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(54) **SOLAR PHOTOVOLTAIC WATER HEATING SYSTEM**

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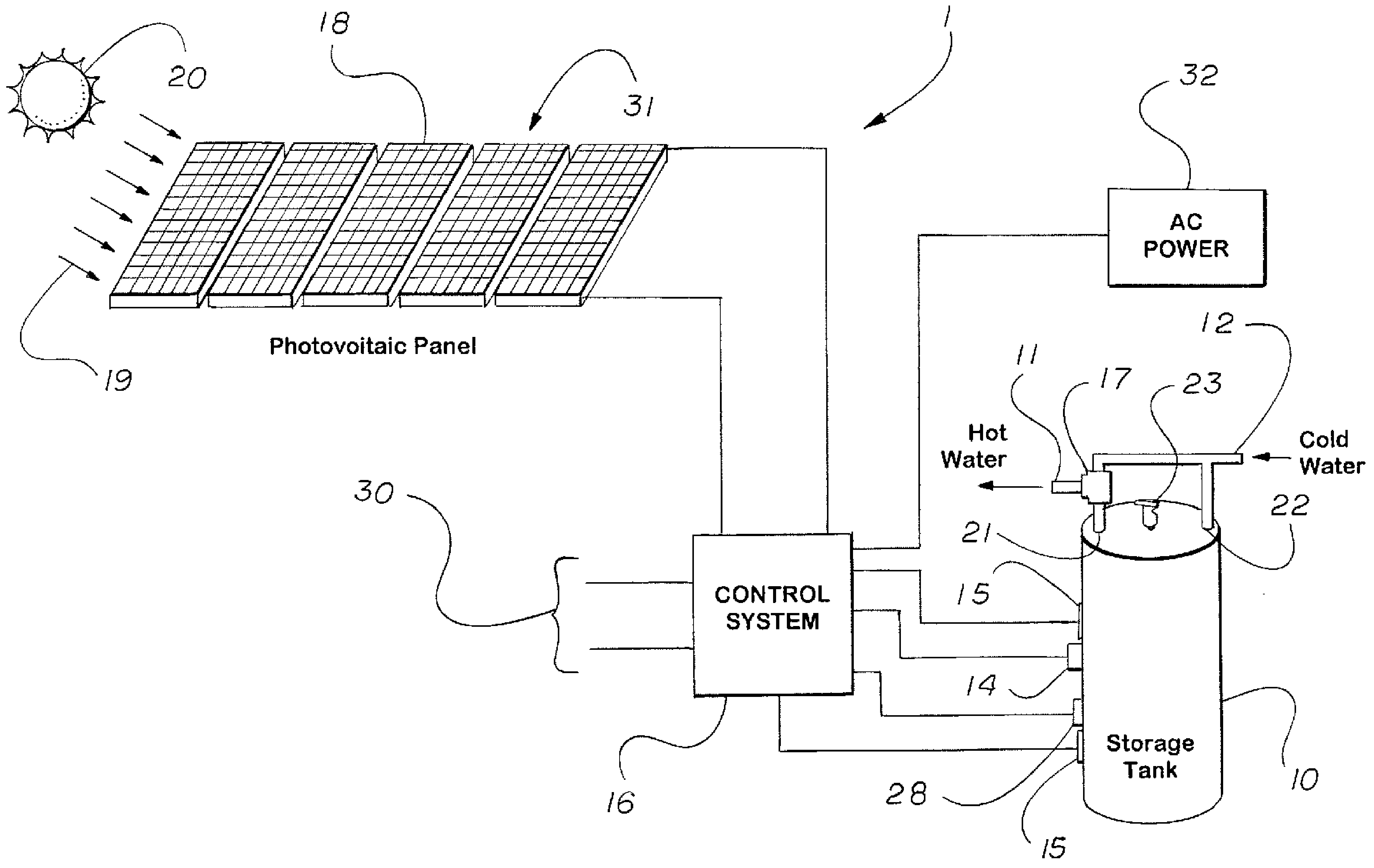
USPC **392/451**; 392/498; 392/500

(57) **ABSTRACT**

A solar photovoltaic water heating system is disclosed having a photovoltaic solar panel array, a storage tank containing water to be heated, a resistance heating element in the water to be heated. The water heating system matches the load resistance of the resistance heating element to the power that is available from the photovoltaic solar panel array in order to maximum energy transferred to the water in the storage tank.



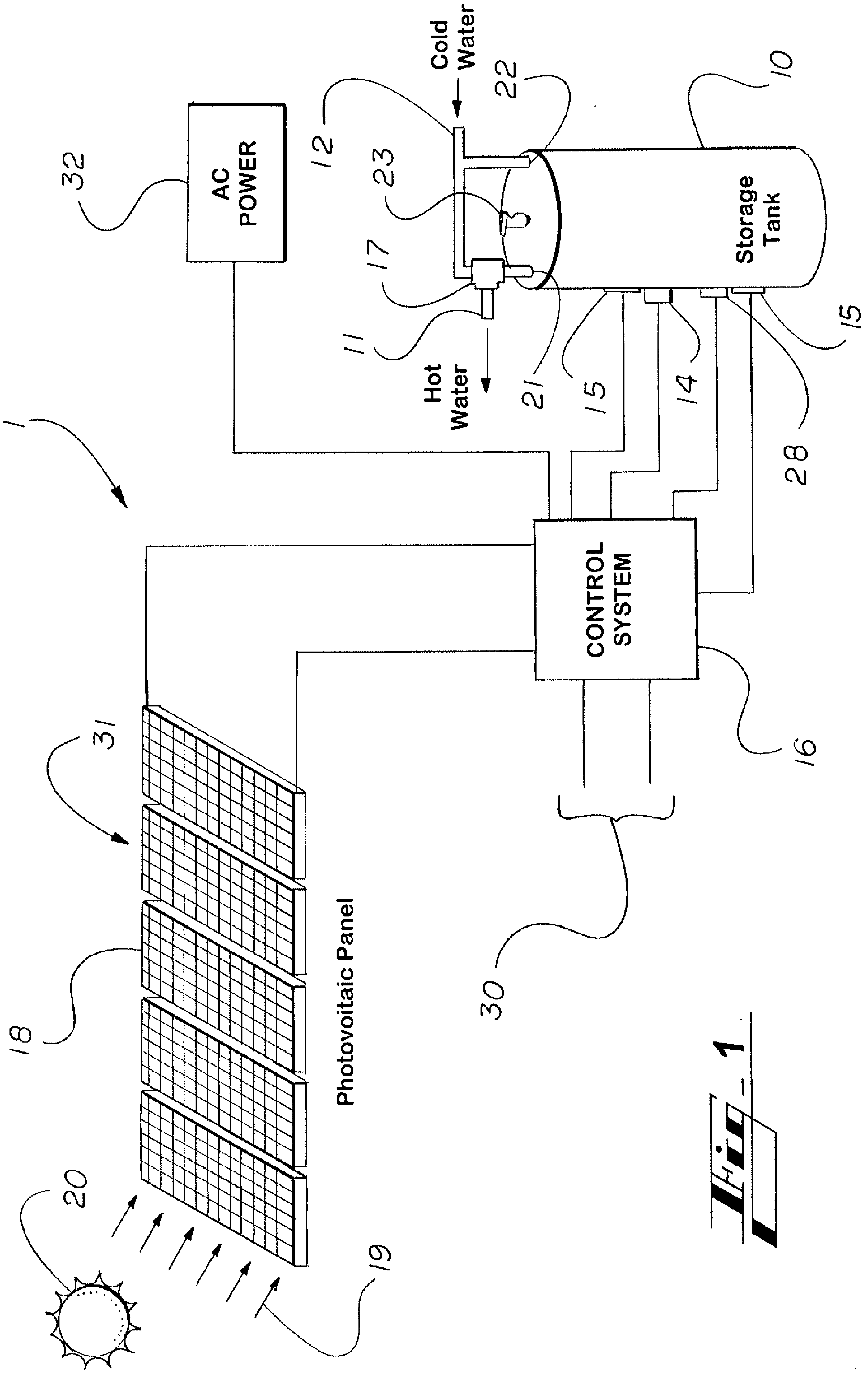

1
AC POWER
32
Cold Water
22
12
23
17
11
Hot Water
21
15
14
28
15
Storage Tank
10
CONTROL SYSTEM
16
30
31
18
Photovoltaic Panel
20
19

Fig_ 1

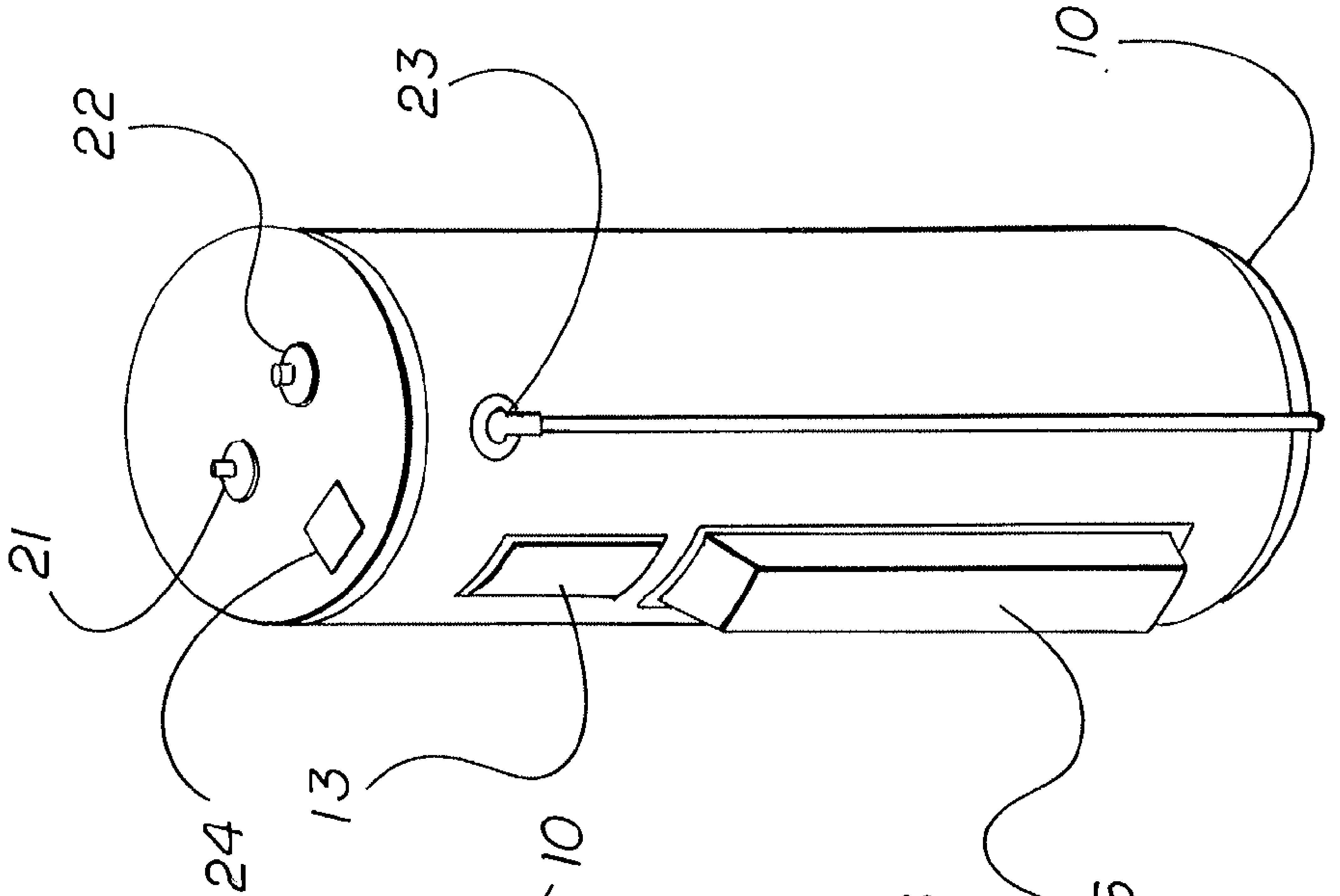


Fig. 2

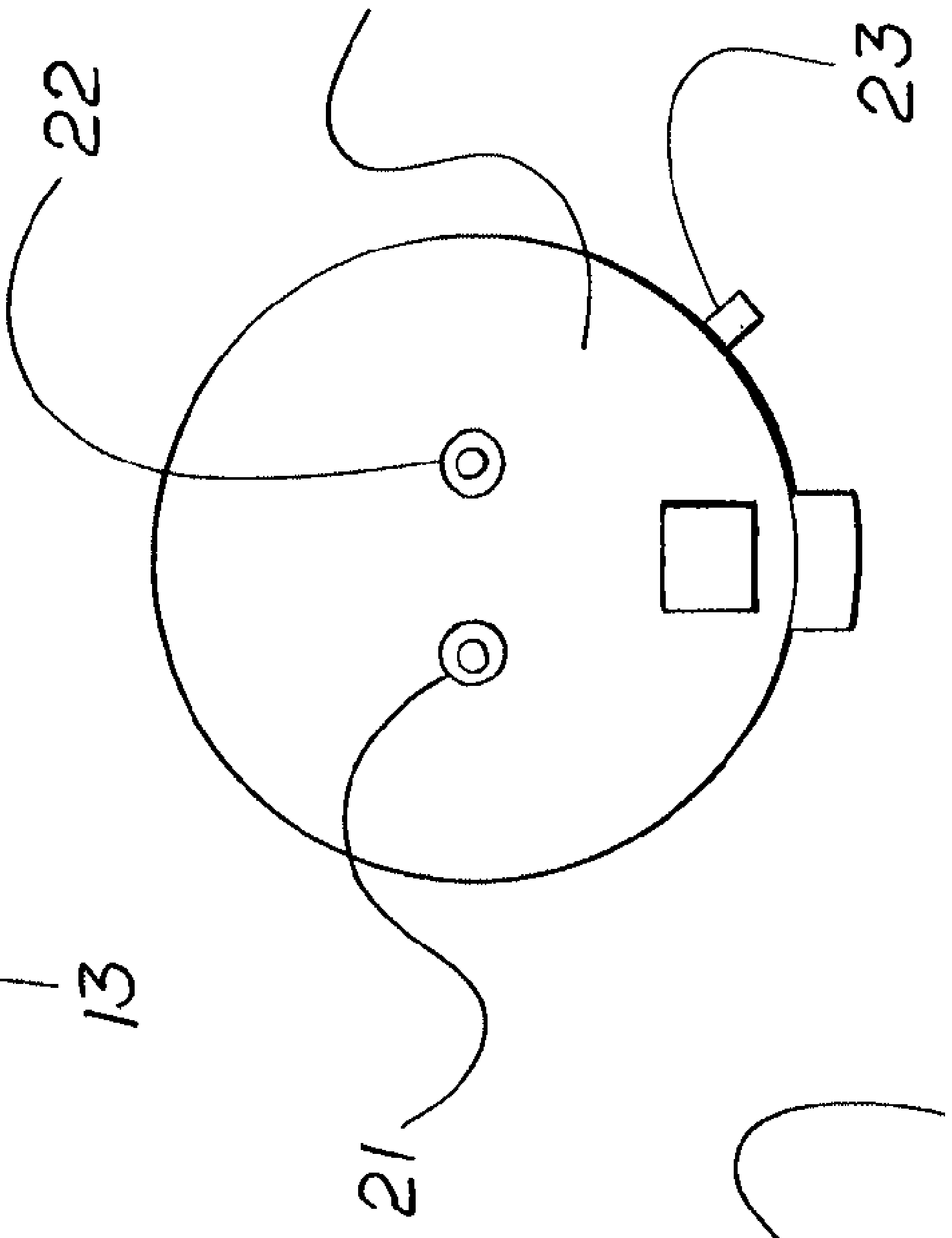


Fig. 3

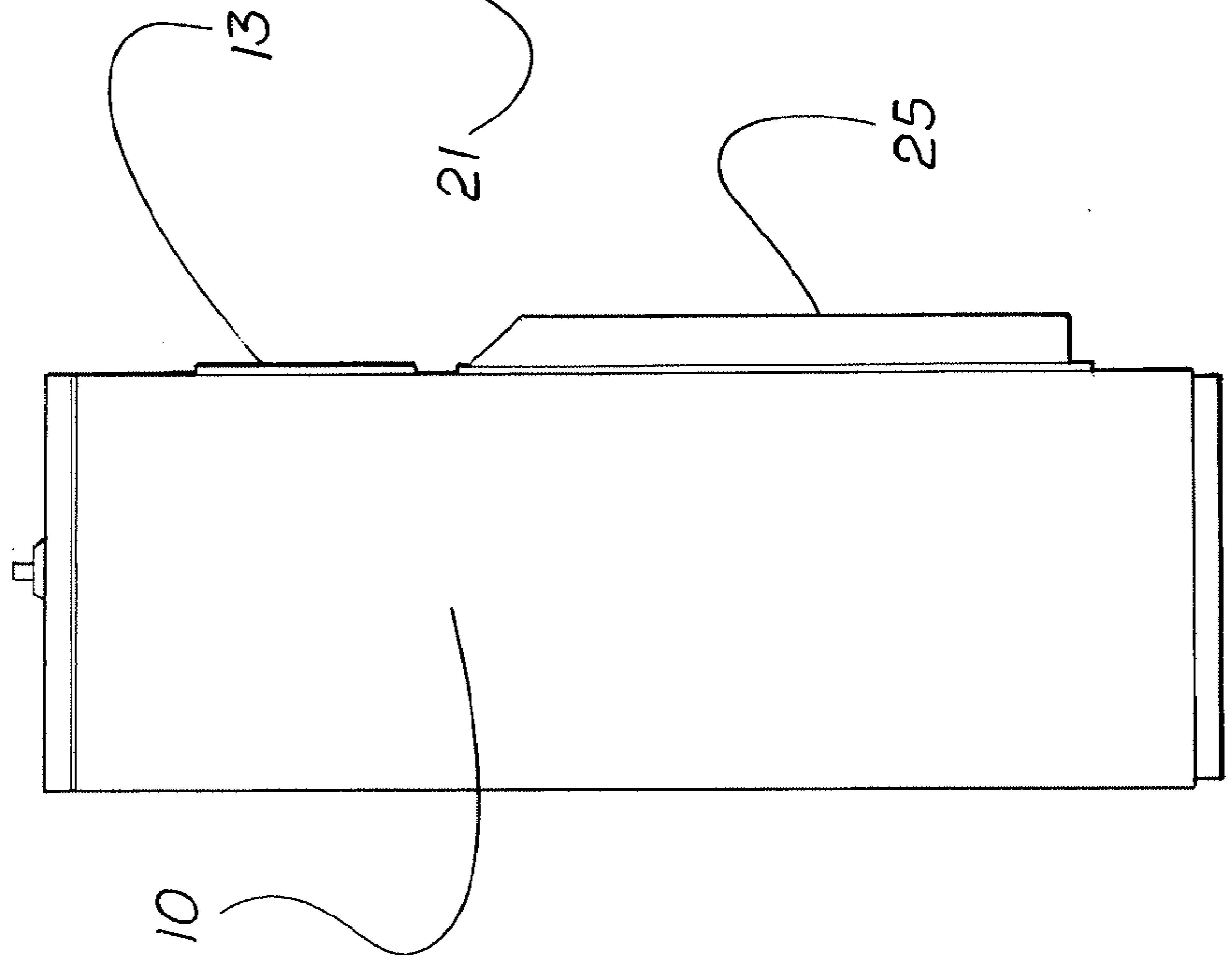


Fig. 4

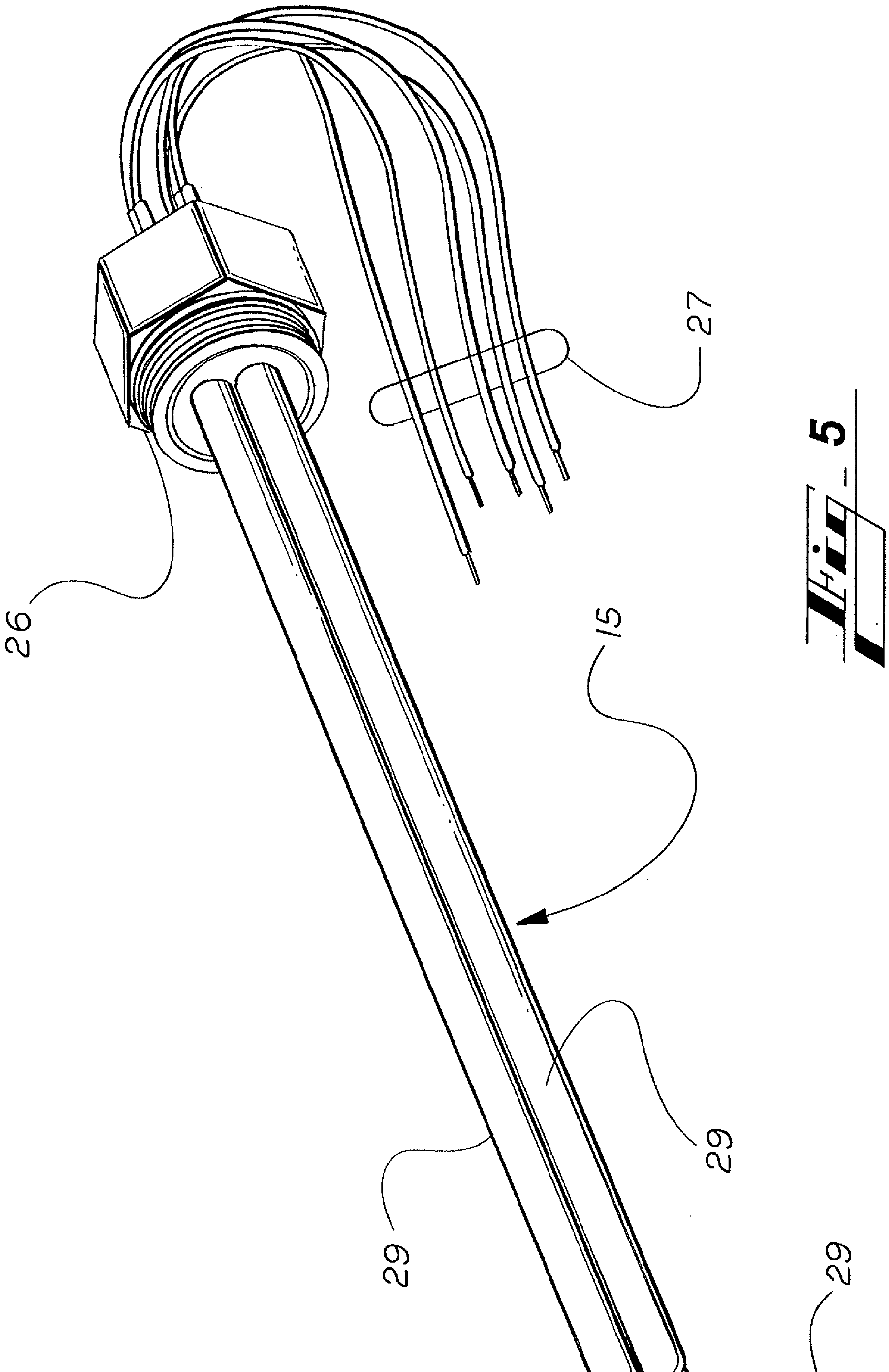


Fig. 5

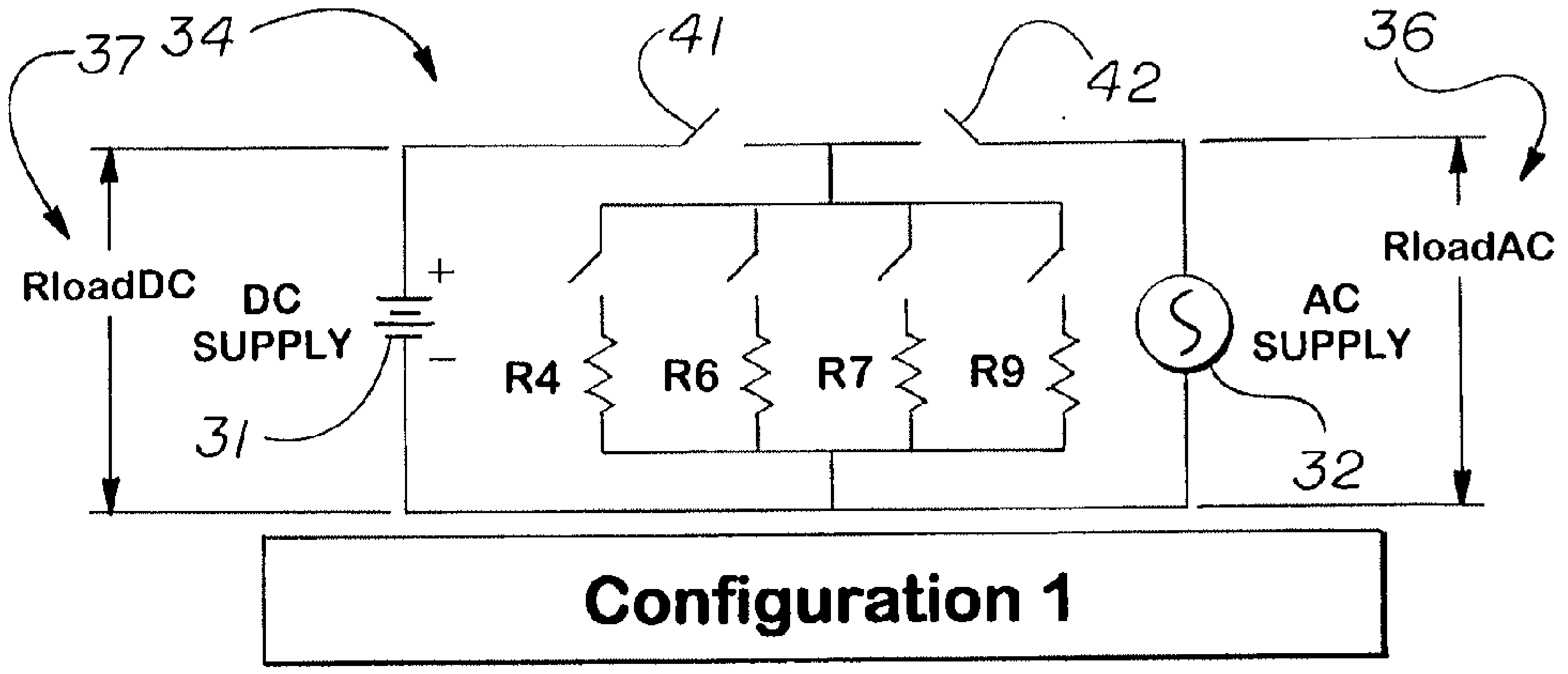


Fig_6

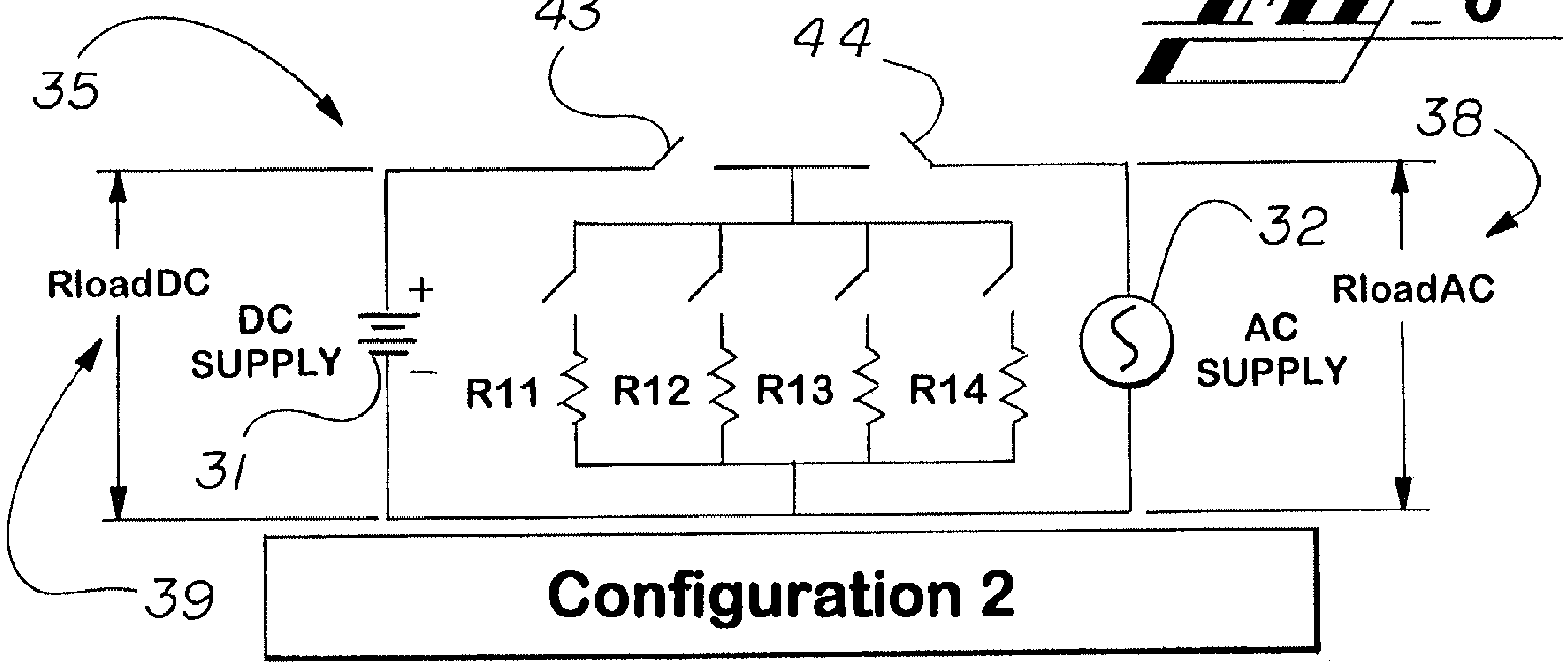


Fig_7

Irradiance Watts/m^2	Panel Volts	Array Volts	Amps	Actual R	Actual W
1,000.00	38.01	190.05	7.98	23.82	1,516.60
900.00	38.32	191.60	7.12	26.91	1,364.19
800.00	37.80	189.00	6.43	29.39	1,215.27
700.00	37.72	188.60	5.63	33.50	1,061.82
600.00	37.19	185.95	4.79	38.82	890.70
500.00	37.01	185.05	3.99	46.38	738.35
400.00	36.83	184.15	3.19	57.73	587.44
300.00	36.64	183.20	2.39	76.65	437.85
200.00	36.16	180.80	1.60	113.00	289.28

Fig_8

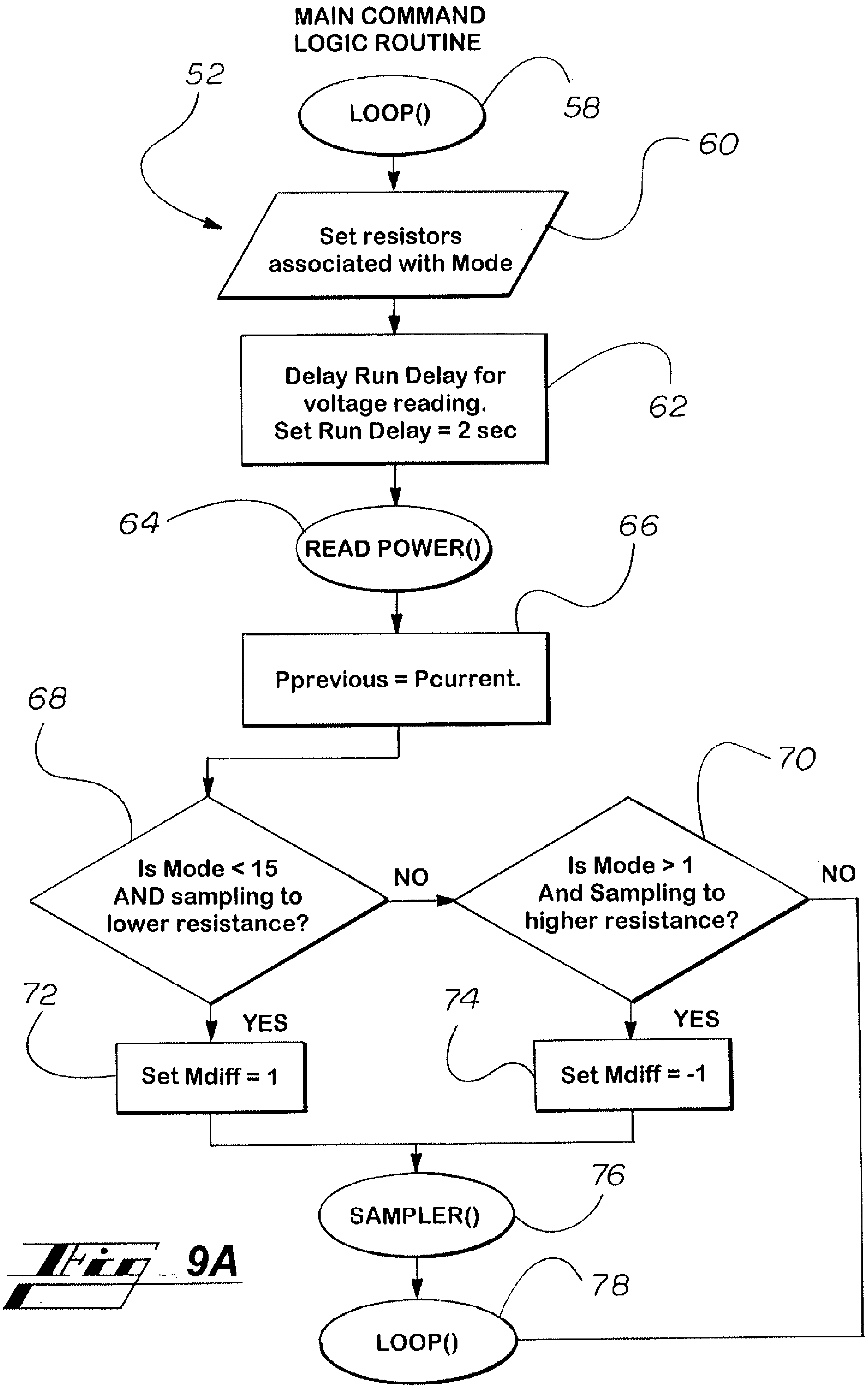

MAIN COMMAND
LOGIC ROUTINE
52
LOOP()
58
60
Set resistors associated with Mode
Delay Run Delay for voltage reading. Set Run Delay = 2 sec
62
64
READ POWER()
66
Pprevious = Pcurrent.
68
70
Is Mode < 15 AND sampling to lower resistance?
NO
Is Mode > 1 And Sampling to higher resistance?
NO
72
YES
74
YES
Set Mdiff = 1
Set Mdiff = -1
76
SAMPLER()
78
LOOP()

Fig. 9A

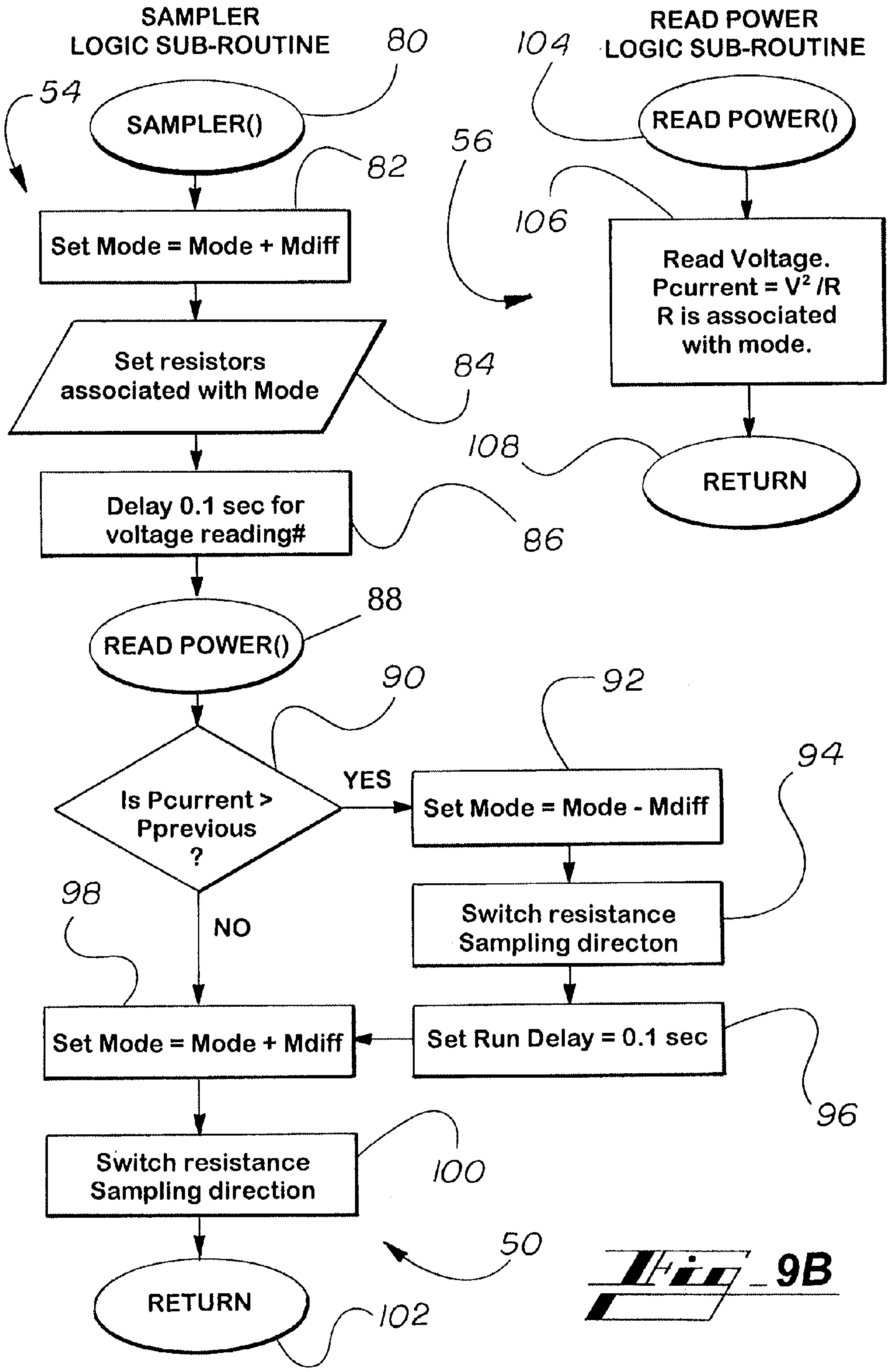

SAMPLER
LOGIC SUB-ROUTINE
80
54
SAMPLER()
82
Set Mode = Mode + Mdiff
Set resistors
associated with Mode
84
Delay 0.1 sec for
voltage reading#
86
READ POWER()
88
90
Is Pcurrent >
Pprevious
?
YES
NO
92
Set Mode = Mode - Mdiff
94
Switch resistance
Sampling directon
Set Run Delay = 0.1 sec
96
98
Set Mode = Mode + Mdiff
Switch resistance
Sampling direction
100
50
RETURN
102
READ POWER
LOGIC SUB-ROUTINE
104
READ POWER()
56
106
Read Voltage.
Pcurrent = V² /R
R is associated
with mode.
108
RETURN

Fig. 9B

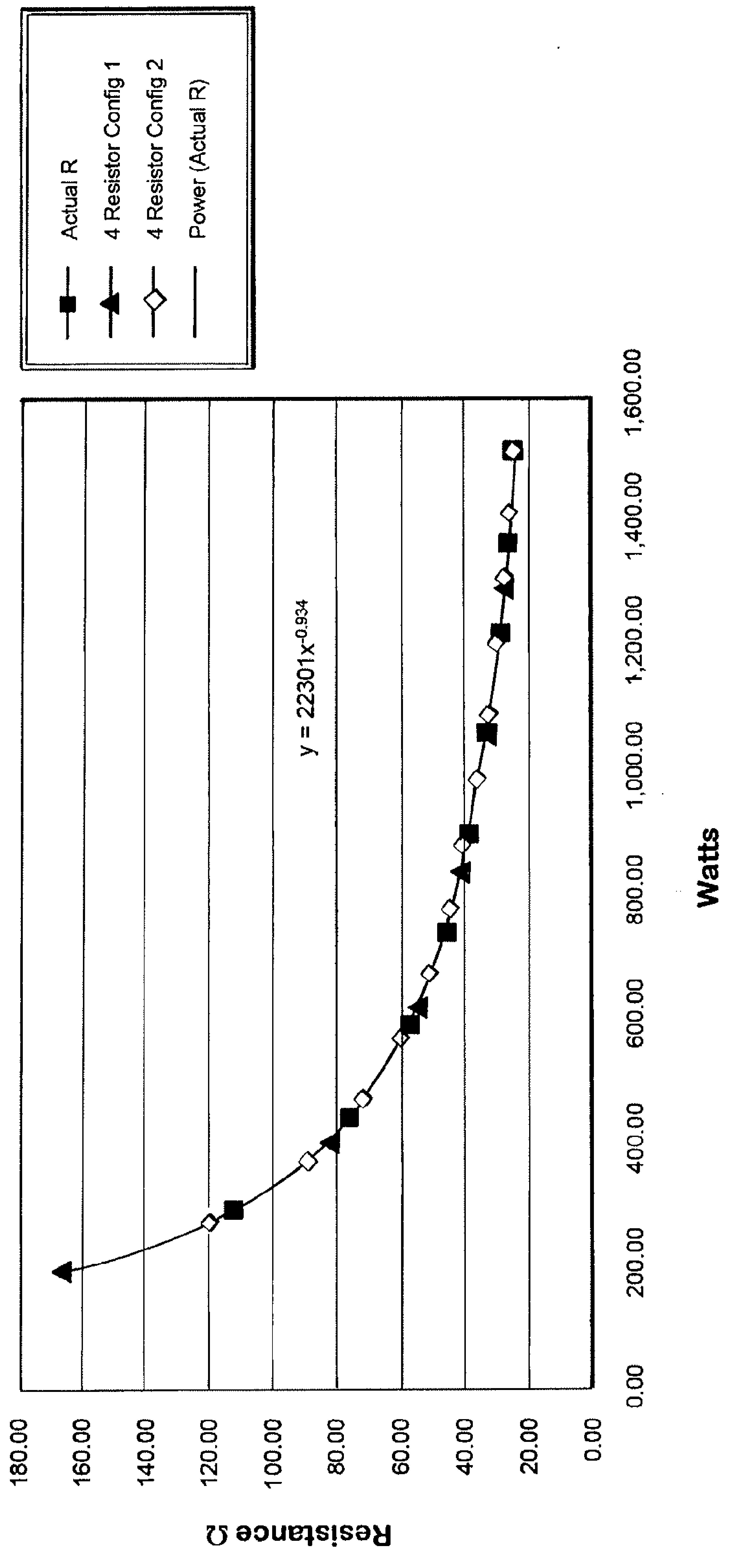

Actual R
4 Resistor Config 1
4 Resistor Config 2
Power (Actual R)
y = 22301x$^{-0.934}$
Resistance Ω
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
200.00
400.00
600.00
800.00
1,000.00
1,200.00
1,400.00
1,600.00
Watts

Fig_10

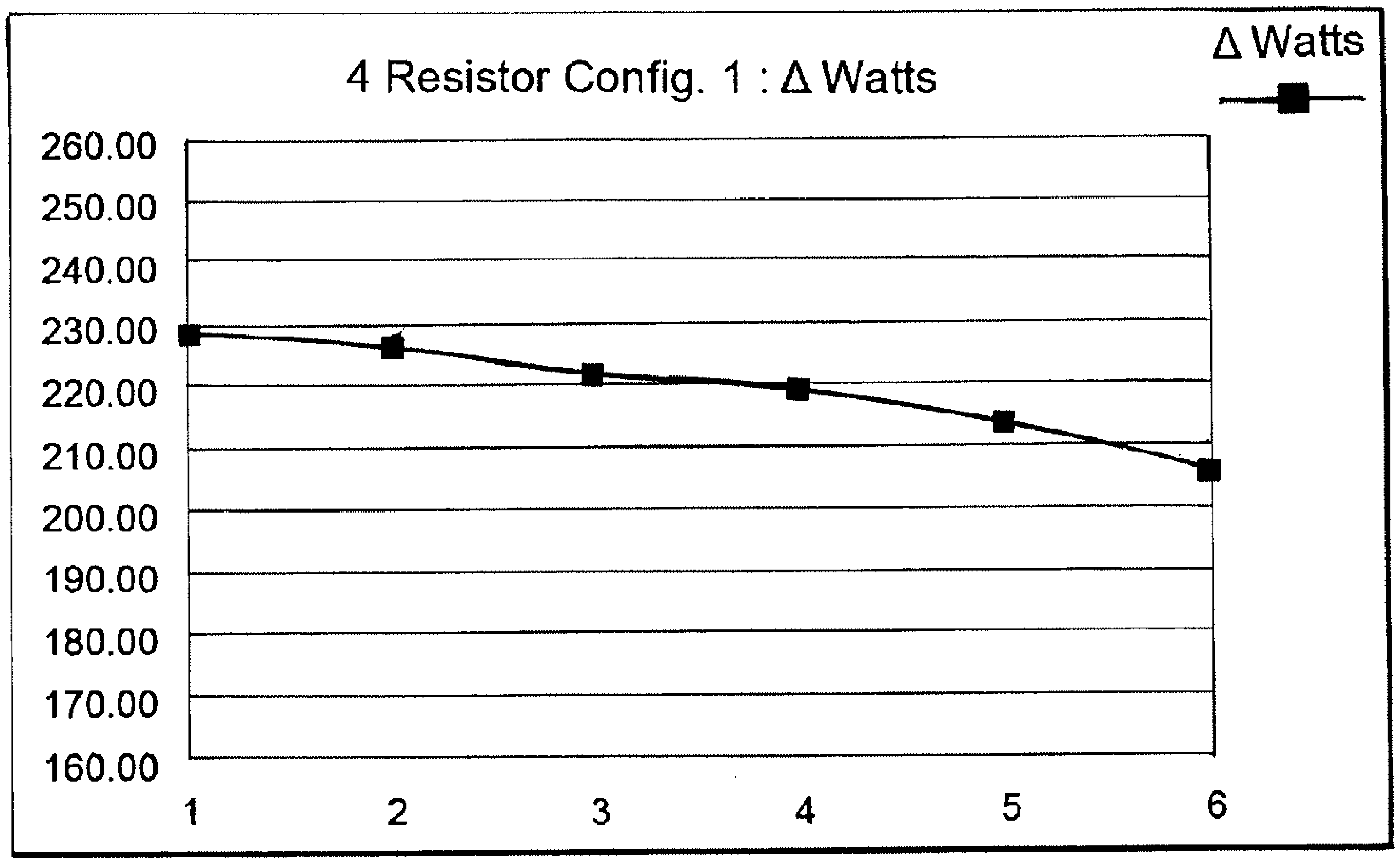


FIG_11A

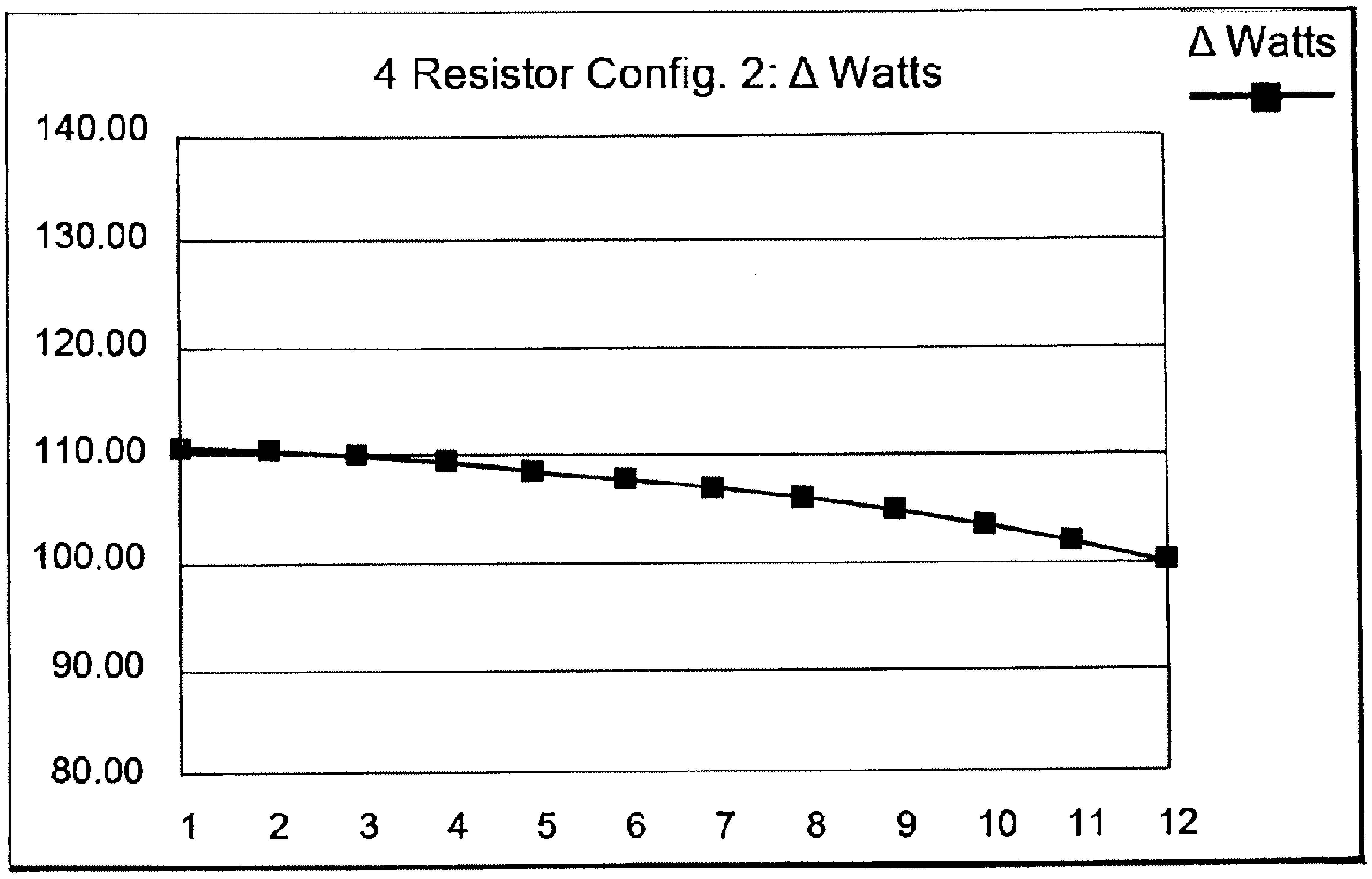


FIG_11B

4 Resistor Config 1	Resistance	Watts	Δ Watts	Volts	Amps	Switch Rs	
R1	23.82	1,518.57		190.17	7.99	1110	
R2	27.79	1,287.53	231.04	189.14	6.81	1100	
R3	33.34	1,059.20	228.32	187.93	5.64	1010	
R4	41.68	834.11	225.10	186.45	4.47	1000	
R5	55.57	612.99	221.12	184.56	3.32	0110	
R6	83.36	397.12	215.87	181.94	2.18	0100	
R7	166.71	189.07	208.05	177.54	1.06	0010	
R8 (AC)	16.46	3,500.00		240.00	14.58	1111	All On
					All off	0000	

Fixed R Values	R	Ratios of R4
R4	41.68	1.00
R6	83.36	2.00
R7	166.71	4.00
		(method determined value)
R9	53.26	

Fig. 12A

4 Resistor config 2	Resistance	Watts	Δ Watts	Volts	Amps	Switch Rs
R1	23.82	1,518.57		190.17	7.99	1110
R2	25.52	1,410.44	108.13	189.71	7.43	1101
R3	27.48	1,302.85	107.59	189.21	6.89	1011
R4	29.77	1,195.85	107.00	188.68	6.34	0111
R5	32.48	1,089.47	106.37	188.10	5.79	1100
R6	35.72	983.78	105.69	187.47	5.25	1010
R7	39.69	878.84	104.95	186.77	4.71	1001
R8	39.69	878.84	0.00	186.77	4.71	0110
R9	44.65	774.71	104.12	186.00	4.17	0101
R10	51.03	671.51	103.21	185.12	3.63	0011
R11	59.54	569.34	102.17	184.12	3.09	1000
R12	71.45	468.38	100.66	182.93	2.56	0100
R13	89.31	368.84	99.54	181.50	2.03	0010
R14	119.08	271.06	97.78	179.66	1.51	0001
R15 (AC)	19.85	2,902.28		240.00	12.09	1111
					All off	0000

All On

Fixed R Values	R	Ratios of R11
R11	59.54	1.00
R12	71.45	1.20
R13	89.31	1.50
R14	119.08	2.00

Fig. 12B

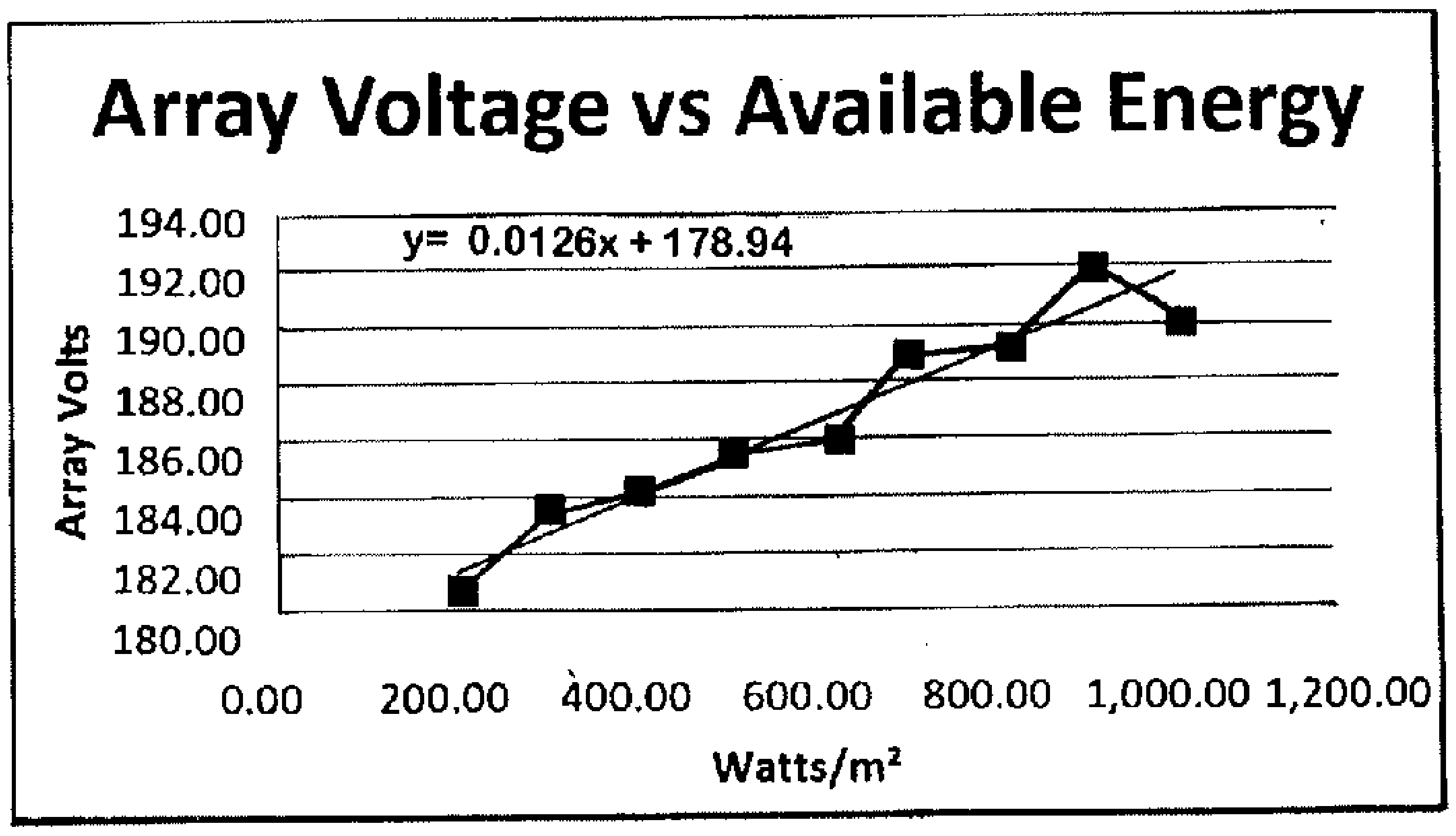


Fig_13A

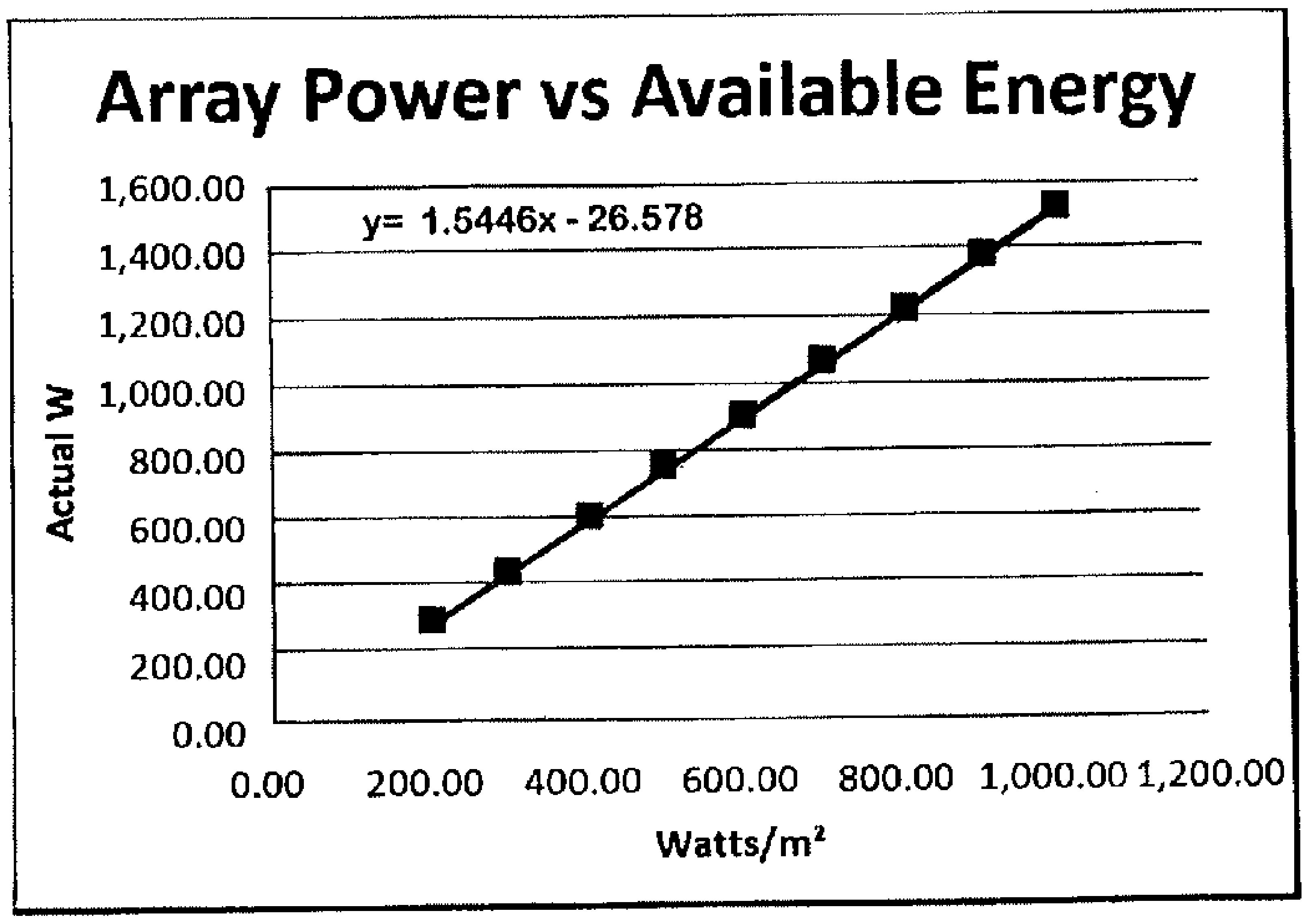


Fig_13B

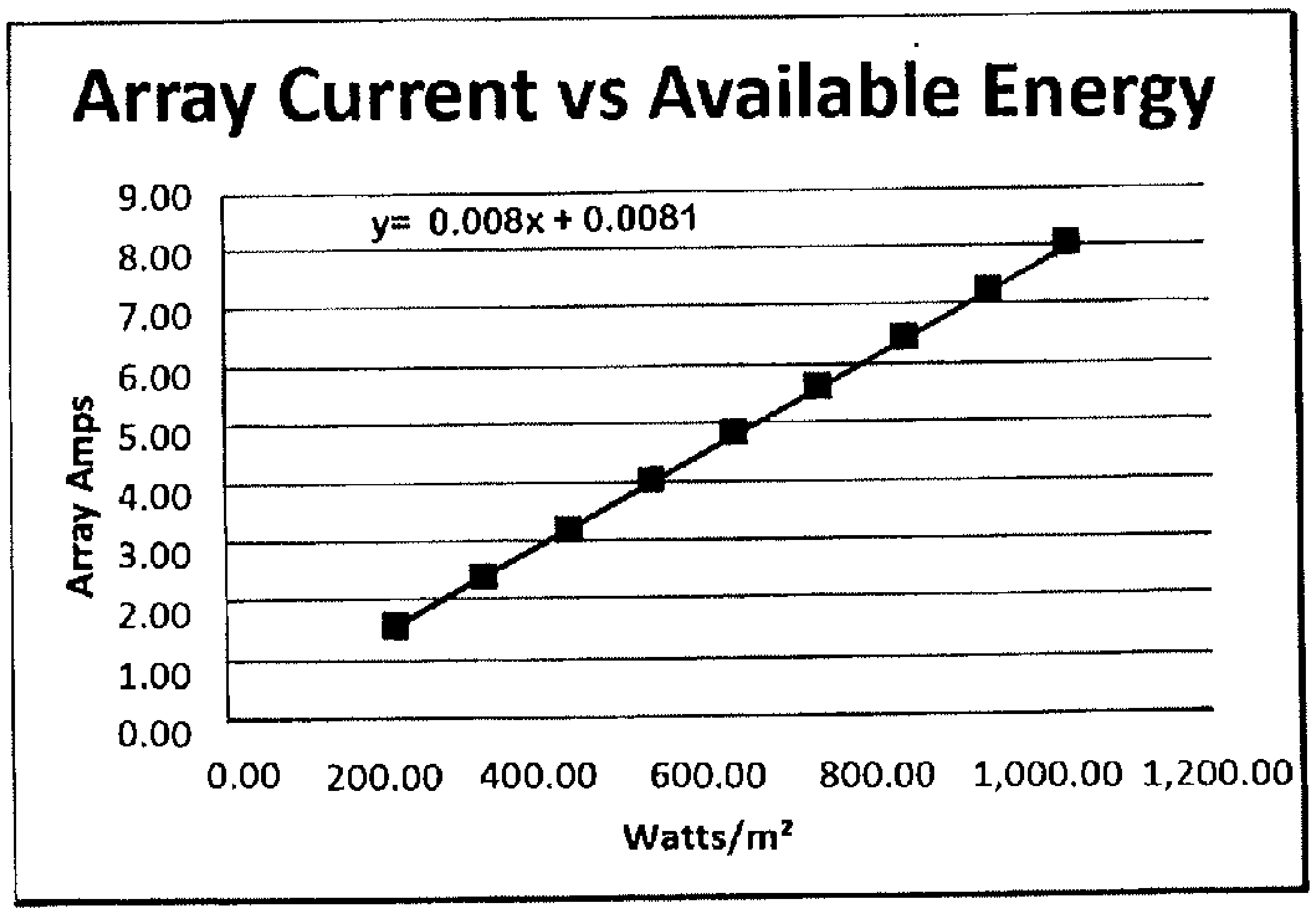


Fig_13C

SOLAR PHOTOVOLTAIC WATER HEATING SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Ser. No. 61/733,595, filed Dec. 5, 2012, which is incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The invention relates to a direct current (DC), photovoltaic (PV) water heating system. In particular, the invention is a photovoltaic water heating system that controls the electrical energy used to heat the water.

BACKGROUND OF THE INVENTION

[0003] Solar water heaters are known in the prior art. Kemp U.S. Pat. No. 451,384, entitled, "Apparatus for Utilizing the Sun's Rays for Heating Water," discloses a solar water heating system that comprises a series of large diameter pipes connected in series in a wooden box, insulated with sand, and covered with green house glass panes. The pipes contained a volume of water that was directly heated by solar irradiance during the day for use in the evening. Subsequent to the Kemp patent, an improved solar water heating system comprised a separate solar collector and a storage tank. The solar collector used the decrease in the density of the water when heated to move water into the tank. This arrangement created a thermosiphonic flow. Solar water heating systems have been evolving along those same technological lines ever since. Essentially, there is a tank, a collector, and a means to move heat energy from the collector to the tank.

[0004] Fanney et al. U.S. Pat. No. 5,293,447, titled "Photovoltaic Solar Water Heating System", issued in 1994, discloses a solar water heating system that uses solar generated electricity from photovoltaic panels to power specialized electric resistance heating elements that are fully immersed in the water heater tank. The resistance heating elements are connected in various parallel combinations, directly to the DC output of the photovoltaic solar panels. A computer control system selects the configuration of resistance elements to match the electric power output characteristics of the photovoltaic panels. The computer control system measures the power characteristics of the photovoltaic panels and operates electrical/mechanical relays that provide the direct connection of the DC power from the photovoltaic array to the resistance heating element combinations. The heating element combinations are determined to extract the optimum amount of power from the photovoltaic array. The solar water heating system of the Fanney et al. patent is, however, limited to a maximum of 7 combinations of resistance and those combinations are not mathematically optimized to achieve even step changes in power delivery from the PV panel array.

[0005] Ashkenazy United States Patent Application Publication No. 20120187106, entitled "Photovoltaic Heater", filed on Mar. 29, 2012, discloses a photovoltaic heating system that relies on an inverter device for the conversion of direct current from a photovoltaic solar array to alternating current (AC) to power a conventional resistance heating element. DC to AC inverters have been used in PV systems for homes for many years to provide AC power for the various loads and appliances including resistance water heaters. The Ashkenazy Application further discloses a switching circuit that disconnects the inverter's AC power from the resistance heating elements and connects the AC power from the electrical grid to the resistance heating elements. Consequently, the resistance heating elements are switched between one AC power source of a variable level (solar) to another AC power source of a known and constant level (electrical grid).

[0006] Yet another patent Thomasson United States Patent Application Publication No. 2009/0188486, entitled "PV Water Heater with Adaptive Control", filed Jan. 24, 2008, discloses a method to detect hot water usage, and interact with the PV that limits the energy delivery to the water heater as a function of hot water usage.

SUMMARY OF THE INVENTION

[0007] The solar photovoltaic water heating system of the present invention comprises a solar PV array consisting of PV panels, a water storage tank for storing heated water, resistance heating elements in the water tank for heating the water, and a programmable control system for delivering DC power from the PV panels to the resistance heating elements.

[0008] In overcoming the deficiencies of the prior art solar heating systems, the solar photovoltaic water heating system of the present invention assures safety for the users of the hot water and assures safety in connection with the use of direct electric current. The solar photovoltaic water heating system is an advancement over other DC power powered direct PV heating systems in that the present invention employs formulae and methods for more accurately determining power output from the PV panels of the PV array in order to optimize energy deliver over a wider range of operating conditions.

[0009] A feature of the present invention is the programmable control system that switches or redirects power available from the PV panels of the PV array when the hot water load demand has been met.

[0010] A further feature of the present invention is a method implemented by the control system that causes the photovoltaic water heating system to store higher temperature water in the storage tank but then safely delivers water at a lower temperature to the users of the hot water, thus allowing more energy to be stored in the tank during periods of high solar irradiance.

[0011] Another feature of the present invention, the programmable control system which includes a high temperature limit switch to insure water temperatures do not exceed the practical operating limit of the particular storage tank being used, thereby prolonging the life of the storage tank and reducing warranty claims and issues.

[0012] An additional feature of the present invention is a method implemented by the control system for determining the best resistance values for multiple resistance heating elements that are used in varied connection arrangements to maximize electrical energy delivery from the PV array. The method includes formulae to determine resistance values for the resistance heating elements that create more even steps in the power point tracking of the energy delivered from the PV array to the resistance heating elements.

[0013] A further feature of the present invention is a method of accumulating and storing data related to the energy delivered by the PV array to the resistance heating elements and to report that data to a remote data acquisition system.

[0014] According to yet a further feature of the present invention is a method to remotely access the control system for programming and data downloads of stored information that users may determine is needed for other purposes.

[0015] Another feature of the present invention is a multiple resistance heating element having four individual and discrete heating elements in a single assembly. The four prong resistance heating element is adaptable for use with either AC or DC electrical power.

[0016] An additional feature of the present invention is a structure for the four pronged resistance heating element that can be used for either AC or DC electrical power.

[0017] Further objects, features and advantages will become apparent upon consideration of the following detailed description of the invention when taken in conjunction with the drawings and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] FIG. **1** is a schematic diagram of a solar photovoltaic water heating system in accordance with the present invention.

[0019] FIG. **2** is a perspective view of a storage tank in accordance with the present invention.

[0020] FIG. **3** is a top plan view of the storage tank in accordance with the present invention.

[0021] FIG. **4** is a side elevation view of the storage tank in accordance with the present invention.

[0022] FIG. **5** is a perspective view of a four pronged electrical resistance heating element in accordance with the present invention.

[0023] FIG. **6** is a schematic diagram of a resistance value switching circuit in accordance with the present invention.

[0024] FIG. **7** is a schematic diagram of another resistance value switching circuit in accordance with the present invention.

[0025] FIG. **8** is a data table showing irradiance performance of a typical photovoltaic panel.

[0026] FIGS. **9**A and **9**B is a flowchart of the control logic that is used in the photovoltaic water heating system to control energy delivery from a solar panel array to the four pronged electrical resistance heating element.

[0027] FIG. **10** is a graph illustrating of a theoretical ideal power curve for an infinitely variable resistance load for a variable direct current power source and illustrating the power curve for the four pronged resistance heating element, connected in various combinations to provide a variable resistance load.

[0028] FIGS. **11**A and **11**B are graphs illustrating two power point matching curves that illustrate step changes in power (wattage) as a function of changes in solar irradiance.

[0029] FIGS. **12**A and **12**B are data tables used in developing resistance values for optimum operation of the photovoltaic water heating system in accordance with the present invention.

[0030] FIGS. **13**A-**13**C are data tables used in developing system resistance values for optimum operation of the photovoltaic water heating system in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0031] Turning to FIG. **1**, a solar photovoltaic water heating system **1** is shown. The solar photovoltaic water heating system **1** includes a photovoltaic panel array **31** consisting of individual solar photovoltaic panels **18**, a water storage tank **10** with resistance heating elements **15**, a programmable control system **16**, and an alternating current power source **32**. The control system **16** is connected between the storage tank **10** and the photovoltaic panel array **31** and the alternating current power source **32** in order to control the delivery of power from either the photovoltaic panel array **31** or the alternating current power source **32** to the resistance heating elements **15**. One of the heating elements **15** may be a standard alternating current resistance heating element that is only connected to the alternating current power source **32**. Alternatively, both heating elements **15** may be alternating current and direct current compatible, resistance heating elements such as the resistance heating element **15** shown in FIG. **5** and described below.

[0032] The photovoltaic panels **18** are conventional and produce direct current power when exposed to irradiance **19** from the Sun **20**. The amount of direct current power produced by each photovoltaic panel **18** depends on the level of irradiance **19** impinging on the photovoltaic panels **18**. Consequently, because the level of irradiance **19** varies based on the time of day and atmospheric conditions, the level of direct current power produced by each photovoltaic panel **18** varies accordingly. FIGS. **13**A-**13**C arc graphs that show the typical energy available from the photovoltaic array **31** for different voltages, power levels, and averages.

[0033] The water storage tank **10** is generally conventional and is shown in FIGS. **2**-**4**. The water storage tank **10** includes a cold water inlet **22** extending to near the bottom of the storage tank **10** for the introduction of cold water **12** into the storage tank **10**. The storage tank **10** further includes a hot water outlet **21** extending into the upper part of the storage tank **10**. A mixing valve **17** is connected to the hot water outlet **21** and to a cold water shunt **33** in order to provide a mixture of hot and cold water to the hot water outlet **11**, which in turn is connected to a consumer water system (not shown). The mixing valve **17** is thermostatically controlled to ensure that the hot water **11** is not too hot for a consumer water system such as residential hot water system. The operation of the mixing valve **17** allows the water in the storage tank **10** to be raised substantially higher than a normal residential consumer water system thereby allowing the solar photovoltaic water heating system **1** to store more energy in the storage tank **10**. The water storage tank **10** further includes a cover **25** for housing and protecting the control systems **16** and associated wiring. A pressure relief safety valve **23** is also connected to and in communication with the interior of the water storage tank **10**. If the pressure inside the water storage tank **10** exceeds a preselected level for the relief safety valve **23**, the relief safety valve **23** opens so that the pressure inside the water storage tank **10** can be relieved.

[0034] The resistance heating elements **15** are located in the water storage tank **10** at one or more levels to ensure consistency of the water temperature in the water storage tank **10**. As shown in FIG. **5**, the resistance heating element **15** comprises, for example, four individual resistance heating rods **29** connected through a stainless steel fitting **26**. The resistance heating rods **29** may be formed of stainless steel, inconel, carbon steel, or copper. The stainless steel fitting **26** is threaded into the side of the water storage tank **10** to form a water and pressure tight seal. Each individual resistance heating rod **29** has a pair of connecting wires **27** that allow each resistance heating rod **29** to be individually connected to either the photovoltaic array **31** or the direct current power source **32** through a switching circuit, such as one of switching circuits **34** (FIG. **6**) and **35** (FIG. **7**).

[0035] The switching circuits **34** and **35** are controlled by the control system **16** in order to select the optimum load resistance, such as direct current load resistance RloadDC **37** or RloadDC **39** for the direct current power source **31** (photovoltaic array **31**) or alternating current load resistance RloadAC **36** or RloadAC **38** for the alternating current power source **32** (public power grid). The switching circuit **34** illustrates a first configuration and is configured to provide seven resistance values for the direct current load resistance RloadDC **37** and one resistance value for the alternating current load resistance RloadAC **36**. The switching circuit **34** comprises a DC switch **41**, an AC switch **42**, and a resistance array including fixed value resistors R**4**, R**6**, R**7**, and R**9** with their associated switches. The resistors R**4**, R**6**, R**7**, and R**9** represent each of the four individual heating rods **29** in the resistance heating element **15**. The control system **16** opens and closes the DC switch **41**, the AC switch **42**, and the switches associated with each of the resistors R**4**, R**6**, R**7**, and R**9** in order to select the optimum direct current load resistance RloadDC **37** for the direct current power source **31** or the optimum alternating current load resistance RloadAC **36** for the alternating current power source **32**. Selection of the optimum load resistance RloadDC **37** or RloadAC **36** maximizes the energy delivered to the water in the water storage tank **10** by either the direct current power source **31** or the alternating current power source **32**.

[0036] Likewise the switching circuit **35** illustrates a second configuration and is configured to provide **14** resistance values for the direct current load resistance RloadDC **39** and one resistance value for the alternating current load resistance RloadAC **38**. The switching circuit **35** comprises a DC switch **43**, an AC switch **44**, and a resistance array including fixed value resistors R**11**, R**12**, R**13**, and R**14** with their associated switches. The resistors R**11**, R**12**, R**13**, and R**14** represent each of the four individual heating rods **29** in the resistance heating element **15**. The control system **16** opens and closes the DC switch **43**, the AC switch **44**, and the switches associated with each of the resistors R**11**, R**12**, R**13**, and R**14** in order to select the optimum direct current load resistance RloadDC **39** for the direct current power source **31** or the optimum alternating current load resistance RloadAC **38** for the alternating current power source **32**. Selection of the optimum load resistance RloadDC **39** or RloadAC **38** maximizes the energy delivered to the water in the water storage tank **10** by either the direct current power source **31** or the alternating current power source **32**.

[0037] With respect to configuration 1, illustrated by switching circuit **34** and by the table shown in FIG. **12**A, the formula set forth below establishes the values for the fixed resistors R**4**, R**6**, R**7**, and R**9** (the resistance heating rods **29** of the resistance heating element **15**). Once the values for the resistors R**4**, R**6**, R**7**, and R**9** have been established, the control system **16** runs an algorithm to open and close the switches in the switching circuit **34** to produce the optimum load resistance for the power source that is available. In order to determine the values for the resistors R**4**, R**6**, R**7**, and R**9**, the formula first solves for the single resistor R**4** (one of the four heating rods **29** of the heating element **15**). The value for the resistor R**4** is then used in a ratio determination method, described in greater detail below, to determine the three other fixed resistance values for resistors R**6**, R**7**, and R**9** (the other three of the four heating rods **29** of the heating element **15**). The fixed resistance values of resistors R**4**, R**6**, R**7**, and R**9** are used by the control system **16** in various single and parallel connection arrangements to create up to seven different direct current load resistance values R**1**, R**2**, R**3**, R**4**, R**5**, R**6**, and R**7**, and one alternating current load resistance value R**8** (see table, FIG. **12**A). The resistance values R**1**-R**7** are used in connection with the direct current power source **31**, and the resistance value R**8** is used in connection with the alternating current power source **32**. The resistance value R**8** is the optimum value for the alternating current power source **32**, and the resistance value R**8** is the lowest available resistance and results from the parallel connection of all four fixed resistors R**4**, R**6**, R**7**, and R**9** (resistance heating rods **29** of the resistance heating element **15**). R**1** is the optimum resistance value for the direct current power source **31** where the direct current power source is delivering maximum energy at 1000 watts per square meter of solar irradiance **19**. See FIG. **8**, first line (resistance=23.82 ohms) and FIG. **12**A (R**1**=23.82 ohms).

[0038] The formula for determining the value of the fixed resistor R**4** for configuration 1 (FIG. **12**A) is as follows:

[0039] P_W=Array Power in watts at solar irradiance level (w)

[0040] MPP=Maximum Power Point (MPP—the optimum transfer of energy from the power source to the resistance load)

[0041] R=Load Resistance

[0042] W=Watts delivered to the load

[0043] W/m^2=Watts per square meter of solar irradiance

[0044] V_K=Photovoltaic array operating MPP voltage (volts) @ 1000 W/m^2

[0045] Photovoltaic array operating MPP source (amps) @ 1000 W/m^2

[0046] V_W=Photovoltaic array MPP voltage at a stated level of solar irradiance (w)

[0047] I_W=Photovoltaic array MPP current at a stated level of solar irradiance (w)

[0048] M_v=Slope of linear equation for calculating Voltage (≈0)

[0049] B_v=y-intercept of linear equation for calculating Voltage (≈V_W)

$$P_W=V_W I_W \qquad \text{Standard Power formula:}$$

[0050] The majority of mono-crystalline photovoltaic panels follow the approximation for input energy between 200 and 1000 W/m^2.

$$V_W \approx M_v W+B_v$$

$$I_W(W/1000)I_K$$

[0051] Formula for determination of optimal value of R_4 is as follows:

$$R_1=1/((1/R_4)+(1/R_6)+(1/R_7))=V_K/I_K$$

$$I_K/V_K=(1/R_4)+(1/2R_4)+(1/4R_4)\rightarrow I_K/V_K=1.75/R_4\rightarrow R_4=1.75(V_K/I_K)$$

[0052] Once the value of R**4** for configuration 1 (FIG. **12**A) is determined, the ratio formula is used to select the optimal resistance values of fixed resistors R**6**, R**7**, and R**9**:

[0053] R_4 is used to determine R_6, and R_7 wherein

[0054] R_6 is a multiple of two (2) times the value of R_4

[0055] R_7 is a multiple of four (4) times the value of the value of R_4.

[0056] R_9 is determined by inserting the derived value for optimal AC operation as follows:

[0057] W_{AC}=desired power output for alternating current power source

[0058] V_{AC}=voltage for the alternating current power source

[0059] $I_{AC}=W_{AC}/V_{AC}$

[0060] $R_{AC}=V_{AC}/I_{AC}$ Example: W_{AC}=3500 watts

$$V_{AC}=240 \text{ volts}$$

[0061] The calculation then proceeds as follows: I_{AC} (current)=3500/240=14.58 mps

$$R_{AC}=240/14.58=16.46$$

$$R_9=1/((1/R_{AC})-(1/R_4)-(1/R_6)-(1/R_7))^*=1/((1/R_{AC})-(1.75/R_4))$$

$$R_8=1/((1/R_4)+(1/R_6)+(1/R_7)+(1/R_9))=R_{AC}^{**}$$

$$R_7=4\ R_4^*$$

$$R_6=2R_4^*$$

$$R_5=1/((1/R_7)+(1/R_6))$$

R_4=Value of resistance to be determined using proprietary formula*

$$R_3=1/((1/R_4)+(1/R_7))$$

$$R_2=1/((1/R_4)+(1/R_6))$$

$$R_1=1/((1/R_4)+(1/R_6)+(1/R_7))$$

$$R_0=\infty \text{ (all off)}$$

[0062] * (these are the fixed values of resistance for the four (4) pronged heating element **15**

[0063] ** (the R_8 value being the optimum resistance for operation on grid alternating current power)

[0064] With reference to FIGS. **6** and **12**A, the direct current load resistance RloadDC **37** and the alternating current load resistance RloadAC **36** for the switching circuit **34** are selected by the switch configurations defined by the binary bits, in the column "Switch RS." Each of the binary bits indicates the status of the associated switches for the fixed resistors R**4**, R**6**, R**7** and R**9**. For example, for the direct current power source **31**, the control system **16**, based on the output from direct current power source **31**, closes the DC switch **41**, opens the AC switch **42**, and sets the binary code to 1110. With the binary code set to 1110, the associated switches for fixed resistors R**4**, R**6**, and R**7** are closed, and the direct current load resistance RloadDC **37** equals the parallel combination of fixed resistors R**4**, R**6**, and R**7**, equals resistance R**1**, and equals 23.82 ohms (FIG. **12**A, line R**1**). As a further example, for the alternating current power source **32**, the control system **16** closes the AC switch **42**, opens the DC switch **41**, and sets the binary code to 1111. With the binary code set to 1111, the associated switches for fixed resistors R**4**, R**6**, R**7**, and R**9** are closed, and the alternating current load resistance RloadAC **36** equals the parallel combination of fixed resistors R**4**, R**6**, R**7** and R**9**, equals resistance R**8**, and equals 16.46 ohms (FIG. **12**A, line R**8**).

[0065] With respect to configuration 2, illustrated by switching circuit **35** (FIG. **7**) and by the table shown in FIG. **12**B, the formula set forth below establishes the values for fixed resistors R**11**, R**12**, R**13**, and R**14** (the four resistance heating rods **29** of the resistance heating element **15**). Once the values for the resistors R**11**, R**12**, R**13**, and R**14** have been established, the control system **16** runs an algorithm to open and close the switches in the switching circuit **35** to produce the optimum load resistance for power source that is available. In order to determine the values for the resistors R**11**, R**12**, R**13**, and R**14**, the formula first solves for the single resistor R**11** (one of the four heating rods **29** of the heating element **15**). The value for the resistor R**11** is then used in a ratio determination method, described in greater detail below, to determine the three other fixed resistance values for resistors R**12**, R**13**, and R**14** (the other three of the four heating rods **29** of the heating element **15**). The fixed resistance values of resistors R**11**, R**12**, R**13**, and R**14** are used by the control system **16** in various single and parallel connection arrangements to create up to 14 different direct current load resistance values R**1**, R**2**, R**3**, R**4**, R**5**, R**6**, R**7**, R**8**, R**9**, R**10**, R**11**, R**12**, R**13**, and R**14** and one alternating current load resistance value R**15** (see table, FIG. **12**B). The resistance values R**1**-R**14** are used in connection with the direct current power source **31**, and the resistance value R**15** is used in connection with the alternating current power source **32**. The resistance value R**15** is the optimum value for the alternating current power source **32**, and the resistance value R**15** is the lowest value and results from the parallel connection of all four fixed resistors R**11**, R**12**, R**13**, and R**14** (resistance heating rods **29** of the resistance heating element **15**). R**1** is the optimum resistance value for the direct current power source **31** where the direct current power source is delivering maximum energy at 1000 watts per square meter of solar irradiance **19**. See FIG. **8**, first line (resistance=23.82 ohms) and FIG. **12**B (R**1**=23.82 ohms).

[0066] The formula for determining the value of the fixed resistor R**11** for configuration 2 (FIG. **12**B) is as follows:

[0067] P_W=Array Power in watts at solar irradiance level (w)

[0068] MPP=Maximum Power Point (MPP-the optimum transfer of energy from the power source to the resistance load)

[0069] R=Load Resistance

[0070] W=Watts

[0071] W/m^2=Watts per square meter of solar irradiance

[0072] V_K=Photovoltaic array operating MPP voltage (volts) @ 1000 W/m^2

[0073] I_K=Photovoltaic array operating MPP current (amps) @ 1000 W/m^2

[0074] V_W=Photovoltaic array MPP voltage at a stated level of solar irradiance (w)

[0075] I_W=Photovoltaic array MPP current at a stated level of solar irradiance (w)

[0076] M_v=Slope of linear equation for calculating Voltage (≈0)

[0077] B_v=y-intercept of linear equation for calculating Voltage (≈V_W)

$$P_W=V_W I_W \qquad \text{Standard Power formula:}$$

[0078] The majority of mono-crystalline PV panels follow the approximation for input energy between 200 and 1000 W/m^2.

$$V_W \approx M_v W+B_v$$

$$I_W \approx (W/1000)I_K$$

R_K≈Optimum resistance for Maximum Power delivery at 1000 W/m^2

[0079] Formula for determination of optimal value of R_{11} is as follows:

$$R_1=R_K=V_K/I_K=1/((1/R_{11})+(1/1.2R_{61})+(1.5/R_{11}))$$

$$I_K/V_K=(1/R_{11})+(0.8333/R_{11})+(0.6666/R_{11})\rightarrow I_K/V_K=2.5/R_{11}\rightarrow R_{11}=2.5(V_K/I_K)$$

[0080] Once the value of R**11** for configuration 2 (FIG. **12**B) is determined, the ratio formula is used to select the optimal resistance values of fixed resistors R**12**, R**13**, and R**14**:

[0081] R_{12} is a 1.20 ratio of R_{11}.

[0082] R_{13} is a 1.50 ratio of R_{11}.

[0083] R_{14} is a 2.00 ratio of R_{11}.

[0084] Thus creating the resistance values:

$R_0=\infty$ (all off)

$R1=1/((1/R11)+(1/R12)+(1/R13))$

$R2=1/((1/R11)+(1/R12)+(1/R14))$

$R3=1/((1/R11)+(1/R13)+(1/R14))$

$R4=1/((1/R12)+(1/R13)+(1/R14))$

$R5=1/((1/R11)+(1/R12))$

$R6=1/((1/R11)+(1/R13))$

$R7=1/((1/R11)+(1/R14))$

$R8=1/((1/R12)+(1/R13))$ Not needed as the step difference is negligible

$R9=1/((1//R13)+(1/R14))$

$R10=1/((1/R13)+(1/R14))$

R11=Fixed resistance value derived using proprietary Formula of Claim **1**.*

$R12$=Fixed resistance value equal to $1.20\times R11$*

$R13$=Fixed resistance value equal to $1.50\times R11$*

$R14$=Fixed resistance value equal to $2.00\times R11$*

$R15=1/((1/R11)+(1/R12)+(1/R13)+(1/R14))$**

[0085] * these are the fixed values of resistance for the four (4) pronged heating element

[0086] ** this value is used for AC operation using grid power

[0087] With reference to FIGS. **6** and **12**B, the direct current load resistance RloadDC **39** and the alternating current load resistance RloadAC **38** for the switching circuit **35** are selected by the switch configurations, defined by the binary bits, in the column "Switch RS." Each of the binary bits indicates the status of the associated switches for the fixed resistors R**11**, R**12**, R**13**, and R**14**. For example, for the direct current power source **31**, the control system **16**, based on the output from direct current power source **31**, closes the DC switch **43**, opens the AC switch **44**, and sets the binary code to 1010. With the binary code set to 1010, the associated switches for fixed resistors R**11** and R**13** are closed, and the direct current load resistance RloadDC **39** equals the parallel combination of fixed resistors R**11** and R**13**, equals resistance R**6**, and equals 35.72 ohms (FIG. **12**A, line R**6**). As a further example, for the alternating current power source **32**, the control system **16** closes the AC switch **44**, opens the DC switch **43**, and sets the binary code to 1111. With the binary code set to 1111, the associated switches for fixed resistors R11, R12, R13, and R14 are closed, and the alternating current load resistance RloadAC **38** equals the parallel combination of fixed resistors R**11**, R**12**, R**13**, and R**14**, equals resistance R**15**, and equals 19.85 ohms (FIG. **12**B, line R**15**).

[0088] Turning to FIGS. **9**A and **9**B, the control system **16** is programmed to implement the control method **50** that controls the selection of the optimized resistance for either the direct current power source **18** or the alternating power source **32**. The control method **50** has a Main Command Logic Routine **52**, a Sampler Logic Subroutine **54** and a Read Power Subroutine **56**. The control method **50** begins at loop step **58** of the Main Command Logic Routine **52**. The internal processor of control system **16** steps through the logic sequence continually while the system has power applied and is in operation. Using the example of the operational resistance values of the 4 resistor configuration 2 of FIG. **12**B, each resistance value corresponds to a "Mode" of operation of the solar photovoltaic water heating system **10**. There are therefore **15** distinct operating modes each corresponding to a lineup of resistors that have been connected in parallel to set a different resistance value depending on the direct current power available for 14 of the modes and one mode where all fixed resistance values R**11**, R**12**, R**13**, and R**14** are switched on in parallel thereby creating an optimized resistance for operation of the resistance heating element **15** in the storage tank using power supplied by the alternating current power source **32**.

[0089] Starting from loop step **58** of the main command logic routine **52**, the routine **52** moves to step **60** where the routine **52** sets the resistance to Mode **14** (R**14** of configuration 2, FIG. **12**B), the highest value for the resistance of the resistance heating element **15**. From step **60**, the routine **52** moves to step **62**, where routine **52** imposes a two second delay. From step **62**, the routine **52** moves to step **64**, and branches to step **104** of the Read Power Subroutine **56**. From step **104**, the subroutine **56** moves to step **106**. At step **106**, the subroutine **56** uses the highest resistance value R**14** to read power available from the photovoltaic array **31**. The power (P) available from the photovoltaic array **31** is determined by measuring the voltage (V) from the photovoltaic array **31** and then calculating the power from the photovoltaic array **31** by using the formula $Pcurrent=V^2/R$ wherein resistance is a function of the Mode at the time Pcurrent is determined. Once the current power (Pcurrent) from the photovoltaic array **31** has been determined at step **106**, the subroutine **56** moves to step **108** and branches to step **66** of the routine **52**.

[0090] At step **66**, the routine **52** compares the previously determined power from the photovoltaic array **31** to the current power from the photovoltaic array **31** (Pprevious=Pcurrent). From step **66**, the routine **52** moves to decision step **68**, where the routine **52** determines if the current Mode is less than 15 and the routine **54** at step **94** is sampling the power from the photovoltaic array **31** using combinations the fixed resistor R**11**, R**12**, R**13**, and R**14** to create progressively lower resistances. If at step **68** the routine **52** determines that the current Mode is less than 15 and subroutine **54** at step **94** is sampling to a lower resistance, the routine **52** follows the yes branch to step **72**. If on the other hand, the routine **52** determines that Mode is greater than 15 or the subroutine **54** is sampling to higher resistances, the routine **52** follows the no branch to step **70**. At step **72**, the routine **52** sets Mdiff=+1. The term "Mdiff" means the difference by which the Mode changes when determining the next power reading by means of subroutine **56**. Particularly, at step **72** the routine **52** decreases the resistance by reconfiguring the fixed resistors R**11**, R**12**, R**13**, and R**14** to create a lower value of total resistance. Lowering the resistance is accomplished by turning on the next resistance value in parallel with the previous Mode resistance value, i.e changing from R**14** to R**13** in FIG. **12**B (0001 to 0010).

[0091] If at step **68** the determination is no, then the routine **52** moves to step **70** where the routine **52** determines if the Mode is greater than 1 and sampling is to a higher resistance. If at step **70** the routine **52** determines that the Mode is greater than 1 and the subroutine for is sampling toward higher resistances, the routine **52** follows the yes branch to step **74**. At step **74**, the routine **52** sets Mdiff=−1, i.e. the routine **52** subtracts one resistance value to change the Mode to a higher resistance. If at step **70** the condition is not satisfied, the routine **52** follows the no branch to step **78**, which then returns the routine **52** to the beginning at step **58**.

[0092] After the routine **52** has processed Mdiff at either step **72** or step **74**, the routine **52** moves to step **76** that branches to step **80** of subroutine **54**. In the Sampler Logic Subroutine **54**, the subroutine **54** sets Mode=Mode+Mdiff. From step **82** of subroutine **54**, the subroutine **54** proceeds to step **84** where the subroutine **54** sets the resistors associated with the Mode (Mode+Mdiff). Particularly, the fixed resistors R**11**, R**12**, R**13**, and R**14** are selected in accordance with the switch configurations shown in FIG. **12**B. From step **84**, the subroutine **54** proceeds to step **86** that imposes a 0.1 second delay. After the delay at step **86**, the subroutine **54** proceeds to step **88**, and then branches to step **104** of subroutine **56**. The Read Power Logic Subroutine **56** again determines the power value for the photovoltaic array **31** as previously described. Once the subroutine **56**, has completed its operation, control is transferred from step **108** back to step **88** any of the subroutine **54**.

[0093] From step **88**, the subroutine **54** proceeds to step **90**. At step **90**, the subroutine **54** determines if Pcurrent is greater than Pprevious. If at step **90** Pcurrent is greater than Pprevious, the subroutine **54** follows the yes branch to step **92**. At step **92**, the subroutine **54** sets Mode=Mode+Mdiff. Once the Mode has been set at step **92**, the subroutine **54** proceeds to step **94** where the sampling direction of the resistance is switched and a 0.1 second delay is imposed at step **96**. From step **96**, the subroutine **54** moves to step **98**. At step **98**, the subroutine **54** sets Mode=Mode−Mdiff. From step **98**, the subroutine **54** proceeds to step **100**, where the sampling direction for the resistance is again switched. From step **100**, the subroutine **54** proceeds to step **102**, which returns to step **76** of the routine **52**. From step **76**, the routine **52** proceeds to step **78**, and then returns to the beginning at step **58**.

[0094] If on the other hand, at step **90** Pcurrent is less than Pprevious, the subroutine **54** follows the no branch to step **98**. At step **98**, the subroutine **54** sets Mode=Mode−Mdiff. From step **98**, the subroutine **54** proceeds to step **100**, where the sampling direction for the resistance is again switched. From step **100**, the subroutine for proceeds to step **102**, which returns to step **76** of the routine **52**. From step **76**, the routine **52** proceeds to step **78**, and then returns to the beginning at step **58**. Consequently, method **50** continues sampling the power from the photovoltaic array **31** until a change is detected against the power trend. The control determination and switching process continues by constantly sampling values at varying time intervals as determined by the change rate of solar irradiance.

[0095] The programmable control system **16** of the present invention also monitors the water temperature and the water pressure in the storage tank **10**. Particularly, the storage tank **10** includes a temperature sensor **28** and a pressure sensor **14**. The temperature sensor **28** and the pressure sensor **14** are connected to the control system **16**. When the water temperature in the storage tank **10** falls below a preselected minimum temperature, the control system **16** connects either the direct current power source **18** or the alternating current power source **32** to the resistance heating elements **15**. Once the water temperature in the storage tank tenant reaches a maximum temperature based on the data received from the temperature sensor **28**, the control system **16** disconnects either the direct current power source **18** or the alternating from the resistance heating elements **15**. Once the direct current power source **18** has been disconnected from the resistance heating elements **15**, the direct current power source **18** can be diverted to a direct current power takeoff **30** that can be used to charge batteries, to power an inverter, or to drive a second resistance heating load such as a hot water space heating system. The control system **16** further monitors the data from the pressure sensor **14** so that the pressure in the storage tank **10** remains in a preselected safe pressure range. If the pressure in the water storage tank **10** rises above the preselected pressure range, the control system **16** disconnects either the direct current power source **18** or the alternating current power source **32** from the resistance heating elements **15**. If the pressure continues to rise in the water storage tank **10**, the pressure relief safety valve **23** will open relieving the pressure in the storage tank **10**. Further, if the pressure drops below the preselected pressure range, the control system **16** disconnects either the direct current power source **18** or the alternating current power source **32** from the resistance heating elements **15** so that the water in the storage tank **10** does not begin to boil at a low-pressure.

[0096] The control system **16** is programmable, either through a direct interface or remotely through a remote interface, and can be programmed to collect operating data including, but not limited to, the temperature and pressure data over time, the power delivered to the resistance heating elements **15**, the amount of energy delivered to the resistance heating elements **15** by the direct current power source **18** over time, and the amount of energy delivered to the resistance heating elements **15** by the alternating current power source **32** over time. Such data can be stored locally by the control system **16** or it can be transmitted to a remote data acquisition system (not shown) either over a wired network or a wireless network. Further, with advanced internal programming, the control system **16** is capable of learning to optimize energy delivery. For example, the control system **16** can monitor the time of day, the solar irradiance **19**, and the temperature of the storage tank **10** and thereby determine the optimal time to switch from the direct current power source **18** to the alternating current power source **32** by means of the switching circuit **34**, switches **41** and **42** or by means of the switching circuit **35**, switches **43** and **44**. Further, the time of the day, from around **2**-**3** pm to **5**-**6** pm depending on geographic location, offers the greatest chance that the solar array **31** will provide sufficient energy to bring the storage tank **10** to its maximum temperature in which case the alternating current power source **32** will not be used thereby increasing the efficiency of the solar photovoltaic water heating system **1**. The time periods above are also the less likely time periods in which a high consumption of hot water will be used while the sun is still out.

[0097] Turning to FIG. **10**, the graph shows an idealized power curve (power from the direct current photovoltaic power source **31** versus load resistance) that defines the maximum power point, i.e., the point of optimum transfer of energy from the power source to the resistance load where the load resistance is infinitely variable. The graph in FIG. **10** compares the idealized power curve to the operating curve for the solar photovoltaic water heating system **1** of the present invention. Particularly, the graph in FIG. **10** shows that by matching the resistance using the switching circuits **34** and **35**, the performance of the solar photovoltaic water heating system **1** of the present invention closely tracks the idealized power curve.

[0098] FIGS. **11**A and **11**B show plots of the step changes in the load resistance that occurs when using the formula and method of the present invention. To maximize energy delivery by maximum power point matching, the steps in the changes of the load resistance must be in as equal incremented values as possible. Resistance values that have changes that create anything other than a smooth curve will vary the load resistance above or below the maximum power point matching for a given level of solar irradiance. Resistance values that cause points to deviate from a smooth curve plotting will cause losses of energy delivery to the medium being heated.

[0099] FIGS. **13**A-**13**C are examples of data tables derived from measured and published performance information regarding photovoltaic panels. The data then is used to determine the various photovoltaic water heating system operating parameters, which in turn is used to determine the resistance values of the heating rods **29**.

[0100] While the invention has been described in connection with heating water, the invention has applicability to heating other media for storing energy. Further, while this invention has been described with reference to preferred embodiments thereof, it is to be understood that variations and modifications can be affected within the spirit and scope of the invention as described herein and as described in the appended claims.

We claim:

1. A solar photovoltaic water heating system comprising:
a. a solar photovoltaic panel for producing direct current power;
b. a water storage tank including:
  i. a cold water inlet;
  ii. a hot-water outlet; and
  iii. a variable resistance heating element having an electrical resistance; and
c. a control system connected between the solar photovoltaic panel and the variable resistance heating element and configured to vary the resistance of the variable resistance heating element to match the direct current power supplied by the solar photovoltaic panel.

2. The water heating system of claim **1**, wherein the variable resistance heating element comprises an array of individual fixed resistance heating rods and the control system is configured to switch the array of individual fixed resistance heating rods into a plurality of single and parallel connections in order to vary the resistance of the variable resistance heating element.

3. The water heating system of claim **2**, wherein the water heating system further includes a switching network connected to the individual fixed resistance heating rods and controlled by the control system to switch the array of individual fixed resistance heating rods into a plurality of single and parallel connections in order to vary the resistance of the variable resistance heating element.

4. The water heating system of claim **1**, wherein the water heating system further comprises a alternating current power source for producing alternating current power connected to the control system, and wherein the control system is configured to alternatively connect the direct current power from the solar photovoltaic panel or the alternating current power from the alternating current power source to the variable resistance heating element.

5. The water heating system of claim **1**, wherein the water heating system further includes a mixing valve having a first hot water inlet connected to the hot water outlet, a second cold water inlet connected to the cold water inlet via a cold water shunt, and a mixing valve outlet for delivering a mixture of hot and cold water to a consumer water system and wherein the control system controls the mixing valve and therefore the mixture of hot and cold water to the consumer water system.

* * * * *