



Review Article

# Review of Seebeck Calorimeters Used in LENR Experiments

Bengisu Sisik and David J. Nagel\*

*The George Washington University, 725 23rd Street NW, Washington DC 20052, USA*

---

## Abstract

Cold Fusion is the name initially applied to what are now called, more generally, Low Energy Nuclear Reactions (LENR). Such reactions produce nuclear products and generate thermal energy. Calorimeters are the instruments used to measure the energy production. They can be based on either mass or heat flow. Some heat flow calorimeters use the Seebeck effect in particular materials, where temperature differences produced by LENR generate measurable voltages from thermoelectric devices. This paper is a review of Seebeck calorimeters that have been used in LENR experiments. Compilations of their characteristics and performance are provided. The scaling of the performance of Seebeck calorimeters with their size is considered. The equations that govern the behavior of both mass flow and heat flow calorimeters are given.

© 2020 ISCMNS. All rights reserved. ISSN 2227-3123

*Keywords:* Calorimeters, Isoperibolic calorimeters, LENR, Low energy nuclear reactions, Mass flow calorimeters, Seebeck calorimeters

---

## 1. Introduction

The Low Energy Nuclear Reaction (LENR) experiments produce a few minor and two major effects. The lesser outputs are some energetic radiations, infrared emission and sound production. The major results are reaction products and thermal energy. The transmutation products are scientifically useful, since they indicate which reactions might have occurred. They are measured with a wide variety of analytical techniques [1]. It is unclear now whether or not the reaction products will be commercially important. The thermal energy has great practical promise as a new source of clean energy. It is quantified by the use of calorimeters of various designs and properties.

This review considers reports where Seebeck calorimeters were used for quantification of LENR thermal power. To set such calorimeters in context, the next section surveys calorimetry in general and, more specifically, the types of calorimeters that have been used in LENR experiments. Seebeck calorimeters are based on thermoelectric materials that exhibit the Seebeck effect and its inverse, the Peltier effect. In the latter, the application of voltages to devices containing thermoelectric materials makes it possible to pump heat from one face of the device to the other. In the Seebeck effect, a temperature difference across the device faces results in an output voltage. One device can be used for both of the reciprocal effects. The third section reviews thermoelectric devices and closely related thermocouples.

---

\*Corresponding author. E-mail: nagel@gwu.edu.

With that background, LENR papers about Seebeck calorimeters are summarized in the fourth section. Their physical and other characteristics, and measures of their performance, are the subject of the fifth section. A simple analytical approach to the geometrical scaling of Seebeck calorimeters is given in Section 6. The last section sketches the characteristics of a new Seebeck calorimeter being built for our LENR laboratory.

## 2. Types and Features of LENR Calorimeters

Calorimetry is both an old and widely used approach to measuring the release of energy. It is employed for assessment of energy released by physical processes, notably radioactive decay. Calorimetry is most commonly used for the quantification of heat from chemical reactions. Foods can be thought of as unreacted chemicals. Measurement of the energy content of foods is routine in some countries, where the caloric content of foods must be on packages.

In general terms, a calorimeter is a vessel in which some heat-releasing reaction occurs, leading to an increase in temperature of the contents of the calorimeter. The temperature increase is usually referenced to some constant-temperature part of the overall calorimeter system. The increase in temperature can be quantified in a variety of ways. A major and universal limitation of calorimeters is their relatively slow response to sudden heat releases due to the time it takes for heat transfer from the source to the calorimeter or from the calorimeter to the surrounding media. The response time constants of most LENR calorimeters are in the range of tens of minutes. Consider the cooling of a cup of hot coffee on a table to gain some appreciation of the slow response time of calorimeters.

Many different types of calorimeters were used in the years following the 1989 announcement by Fleischmann and Pons that they were able to use (low) chemical energies to trigger (high) nuclear energies. They performed “cold fusion” experiments within electrochemical cells inside of calorimeters [2]. The electrochemical cells contained heavy water, which was electrolyzed into deuterium and oxygen. The deuterium interacted with a metal cathode, usually palladium, to produce heat-releasing LENR reactions. The calorimeter was calibrated to permit quantification of the power and energy from the LENR. A review of many of those types of calorimeters was featured in a session of the *14th International Conference on Cold Fusion* in 2008 [3]. Both books by Storms have useful discussions of calorimeters employed in LENR experiments [4,5]. There are many published or posted papers on the design and performance of diverse LENR calorimeters. We will not consider all known possibilities, but instead will review the most used and important types of LENR calorimeters. The Appendix contains a qualitative comparison of the three major types of the LENR calorimeters.

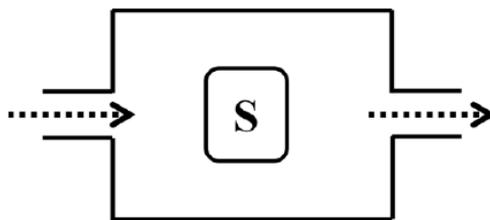
During the past thirty years of the experimental study of LENR, a few basic calorimeter designs have stood the test of time, and are still in use. They fall into two major categories, Mass Flow Calorimeters and Heat Flow Calorimeters. Each is considered in the remainder of this section.

### 2.1. Mass flow calorimeters

In mass flow systems, the heat produced by electrical, chemical or nuclear means is transferred directly to a liquid that surrounds and flows past the reaction volume. Figure 1 is a simple schematic of such a system. The energy  $\Delta E$  produced and transferred by conduction to the liquid raises the temperature of the liquid  $\Delta T$ . The governing equation is

$$\Delta E = M C_p \Delta T \quad \text{or} \quad \Delta P = \frac{dM}{dt} C_p \Delta T, \quad (1)$$

where  $dM$  is the mass of the liquid that flows through the calorimeter in time period  $dt$ ,  $C_p$  is the specific heat of the liquid and  $P$  is the transferred thermal power. Measurements of the flow rate ( $dM/dt$ ) and the input and output temperatures of the liquid enable calculation of the generated power  $\Delta P$ , all as a function of time.



**Figure 1.** Schematic of a mass flow calorimeter, showing the liquid flowing into and out of a chamber surrounding the heat source S. Not shown are the temperature sensors at the inlet and outlet, or the means of measuring the flow rate.

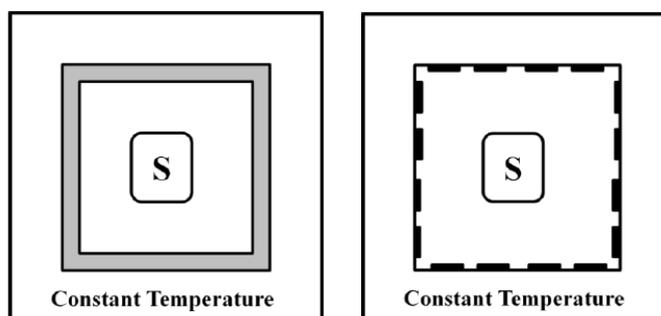
The mass flow rate can be determined with flow meters, or more precisely, by weighing. The temperatures of the liquid are measured by any temperature sensors, such as thermocouples (TC) or resistance thermal detectors (RTD). Modern mass flow calorimeters use digital scales, and digitize the temperature readings for computer recording. Mass flow calorimeters with water as the working fluid have been used extensively by McKubre and his colleagues [6]. Oil flow systems are employed for operation at temperatures higher than the boiling point of water. They are employed by a Japanese collaboration, which is using nano-scale materials for LENR experiments in the range of 200–300°C [7]. The response time of mass flow calorimeters is determined by the time needed to transport thermal energy from within the calorimeter to the surrounding flowing liquid. Mass flow calorimeters have an important advantage, since they do not require a stable temperature reference.

## 2.2. Heat flow calorimeters

These systems can be contrasted with mass flow calorimeters in two ways. The first is the fact that they require a stable temperature reference. It is often a water bath, but can also be solids, the temperature of which is controlled by an active (feedback) thermoelectric system. And, they seek to either restrict or exploit energy flow to their surroundings. The result of internal energy releases of any kind within a heat flow calorimeter is an increase in temperature of the contents of the reaction vessel. There are two major types of LENR Heat Flow calorimeters, Isoperibolic calorimeters [2] and Seebeck calorimeters [3,4]. Both have constant temperature surroundings, but they differ in what is measured to determine LENR power production. With Isoperibolic calorimeters, the temperature of the contents of the LENR cell provides the data to compute the rate of nuclear energy generation as a function of time [8]. They can be used with closed LENR cells, where a recombiner catalyzes the combination of any hydrogen (deuterium) and oxygen to avoid explosions, or in an open configuration, where the gases are permitted to escape from the cell and calorimeter. For Seebeck calorimeters, the produced LENR energy is conducted through active thermoelectric elements, providing the raw voltage data for power history determinations [9,10]. Such calorimeters are generally used with closed LENR cells having recombiners. Such calorimeters are named after Thomas Seebeck, an Estonian, German physicist, who discovered in 1821 that the junctions between dissimilar metals produce voltages when they are heated [11]. Both variants of heat flow calorimeters are considered in the following paragraphs.

### 2.2.1. Isoperibolic calorimeters

Figure 2 contains a simple schematic of an isoperibolic calorimeter. Heat flows from the source to the gas or liquid inside of the calorimeter, and thence, through the insulation to the constant temperature region. Measurements of the internal cell temperature as a function of time can be converted into data on the internally generated power, also as a function of time. The simplest equation for an isoperibolic heat flow calorimeter is:



**Figure 2.** Schematics of two types of heat flow calorimeters surrounding a heat source S, an Isoperibolic calorimeter on the *left* and a Seebeck calorimeter on the *right*. The Isoperibolic calorimeter consists of a thermal barrier, shown in *grey*. The interior air or liquid of the calorimeter is heated by the source, which raises the internal temperature. That temperature as a function of time is the output data. The Seebeck calorimeter consists of walls held at constant temperature, which are covered by small thermoelectric elements shown in *black*. Their voltage, also measured as a function of time, constitutes the output signal. It depends on the temperature difference between the interior of the Seebeck calorimeter and the colder outside temperature.

$$M C_p \frac{dT}{dt} = \text{Input powers} - \text{Output thermal power}, \quad (2)$$

where  $M$  is the mass of the contents of the reaction vessel,  $C_p$  is the specific heat of those contents and  $(dT/dt)$  is the rate of change of the internal temperature. The input electrical power needed to free the protons from light water or the deuterons from heavy water can be written as  $I(V_c - V_h)$ , where  $I$  is the usually constant electrical current,  $V_c$  is the voltage across the electrochemical cell and  $V_h$  is the thermoneutral potential for electrolysis of water. Any power due to LENR is also part of the input power.

The output thermal power term is different for conductive or radiative losses. In the case of conduction, it is  $K_c (T - T_b)$ , where  $K_c$  is a “cell constant” in  $W/^\circ C$ , which can be determined in multiple ways. They include (a) measuring the slope of the cell temperature vs. input electrical power calibration curve, (b) fitting an analytical equation to the cooling history of a cell after the input power is turned off or (c) computing the constant from the conductivity and geometry of the thermal barrier. The  $T_b$  is the temperature of the usually water bath surrounding a heat flow calorimeter.

Conductive heat flow calorimeters have been used often in LENR experiments by Miles and others [12]. Radiative heat loss, without significant conduction is possible by the use of Dewar calorimeters, which have two walls with a vacuum between them, and cannot support conduction. The original Fleischmann and Pons calorimeters were such Dewars [2]. For them, the output thermal power term is  $K_r (T^4 - T_b^4)$ , where  $K_r$  is the coefficient for radiative heat transfer and the fourth power dependence is due to the Stefan–Boltzmann law. Like conductive systems, the radiative systems also required a stable outside temperature, usually a water bath. For both conductive and radiative heat flow calorimeters, the response times (time constants) are determined by the time it takes for the contents of the system to be transferred from the interior to the surroundings.

Equation (2) has two types of deficiencies. The first deals with the existing terms. There are multiple materials within the calorimeter. For electrolytic experiments, they include the electrolyte, metal electrodes and leads, plastic holders and electrical lead covers, a glass test tube and the oil. For Seebeck systems, they include those items, and also the air within the calorimeter. So, the first term is actually a sum of  $MC_p$  products,  $\Sigma M_i C_{p_i}$ .  $V_H$  is not constant

and varies during loading. And, the cell constant is sensitive to the electrolyte level. Secondly, there are two missing terms, one for work done on the atmosphere by the bubbles and the other for energy carried out of the open cell by the gases. These terms are small for low input powers and temperatures [13].

Given the above considerations, the equation for an isoperibolic calorimeter can be written, for low power operation, as:

$$\sum M_i C_{pi} \frac{dT}{dt} = I(V - V_h) + P_{LENR} - K_c (T - T_b). \quad (3)$$

The only unknown in this equation is  $P_{LENR}$ . The masses, specific heats and  $V_h$  are known from construction and tables. The cell constant is known from any of the methods already noted above. During a run, the input electrolysis current and voltage are measured. Both the cell temperature  $T$  and the bath temperature  $T_b$  are also measured as a function of time. If temperature readings from the cell are taken frequently, such as every second, then it is possible to smooth the  $T(t)$  readings and fit them with an analytical curve to obtain good values for  $(dT/dt)$ .

### 2.2.2. Seebeck calorimeters

Figure 2 contains a schematic of a Seebeck heat flow calorimeter. Such heat flow calorimeter systems are containers, the walls of which are covered with thermoelectric devices or thermocouples (both called TE elements). Heat flows from the source to the interior air, and then through the thermoelectric elements to the constant temperature region. Experiments performed within Seebeck Calorimeters produce heat by (a) the electrolysis needed to free protons or deuterons for LENR, (b) one or more fans that are always on to produce a uniform internal air temperature, (c) resistive heaters to provide calibrations before, during or after LENR runs, and (d) the LENR. The action of these heat sources raises the temperature of one side of the TE devices relative to the other side, which is heat-sunked to the exterior reference temperature. Walls with water cooling or other means of producing a uniform temperature, such as the use of TE elements as heat pumps, are common. The voltages produced by individual TE elements are added by connecting them in series. The resistance of the TE elements is ignorable because virtually no current flows through them due to the high impedance of voltage measuring devices.

Like most instruments, Seebeck calorimeters have advantages and disadvantages. They can have larger internal volumes than other calorimeters. Seebeck calorimeters provide an alternative means of calorimetry, with a few different challenges to accurate measurements. Thermoelectric Devices and Thermocouples can respond quickly to changes in temperature. Like all calorimeters, Seebeck systems require understanding and calibration. The response time is set by thermal conductivity out of the LENR cell into the air within the Seebeck calorimeter.

Storms published an equation for performance of Seebeck calorimeters [14]. He wrote “Excess power (EP) is calculated according to the equation:

$$EP = A + B * V + C * V^2 - V_c * I_c - V_f * I_f \quad (4)$$

where  $V$  is the Seebeck voltage,  $V_c$  the voltage between the anode and cathode,  $I_c$  the current passing through the cell,  $V_f$  the voltage applied to the fans,  $I_f$  the current passing through the fans, and  $A$ ,  $B$ , and  $C$  are constants obtained from calibrations”.

Another approach to the equation for a Seebeck calorimeter is based on the concept behind Eq. (2). There, the energy deposited within the calorimeter in some unit of time, that is, the net input power, is the difference between the total power entering the calorimeter and the thermal power leaving the calorimeter. As already noted, the increase in energy within the instrument in the time increment is the sum of the products of the interior masses and specific heats, times the rate of temperature change. Unlike most mass flow or isoperibolic calorimeters, there is a substantial volume of air within a Seebeck calorimeter. If both the Seebeck calorimeter and the interior experiment are taken to be cubic,

and it is assumed that the length of the side of the experiment is 10% of the length of a side of the calorimeter, the heat capacity of the air is about 3% of the heat capacity of the experiment, assumed to be all water.

The input power to Seebeck calorimeter with a fan to homogenize the internal air temperature can be written as:

$$P_{\text{in}} = I(V_c - V_h) + I_f V_f + P_{\text{LENR}} \quad (5)$$

The first term is the power needed for electrolysis of the light or heavy water in the LENR experiment, as above for isoperibolic calorimeters. The fan power is the product of the fan current  $I_f$  and voltage  $V_f$ , and  $P_{\text{LENR}}$  is the LENR power. The power exiting the calorimeter consists of (a) that passing by conduction through the TE modules, if they are used, (b) that passing through the parts of surfaces not covered with TE modules, also by conduction, and (c) power that is conducted through any other path, such as electrical or fluidic feedthroughs. If thermocouples, rather than TE modules, are used in a Seebeck calorimeter, the power exits by conduction through the four walls, top and bottom of the calorimeter. In either case, the overall Seebeck Calorimeter equation is:

$$\sum M_i C_{p_i} = I(V_c - V_h) + I_f V_f + P_{\text{LENR}} - \sum K_i (T_{\text{int}} - T_{\text{R}}), \quad (6)$$

where the  $K_i$  are constants related to the thermal conductivity and geometry of the walls and the temperature difference is between the interior of the calorimeter ( $T_{\text{int}}$ ) and the reference temperature ( $T_{\text{R}}$ ) of the walls or the exterior of the calorimeter.

### 2.2.3. Characteristics of calorimeters

Before reviewing the major specifications of calorimeters, in general, we note that it is possible to use some calorimeters in a differential mode. This involves having two identical calorimeters, one of which has the active LENR cell while the other contains an inactive (unpowered) cell with the same configuration. If they are near each other, both cells are subject to the same fluctuations in the temperature of the surroundings. Hence, comparison of the active and inactive cells enables computational removal of the effects of unwanted exterior fluctuations. Isoperibolic calorimeters can be configured as differential calorimeters if they are placed near each other in the same water bath. Seebeck calorimeters can be used similarly if they have a cylindrical shape, where the sides of the cylinder are heavily insulated. The bottom of the cylinder can be capped and placed on a single TE element. A colder constant temperature heat sink has to be on the other side of the TE element. It can be clamped at a constant temperature by use of TE elements, or by flow of water that has a well-controlled temperature. Then, heat flow from the calorimeter containing the LENR experiment to the heat sink will produce a voltage, which is measured. Similarly, heat will flow from another similar calorimeter and dead experiment to the same heat sink. Again, comparison of the two voltage signals permits cancellation of the effects of room temperature fluctuations. Loss of heat out of the top of the LENR experiment and calorimeter is an issue for cylindrical Seebeck calorimeters used in any configurations, either singly or in a differential mode.

Calorimeters for LENR experiments are scientific instruments, and like most instruments, they have a few key performance characteristics. They include:

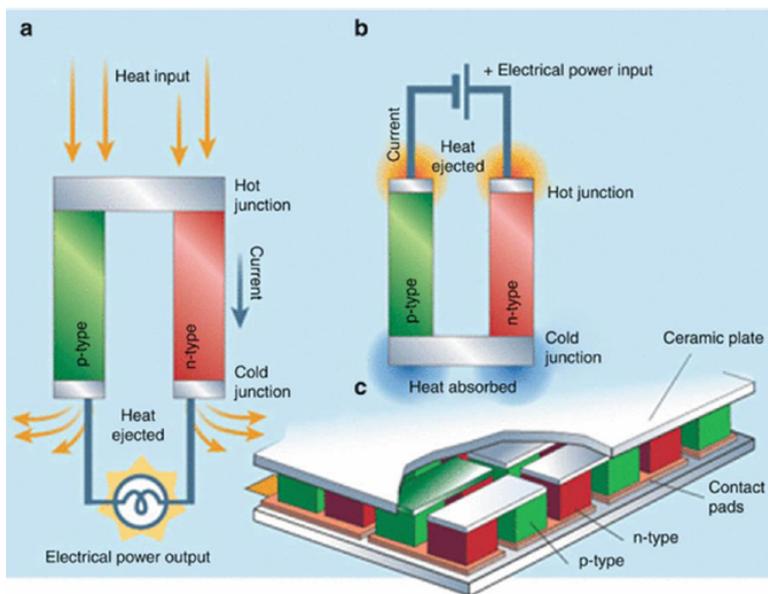
- *Sensitivity*: Output value per internal Watt, usually Temperature ( $dT/dW$ ) for Isoperibolic calorimeters or voltage ( $dV/dW$ ) for Seebeck calorimeters. This is the slope of the calibration curve, which plots output values ( $T$  or  $V$ ) versus input power ( $W$ ).
- *Minimum Detectable Limit (MDL)*: The lowest LENR power that can be measured. The MDL is determined by the noise on the output measurement.

- *Power range:* The lowest and highest powers, electrical and LENR, which can be handled by the calorimeter. The lowest powers are set by the MDL. The highest are due to temperature or voltage limitations of components of the LENR cell or calorimeter, or the sensors.
- *Time constants:* These limit the fastest temperature excursions in an experiment, which can be resolved. Ultimately are set by heat capacity and thermal conductivity of the experiment and calorimeter. They include the times it takes to heat up or cool down components of the cell and calorimeter, or the times it takes for heat to be transported to flowing coolant (for Mass Flow system) or to exterior temperature baths (for Heat Flow calorimeters).

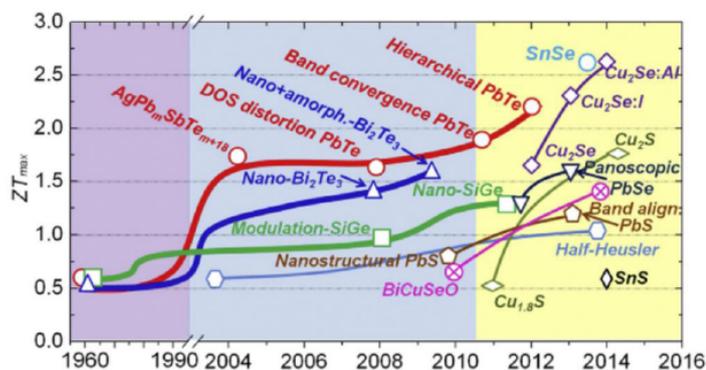
### 3. Thermoelectric Devices and Thermocouples

Thermoelectric materials and devices are reciprocal, when they are configured properly. If they are powered electrically, they can pump heat from one side of a device to the other side (the Peltier effect). If they have different temperatures on two sides, a voltage will appear across the output leads (the Seebeck effect). Thermoelectric devices have a few chemical and geometrical characteristics, and one dominant performance parameter. Materials that exhibit thermoelectric effects are commonly doped semiconductors [15]. In the most common configurations, the thermoelectric materials are sandwiched between two ceramic plates, and connected in series. Figure 3 shows both the Peltier and Seebeck modes of operation, and the general design of a thermoelectric device [16].

The main performance parameter for thermoelectric materials and devices is denoted ZT, the TE Figure of Merit. It is determined by the material's electrical conductivity, thermal conductivity, and Seebeck coefficient (the ratio of generated volts to temperature difference) [17]. Values for ZT have increased over the decades due to the high interest



**Figure 3.** Schematic diagrams of thermoelectric elements (a) in the Peltier heat pump mode, (b) as Seebeck sensors of temperature differences, and (c) arrayed within a thermoelectric device.



**Figure 4.** History of the primary performance specification ( $ZT$ ) of thermoelectric materials for diverse thermoelectric materials.

in both use of thermoelectric materials, generation of electricity from waste heat and solid-state refrigeration free of compressor systems. Figure 4 shows the history of the evolution [18]. It also exhibits the compositions of diverse thermoelectric materials. In the recent past, there has been a great deal of interest and progress in thermoelectric materials with micro- and nano-structures. However, current performance remains short of the  $ZT$  value of about 4, which is needed for massive uses of thermoelectric devices in solid-state refrigerators and other applications.

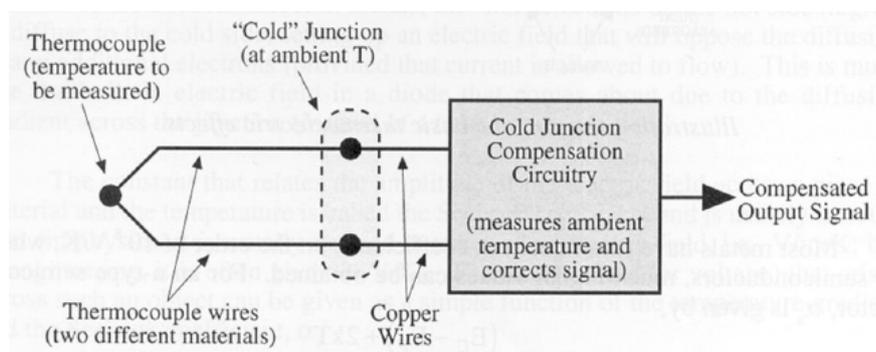
As will be seen, thermocouples have also been used in Seebeck calorimeters for LENR experiments. They are intimate contacts between two metals with dissimilar electronic structures, usually produced by melting or welding together wires of the two materials. Like semiconductor thermoelectric materials, thermocouples produce voltages due to temperature differences. The voltage vs. temperature characteristics, and the compositions, of common thermocouples are available [19]. Figure 5 shows how thermocouples are used for practical temperature measurements [20]. Thermocouples have the important advantage of being small (less than 1 mm), so they can be inserted into systems to measure temperatures at specific points.

#### 4. LENR Papers about Seebeck Calorimeters

Seebeck calorimeters were used for LENR experiments, and described in papers from 1990 to 2019. Table 1 contains a list of the papers, the references to which are in Appendix B. It is evident that Storms was one of the primary practitioners of Seebeck calorimetry. Figure 6 contains images of his Seebeck systems. The cylindrical 2003 system used thermocouples to develop a temperature-sensitive voltage. The other rectangular systems employed thermoelectric devices. Zhang was also a leader in the development and use of Seebeck calorimeters for LENR experiments. Plots in his papers show that the calorimeter is only one part of a system that supplies proper electrical voltages to and from the instrument and records data from it. The system also provides a stable temperature reference for the Seebeck calorimeters. Figure 7 contains examples of the published calibration curves for LENR Seebeck calorimeters

#### 5. Tabulation of Characteristics and Performance of Published Seebeck Calorimeters

The geometrical, physical and performance characteristics of the described calorimeters varied widely. A spread sheet of these factors was produced from the papers. Plots of the quantitative features of the reviewed calorimeters have been produced. Tables 2 and 3 summarize the physical and other characteristics, and the performance of published Seebeck calorimeters that were used in LENR experiments.



**Figure 5.** Schematic of a thermocouple with compensating circuitry for having the “cold junction” at temperatures above absolute zero.

The relationships between characteristics and performance of calorimeters are important, as they are for most scientific instruments. The Tables 2 and 3 provide quantitative information for making plots of such relationships. Four such graphs are shown in Fig. 8. Two data with the values of (4056, 190) and (4056, 160) were omitted from the plot of the inverse of the calibration constant (mV/W) vs. surface area (cm<sup>2</sup>) in order to make the lower such values more visible.

**Table 1.** Summary of the papers on LENR Seebeck calorimeters examined in this review.

Authors	Year	Paper
Oriani, Nelson, Lee, Broadhurst	1990	Calorimetric Measurements of Excess Power Output During the Cathodic Charging of Deuterium into Palladium
Oriani	1996	An Investigation of Anomalous Thermal Power Generation from a Proton Conducting Oxide
Bush, Lagowski	1998	Methods of Generating Excess Heat With the Pons and Fleischmann Effect: Rigorous and Cost-Effective Calorimetry, Nuclear Products Analysis of the Cathode and Helium Analysis
Zhang, Zhang Zhang	2001	Primary Calorimetric Results on Closed Pd/D <sub>2</sub> O Electrolysis Systems by Calvet Calorimetry
Storms	2003	Maw to Make a Cheap and Effective Seebeck Calorimeter
Storms	2003	Use of a Very Sensitive Seebeck Calorimeter to Study the Pons–Fleischmann and Letts Effects
Storms	2005	Description of a Sensitive Seebeck Calorimeter Used for Cold Fusion Studies
Zhang, Dash, Wang	2005	Seebeck Envelope Calorimetry with a Pd/D <sub>2</sub> O + H <sub>2</sub> SO <sub>4</sub> Electrolytic Cell
Zhang, Dash	2007	Excess Heat Reproducibility and Evidence of Anomalous Elements After Electrolysis in Pd in D <sub>2</sub> O + H <sub>2</sub> SO <sub>4</sub>
Storms	2008	The Method and Results Using Seebeck Calorimetry
Zhang, Dash, Zhang	2008	Construction of a Seebeck Envelope Calorimeter and Reproducibility of Excess Heat
Zhang	2009	Construction, Calibration and Testing of a Decimeter-Size Heat-Flow Calorimeter
Macleod, Fork, Lam, Berlinguette	2018	Electronic Supplementary Material for System Identification Calorimetry
Letts, Cravens	2019	Building and Testing a High Temperature Seebeck Calorimeter

Authors	Dimensions	Shape	Frame	TEs or TCs	Insulation
Oriani, Nelson, Lee, Broadhurst (1990)	25cm (D) x 81 cm (H)		Cylinder	1961 TCs	Thermal & electrical insulation
Oriani (1996)			Box	335 x 2 TCs	Insulated jacket
Bush, Lagowski (1998)	3 cm x 3cm x 9 cm		Box	~100 TCs	Thermal insulation
Zhang, Zhang, Zhang (2002)	15 mm (D) x 80 mm (H)		Cylinder	496 TCs	Asbestos
Storms (2003)	12.7 cm (inner D)		PVC Pipes	~1000 TCs	Cooling water
Storms (2003)	17.78 cm x 17.78 cm x 17.78 cm		Box		Wooden enclosure
Storms (2005)	13.9 cm x 6.9 cm x 14.8 cm		Box		Waterproof Epoxy Paint
Zhang, Dash, Wang (2005)	18.3 cm x 18.3 cm x 18.3 cm		Box		Styrofoam
Zhang, Dash (2007)	18.3 cm x 18.3 cm x 18.3 cm		Box		Styrofoam
Storms (2008)	17.78 cm x 17.78 cm x 17.78 cm		Box		Waterproof paint
Zhang, Dash, Zhang (2008)	26 cm x 26 cm x 26 cm		Box	18796 TCs	Styrofoam
Zhang (2009)	26 cm x 26 cm x 26 cm		Box	18796 TCs	Styrofoam
Macleod, Fork, Lam, Berlinguette	25.9 cm x 25.9 cm x 23.4 cm		Box	6 Heat Flow Sensors	Aluminum isothermal enclosure
Letts, Cravens (2019)	7.62 cm x 7.62 cm x 38.1 cm		Rectangular Block	16 TCs + TE devices	A layer of high temperature insulation

**Table 2.** Compilation of the characteristics in LENR reports on Seebeck calorimeters. D is the diameter, H the height, R the rectangular prism, and C is the cube.

Another plot relates the maximum power that can be dissipated within the published LENR Seebeck calorimeters to their volume. It is shown in Fig. 9. The data in Tables 2 and 3, and the plots in Figs. 8 and 9 are discussed in Section 6.

## 6. Discussion of Published LENR Seebeck Calorimeters

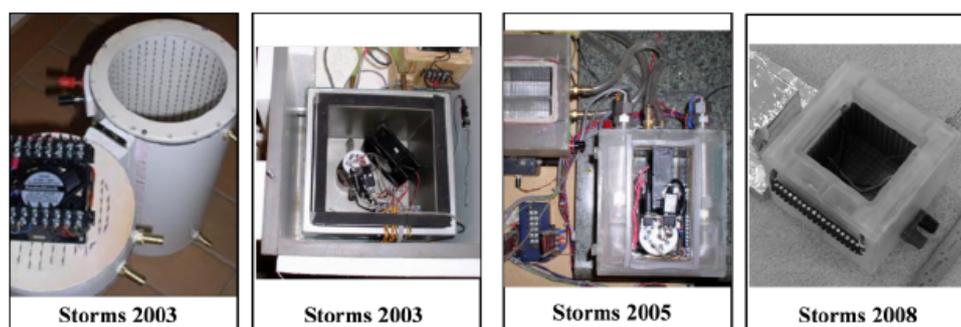
The data in Figs. 7–9 show that Seebeck calorimeters used for LENR experiments have some commonalities and differences. Their shapes are cylindrical, or prismatic in most cases cubic (C) or rectangular (R). But, the volumes of the calorimeters varied widely from 81 to 39 760 cm<sup>3</sup>. The number of TE elements was also highly variable from less than 10 to about 1000 thermocouples. The type of exterior insulations was also quite variable.

The performance of the published Seebeck calorimeters was also quite different. The power handling capacities ranged from 0 to 80 W. Most of the instruments were limited in their maximum input power to about 10–25 W. Two instruments were designed for powers of only less than 1 W. The output signals ranged from a few mV to 9 V. The uncertainty related to the Minimum Detectable Limit (MDL) of input power was in the range of 10–87 mW. The

Authors	Power Range	Voltage Range	Minimum milliWatts	Temp. Range	mV/W	Fan & Power	Calibration Method
Oriani, Nelson, Lee, Broadhurst (1990)	0 – 18 W	0 – 0.009 V	+/- 20 mW		0.5		Electric current through coil of nichrome wire set
Oriani (1996)	63 – 80 W	0.072 – 0.083 V		400 – 410 °C	1.1	1	Electric power
Bush, Lagowski (1998)	0 – 0.1 W		+/- 10 mW	450 °C			Controller
Zhang, Zhang, Zhang (2002)	0 – 0.5 W						Pd electrode acting as heater
Storms (2003)	0 – 10 W	0 – 0.06 V	+/- 35 mW		5.2	2	
Storms (2003)	5 – 20 W	0.02 – 0.09 V		47 °C	5	3 (5.3W)	Resistor made from platinum
Storms (2005)	2 – 16 W	0.02 – 0.21 V	+/- 60 mW		13.2	1	Resistor heat
Zhang, Dash, Wang (2005)	0 – 20 W	0 – 0.1 V		10 – 90 °C	5.5	1 (2.08W)	Pt/H <sub>2</sub> O + H <sub>2</sub> SO <sub>4</sub> electrolytic cell
Zhang, Dash (2007)	9.3 – 11.1 W		+/- 87 mW	79 – 90 °C	5.7		Calibration resistor
Storms (2008)	0 – 12 W	0 – 0.14 V	+/- 35 mW	20 – 70 °C	12	1 (0.75W)	Dual calibration with Joule & electrolytic power
Zhang, Dash, Zhang (2008)	0 – 22.3 W	0 – 4 V	+/- 40 mW		190	1 (2.5W)	Electrical heater
Zhang (2009)	0.1 – 50 W	0 – 9 V			160	1 (2.5W)	Electrical heater
Macleod, Fork, Lam, Berlinguette (2018)	0 – 5 W	0 – 5 V					
Letts, Cravens (2019)	0 – 75 W	2.5 – 3.9 V		200 – 300°C	15.8		Resistive heating power

**Table 3.** Compilation of the performance of LENR Seebeck calorimeters.

temperature ranges that the published data showed were as low as 20°C and as high as 450°C. Powers required for the internal air circulation fans ranged from 0.75 W to a rather high value of 5.3 W. Electrical (resistive) heating was most commonly used for calibration, although electrolysis power was employed in three cases.



**Figure 6.** Images of Seebeck LENR calorimeters designed, constructed, calibrated and used by Storms.

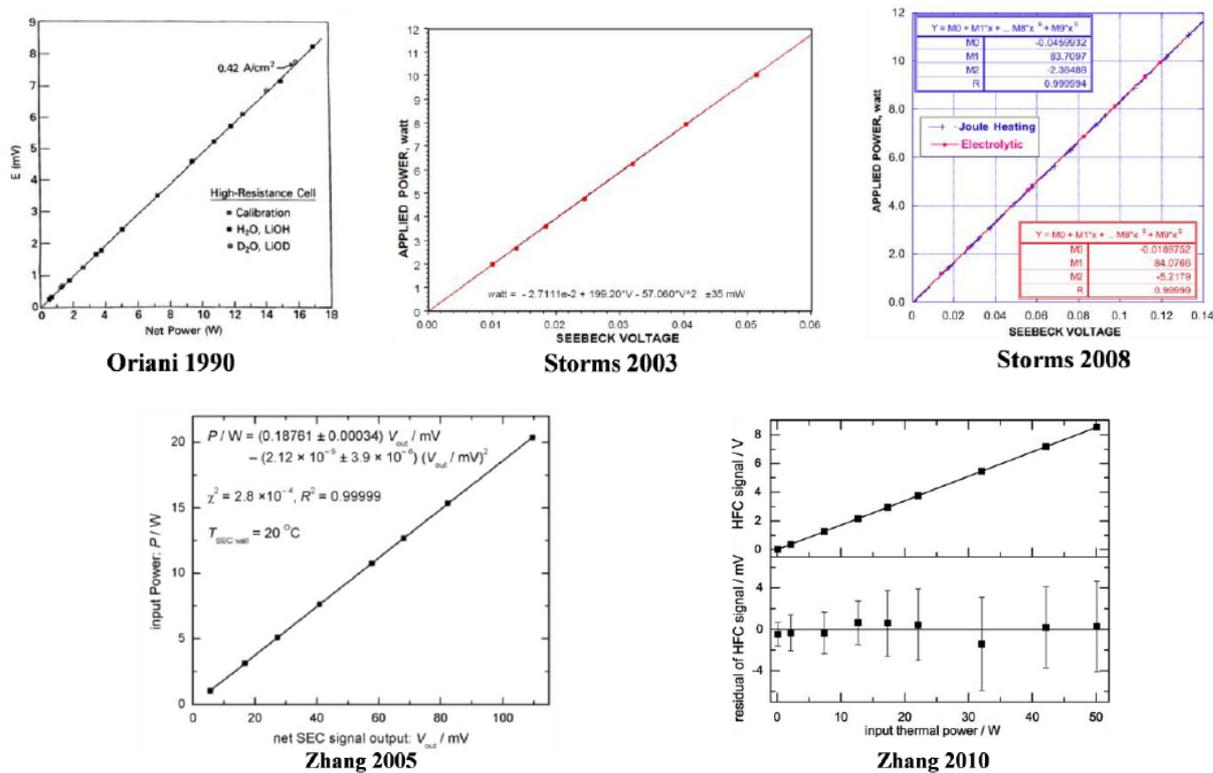
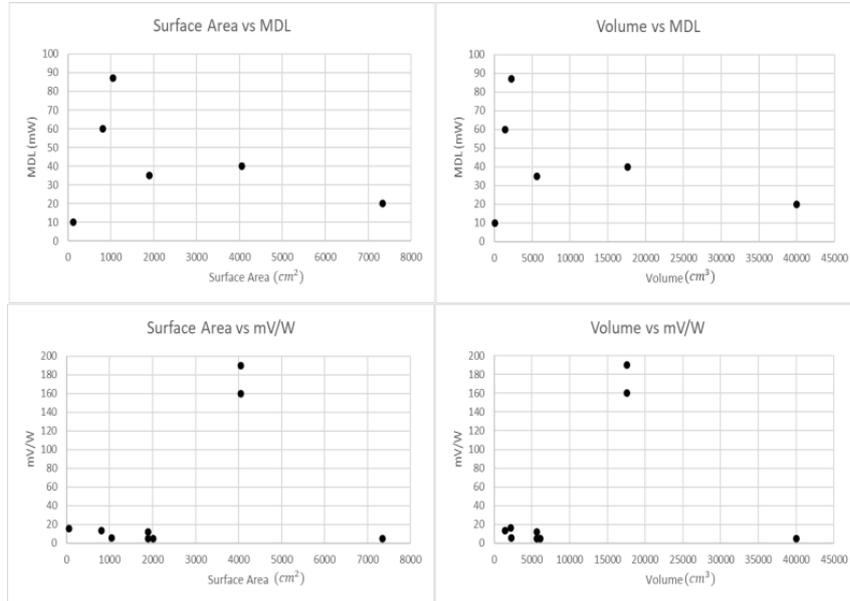


Figure 7. Example calibration curves of Seebeck calorimeters for LENR experiments.

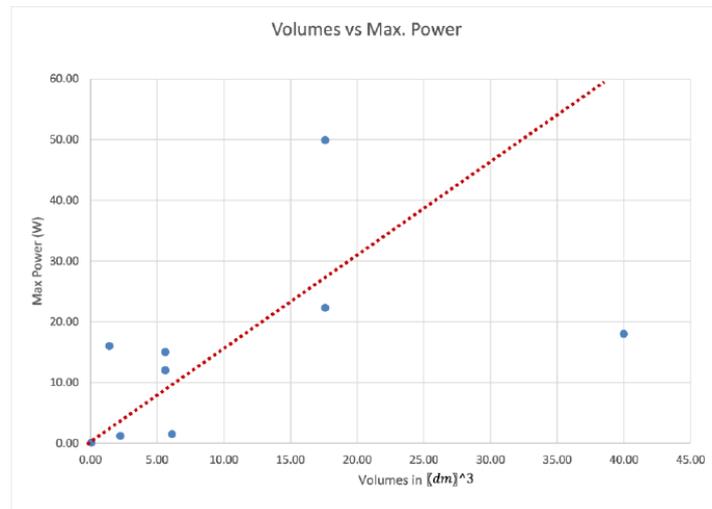
It is important to relate the static descriptive characteristics of LENR calorimeters to their dynamic performance. Such correlations might provide significant information for designing new Seebeck calorimeters. The relationships between two characteristics (area and volume) and two performance parameters (MDL and inverse of the calibration constant), shown in Fig. 8 are not helpful. There is no clear trend in any of the four plots. We also plotted the maximum power that would be handled by the calorimeters against their volume. The result is in Fig. 9. It might be expected that the larger the calorimeter, the more power it could handle. The red curve is a linear fit to the (0,0) point and tabulated data. The correlation is poor. The lack of clear trends in performance with the calorimeter characteristics motivated us to consider ways to estimate such relationships, which are the subject of Section 7.

### 7. Scaling of the Size and Performance of Seebeck Calorimeters

It is possible to write a simple equation for how the performance (output) of a Seebeck calorimeter scales with its size. Assume that the calorimeter is a cube with edge length of  $D$ , that the thermoelectric units covering all interior walls have area  $A$ , and that the TE calibration factor is  $K_{TE}$ , so that the voltage output of each TE elements is  $K_{TE} \Delta T$ , where the temperature difference is that between the inside of the calorimeter and the thermally stabilized walls. Hence, the voltage output of the calorimeter is the number of TE elements times their individual output voltages, assuming the usual serial connection:



**Figure 8.** Relationships of the Minimum Detectable Power (MDL) (*top*) and inverse of the calibration constant (mV/W) (*bottom*) to the calorimeter area (*left*) and calorimeter volume (*right*).



**Figure 9.** Plot of the maximum power of LENR Seebeck calorimeters as a function of their volume. The red line is a fit to the scattered data.

$$V = (6D^2/A) K_{TE}\Delta T. \tag{7}$$

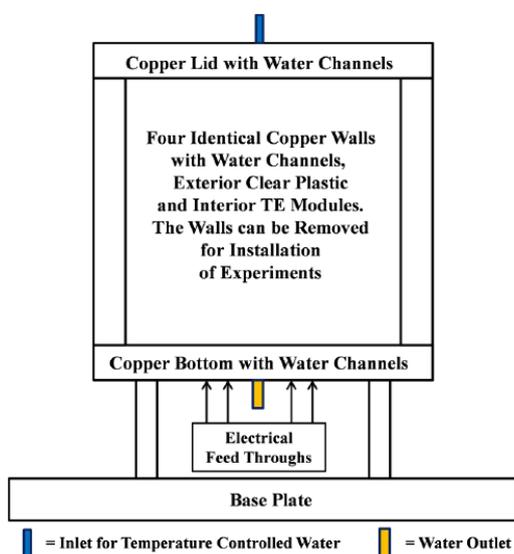
This equation shows that the output performance varies with the square of the calorimeter linear size for fixed TE elements ( $K_{TE}$  and  $A$ ).

Another relationship of interest is the maximum steady state power  $P_M$  of a Seebeck calorimeter as a function of volume  $D^3$  [3]. Assume that the highest air temperature that the TE elements can tolerate is  $T_M$ . The power balance between the air inside of the calorimeter, heated by the combination of electrolysis, the fan and LENR, and the conduction of thermal power through the six walls, can be written as  $P = [K_W (T_M - T_R)/W] 6D^2$ , where  $K_W$  is the thermal conductivity of the walls of thickness  $W$ . Hence, the ratio of maximum total input power (not only  $i_{LENR}$ ) to the calorimeter volume is

$$P_M/\text{Volume} = [K_W(T_M - T_R)/W] 6/D. \quad (8)$$

## 8. Conclusion

The review of Seebeck calorimeters in this paper raises the question about similar reviews of calorimeter characteristics and performance for other types of calorimeters. We do not know of related reviews for either LENR mass flow calorimeters, of which there are few, or LENR heat flow isoperibolic calorimeters, of which there are many. It is unclear now if there is any one best type of calorimeter, or if there is a best design for any type of calorimeter for LENR experiments. It ought to be possible to rank the minimum detectable LENR power levels for all published designs, but that is not particularly useful. The goal of LENR research is to produce LENR powers that are much larger than such minimum detectable limits. And, there are several other important factors, such as the maximum power that can be handled and the size of the experiments that a calorimeter can accommodate.



**Figure 10.** Schematic diagram of the calorimeter being made for the LENR Energy and Spectroscopy Laboratory of The George Washington University. Insulation, which will cover all sides, is not shown. A fan will be mounted on the interior of the calorimeter lid.

The results of this review might be useful to scientists considering the use of Seebeck calorimeters for LENR experiments. They also form the basis for the design of a new Seebeck calorimeter being made for our laboratory. The conceptual design for that instrument is shown in Fig. 10. There are two major design goals for this Seebeck calorimeter. One is performance, with a sensitivity and noise level that will enable detection of LENR powers as low as a few tens of milliwatts. The other goal is ease of use. The base plate, legs and calorimeter bottom will form a unit, with walls and calorimeter top that are removable for set up of experiments.

## References

- [1] [https://en.wikipedia.org/wiki/List\\_of\\_chemical\\_analysis\\_methods](https://en.wikipedia.org/wiki/List_of_chemical_analysis_methods).
- [2] M. Fleischmann and S. Pons, Electrochemically induced nuclear fusion of deuterium, *J. Electroanal. Chem.* **261** (1989) 301–308 and Errata in Vol. 263.
- [3] D.J. Nagel and M.E. Melich (Eds.), Calorimetry, *Proc. of ICCF-14*, 2008, pp. 1–16.
- [4] E. Storms, *The Science of Low Energy Nuclear Reactions*, World Scientific, 2007, pp. 53–61.
- [5] E. Storms, *The Explanation of Low Energy Nuclear Reaction*, Infinite Energy Press, 2014, pp. 106–109.
- [6] M.C.H. McKubre and F. Tanzella, Mass flow calorimetry, *Proc of ICCF-14*, D.J. Nagel and M.E. Melich (Eds.), 2008, pp. 32–46.
- [7] A. Kitamura, A. Takahashi, R. Seto, Y. Fujita, A. Taniike and Y. Furuyama, Brief summary of latest experimental results with a mass-flow calorimetry system for anomalous heat effect of nano-composite metals under D(H)-gas charging, *Current Science* **108** (4) (2015) 589–593.
- [8] M. Fleischmann and S. Pons, Calorimetry of the Pd–D<sub>2</sub>O systems from simplicity via complications to simplicity, *Phys. Lett. A* **176** (1993) 118–129.
- [9] W.-S. Zhang, Construction, calibration and testing of a decimeter-size heat-flow calorimeter, *Thermochimica Acta* **499** (2010) 128–132.
- [10] E. Storms, The method and results using Seebeck calorimetry, in *Proc of ICCF-14*, 2008.
- [11] <http://www.ling.fju.edu.tw/hearing/historical%20review1821.htm>.
- [12] M.H. Miles, Fundamentals of isoperibolic calorimetric measurements in cold fusion experiments, to be published.
- [13] M.H. Miles, Private communication.
- [14] E. Storms, Use of a very sensitive Seebeck calorimeter to study the Pons–Fleischmann and Letts effects, *Proc. of the Tenth Int. Conf. on Cold Fusion*, P.L. Hagelstein and S.R. Chubb (Eds.), World Scientific, New York, 2006, pp. 183–197.
- [15] [https://en.wikipedia.org/wiki/Thermoelectric\\_materials](https://en.wikipedia.org/wiki/Thermoelectric_materials).
- [16] M. Zhou and J. He, Nanostructured thermoelectric materials, in *Encyclopedia of Nanotechnology* B. Bhushan (Ed.), Springer, Dordrecht, 2012.
- [17] [https://en.wikipedia.org/wiki/Thermoelectric\\_materials#device\\_efficiency](https://en.wikipedia.org/wiki/Thermoelectric_materials#device_efficiency).
- [18] X. Zhang and L.-D. Zhao, Thermoelectric materials: Energy conversion between heat and electricity, *J. Materiomics* **1** (2015) 92–105, <http://dx.doi.org/10.1016/j.jmat.2015.01.001>.
- [19] [https://www.engineeringtoolbox.com/thermocouples-d\\_496.html](https://www.engineeringtoolbox.com/thermocouples-d_496.html).
- [20] <https://www.sciencedirect.com/topics/engineering/cold-junction>.

## Appendix A. Qualitative Comparison of the Major Types of LENR Calorimeters

The varied types and designs of calorimeters, which have been used in LENR research, are the result of the preferences of experimenters, the tools available to them, and the characteristics and performance of particular calorimeters. A qualitative comparison of the three major types of calorimeters used to date for LENR experiments follows.

### Appendix A.1. Volume

LENR calorimeters can be made for diverse internal shapes and sizes. Simple geometrical forms, such as cylinders or rectangular prisms are commonly used. The volumes for most mass flow and isoperibolic heat flow calorimeters

have commonly been relatively small. For Seebeck calorimeters, one can place the temperature sensing devices, the TE elements, in electrical series surrounding the internal volume. Doing this allows studying heat production in larger volumes compared to mass flow and isoperibolic calorimeters.

#### Appendix A.2. Sensors

For mass flow calorimeters, temperature sensors for measuring inlet and outlet temperature of the surrounding fluid, and flow rate sensors for measuring the surrounding fluid flow rate, are required. For heat flow isoperibolic calorimeters, temperature sensors are sufficient. Either thermoelectric devices or thermocouples can be used for heat flow Seebeck calorimeters, with TE devices being the most common.

**Table A1.** Comparison of types of calorimeters.

Characteristics	Mass flow calorimeters	Heat flow calorimeters	
		Isoperibolic	Seebeck
Internal volumes	Medium	Small to medium	Medium to large
Sensors	$T$ and flow rate	Temperature	TE devices
Heat Paths	<b>Cathode to electrolyte to solids and to:</b> Water or oil	Water bath	Constant $T$ walls
Time constant due to:	<b>Thermal conductivity and thermal capacity of:</b> Water or oil	Thermal barrier	Air in calorimeter
MDL limited by:	<b>Cathode area changes due to bubbles and:</b> Flow fluctuations	Bath $T$ variations	Reference $T$ variations

$T$  is the Temperature, TE the thermoelectric and MDL is the minimum detectable power level.

#### Appendix A.3. Heat paths

For mass flow calorimeters, the temperature difference between inlet and outlet of the surrounding liquid occurs due to the heat production inside the container. Thus, the heat path for this type of calorimeter is through the walls of the experiment to the surrounding fluid. For isoperibolic calorimeters, heat flow is from heat source to a constant temperature surrounding water bath. For Seebeck calorimeters heat path is from the heat source through the internal air to the constant temperature walls. Insulation is commonly used for heat flow calorimeters to help maintain the constancy of the surrounding temperature.

#### Appendix A.4. Time constants

The response times of all of the LENR calorimeter types are limited to the medium into or through which the heat flows. For mass flow calorimeter, this is surrounding liquid. For isoperibolic calorimeters, the path is through the thermal barrier between the heat source and the surroundings. For Seebeck calorimeters, the generated heat must warm the air inside calorimeter.

#### Appendix A.5. Minimum detectable powers

For all electrochemical LENR experiments, variations in the cathode area due to transient coverage by bubbles can influence or limit the minimum detectable LENR power level. For mass flow calorimeters, fluctuations in the flow

rate determine the minimum detectable power of the calorimeter. Therefore, using mass flow controllers, or weighing and timing, is usually done to obtain precision in the flow measurement. Both of the heat flow calorimeters require a reference temperature. Therefore, their minimum detectable LENR power levels are limited to the precision and stability of the measured reference temperature.

The following table shows the bibliography of papers on use of Seebeck calorimeters for LENR experiments.

#### Appendix B. The bibliography of papers on use of Seebeck calorimeters for LENR experiments.

Authors	Title	Reference
R.A. Oriani, John C. Nelson, Sung-Kyu Lee, J. H. Broadhurst	Calorimetric measurements of excess power output during the cathodic charging of deuterium into palladium	<i>Fusion Technol.</i> <b>18</b> (1990) 652
R.A. Oriani	An investigation of anomalous thermal power generation from a proton conducting oxide	<i>Fusion Technol.</i> <b>30</b> (1996) 281
Ben Bush and J. J. Lagowski	Methods of generating excess heat with Pons and Fleischmann effect: rigorous and cost-effective calorimetry, nuclear products analysis of the cathode and helium analysis	<i>Proc. of 7th Int.. Conf. on Cold Fusion</i> , 1998, p. 98
Wu-Shou Zhang, Zhao-Fu Zhang, Zhong-Lianf Zhang	Primary calorimetric results on closed Pd/D <sub>2</sub> O electrolysis systems by calvet calorimetry	<i>Proc. of 9th Int.. Conf. on Cold Fusion</i> , 2002, p. 431
Edmund Storms	How To make a cheap and effective Seebeck calorimeter	<i>Proc. of 10th Int.. Conf. on Cold Fusion</i> , 2003, pp. 269–272
Edmund Storms	Use of a very sensitive Seebeck calorimeter to study the Pons–Fleischmann and Letts effects	<i>Proc. of 10th Int.. Conf. on Cold Fusion</i> , 2003, pp. 183–197
Edmund Storms	Description of a sensitive Seebeck calorimeter used for cold fusion studies	<i>Proc. of 10th Int.. Conf. on Cold Fusion</i> , 2005, pp. 108–116
Wu-Shou Zhang, John Dash, Qiongshu Wang	Seebeck envelope calorimetry with A Pd–D <sub>2</sub> O + H <sub>2</sub> (SO) <sub>4</sub> electrolytic cell	<i>J. Condensed Matter Nucl. Sci.</i> 2005, pp. 86–96
Wu-Shou Zhang and John Dash	Excess heat reproducibility and evidence of anomalous elements after electrolysis in Pd in D <sub>2</sub> O + H <sub>2</sub> SO <sub>4</sub>	<i>Proc. of 10th Int.. Conf. on Condensed Matter Nucl. Sci.</i> , 2007, pp. 202–216
Edmund Storms	The method and results using Seebeck calorimetry	<i>Proc. of 14th Int.. Conf. on Condensed Matter Nucl. Sci.</i> , 2008, pp. 11–25
Wu-Shou Zhang, John Dash, Zhong-Liang Zhang	Construction of a Seebeck envelope calorimeter and reproducibility of excess heat	<i>Proc. of 14th Int.. Conf. on Condensed Matter Nucl. Sci.</i> , 2008, pp. 26–31
Wu-Shou Zhang	Construction, calibration and testing of a decimeter-size heat-flow calorimeter	<i>Thermochimica Acta</i> <b>499</b> (1–2) (2009) 128–132

Macleod, Fork, Lam, Berlinguette Letts and Cravens	Electronic supplementary material for system identification calorimetry Building and testing a high temperature Seebeck calorimeter	<a href="https://arxiv.org/ftp/arxiv/papers/1808/1808.04518.pdf">https://arxiv.org/ftp/arxiv/papers/ 1808/1808.04518.pdf</a> , 2018 <i>J. Condensed Matter Nucl. Sci.</i> <b>29</b> (2019) 334–347
--	--	--

---