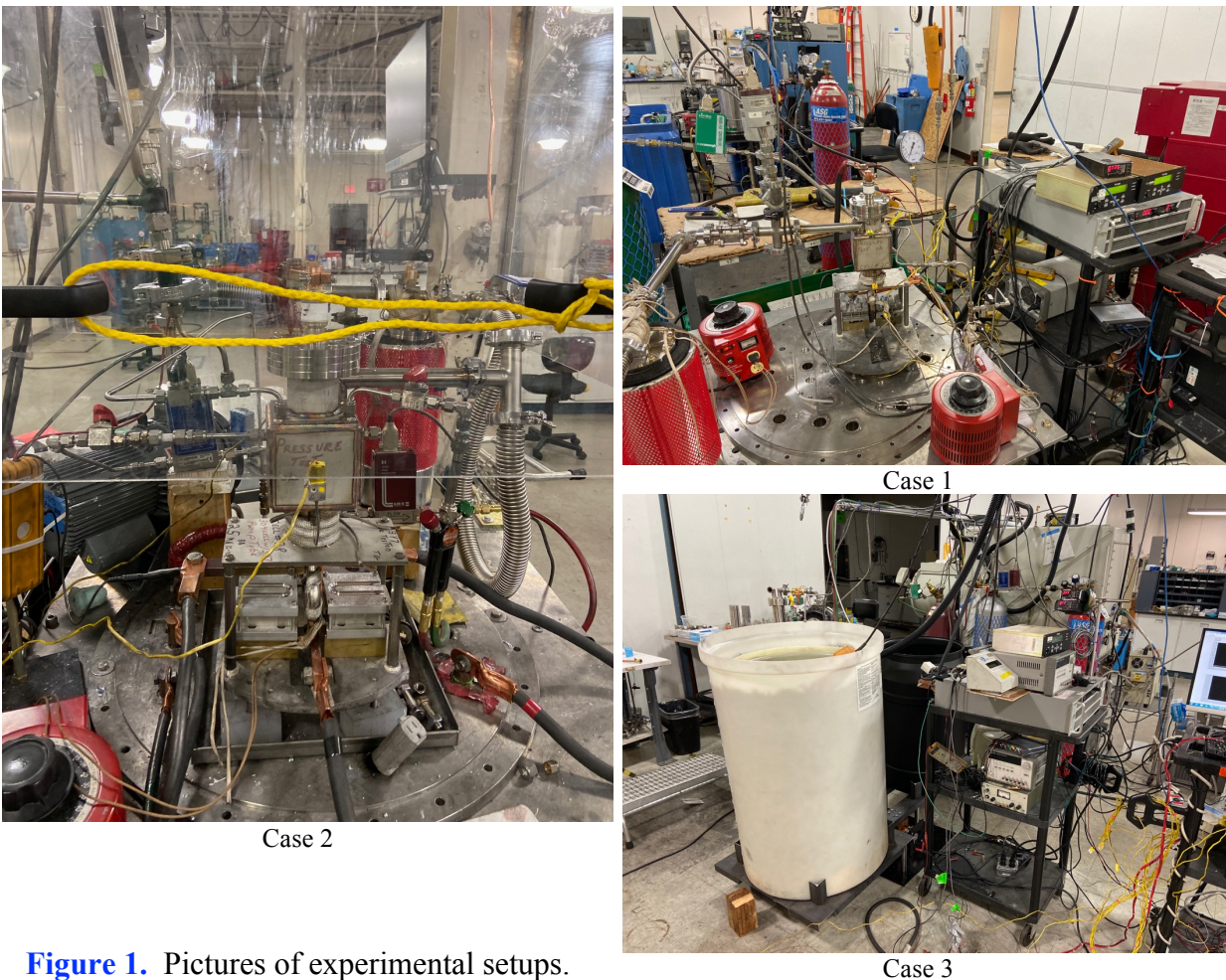
Additionally, I observed demonstration tests that elucidated the procedures and capabilities of the systems. Data for these demonstration tests were not presented to me for evaluation.

- a. Running of a 4" cubical tungsten-liner cell from a high-current low-voltage power source with H<sub>2</sub> and O<sub>2</sub> flow at 6 torr. This experiment was conducted by Mr. Swapnil Mhatre on the morning of Dec. 16.
- b. Running of a 4" cubical tungsten-liner cell from a high-current low-voltage power source with no flow but filled with 980 torr of H<sub>2</sub>. This experiment was conducted by Mr. Swapnil Mhatre on the morning of Dec. 16.
- c. Running continuously of an immersed 4" cubical cell in a water bath with H<sub>2</sub> (1000 SCCM) and O<sub>2</sub> (40 SCCM) flowing through the cell at 5.3 torr. This experiment was conducted by Dr. Pawan Sharma on the afternoon of Dec. 17.

From the former 3 Cases, where data were provided, the cells generated heat energy that were 2.51, 2.79, and 4.74 times the input electrical work energy. The enthalpies that would have been derived from conventional combustion of H<sub>2</sub> and O<sub>2</sub> gases in the cells for the 3 cases are deemed negligible and not on the order of the excess energies produced. Based on my observations and review of the data, the excess energies produced by the devices are substantial. I would note that

since the energy produced is in heat form, more than 3 times heat energy output would be likely needed to break even in terms of global net-work output, i.e., converting the produced heat back into work using a standard 33% efficient power cycle. Nevertheless, it seems that Case 3 is capable of producing global net-work output. Moreover, the operational parameters in the observed experiments can probably be optimized and adjusted to produce more excess power.

Pictures of molten-metal reaction cells used in Cases 1-3 are displayed in [Fig. 1](#).



**Figure 1.** Pictures of experimental setups.

## **Background**

### Reaction Cell

The SunCell® is a reaction cell chamber which produces significant output heat energy, operating on flowing gas reactants, i.e., atomic hydrogen and water vapor, and high-current electrical energy to form a plasma. It is based on Dr. Randell Mills' theory on the dynamics of electrons involving non-radiative stable bound states, leading to the prediction of the hydrino and reactions involving it. Briefly, liquid gallium within the cell serves both as electrode and as working fluid, with fuel for the reaction provided in the form of atomic hydrogen, with water vapor as catalyst. The atomic hydrogen and H<sub>2</sub>O are produced by flowing H<sub>2</sub> and ~1% O<sub>2</sub> into an oxyhydrogen torch, which creates a mixture that is then introduced into a heated (> 90°C) tube with granular Pt catalyst (~1g

10%Pt/Al<sub>2</sub>O<sub>3</sub> beads). The resultant reactants are then input into the cell, which is maintained at low pressure (e.g., ~5 torr).

A reservoir of molten gallium is pumped into the cell by a DC electromagnetic (EM) pump. The injector nozzle and liquid Ga serves as cathode, which is aimed at a solid tungsten (W) counter electrode serving as anode. During typical operation, the flow rate of Ga is ~40 cm<sup>3</sup>/sec. An ignition system (either capacitor bank or power supply) supplies the electrical input energy to initiate the reaction. In typical operation, 3 to 6 kA of current is input into the system. The electrical input is recorded by a high-sample-rate and high-resolution oscilloscope using a voltage differential probe and a DC Hall effect sensor.

#### Molten metal calorimetry

The output heat energy of the cell can be measured via calorimetry of the working fluid, i.e., liquid Ga, which absorbs the thermal energy released during the reaction. Other components of the cell that can absorb thermal energy are also accounted for. Two K-type ungrounded thermocouples are used to monitor the temperature response.

After the input electrical energy is shut off, the EM pump continues to circulate the liquid Ga to equilibrate any thermal gradients within the cell. This equilibrium final temperature can be used to calculate the change in temperature from the heat released, which is absorbed by the liquid Ga and other major components comprising the cell, i.e.,

$$E_{\text{stored,cell}} = \sum m_i c_{pi} \Delta T$$

where  $m_i$  [kg] is the mass of a component within the cell;  $c_{pi}$  [kJ/kg·K] is the specific heat capacity of a component; and  $\Delta T$  is the difference between final equilibrium temperature and the initial temperature [K]. Thus, a portion of the output energy can be determined by adding the cumulative stored energy values of all components within the cell.

#### Water bath calorimetry

The thermal output energy produced by a SunCell® can also be measured via calorimetry by immersing the entire cell assembly in a water bath, which better accounts for heat transfer losses from the reaction cell.

The water bath is enclosed by a cylindrical tank (22" diam. × 36" height) made out of 0.125" thick high-density polyethylene (HDPE) inserted inside a larger HDPE tank (27.5" diam. × 44" height), where the space in-between the tanks are insulated with mineral fiber wool to minimize thermal losses to the surrounding environment. The inner tank, containing the water, houses a water circulator fitted with a plastic manifold to create water jets directed at the cell for forced convection and flow-field mixing to uniformize the temperature field. The temperature of the water bath is measured using two high-accuracy digital thermistors with a resolution of 0.001°C.

Typically, the tank is filled with 40 gallons of deionized (DI) water. The water is initially held above 32°C to prevent solidification of the liquid Ga within the submerged cell. The electrical conductivity of the water is carefully monitored. A conductivity value of < 15 μS/cm is deemed

to be acceptable for curtailing electrical short circuits and cell corrosion. Otherwise the DI water is replaced if the threshold is exceeded.

The input power can be delivered via a DC switch-mode power supply with specified voltage and current set points. Or, it can be delivered via a capacitor bank comprised of 4 parallel banks of 18 capacitors in series that provided a total bank voltage capability of 51.3V with a total bank capacitance of 755.6 Farads. The energy input is calculated using point-by-point integration of the current and voltage history data over the duration of the experiment.

During the experiments, the intense thermal power generated by the cell rapidly heats its exterior walls to a temperature that gives rise to immediate flash boiling at the wall-water interface. Thus the calorimetric measurements should account for the heat of water vaporization and mass loss to steam.

The water weight loss ( $\pm 0.5$  g) is determined using a mechanical balance comprising of a 1st class lever wherein a steel frame is mounted on a cylindrical shaft with 2 rolling bearings, functioning as a fulcrum. The calorimeter is placed on one side of the lever, while an identical tank filled with about 200 kg of water is placed on the other side as a counterweight. The two tanks are fixed in place on the frame such that the moments on either side of the fulcrum are balanced. See Fig. 2. A digital scale with an accuracy of  $\pm 0.1$  g is placed under the counterweight, and the amount of water in the tanks are adjusted such that the counterbalance is slightly heavier than the calorimeter tank, with the scale reading a stable, non-zero number. The scale balances the torques on the arms of the lever in proportion to the weight differential. Calibration allows for precise measurement of weight loss from the water calorimeter tank.



**Figure 2.** Image showing weighing system composed of cantilever with (from left to right) scale, counterweight, and water-bath tank for submerged cell.

Upon completion of a test, the cell is left to cool down until it and the water bath reach an equilibrium temperature, from which the energy captured by the calorimeter can be calculated.



The water loss (+/- < 1%) measurement accounts for the heat loss from vaporization. The thermal contribution from the water circulator in the tank is accounted for in the analysis.

## Results and Discussion

### Case 1: Molten-metal-based calorimetry of a 4" cubical tungsten-liner cell with energy input from a capacitor bank (Mr. Rahul Gandhi)

The transient energy equation for a control volume (C.V.) (e.g., the reaction cell) can be expressed as:

$$\int_0^t \frac{dE_{C.V.}}{dt} dt = \int_0^t \dot{Q}_{C.V.} dt - \int_0^t \dot{W}_{C.V.} dt + \int_0^t \left[ \sum \dot{m}_i h_i \right] dt - \int_0^t \left[ \sum \dot{m}_e h_e \right] dt$$

following the thermodynamic 1<sup>st</sup> Law C.V. convention *where heat in (out) is defined as positive (negative), and work out (in) is defined as positive (negative)*.

For the period of time  $t$ , the transient process energy equation can be written as:

$$E_{1,cell} + m_1 u_1 + Q_{C.V.,in} - W_{C.V.,in} + \sum m_i h_i = E_{2,cell} + m_2 u_2 - Q_{C.V.,out} + W_{C.V.,out} + \sum m_e h_e$$

where

$E_{2,cell} - E_{1,cell}$  is the energy stored in the cell by the gallium, SS structure, electrode(s), and tungsten liner;

$Q_{C.V.,in} = 0$  (positive);

$Q_{C.V.,out}$  comprises the heat transfer losses from the cell to the surroundings (negative);

$W_{C.V.,in}$  is the electrical work input (negative);

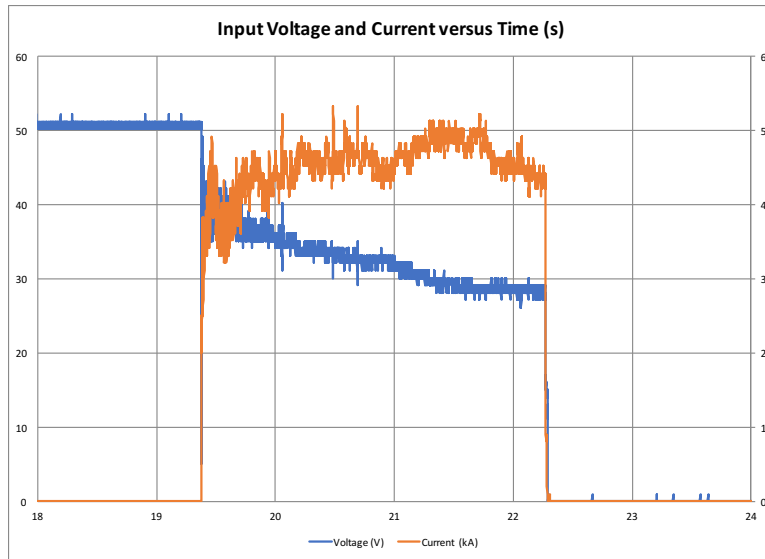
$W_{C.V.,out} = 0$  (positive);

$m_2 u_2 - m_1 u_1$  is the internal energy stored by the gas in the cell;

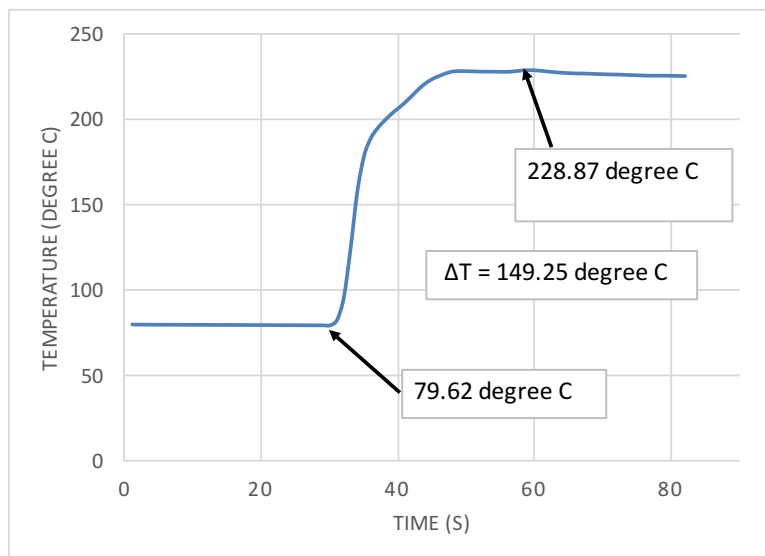
$\sum m_e h_e - \sum m_i h_i$  is the net reactant enthalpy that flows through the cell.

$W_{C.V.,in}$  can be obtained by integrating the input voltage  $\times$  current versus time curve from the data shown in Fig. 3. As mentioned in the Background Section,  $E_{2,cell} - E_{1,cell}$  (which is  $E_{\text{stored,cell}}$ ) can be obtained by  $\sum m_i c_{pi} \Delta T$  of all the components of the cell (see Table 1), with the initial and final temperatures determined by the plot in Fig. 4.

NB: For  $Q_{C.V.,out}$ , i.e., heat transfer losses from the cell to the surroundings (negative), it was determined through calibration experiments by BLP, where there was no plasma reaction, that the losses were about 25% of the energy stored by the components making up the cell. As such, this factor is used for heat losses; however, more detailed heat transfer analyses and measurements should be conducted to assess better this value. Such estimation of the heat losses from the cell to the surroundings has the largest margin of error in the energy balance calculation.



**Figure 3.** Input voltage and current history plots into the cell.



**Figure 4.** Temperature history plot of gallium response, with 79.62°C initial temperature, 228.87°C final temperature, and 149.25°C change in temperature.

**Table 1.** Individual weights and corresponding specific heats of components comprising the cell.

Component	Weight [kg]	Specific heat [kJ/(kg·°C)]
Gallium	2.5	0.383
Stainless steel cell	6.5	0.5024
Stainless steel electrode component	1.26	0.5024
Tungsten electrode component	1.52	0.1339
Copper electrode component	0.369	0.39
Boron Nitride electrode component	0.22	0.85
Tungsten liner weight	2.1	0.1339

Therefore, to assess *the enthalpy released by the plasma reaction*, we can rearrange the energy equation, such that:

$$\left[ \sum m_e h_e - \sum m_i h_i \right] = -(E_{2,cell} - E_{1,cell}) - (m_2 u_2 - m_1 u_1) + Q_{C.V.,out} - W_{C.V.,in}$$

Table 2 gives the values of the energy terms from the analysis and extracted data provided by BLP (Mr. Gandhi), for a gallium change in temperature of 149.25°C. The electrical work input duration is 2.917s.

**Table 2.** Calculated values of energy terms in the “double boxed” energy equation with reaction cell as C.V. for Case 1.

Energy term	Value
$(E_{2,cell} - E_{1,cell})$	846.5 kJ
$(m_2 u_2 - m_1 u_1)$	0 kJ (Assumed negligible given the low pressure (~5 torr) and low heat capacity of the gas compared with those of the solid components of the cell)
$Q_{C.V.,out}$	-211.625 kJ (= -846.5 kJ × 0.25)
$W_{C.V.,in}$	-422.1 kJ
$\left[ \sum m_e h_e - \sum m_i h_i \right]$	-636.025 kJ (exothermic)
$\left[ -(E_{2,cell} - E_{1,cell}) - (m_2 u_2 - m_1 u_1) + Q_{C.V.,out} \right]$	-1058.125 kJ

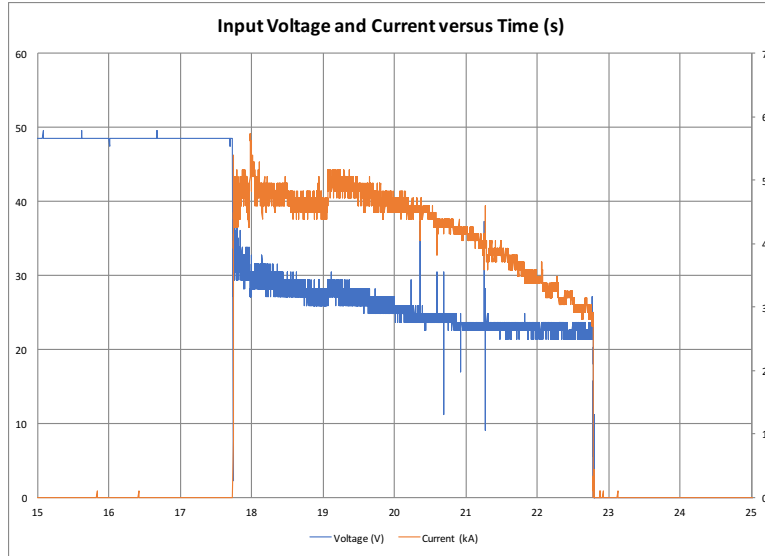
Therefore,  $\frac{\text{output heat (including energy going into storage)}}{\text{input work}} = \frac{-1058.125 \text{ kJ}}{-422.1 \text{ kJ}} = 2.51$ .

The flow rates of H<sub>2</sub> and O<sub>2</sub> into the reaction cell are 6000 SCCM and 110 SCCM, respectively. With O<sub>2</sub> serving as the limiting reactant, conventional combustion would produce an average of -46.8 W (exothermic) over 2.917s, resulting in -0.136 kJ. As seen in Table 2, the excess heat produced by the reaction cell is -636.025 kJ (exothermic), or an average excess power of -218 kW, constituting a very substantial difference.

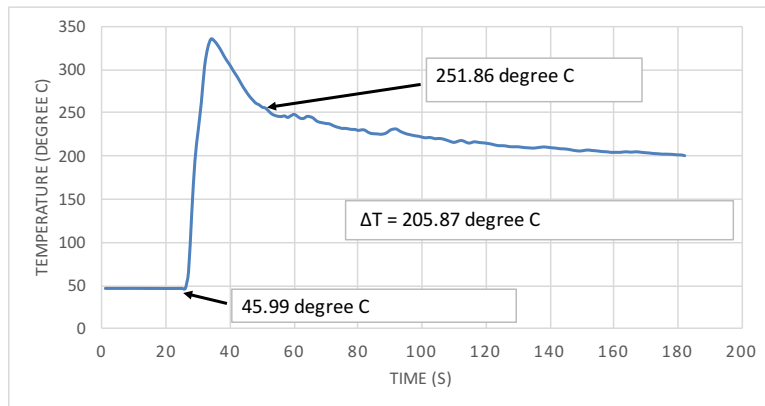
Case 2: Molten-metal-based calorimetry of a 4" cubical tungsten-liner cell with energy input from a capacitor bank (Mr. Swapnil Mhatre)

The input electrical power and gallium temperature responses versus time of the experiment are given in Figs. 5 and 6, respectively. As mentioned in the Background Section,  $E_{2,cell} - E_{1,cell}$  (which is  $E_{\text{stored,cell}}$ ) can be obtained by  $\sum m_i c_{pi} \Delta T$  of all the components of the cell (see Table 3), with the initial and final temperatures determined by the plot in Fig. 6.





**Figure 5.** Input voltage and current versus time (s) into the cell.



**Figure 6.** Temperature plot of gallium response, with 45.99°C initial temperature, 251.86°C final temperature, and 205.87°C change in temperature.

**Table 3.** Individual weights and corresponding specific heats of components comprising the cell.

Component	Weight [kg]	Specific heat [kJ/(kg·°C)]
Gallium	3.4	0.383
Stainless steel cell	6.5	0.5024
Stainless steel electrode component	1.26	0.5024
Tungsten electrode component	1.52	0.1339
Copper electrode component	0.369	0.39
Boron Nitride electrode component	0.22	0.85
Tungsten liner weight	2.1	0.1339

Using the same “double boxed” thermodynamic equation as in Case 1 for *the enthalpy released by the plasma reaction* with the reaction cell as a control volume (C.V.), [Table 4](#) gives the values of the energy terms from the preliminary analysis and extracted data provided by BLP (Mr. Mhatre), for a gallium change in temperature of 205.87°C. The electrical work input duration is 5.055s.

**Table 4.** Calculated values of energy terms in the “double boxed” energy equation with reaction cell as C.V. for Case 2.

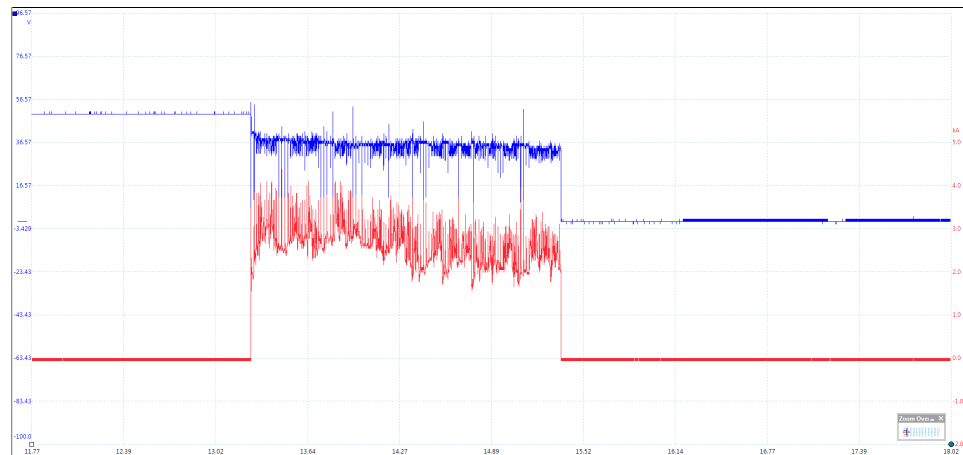
Energy term	Value
$(E_{2,cell} - E_{1,cell})$	1238.6 kJ
$(m_2u_2 - m_1u_1)$	0 kJ (Assumed negligible given the low pressure (3.14 torr) and low heat capacity of the gas compared with those of the solid components of the cell)
$Q_{C.V.,out}$	-309.5 kJ (= -1238 kJ × 0.25)
$W_{C.V.,in}$	-554.7 kJ
$\left[ \sum m_e h_e - \sum m_i h_i \right]$	-993.4 kJ (exothermic)
$\left[ -(E_{2,cell} - E_{1,cell}) - (m_2u_2 - m_1u_1) + Q_{C.V.,out} \right]$	-1548.1 kJ

Therefore,  $\frac{\text{output heat (including energy going into storage)}}{\text{input work}} = \frac{-1548.1 \text{ kJ}}{-554.7 \text{ kJ}} = 2.79$ .

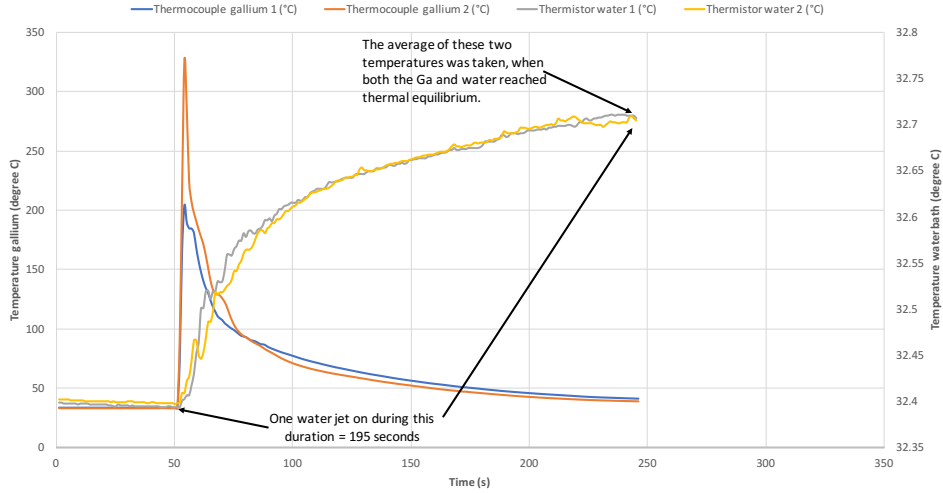
The flow rates of H<sub>2</sub> and O<sub>2</sub> into the reaction cell are 4000 SCCM and 50 SCCM, respectively. With O<sub>2</sub> serving as the limiting reactant, conventional combustion would produce an average of -21.28 W (exothermic) over 5.055s, resulting in -0.1075 kJ. As seen in Table 4, the excess heat produced by the reaction cell is -993.4 kJ (exothermic), or an average excess power of -196.5 kW, representing an extremely sizeable difference.

Case 3: Water-bath-based calorimetry of an immersed 4" cubical cell without inside liner, involving a cantilever system that measures the water mass loss from evaporation (Dr. Pawan Sharma)

Here, the entire reaction cell is immersed in a large (~40 gallon) cold water bath, providing a more accurate assessment of the heat transfer losses from the cell. The input electrical power versus time of the experiment can be calculated from the data given in Fig. 7. The temperature histories of the gallium in the cell and the encompassing water bath are shown in Fig. 8.



**Figure 7.** Input voltage and current versus time (s) into the cell.



**Figure 8.** Cell (gallium) and water bath temperature traces for experiment.

For the period of time  $t$ , the transient process energy equation for the **water bath** as C.V. can be reduced to:

$$m_1 u_1 + Q_{C.V.,in} + Q_{circulator} = m_2 u_2 + m_e h_e$$

where

$$-[Q_{C.V.,out}]_{cell} = [Q_{C.V.,in}]_{water\ bath};$$

$m_2 u_2 - m_1 u_1$  is the internal energy stored by the liquid water bath;

$m_e = m_1 - m_2$  is the mass lost from the bath by water vaporization because of the hot cell;

$m_e h_e$  is the enthalpy of steam (assumed to be 100°C) leaving the water bath at 1 atm.

Table 5 gives the values of the energy terms based on the analysis and extracted data provided by BLP (Dr. Sharma), for a water bath change in temperature of 0.3095°C, as deduced from Fig. 8. The initial mass of water is 153.20 kg. The mass of water lost is measured to be 268.5 g. The enthalpy of steam at 100°C at atmospheric pressure is 2676.05 kJ/kg.

**Table 5.** Calculated values of energy terms in the “single boxed” energy equation with water bath as C.V. for Case 3.

Energy term	Value
$(m_2 u_2 - m_1 u_1)$	198 kJ
$Q_{circulator}$	39.0 kJ
$m_e h_e$	718.5 kJ
$Q_{C.V.,in}$	877.5 kJ

Again, using the previously shown “double boxed” thermodynamic equation for **the enthalpy released by the plasma reaction** with the cell as C.V., Table 6 gives the values of the energy terms based on the analysis and extracted data provided by BLP (Dr. Sharma), for a gallium change in

temperature of 6.8°C as deduced from Fig. 8. The electrical work input duration is 2.115 s. Since a list of individual weights and corresponding specific heats of components comprising the cell were not provided for this experiment, average values from the two previous cases minus the tungsten liner are used for the calculation.

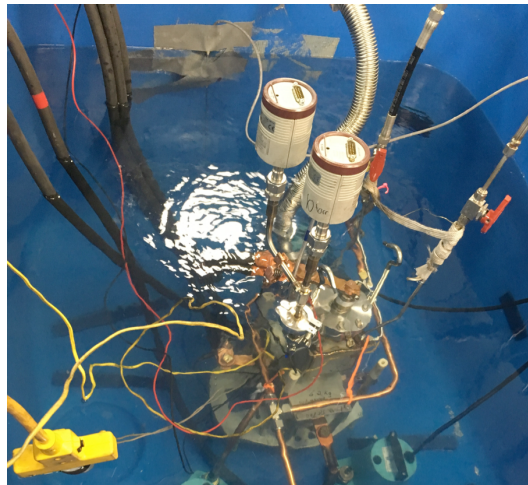
**Table 6.** Calculated values of energy terms in the “double boxed” energy equation with reaction cell as C.V. for Case 3.

Energy term	Value
$(E_{2,cell} - E_{1,cell})$	37.85 kJ
$(m_2u_2 - m_1u_1)$	0 kJ (Assumed negligible given the low pressure (5.3 torr) and low heat capacity of the gas compared with those of the solid components of the cell)
$Q_{C.V.,out}$	-877.5 kJ (from water bath calculation)
$W_{C.V.,in}$	-192.95 kJ
$\left[ \sum m_e h_e - \sum m_i h_i \right]$	-722.4 kJ (exothermic)
$\left[ -(E_{2,cell} - E_{1,cell}) - (m_2u_2 - m_1u_1) + Q_{C.V.,out} \right]$	-915.35 kJ

Therefore,  $\frac{\text{output heat (including energy going into storage)}}{\text{input work}} = \frac{-915.35 \text{ kJ}}{-192.95 \text{ kJ}} = 4.74$ .

The flow rates of H<sub>2</sub> and O<sub>2</sub> into the reaction cell are 3000 SCCM and 50 SCCM, respectively. With O<sub>2</sub> serving as the limiting reactant, conventional combustion would produce an average of -21.28 W (exothermic) over 2.115s, resulting in -0.045 kJ. As seen in Table 6, the excess heat produced by the reaction cell is -722.4 kJ (exothermic), or an average excess power of -341.56 kW, presenting a very large difference.

### Demonstration tests

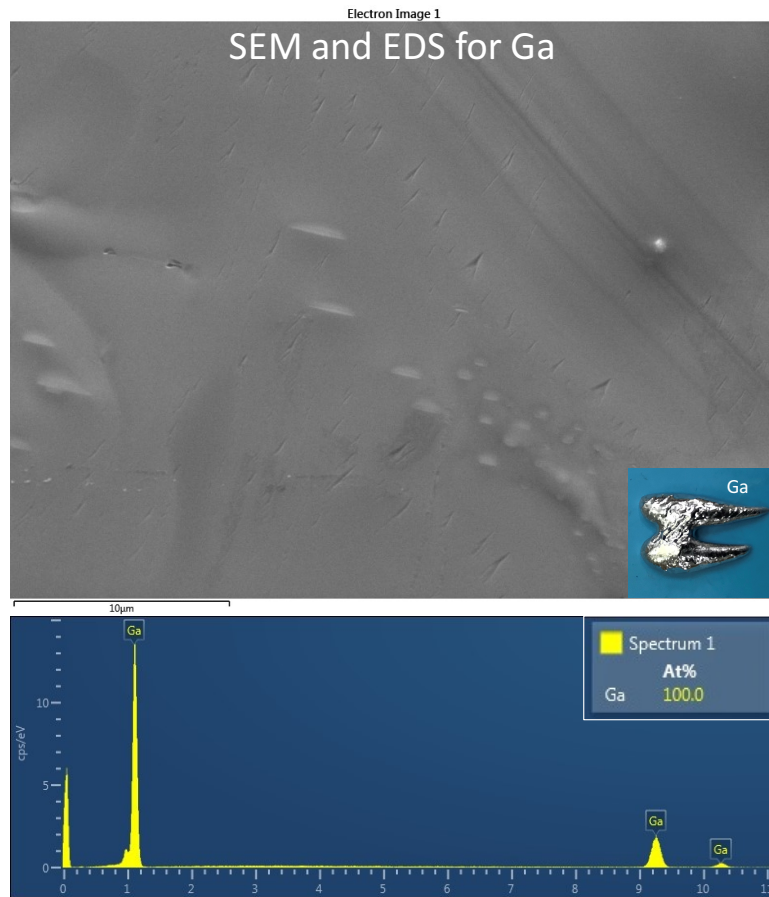


**Figure 9.** Image of reaction cell submerged in water running for an extended duration.

Demonstration Tests a and b running a 4" cubical tungsten-liner cell from a high-current low-voltage power source, as conducted by Mr. Mhatre, clearly showed the protocols and capabilities of the system. The cell pressures were not optimal for plasma reactions, hence data for the tests were not analyzed. Demonstration Test c (Fig. 9) running for long duration of an immersed 4" cubical cell in a water bath evinced the practical potential of the system.

#### Other considerations

Energy dispersive X-ray spectroscopy (EDS) was conducted on gallium samples before and after an experiment. The results reveal no chemical change in the liquid gallium composition, as shown Fig. 10.



**Figure 10.** SEM and EDS of gallium after an experiment run.

#### **Conclusions**

Brilliant Light Power has developed a novel power device, known as the liquid gallium SunCell®, which generates an excess amount of output heat from input electrical work. For 3 cases that I witnessed running and was provided input and output data along with preliminary analyses, the cells generated heat that were 2.51, 2.79, and 4.74 times the input electrical work. The former two cases utilized molten-metal calorimetry to evaluate their output energies, while the latter single case employed water bath calorimetry. Since the cells are very hot during operation, I believe that

heat losses from them to the surroundings may not be sufficiently assessed in the molten-metal-calorimetry analyses. For the water-bath-calorimetry analysis, the much higher ratio of output heat to input work (i.e., 4.74) is likely more appropriate since heat losses to the water bath can be better evaluated. Furthermore, the calculated gain may be larger if superheated steam is considered to arise from the observed flash boiling at the cell-wall/water-bath interface, rather than the saturated steam assumed in my analysis. I would suggest using less water (e.g., 20 gal versus 40 gal) in the water-bath-calorimetry tests to resolve better the change in temperature of the water, improving accuracy.

EDS data shows that there is no reaction of the working-fluid gallium in the process to account for the output heat. The reaction enthalpies that would have resulted from typical combustion of the H<sub>2</sub> and O<sub>2</sub> gases flowing through the cells for the 3 cases are regarded as insignificant and not on the order of the excess energy produced. Analyses of the results indicate other explanations are needed for the observed energy releases, for which Dr. Mills' theory could be tested along with more experimental measurements, e.g., spectroscopy-based.

In observing the experiments at BLP, I approve of the protocols and approaches used in running the cells, which were conducted carefully with real and reproducible results. Proper considerations were made to eschew experimental and analytical bias.

Based on my observations of the experiments and evaluation of the supplied data, the excess energies produced by the devices are significant. As aforementioned, cases like the water-bath-calorimetry one where the output heat gain is more than 3 times the input work would be needed to make the devices commercially viable.