Appendix A

Bayard-Alpert Ionization Gauges

This appendix attempts to explain the principles of operation of the Bayard-Alpert Ionization Gauge, or BAG, outline its fundamental limitations and describe the ion gauge types that have successfully surmounted some of them. A few practical tips are also provided along the way. The emphasis has been placed on gauges that are commercially available.

In This Appendix

Principle of Operation

Introduction

The Bayard-Alpert ionization gauge (BAG) was first described in 1950[1]. Modern versions of the gauge have preserved most of the basic elements of its original implementation. Standardization of the BAG design has made it possible for vacuum equipment manufacturers to produce generic ion gauge controllers, such as the IGC100, capable of controlling BAGs from many different manufacturers.

BAGs are not perfect, and the user who believes their pressure indications without a basic understanding of their operation is likely to be fooled.

This appendix attempts to explain the principles of operation of the BAG, outline its fundamental limitations and describe the ion gauge types that have successfully surmounted some of them. A few practical tips are also provided along the way. The emphasis has been placed on gauges that are commercially available.

Since it is not possible to cover this complex gauge in a short note, a comprehensive list of references is provided at the end that should allow the reader to find answers to most problems.

Gauge Principles

Figure A-1 describes a prototypical BAG design. Electrons boil from the hot filament (30Vdc) and are accelerated towards the anode grid (180Vdc). As the current (0.1-10 mA typical) of highly energetic (150eV) electrons traverse the inner volume of the grid cage, they ionize some of the gas molecules they encounter in their path. Electrons that do not encounter any obstacles in their path, exit the grid and are immediately directed back into its inner volume by the electrostatic field, resulting in a multiple-pass ionization path that ultimately ends by collision with a grid wire. The ions formed inside the anode grid are efficiently collected by the grounded (0Vdc) collector wire that is located along the axis of the cylindrical grid and connected to the controller's electrometer. If the electron emission current and the temperature of the gas are constant, then the ion current is proportional to the number density and the pressure of the gas. *The positive ion current provides an indirect measurement of the gas pressure.*

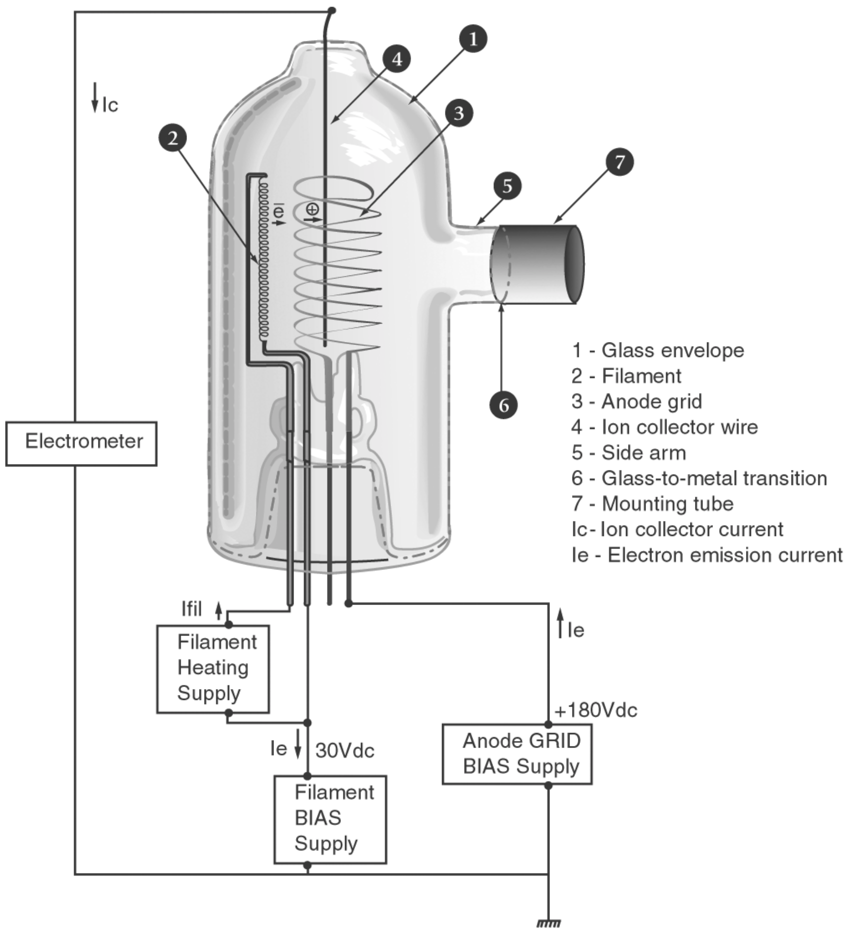

Figure A-1. Typical Bayard-Alpert configuration (glass-tubulated design)

Gauge Sensitivity

Definition

The number of ions formed inside the anode grid, and therefore the current measured by the electrometer of Figure A-1, is a function of

- the number of molecules per unit volume
- the ionization cross section for the particular gas at the specified electron energy
- the arrival rate of the electrons (i.e. emission current)
- the path length of the electrons.

A simple ionization gauge equation, based on very simple assumptions[2], that connects these quantities is derived below and used to define a sensitivity factor for the BAG.

Let σ_i be the ionization cross section for a gas molecule, L the length of the ionizing space, and A the cross-sectional area of the electron beam. The number of molecules included in this volume is $n \cdot L \cdot A$, where n is the molecular density, related to the gas pressure by $n = P/(k \cdot T)$. The collective ionization cross area of the molecules contained in this volume is $A_\sigma = (n \cdot L \cdot A) \cdot \sigma_i = \sigma_i \cdot L \cdot A \cdot P/(k \cdot T)$ and the fraction of incoming electrons that participate in ionizing collisions is $A_\sigma / A = n \cdot L \cdot \sigma_i = \sigma_i \cdot L \cdot P/(k \cdot T)$. Let N be the number of electrons entering the anode grid cage per unit time. The number of ionizing collisions per unit time is then $N \cdot \sigma_i \cdot L \cdot P/(k \cdot T)$ and, assuming all ions are effectively collected, the corresponding collector current I_c measured by the electrometer can then be expressed as:

$$I_c = \sigma_i \cdot L \cdot [P/(k \cdot T)] \cdot N \cdot e \qquad \text{(eqn.1)}$$

where e is the electron charge.

Substituting the electron emission current $I_e = N \cdot e$ into eqn. 1 leads to the expression

$$I_c = [\sigma_i \cdot L/(k \cdot T)] \cdot I_e \cdot P \qquad \text{(eqn. 2)}$$

The factor $[\sigma_i \cdot L/(k \cdot T)]$ is a function of (1) the gas type (σ_i), (2) the geometry of the gauge (L), and (3) the absolute temperature (T), and is generally defined as the *gauge sensitivity factor*, or S. Substituting this sensitivity factor into eqn. 2 leads to the standard ionization gauge equation

$$I_c = S \cdot I_e \cdot P \qquad \text{(eqn. 3)}$$

And rearranging terms leads to the well-known expression for the gauge sensitivity factor

$$\text{Sensitivity} = (\text{Ion Current}) / [(\text{Electron Current}) \cdot (\text{Pressure})] \qquad \text{(eqn. 4)}$$

This definition assumes a linear relationship between the pressure, the ion current and the electron emission current, and provides a proportionality constant independent of the electron current and dependent only on gas species, gauge geometry and operating temperature. As defined, the sensitivity factor has units of reciprocal pressure (i.e. $Torr^{-1}$).

Some gauge manufacturers prefer to use the term *gauge constant* or *gauge coefficient* for S. Then *sensitivity* can be reserved for the product $S \cdot I_e$, which is also an important parameter for the gauge.

Knowing the sensitivity factor S_g for a gas g, and assuming the electron emission current is also available, the total pressure for the pure gas can be easily calculated from the collector current using the following equation

$$P = I_c / (S_g \cdot I_e) \qquad \text{(eqn. 5)}$$

A nominal sensitivity factor for nitrogen is usually provided by the gauge manufacturer. *This value should not be relied upon for accurate work* since the precise values will vary significantly between seemingly identical gauges and even more between different gauge types, filament materials and operating potentials. Typical nitrogen sensitivity factors for commercially available BAGs fall in the range of 8 to 45 $Torr^{-1}$. Several aging mechanisms are also responsible for changes in gauge sensitivity with time, affecting the long term stability and reproducibility of BAG pressure readings.

IMPORTANT!
The only truly reliable method of determining a BAG sensitivity factor is through direct and careful calibration.

The electron emission current of many modern ion gauge controllers, including the IGC100, is fully adjustable and generally available to the user.

The sensitivity of a BAG, and the reliability of its measurements, is affected by several different variables. Some of these variables may be beyond operator control, or are controllable only with significant effort. Attempts to calculate sensitivity factors for BAGs, based on ionization efficiencies and geometrical considerations, have not proven useful because of a number of ill-defined parameters such as temperature, field distribution and ion collection efficiency. The effects of some of the variables are readily quantified, others are not, and only the magnitude of potential errors can be indicated.

The following sections cover some of the variables that can significantly affect the sensitivity of BAGs.

Pressure Dependence

A strict linear relationship between the pressure and the ion current makes the BAG the most accurate continuous indicator of total pressure in high vacuum applications.

The upper limit of BAG operation is about 10^{-3} Torr for most gauge designs, and is defined as the pressure at which the ion current vs. pressure relationship deviates from linearity. Specification claims beyond this range must be approached with caution!

The exact pressure value at which a BAG deviates from linearity differs significantly between gauge types and is a function of the electron emission current setting, I_e. In general, a reduction of the electron emission current results in an extension of the linearity range, and it is generally agreed that I_e must be kept at the lowest practical value (certainly no more than 0.1 mA) for all work at and above 10^{-3} Torr. Some commercially available ion gauge controllers are programmed to automatically reduce the electron emission current to 0.1 mA, or less, as the pressure approaches this upper limit. This approach is only adequate for moderately accurate measurements since, as described later, the sensitivity factor is dependent on the electron current[3] at these higher pressures and that effect is generally not accounted for in those controllers. A more accurate approach (available on the IGC100) that does not rely on linear behavior of the sensitivity, and has been shown to effectively extend the usable range of conventional BAGs into the 10^{-2} Torr range, involves the use of fixed low electron emission currents (0.1 mA typical) and the calculation of pressure values from a gauge calibration curve (P vs. I_c) stored in the controller's memory.

An interesting trick to extend the high-pressure operation of a conventional BAG and implemented in at least one commercially available controller, is given in a patent by Paitich and Briglia[4] describing a method of measuring pressure up to 1 Torr by modulating the anode grid voltage and using a non-linear amplifier. This method is not recommended if moderate accuracy is required at the higher pressures where capacitance manometers are a much better choice. Thoria coated filaments are the only option at these high pressures.

Non-linearity at the high end of the pressure scale is caused by several effects[5]. Increased positive ion density and multiple non-elastic collisions with neutral molecules (due to the reduced mean free path) can alter the path[6] and energy of the electron beam and also force some of the newly formed ions out of the anode grid without a chance of being captured by the collector. As the pressure increases, the secondary electrons and ions produced by ionization become a significant fraction of the electron stream. These secondary electrons do not contribute to ionization but are part of the electron emission current. These effects were thoroughly investigated by Schultz and Phelps and the reader is referred to their publications for further information[7].

Various attempts have been made to extend the range of BAGs[8], but very few have been commercial successes. One such commercial design, available under several different trade names[9], uses a narrow grid (12mm diameter x 46mm long), a thoria-coated filament, and a grounded platinum coating on the inside of the 41mm diameter glass tube. These broad-range glass tubulated gauges are designed to operate all the way up to 10^{-1} Torr (with 0.01 mA emission current above 10^{-3} Torr) while still providing a sensitivity factor of 8 $Torr^{-1}$. However, they have been shown to be susceptible to large time-dependent instabilities and non-linearities[10]. A miniaturized, all-metal ionization gauge that retains the traditional design, operating voltages, good sensitivity and low X-ray limit of the conventional BAG has recently become commercially available[11]. This tiny gauge (5% of the conventional volume) utilizes a dual collector design to increase ion collection efficiency (20 $Torr^{-1}$ typical) while at the same time providing a wider usable pressure range that extends from $3x10^{-10}$ to $5x10^{-2}$ Torr. Tiny gauges are a modern alternative to glass tubulated gauges and will likely become relatively more important in the future.

Note

The IGC100 controller is compatible with most commercially available BAG designs including: Glass-tubulated, Nude, Nude-UHV, STABIL-ION® (Granville-Phillips, Helix Corporation), and MICRO-ION® (Granville-Phillips, Helix Corporation). Default setup files are stored in the controller’s memory to facilitate configuration of the instrument for operation with any of these gauges.

As the total pressure is decreased below $\approx 10^{-4}$ Torr, the gauge sensitivity factor is expected to become pressure independent. For most common gases encountered in high vacuum applications, this behavior has been confirmed experimentally for total pressures down to 10^{-9} Torr [12]. Consequently, in all cases (including the IGC100 controller), pressure measurements with a BAG in the UHV region below 10^{-7} Torr are based on linear extrapolation of gauge response determined at higher pressures.

Gas Dependence

BAG sensitivity depends upon the gas composition.

For electrons to produce ionization of gas molecules by bombardment, they must have a certain minimum kinetic energy. This minimum energy is called the *ionization potential* and is different for every type of molecule. Above the threshold energy, the ionization efficiency increases linearly with the electron energy until a maximum is reached. For most molecules, this maximum occurs between 50 and 150 eV. For electron energies above the maximum, the ionization efficiency slowly decreases with electron energy.

Plots of ionization efficiency vs. incident electron energy can be obtained from the careful data of Smith and Tate[13]. Their results show that ionization cross sections, σ_i, of common gases differ by almost a decade at the electron energies of 150 eV that are typical in BAGs. Furthermore, the relative ionization efficiencies R_σ - the ratio of the ionization efficiency for a given gas to the ionization efficiency for a standard gas (usually nitrogen) - is a function of electron energy.

Since the BAG sensitivity for a specific gas is directly related to the value of the ionization cross section of the corresponding gas molecules (eqn. 2), the sensitivity factor S_g, supplied by the gauge manufacturer, is *only valid for the gas for which it is specified* and the pressure readout of the controller provides a direct reading only for that specific gas. The standard gas, used by the entire industry for gauge specification, is *nitrogen* and, unless correction factors are applied, all readings are considered to be *nitrogen-equivalent pressures.*

The sensitivity of a generic BAG to some of the most common gases encountered in a high vacuum environment follows the order: He < Ne < D_2 < H_2 < N_2 ≈ Air < O_2 < CO < H_2O < NO < Ar < CO_2 < Kr < Xe. Nominal *relative sensitivity factors*, R_g, to convert nitrogen-equivalent readings into direct pressure readouts for gases other than nitrogen, are available from all gauge manufacturers and from the general vacuum literature[14]. For gases where little or no data are available, it has been shown that a reasonable approximation to the relative sensitivity factor R_g can be obtained from the ratio of ionization cross sections for those gases at 150 eV of electron collisional energy. Several ionization cross section tables are available in the scientific literature[15].

Once the relative sensitivity factor is known, direct pressure readings are calculated from the straightforward mathematical equation

$$P = [I_c/(S_g \cdot I_e)] \qquad \text{where } S_g = S_{N2} \cdot R_g \qquad \text{(eqn. 6)}$$

Nominal relative sensitivity factors cannot be relied upon for accurate measurements since they are known to vary significantly between seemingly identical gauges and even more for different gauge types, filament materials, and operating potentials. For general vacuum use, the discrepancy in reported measurements is not greater than 10% for the common gases rising to a little above 20% for the less common gases where less accurate information is available. Relative sensitivities are pressure dependent and become particularly unreliable above 10^{-5} Torr[16]. Where greater precision is required, gauges must be calibrated individually against the specific gases and under conditions as near as possible to the operating conditions of the vacuum system.

Note

The IGC100 controller uses a nitrogen sensitivity factor, S_{N2}, and a single relative sensitivity factor R_g (labeled 'gas correction factor') for every BAG connected to its back panel. The two parameters are automatically applied to the calculation of pressures when N2 Sense Factor is used as the pressure calibration source.

Note

The nominal gas correction factors, used by most high vacuum practitioners to correct their 'nitrogen-equivalent' pressure readings for other common gases, can be found in Appendix D, 'Gas Correction Factors for Bayard-Alpert Ionization Gauge Readings'.

Electrode Geometry Dependence

Many design parameters affect the probability of creating and collecting ions in a BAG, and thus the value of the sensitivity. This section focuses on the effects that electrode geometry have on BAG sensitivity. Important geometrical factors include

- filament to grid spacing
- collector wire location and diameter
- anode grid end closures
- grid diameter

To the extent that any of these parameters change with time of operation, or differ from gauge to gauge, the sensitivity will change or be different gauge-to-gauge.

The sensitivity of a 'conventional' BAG (available from almost any gauge supplier) with 22 mm diameter anode grid x 45 mm length, with filament to grid spacing of 6 mm and collector wire 0.25 mm diameter, is nominally 10 $Torr^{-1}$. Adding grid end closures roughly doubles this. Increasing the collector wire diameter to 1 mm adds another factor of two to the sensitivity and extends the high-pressure range.

The effect of grid-filament spacing on sensitivity has received considerable attention. Redhead[17] was the first researcher to illustrate the significance of the precise positioning and biasing of the filament. More recently, Bills[18] utilized computer simulations to demonstrate and prove that filament position displacements as small as 1 mm can significantly affect the electron trajectories within the anode volume. Any change in electron trajectories will automatically affect the sensitivity of a BAG. Sources for grid-filament spacing variations are (1) relaxed manufacturing tolerances resulting in significant gauge-to-gauge variations, (2) changes in filament position and/or shape due to rough handling (i.e. mounting accidents in nude gauges), (3) changes in filament position and/or shape due to thermal cycling.

Some investigators[19] have obtained results suggesting that gauges with tungsten filaments provide better stability than do gauges with thoria coated filaments. The current belief is it is not the filament material that causes the improvement, but rather the shape of the cathode. Tungsten cathodes are typically made as tight springs stretched between rigid posts that tend to move relatively little during long term use as compared to the hairpin shaped or relatively unsupported ribbon shaped thoria coated cathodes. BAGs with spring-tensioned filament assemblies have recently become commercially available and should be considered if long term accuracy and stability are a concern[20].

The preferred mounting orientation is with the filament and anode grid in a vertical position to minimize electrode distortion caused by gravity pull and thermal cycles. Whenever possible, choose the gauge with the strongest electrode-support posts.

Note

Spring tensioned filament assemblies are standard in all Bayard-Alpert gauges purchased directly from Stanford Research Systems.

The ion collection efficiency of an ionization gauge is affected by the diameter of the collector wire. This effect has been extensively studied and discussed in the vacuum literature[21]. The 'conventional' BAG has a 0.25 mm diameter ion collector wire. This small diameter is required to extend the low pressure operating limit of the BAG into the 10^{-10} Torr range as described later. Many ions have too much angular momentum to be collected by the small diameter wire. Ions that are not collected on their first pass at the ion collector continue to orbit until they strike a low potential surface such as the cathode or gauge envelope[22]. Thus, it is likely that a space charge cloud of orbiting ions surrounds the collector and is susceptible to small changes in geometry or local potentials. Any variation in this space charge affects electron trajectories and thus the sensitivity. This space charge effect becomes more noticeable with increases in either pressure or emission current. It is not unusual to detect drops in BAG sensitivity factors as the emission current is increased from 1 to 10 mA at pressures as low as 10^{-6} Torr[23]. In fact, in gauges with very fine (< 0.1 mm) wires, sensitivity decreases can be observed as early as 10^{-8} Torr[24].

It is generally accepted that there is no advantage to using collector wires with a diameter smaller than 0.125 mm (as typically found in nude BAGs for UHV applications). High accuracy BAGs with a 1 mm diameter ion collector have recently become commercially available[25]. The thicker wire provides increased mechanical stability, a higher overall sensitivity (as a result of the more efficient capture of high angular momentum ions) and an extended upper limit range extending to 10^{-2} Torr for 0.1 mA electron emission current. The extended upper range is due to the reduced space charge around the collector that results from the more efficient ion collection. These improvements are achieved with no significant compromise at the low pressure end, which still remains at 1.6×10^{-10} Torr for 4 mA of emission current.

Until recently, few gauge manufacturers have made an effort to produce electrode structures with sufficiently close tolerances. It is not unusual to see gauges where the center collector is curved, not coaxial with the anode grid, or is at an angle with respect to the anode’s axis. In some gauges, a slight lateral force on the collector feedthru, such as might be caused by the collector wire, can visibly change the position of the collector. As demonstrated by Bills[26], a 2 mm displacement of the collector wire from the axis is enough to show changes in electron trajectories and sensitivity. High accuracy gauges manufactured to very tight mechanical tolerances are now commercially available and should be carefully considered if gauge-to-gauge reproducibility and long term stability are important. Whenever possible, mount the BAG in a vertical position, with the collector pin pointing down, to avoid electrode shape distortions by gravity pull.

Conventional BAGs traditionally include wire helix anode grid structures with open ends. A popular double-helix design allows for safe resistive heating of the electrode assembly during degas, and also provides a fairly robust structure. Nude ultrahigh vacuum gauges usually include a more delicate (i.e. very fine wire) 'squirrel-cage' anode grid design with closed ends. Nottingham[27] was the first to report the addition of grid end closures to the BAG to prevent the escape of uncaptured ions from the open ends of the cylindrical grid, thereby increasing the sensitivity of the gauge and extending the low pressure limit into the 10^{-11} Torr range. As a rule-of-thumb, adding grid end closures roughly doubles the sensitivity factor of a BAG. A typical UHV nude BAG has a specified sensitivity factor of 25 $Torr^{-1}$ for 4 mA of electron emission current. However, as demonstrated by Peacock and Peacock[28], the sensitivity of gauges with grid end closures declines sharply above 10^{-5} Torr when operating at an emission current of 1 mA. With open grids, the sensitivity remains constant up to 10^{-3} Torr under identical operating conditions. The origin of this effect is poorly understood, but it is most likely caused by the relative increase in space charge from the non-collectable ions that accumulate inside the enclosed grid volume[29].

As mentioned before, the high pressure limit of UHV BAGs with closed grids can be extended operating at an emission current of ≤0.1 mA.

Most commercially available BAGs are manufactured with 22 mm diameter x 45 mm long anode grid cages. A narrow grid design, 12 mm diameter, can be found in broad-range ionization BAGs that extend the operating limit into the 10^{-1} Torr range. The larger length-to-diameter ratio is designed to minimize axial drift of ions out of the collector region. An internal conductive coating is used in these glass tubulated gauges to control the electrostatic environment and maximize electron ionization paths. Performance characteristics for these gauges have been published in the vacuum literature, and the reader should consult the references for further information[30].

Bias Voltage and Emission Current Dependence

A survey of the specifications for all commercially available BAGs quickly reveals that they all share the same electrode potential requirements

- collector potential of 0 Vdc
- filament bias of +30 Vdc
- anode grid bias +150-180 Vdc
- shield potential 0 Vdc.

Manufacturer recommended electrode emission currents are usually 10 mA for conventional BAGs (10 $Torr^{-1}$) and 4 mA for UHV nude BAGs (25 $Torr^{-1}$).

Changes in electrode potentials cause shifts in sensitivity[31]. As may be expected, the collector current is a complex function of the electrode potentials because both the electron trajectories and ionization efficiencies depend on these voltages.

The positive (+30 Vdc) filament bias assures that all electrons emitted from the filament stay away from the relatively negative (0 Vdc) ion collector[32]. Any increase in collector voltage results in a decrease in the ion current because of the decreased electron penetration (i.e. reduced pathlength) of electrons into the anode grid space and the reduction in electron energy. Sensitivity differences up to 2% have been observed when the cathode bias was applied to the top rather than bottom of the filament.

The filament-to-anode voltage determines the collisional energy of the electrons that traverse the inner volume of the grid cage. The electron energy is simply calculated, in eV, as the difference in bias voltage between the anode grid and the filament. The electron energy for the prototypical ion gauge controller is 150 eV. If the collector current is measured for varying grid potentials, at a fixed pressure (above 10^{-7} Torr), filament bias and electron current, the curve showing I_c vs. V_g follows the expected characteristic shape of gas ionization probability vs. electron impact energy - I_c rises rapidly with V_g up to 200 V and varies slowly with grid voltages above this value[33].

As a rule of thumb, the sensitivity of an ion gauge is observed to change 0.1%/V and 1%/V for filament-to-grid and filament-to-ground voltage variations, respectively. Broad-range BAGs have been reported to exhibit the largest sensitivities to electrode bias variations of all current designs[34]. Most BAGs are so non-stable and so non-reproducible for other causes that the relatively minor effects of variations in potentials applied by traditional controllers[35] have been generally ignored. However, with the recent introduction of high-accuracy (and highly stable) BAGs, the need for accurate and reproducible electronic control of the biasing voltages has been finally established.

The sensitivity factor of a BAG is a function of the emission current[36]. Changing the emission current from 0.1 to 1 mA usually causes no significant changes in nitrogen sensitivity, but increasing it to 10 mA can decrease the sensitivity factor by more than 20% and cause marked high pressure non-linearities above 10^{-5} Torr. The extent of this effect is highly dependent on gauge geometry. In general, a reduction of the electron emission current results in an extension of the linearity range, and it is generally agreed that I_e must be kept at the lowest practical value (certainly no more than 0.1 mA) for all work at and above 10^{-3} Torr.

Sensitivity differences of several percent have been observed at the same filament heating power, emission current and pressure when AC rather than DC power is used. Changes in the duty cycle of the AC power also cause observable changes in sensitivity[37].

The *recommended operating procedure* from the Vacuum Group of the National Institute of Standards includes

- Operate all BAGs with 1 mA, or less, emission current . The only reason to operate a modern gauge with 10 mA of emission is to increase the temperature of the gauge and speed outgassing.

- The linearity of BAG response is also improved if a noise free, direct-current filament current supply is used (such as the IGC100).

A quality ionization gauge controller designed for high accuracy measurements (such as the IGC100) must control biasing voltages to within a few volts directly at the gauge head[38] and emission currents[39] to within a few percent.

Note

In conventional controller designs, the filament bias voltage is measured and controlled inside the box. As a result, the filament bias can vary with heating current because of the resistive voltage drop across the cable. This voltage drop may be substantial when using long cables and typical heating currents (between 3 and 10 amps). This variability is of no consequence for conventional (nude or glass) BAGs because these minute instabilities are overwhelmed by much larger effects. However, controlling filament bias at the controller is inadequate for measurements with modern high-accuracy gauges. In the IGC100, the filament bias voltage is measured at the gauge head, and hence, electrode potentials are independent of cable length[40].

Gauge Envelope Dependence

Several researchers have shown that the sensitivity of a BAG assembly can be influenced significantly by the relative positioning and electrical potential of the gauge envelope[41].

In a glass tubulated gauge, the inner insulating surfaces of the glass tube can change potential abruptly due to the accumulation of electrical charge, causing sudden shifts in pressure indication unrelated to any gas density variation. The effect was first described and explained by Carter and Leck[42] as early as 1959, and analyzed by Redhead[43] and

Pittaway[44] based on the dependence of electron paths on changing electrical boundary conditions. As a conductive film builds up on these surfaces with time of use, sudden mode shifts tend to occur less frequently and eventually disappear. This gradual change in potential affects the long-term stability of glass tubulated ion gauges. Keep in mind that exposed insulators in nude gauges may cause similar effects if conductive films deposit on them.

Several glass BAGs utilize a platinum conductive thin-coating on the inner glass wall to help stabilize the wall potential. The shield potential is either electrically grounded through a separate connection pin, or internally connected to the filament return electrode. Tilford, McCulloh and Woong[45] demonstrated the effect of these coatings and observed that when the shield of one gauge, normally held at ground potential, was allowed to float up to filament potential, the collector current increased by 23%. Abbott and Looney[46] performed a detailed study of the influence of inner potential on the sensitivity of platinum-coated glass gauges and found that the shield potential depended on pressure and also on the details of the filament potential waveform provided by the gauge controller. They concluded that sensitivity non-linearities in those gauges could be minimized by holding the inner surface to a fixed direct current potential or by using a controller (such as the IGC100) that provides a noise-free filament heating DC current.

Note

These effects are not commonly considered by the users of glass ionization gauges because very often the gauge envelope is an integral part of the gauge structure (i.e. glass tubulated gauges) and the dimensions and relative spacing of the envelope and electrode assembly cannot be altered by the user. The potential of the glass wall also influences the residual current produced as a result of the reverse X-ray effect described later in this application note.

The sensitivity value of a nude gauge is dependent on the way it is mounted on the system. This is not new knowledge, but there is no widespread appreciation of the effect among current users of nude gauges. Filippelli[47] investigated the influence of envelope size and shape on the nitrogen sensitivity of conventional nude BAGs. His report shows that changes in gauge envelope can result in measurement errors as large as 50% with some BAGs. Thus, the envelope must be considered a proper part of an ionization gauge, and a specification of nude gauge sensitivity is not complete unless the geometry and potential of its envelope are also given. It is common practice to calibrate and operate nude ion gauges inside a nipple 38 mm ID x 100 mm long, with a screen at the input port.

Modern high accuracy gauges rely on heavy shielding to (1) protect the electrode structure from external or uncontrollable fields, (2) better define charged particle trajectories and (3) improve gauge-to-gauge reproducibility and long term stability. In a commercially available design[48], the entire electrode assembly, is housed inside a grounded metal envelope. This envelope completely surrounds the anode-filament-collector structure to help provide a stable electrical environment for charged particle trajectories. A grounded, perforated, high conductance shield over the port helps to electrically isolate the transducer from the remaining of the vacuum system, and grounded conducting shield between anode and the feedthrus prevents the ceramic insulators from becoming contaminated and charged.

Temperature Dependence

For most room temperature measurements the effects of ambient temperature variations on BAG readings are insignificant.

Studies of this effect have generally shown that it is not as large as would be predicted from theoretical considerations accounting for both density and thermal transpiration effects, i.e. the sensitivity varying inversely with the square root of the absolute temperature of the gas inside the gauge[49].

Determining the gas temperature is a difficult task in a tubulated BAG. It is probably accurate to say that most of the molecules equilibrate with the envelope, but the envelope temperature is not symmetric because of the asymmetric location of the filament. The envelope (glass or metal) of a BAG is usually at a temperature much higher than ambient as determined by the power (10 W) radiated by the hot filament and absorbed by the envelope's walls. For example, some metal encapsulated gauges are actually provided with vented guards to protect users against burns. The absorption of energy from the filament by the envelope increases with age as the walls get progressively darker due to contamination. Variations in filament work-function and emissivity due to aging, contamination or chemical reaction with the gas will result in changes in filament and envelope temperature that might require correction for accurate measurements. Bills, Borenstein and Arnold[50] suggested a pressure calculation procedure that includes the filament heating power as a parameter, increasing gauge-to-gauge reproducibility and long term stability.

Haefer[51] did find a correlation with the square root of the temperature of the flange of a nude BAG mounted in an enclosure. Close, Lane and Yarwood[52] found the ion current to change 0.075%/K, approximately half what one would expect from the envelope temperature of a BAG. If a BAG is not used under the same temperature conditions as those during its calibration, a correction might be required in high accuracy measurements[53].

There is always a delay between turning on a BAG and obtaining a reliable reading. It is necessary to wait for thermal equilibrium of the gauge[54] and its surroundings (not that easy under vacuum).

Magnetic Field Dependence

Magnetic fields have a strong and rather unpredictable effect on gauge sensitivity by changing the trajectories of the charged particles (especially the electrons which perform spiral trajectories). Since many vacuum experiments operate in a magnetic field environment, often of varying or unknown magnitude and direction, it is surprising how little data is available on magnetic field dependencies of BAGs. A few studies[55] are available that do not lead to summary conclusions. Investigation of the effect of the magnetic field on the accuracy of pressure measurement with BAGs has not been made yet.

The effect depends on the direction and magnitude of the field as well as gauge design and pressure. The effects are generally non-linear with both magnetic field and pressure. The common approach is to either remove the gauge from the magnetic field or to try shielding it. In both cases, it is a good idea to test the gauge readings by changing the magnitude and/or direction of the magnetic field to see if the readings are affected. In general, operation of a BAG in a magnetic field is possible with suitable orientation and altered gauge constant.

Note

Remember that cold cathode (i.e. Penning) gauges and ion pumps include magnets in their assembly.

History Dependence

A major factor affecting a gauge's stability is its history.

It is well known that all BAGs can exhibit general drifts in sensitivity, usually downward, when operated for long periods. The dependence of the sensitivity drifts on the type of gauge and its operating conditions has made it impossible to develop a unified model or theory that completely and systematically explains all experimental observations. Most knowledge is phenomenological and based on the experience accumulated over several decades of pressure measurements with commercial BAGs.

Many instabilities in commercial ionization gauges can be traced back to changes in the path of the electron beam[56] caused by several different aging effects. Most ion gauge controllers do an adequate job at maintaining the electron emission current and bias voltages at a constant value; however, they have no influence over the trajectories of the electrons once they leave the hot filament surface.

Changes in the emission characteristics of the filament are of high concern since they directly affect the electron trajectories and can result in changes in both the potential distribution and the charged particle trajectories inside the anode grid[57]. Large variations in the emission characteristics of the filament can be caused by the following effects.

- Changes in geometry of the electrode structure, due to repeated thermal cycling and/or mechanical shock.

  This effect is most prevalent in BAGs with poorly-supported hairpin shaped filaments and open-ended, helix-shaped grids. To avoid filament sag and accumulation of 'rubbish', BAGs should be mounted vertically with their electrical connections uppermost. High accuracy BAGs with spring-tensioned filaments and improved electrode supports have recently become commercially available and should be considered if accuracy and long term stability are a concern. Filament sag is eliminated allowing the user to mount the gauge in any position.

- Local temperature variations in the filament wire.

  Changes in filament temperature are usually associated to changes in temperature distribution along the filament and changes in the distribution of emission along the cathode. In general, a temperature increase results in a longer segment of the cathode being heated and emission from a relatively larger area of its surface. The temperature of operation of a filament is affected by the gauge history as described next.

- Changes in cathode dimensions (i.e. diameter).

Refractory metal filaments (i.e. tungsten, rhenium, tantalum, etc) do not last forever, and are the subject of continuous metal evaporation during emission[58]. Certain gases can accelerate the thinning of the filament through catalytic cycles that transfer material from the filament surface to the inner walls of the gauge tubulation. As the filament becomes thinner, the ion gauge controller automatically maintains the levels of emission current by increasing the filament temperature to compensate for the reduced surface area[59]. The increased temperature, combined with the change in filament shape (i.e. preferential depletion of the central portion) and temperature distribution, causes the distribution of emitted electrons to change.

- Changes in the electrode potentials due to power supply inaccuracies, grid wire contamination and space charge effects.

  At the higher emission currents, the efficiency of electron emission is affected by the extraction potential responsible for removing the electrons from the filament boundaries.

- Surface contamination.

  Impurity diffusion can change both the work function and emissivity of the cathode surface. For example, W can react with hydrocarbon molecules and form a layer of WC that can slowly diffuse into the bulk of the metal.

- Chemical reaction with an active gas.

  Cathode poisoning by gases, such as Oxygen, water, CO and CO_2 increases the work function of the filament, which in term affects its temperature of operation.

  Several reducing gases (such as SiH_4 and diborane) used routinely in the semiconductor industry are incompatible with the rare earth oxides used in filament coatings (W is recommended instead).

- Detachment and/or aging of the filament coating (i.e. Thoria detachment)

  Several different methods are used to deposit low-work-function oxide layers on refractory metal wires. Some methods are better than others. Evaporation and ion bombardment may also deplete the central portion of the coating, causing the emission distribution to gradually shift towards the ends of the wire.

- Changes in envelope bias and appearance can also affect the charged particle trajectories in a BAG.

  The electrons emitted by the filament spend time outside the anode grid and are affected by the gauge's boundary conditions. Changes in the potential distribution around the gauge caused by contamination will affect its sensitivity. The progressive darkening of the bulb in glass gauges results in higher envelope temperatures due to increased absorption of filament radiated power.

Limiting Factors for Low Pressure Operation

Based on eqn. 3, it appears that the lower limit to the pressure range of a BAG, is entirely determined by the current detection capabilities of the electrometer used to measure the collector current. However, it is well known, from experiments, that the total collector current of a BAG is better represented by the more general equation

$$I_c = S \cdot I_e \cdot P + I_r \qquad \text{(eqn. 7)}$$

where the *residual current*, I_r, is a *pressure-independent* term. Residual currents are often defined as those which would exist at the collector electrode if the molecular density within the gauge head were zero, and result in erroneously high readings at low pressures that must be accounted for in accurate measurements.

The main known contributors to I_r are

- X-ray induced photo-emission of electrons from the ion collector and gauge envelope
- ion currents caused by electron stimulated desorption (ESD)
- leakage currents at the electrodes
- electrometer offset errors.

Any BAG, depending on its past history of operation and the precise atmosphere in the vacuum system, can act as either a source (outgassing) or sink (pumping) of gas[60]. Its operation can cause significant changes to the gas composition in the system. The relative importance of these effects depends upon the overall vacuum system characteristics and operating conditions. For example, changes in pressure and gas composition due to pumping or outgassing will be relatively more significant in a small UHV system with low pumping speed, than in a large industrial vacuum chamber with large diffusion pumps. Similarly, any pressure gradient between the gauge and the main chamber will depend upon the conductance of the tube connecting the two, and will be zero when the gauge is inserted directly into the chamber (i.e. nude gauge).

Reactions of the gas molecules with the hot filament can seriously affect the composition of the gas, and the reliability of the pressure measurements, in a BAG. This effect must also be accounted for in high accuracy measurements at low pressures.

Gas permeation through the envelope, particularly of He and other light gases, must be considered in UHV systems at base pressure, and provides another good reason to use nude all-metal gauges in those applications.

X-ray Limit

X-rays are produced when the energetic electrons emitted by the filament impact the grid and support posts[61]. Some of these X-rays strike the collector wire and cause electrons to be photo-electrically ejected. The resulting 'X-ray induced' electron current, I_x, cannot be electrically distinguished from the pressure dependent ion current at the collector, and results in erroneously high readings at low pressures. The 'X-ray induced' contribution to the pressure indication, in terms of pressure, is calculated as

$$P_x = I_x / (S \cdot I_e) \qquad \text{(eqn. 8)}$$

This pressure equivalent value is often called the *X-ray limit*, and is part of the manufacturer specifications for a BAG. As expressed by eqn. 8, the X-ray limit is simply defined as the lowest pressure indication which may be obtained in a BAG when all the output current is due to X-ray induced photoemission and there is an absence of gas.

The X-ray limit varies with different gauge designs. The nominal over-reading typically amounts to 1-3x10^{-10} Torr for BAGs of the most popular type (i.e. continuous helical anode grid and a 0.25 mm diameter collector). Special design features, such as closed grid ends and reduced collector diameter (0.125 mm) reduce these levels to 2x10^{-11} Torr, as is typically specified for UHV nude BAGs. The X-ray contribution dominates the residual current, I_r, of eqn. 8 in reasonably clean BAGs. For accurate HV and UHV measurements with BAGs, it is necessary to correct the gauge indication for X-ray contributions. Variations in the X-ray limit for a given gauge as well as variations between supposedly identical gauges, make it difficult to use a nominal X-ray limit for correction. Instead, the X-ray limit should be determined for each gauge and rechecked periodically. A useful collection of X-ray limit measurement techniques can be found in the vacuum literature[62].

Earlier ionization gauges (i.e. triode gauges), which had a solid cylindrical collector outside an anode grid, and a fine filament inside, experienced a much larger X-ray limit of about 10^{-8} Torr as expected from the larger exposed surface area of the collector. Bayard and Alpert were the first ones to systematically test the validity of the X-ray induced current theory[63] around 1950. The direct result of their studies was the invention of the inverted-triode ionization gauge design that bears their names[64]. By replacing the large surface area external collector with a thin internal wire, and placing the filament outside the grid cage, they were able to realize two to three order of magnitude reductions in residual currents, extending the lower operating limit into the 10^{-11} Torr range. A commercial version of the BAG soon followed their initial report[65]. A period of rapid exploration after their early implementation, proved it difficult to improve upon the original. The BAG provided an ingenious solution to the X-ray current limit problem while at the same time preserving the high levels of sensitivity of previous designs. The thinner collector wire intercepts only a small fraction of the X-rays produced at the grid. The positive potential of the grid forms a potential well for the ions created inside the ionization volume so that many of them are collected at the center wire.

The X-ray limit of a BAG is affected by several different variables. A few are discussed below.

Gauge design

As mentioned above, the value of the X-ray limit is strongly dependent on gauge design. All UHV gauges, designed to operate into the 10^{-11} Torr range, have closed-end grids (i.e. squirrel-cage design) and use very fine wires in their electrode structure. The fine anode grid wires provide an enhanced open area, increasing the pathlength of the electrons before colliding with the grid. This effect, along with the closed ends, increases the sensitivity of the gauge by about a factor of two, relative to conventional BAG designs with open grids. The thin collector wire reduces the X-ray induced residual current by minimizing the collisional cross section with the X-rays emitted from the grid. The combination of enhanced sensitivity and reduced X-ray induced residual current is responsible for the extended X-ray limit.

Further reducing the surface area (and/or length) of the collector wire of the BAG will, of course, reduce the X-ray current. For example, Hseuh and Lanni[66], were able to extend the X-ray limit of BAGs into the 10^{-12} Torr range by reducing the collector diameter of mass produced gauges to 0.05 mm. However, there are two problems associated with this approach: (1) the reduction in mechanical strength of the wire and (2) a drop in sensitivity and linearity due to the difficulty in collecting ions with a high tangential velocity about the collector. In practice, there is a critical size of the wire below which the probability of collecting ions goes down as rapidly as (or faster than) the X-ray effect. It is generally accepted that there is no advantage to use collector wires with a diameter smaller than 0.1 mm in a BAG[67].

Recently, high accuracy BAGs with 1 mm diameter collectors have become commercially available. As demonstrated by Bills and collaborators, the thick wire provides mechanical stability, higher sensitivity (50 $Torr^{-1}$) while at the same time preserving a typical $1.6x10^{-10}$ Torr X-ray limit at 4 mA of emission current. The only disadvantage of the thicker wire is a higher sensitivity to the energetic ions formed by ESD, but this problem is generally avoided by careful bakeout and/or degas.

Electrode Surface conditions

The X-ray limit is affected by the conditions of the electrode surfaces.

For example, the X-ray limit is increased as a result of hydrocarbon contamination of the electrodes, since the contaminated surface releases relatively more electrons under identical X-ray bombardment conditions.

In a similar fashion, the efficiency of emission of X-rays from the grid wires is also affected by contamination.

Emission Current

The X-ray limit has been experimentally shown to be dependent on the emission current value. A 25% (typical) reduction on the X-ray limit of commercial BAGs was reported by Peacock when the emission current was increased from 1 mA to 10 mA[68].

Envelope Bias (Forward vs. Reverse X-ray Effect)

X-ray induced photoemission of electrons from the ion collector is known as the *forward X-ray effect*. Less well known is the *reverse X-ray effect* leading to a superimposed, but usually smaller error signal in the opposite direction. The reverse X-ray effect is caused by X-ray induced photoelectrons from the gauge envelope. The effect is particularly noticeable if the gauge envelope is at or below the collector potential. Several different situations can be envisioned. (1) If the potential of the envelope is near that of the cathode, as is usually the case in glass envelope gauges, photoelectrons emitted from the envelope do not have enough energy to reach the ion collector and do not contribute to I_r. (2) If the gauge envelope is at ground potential, like in a nude BAG, the reverse X-ray effect may be large enough to significantly reduce the net X-ray induced residual current. (3) If the gauge envelope is at a suitable negative potential relative to the collector, the two effects might be adjusted to temporarily cancel[69]. B. R. F. Kendall and E. Drubetsky[70] were able to successfully stabilize this cancellation process by the use of identical materials (i.e. gold or Rhodium) in the two photoemission surfaces. The result was a shielded BAG of conventional internal geometry, with a net X-ray error reduced by well over one order of magnitude over a period exceeding one year. Short-term improvements, by a factor of 100, were also achieved by the same authors. Metal and glass encapsulated gauges using the X-ray cancellation technique are now commercially available[71] and are fully compatible with the IGC100.

Electron-Stimulated Desorption (ESD)

In the context of BAGs, ESD[72] implies desorption of atoms, molecules, ions and fragments from the *anode* grid surface *as the direct result of electron impact excitation*. The pressure-independent ions generated by this process reach the ion collector and are registered as falsely-high pressure readings. The mechanism is initiated by the electron excitation or dissociation of the molecules previously adsorbed on the surface of the grid wires. The most common species desorbed are CO, CO_2, H_2, O_2, H_2O, halogens and hydrocarbons. The number of neutrals desorbed is usually large compared with that of ions.

ESD can make a significant contribution to the residual current[73] of eqn. 7; however, the resulting errors are unusual in that they are completely unpredictable. They seem to come and go for no apparent reason, they might affect one batch of gauges and not another and can be mysteriously affected by gauge history. The effect has been the subject of extensive work and several review articles[74]. Readers are referred to the vacuum literature for details beyond what is covered in this appendix.

The gas used in a gauge can cause permanent or semi-permanent changes in its pressure reading as a result of electron-stimulated and thermal-induced desorption of the gas molecules (ions and neutrals) that remain adsorbed on the electrode surfaces. Some gases are worse than others, with hydrocarbons, oxygen and reactive or corrosive gases yielding some of the biggest effects. For example, if a burst of oxygen gas is introduced into a clean HV system increasing the pressure from 10^{-9} to 10^{-6} Torr for only one minute, then the reading of the BAG will be spurious for many hours or even days. The pressure indication continues to drop back to the original base pressure reading with a time constant between one hour and one week depending on the operation of the gauge.

A typical procedure used to minimize the residual current due to ESD is to operate the BAG at 10 mA of emission current to keep the anode grid clean. Electron bombardment degassing of the grid is recommended for fast recovery from exposure to gases known to cause significant ESD (i.e. oxygen, oxygen containing molecules such as water, CO and hydrogen). ESD can be minimized by a correct choice of material for the anode grid, for example, platinum clad molybdenum or gold.

The ions generated by the ESD process are more energetic (i.e. several eV) than the ions formed by electron ionization of the bulk gas[75], and are not very effectively collected by the thin collector wires (0.125mm diameter) used in UHV nude gauges. Another reason to use nude UHV gauges for low pressure measurements in UHV applications!

Leakage Currents

The output of a BAG is a very small current and even relatively small leakage currents can add significant errors to the measurements at low pressures. Some useful tips to reduce leakage currents include

- The area around the collector pin on the gauge must be kept clean at all times on both the air and vacuum sides of the feedthrough connectors.
- A collector insulator shield is present in most BAG designs to avoid the development of leakage currents due to contamination of the ceramic or glass insulators with conductive layers of impurities. Internal leakage usually results from the evaporation of tungsten or thoria molecules from the filament. Do not use nude gauges that do not include such shields.
- The collector terminal of glass tubulated gauges is purposely located at the opposite end of the envelope from the grid and filament conductors, and usually has a built in glass skirt that acts as a shield against contamination deposits.
- It is important to use good quality leads to make connections to the controller. Gold plated connector pins are often used, and assure that the gauge tube can be easily removed from the connector after extended use.
- Changes in the glass conductivity can occur at the elevated temperatures used to make some pressure measurements. For such situations, envelopes of metal and alumina are recommended.

Outgassing

Outgassing of BAGs occurs when heating by the filament and electron bombardment of the grid raises the temperature of the electrodes and surrounding surfaces considerably above ambient temperature, resulting in an increased thermal desorption rate of gas molecules from those surfaces. The outgassing of hot cathode gauges is a potentially large source of error when such gauges are used at base pressure levels in high vacuum systems. Outgassing levels are particularly high when a gauge is turned on for the first time after exposure to ambient or high gas pressures.

It is well known by ultra high vacuum practitioners that the gas composition and pressure in even a rather large vacuum system may be dominated by gases released from a single BAG and its surroundings. This is particularly true when nude and metal-coated glass gauges are used, because the high infrared absorption of the metal envelope results in increased heating of metal components in and adjacent to the gauge.

The easiest way to detect outgassing levels from a test gauge is to use a second gauge to monitor the change of pressure in the vacuum chamber as the test gauge filament is turned on and off. Residual gas analyzers (such as the SRS RGA100[76]) are routinely used in a similar fashion to selectively detect the particular species outgassed into the vacuum system by a test BAG. It is generally accepted that BAGs outgas at rates about 10-100 times faster than cold cathode gauges under identical conditions.

Outgassing is a pervasive effect that is observed in even the most carefully handled gauges. An aggressive and prolonged degassing and/or bakeout can dramatically reduce gauge outgassing but it will rarely completely eliminate it![77]

As expected, outgassing rates are a function of ambient temperature. When a glass BAG operated at a pressures of 10^{-8} Torr, with a typical envelope temperature of 50°C, is cooled down with an air blast jet, the pressure in the measuring system can change by as much as a factor of two and the composition of the gas is seen to change radically. The effect is a direct consequence of changes in the desorption and permeation rates of the envelope as a function of temperature[78].

The most effective way to reduce the contribution of gauge outgassing to system pressure is to bake out the gauge, along with as much of the rest of the vacuum system as possible, for an extended period of time (i.e. overnight typical).

Frequently, a BAG is automatically degassed and/or the system baked after the gauge is exposed to ambient, or after surface contamination is suspected. BAGs will be unstable for several hours following degassing until the chemical composition and adsorbed layers on the newly cleaned surfaces reach equilibrium. This effect must be carefully considered for high accuracy determinations. The recommendation from the NIST High Vacuum Group is to eliminate degassing by high temperature heating of the grid (whether resistive or electron bombardment). For baked systems, their observation is that gauges can be effectively outgassed by simply operating them at normal emission currents while the BAG and vacuum system are baked. For unbaked systems, the gauge can be baked and outgassed by thermally insulating it with fiberglass. Degassing by electron bombardment is only recommended if (1) the gauge is heavily contaminated or (2) after exposure to surface active gases such as O_2[79]. Whenever possible minimize the emission current during degas and extend the degas time to compensate.

Note

The IGC100 offers fully adjustable Degas power and Degas time as part of its Gauge Setup Parameters.

Gauge Pumping

It is well known that all BAGs have gas-sinking capacity at pressures below 10^{-3} Torr. For the purpose of calculation, the gas pumping action of a BAG is represented by a vacuum pump with a constant speed, S, normally expressed in units of $L \cdot s^{-1}$.

The effect is gas dependent and constitutes another mechanism by which a BAG can affect the pressure and composition of the gas in an ultra high vacuum system.

The pumping speed is also a strong function of the history of the gauge.

The pumping is generally considered to be the sum of several contributions:

Ionic Pumping

Ions formed by electron impact ionization inside and outside the anode grid, are transported to the electrodes and surrounding walls and driven to the interior of their surfaces where they are neutralized. This is the mechanism by which inert gases are removed in ionization gauge heads. The number of ions that goes to the walls depends on the region in which they are formed, the design of the electrodes, the geometry of the gauge head, and the electrode biasing voltages[80]. Ionic pumping usually stabilizes after three months of operation at 10^{-9} Torr.

Chemical pumping

Thermally activated gas molecules are chemisorbed by the clean surfaces of the surrounding walls (i.e. glass envelope) of a gauge operated for the first time. The bonding is much stronger than that produced by van der Waals forces and effectively removes the molecules from the vacuum. Chemical pumping continues even after switching off the emission current and may greatly exceed the ionic pumping under certain conditions. The gettering effect is perpetuated when tungsten is used as the filament material, by a surface regeneration effect based on the constant deposition of fresh layers of tungsten molecules on all exposed internal surfaces. The effect is simply driven by the affinity of gases for very clean surfaces. As the surface becomes saturated the pumping speed diminishes to near zero and stabilizes. The duration of this stabilization process is of the order of four hours for a freshly baked gauge operated at 10^{-9} Torr.

Filament pumping

When chemically active gases such as hydrocarbons are present within a BAG head, their removal may occur via chemical reaction with the filament. This process usually also affects the overall sensitivity of the gauge, and is most marked for oxygen, nitrogen, water and hydrogen.

Several studies and reviews are available in the literature that show that for an electron emission current of 1 mA, the initial effective pumping speed in a glass tubulated gauge varies from about 0.001 Ls^{-1} for inert gases to 10 Ls^{-1} for nitrogen[81].

The pumping effect is particularly significant in the measurement of the background or residual pressures in any vacuum environment where there is a large contribution of heavy hydrocarbon vapor. Blears[82] demonstrated that glass tubulated gauges are very effective at pumping oils, and the pumping speed is maintained intact almost indefinitely. Large errors (up to a factor of 10) can be expected at base pressures when using glass tubulated gauges under these conditions. The process is also responsible for the typical dark coatings that develop on the internal walls and side tubes of tubulated gauges operated in the presence of hydrocarbons.

The most common remedy for pumping effects is to provide a large conductance connection between the gauge and the vacuum system.

- Nude gauges are the best solution to severe gauge pumping problems, since no tubulation is necessary, and the electrodes can be positioned directly into the chamber.
- In a glass tubulated BAG a gauge tubulation conductance greater than 10 Ls^{-1} is recommended to avoid pressure errors due to pumping effects at low pressures. A glass envelope gauge with a 0.75" side-arm tubulation has adequate conductance for use down to 10^{-8} Torr. Operation into the 10^{-10} Torr range requires minimum 1" diameter connection.

Filament reactions and outgassing

Chemical reactions involving the hot filament surface and the gas molecules can significantly affect the chemical composition and the total pressure of the gas environment in a high vacuum system[83]. There is a large dependence of these reactions on the material chosen for the cathode and the type of gas in the environment. Some of the processes triggered by these reactions include

- active pumping of selected gas components
- outgassing of impurities into the vacuum environment
- thinning of the filament
- poisoning of the filament surface (change in work function and emissivity).

The high temperature of the filament and its specific chemical composition contribute to the emission of neutrals and charged particles from the cathode that affect the gas composition at the gauge head, and the rest of the vacuum environment.

A detailed analysis of filament materials, filament-gas reactions, and filament outgassing is provided in the 'Filament Considerations' section of this appendix and will not be repeated here.

Gas Permeation

Pressure measurement in UHV chambers at base pressure may be impaired by the presence of He diffused through the glass envelope of the BAG. Permeation rates, involving sequential diffusion and desorption steps, depend on the material and temperature of the gauge head.

The simplest way to eliminate this problem in UHV systems is to use metal envelopes and all-metal BAGs.

Note

Remember this effect while leak testing your vacuum system! If helium leak testing with the ion gauge is common practice in your facility, consider an all metal gauge instead.

Mechanical Construction

Two basic mechanical variants of the BAG are commonly encountered in high vacuum systems: (1) nude gauges and (2) glass tubulated gauges. More recently, all-metal encapsulated BAGs have become commercially available with special specifications such as (3) miniaturized design (tiny gauges) and (4) enhanced accuracy and stability (high-accuracy gauges).

All commercially available gauges use the same basic electrode configuration, (virtually identical to the original) and, with few exceptions, the same electrode dimensions, materials, and biasing voltages.

Most BAG designs are offered with at least two different choices of filament material: (1) tungsten (W) and (2) Thoriated Iridium (ThO_2Ir). Some gauges include a dual-filament assembly to avoid having to break vacuum in cause of filament failure. For details on filament choices consult the 'Filament Options' section of this appendix.

Cross-reference tables for all current, and even obsolete, BAGs are available from many gauge manufacturers (including Stanford Research Systems). This makes it easy to buy and compare gauges from several different vendors without having to worry about gauge incompatibilities.

The most important and interesting features of commercially available BAGs are discussed next[84]. For information on the accuracy and stability of the different designs consult the 'Accuracy and Stability' section of this appendix.

Glass tubulated gauges

The glass tubulated BAG is, by far, the most commonly used gauge design in the world.

Glass tubulated gauges are the most inexpensive BAGs available.

When connected to a suitable controller, they provide pressure readings between 10^{-3} and $\approx 5.10^{-10}$ Torr (typical X-ray limit). Specification claims beyond this range must be approached with caution!

The glass tubulated gauge (Figure A-2) has its electrodes surrounded by a glass envelope (57 mm diameter typical) with a side tube that attaches to the vacuum system. The most common construction materials for the glass envelope are Nonex (an inexpensive glass used in old vacuum tubes), Pyrex and 7052 (another soft glass similar to Nonex).

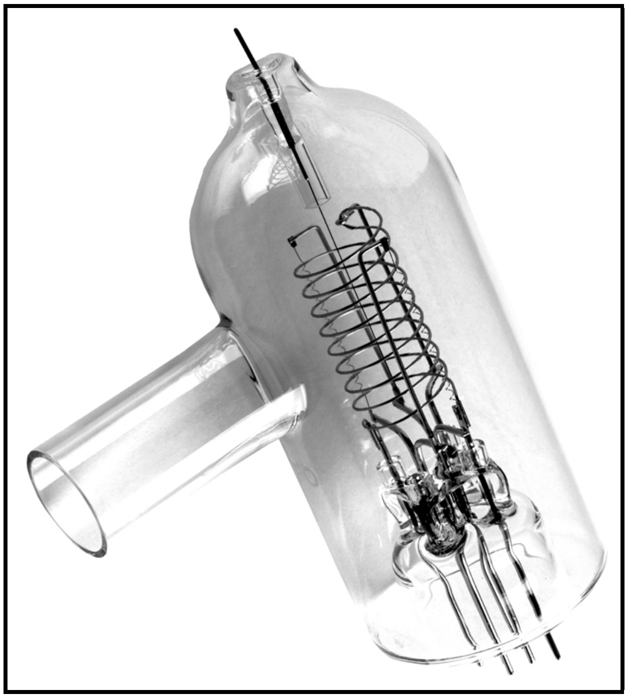

Figure A-2. Glass-tubulated Bayard-Alpert gauge with glass side tube connection.

Most tubulated BAGs are connected to the vacuum system through an O-ring compression fitting. Pyrex is the material selected when the side tube must be directly glass-blown on to the vacuum system. Kovar alloy is the material of choice when metallic tubulation is required for the side port[85]. Kovar tubulation is sometimes combined with compression fittings, but most often it is welded to Quick-Connect or ConFlat® flanges for compatibility with standard vacuum ports. While slightly more expensive, flanged tubulated BAGs offer better vacuum integrity and higher bakeout temperatures than compression fitting options.

Side tube diameters are set by standard compression fitting diameters to ½", ¾" and 1" OD. Whenever possible, choose the widest possible bore to assure structural integrity and maximum gas conductance between the vacuum chamber and the BAG ionization region.

All glass tubulated gauges use the same bias voltages and emission currents, making them compatible with generic ion-gauge controllers (such as the IGC100**)**. The anode grid structure is always a wire helix with open ends. A popular double-helix design allows for resistive, as well as electron bombardment, heating of the electrode assembly during degas, and also provides a fairly robust structure. Typical sensitivities fall in the range of 8-10 $Torr^{-1}$. A typical outgassing procedure includes heating the envelope to 250-400°C for 1 hour followed by a 15 minute degas step.

Several gauge manufacturers offer internal precious metal coatings (Pt) in their BAG tubes. The coating is electrically connected to the filament to reduce electrostatic charge on the glass surface and improve repeatability providing a slight advantage over uncoated gauges. With uncoated glass it impossible to control the potential of the internal surfaces, which results in uncontrolled electron and ion trajectories within the gauge and reduced measurement accuracy and repeatability.

Long term stability is affected by changes in the electrode structure particularly after repeated thermal cycling. High stability tubulated gauges with spring tensioned (sag-free) filaments and reinforced supports that provide improved measurement stability and accuracy without adding any significant cost are available from at least one manufacturer and are worth considering.

Broad-range glass tubulated BAGs are available from many different manufacturers, and under several different trade names. These gauges are designed to operate all the way up to 10^{-1} Torr (with 0.01 mA emission current above 10^{-3} Torr) while still providing a sensitivity factor of 8 $Torr^{-1}$. They are easily identified because of the narrow grid design (12 mm diameter x 46 mm long), a thoria-coated filament, and a grounded platinum coating on the inside of a reduced diameter (41 mm vs. the traditional 57 mm) glass tube. However, they have been shown to be susceptible to large time-dependent instabilities and non-linearities[86] that must be carefully considered during measurements.

Glass-tubulated BAGs are fragile and present a safety hazard due to implosion if not adequately shielded. Whenever possible, place them where they cannot be bumped, and be particularly careful during installation. A common problem is crushed side tubes due to excessive tightening of compression fittings. If possible, install the gauge so that the filament is visible during operation. A quick visual check might save a tungsten filament from burnout during a venting or gas loading operation. The preferred mounting orientation is with the filament and anode grid in a vertical position, with the connectors on top. This position minimizes the electrode distortion caused by gravity pull and thermal cycles.

Tubulated gauges with single and dual filament designs are available. Both tungsten and thoriated-iridium filament options are offered. Filaments are not replaceable, making the single filament gauges disposable after a burnout (A maintenance cost that must be considered!). The amount of power required to operate the filament can vary significantly from one gauge to another, depending on filament dimensions and material.

Glass tubulated gauges may be significant sinks of gas molecules and exhibit a certain pumping capacity that is usually time-dependent. This pumping is due to both chemical and electrical effects. The effect usually saturates after approximately three months of operation. The best way to handle this, is to provide a large conductance connection between the gauge and the vacuum system. A glass envelope gauge with 1" tubulation is recommended for applications requiring pressure measurements down to the 10^{-10} scale, ¾" tubulation is adequate for routine pressure measurements above 10^{-8} Torr.

Glass when heated permits permeation of helium from the atmosphere. Remember this effect while leak testing your vacuum system! If helium leak testing with the ion gauge is common practice in your facility consider an all metal gauge instead.

BAGs require few electrical connections; however, there is no standard mating socket that will work with all gauge designs. It is usually the user’s responsibility to assure that the correct electrical connections are made at the gauge pins. The correct pinouts for a gauge can be obtained from the original manufacturer. Experienced users can usually identify the different pins by visual inspection. Wrong connections can cause damage to equipment and may be dangerous for the vacuum system operator.

Note
Stanford Research Systems offers a line of BAG connection cables (O100C1, O100C2 and O100C3) that make it easy and safe to connect almost any commercially available gauge to the IGC100 controller without having to be a gauge expert!

Tubulated gauges owe their popularity to their low cost, convenient measurement range, and ease of mounting. Their accuracy is more than adequate for most vacuum applications since very often a 'rough' pressure indication is all that is required by the vacuum operator to define the status of a vacuum system.

Nude gauges

In nude BAGs (see Figures A-3 and A-4) the electrode structures are welded onto insulating feedthroughs mounted on a vacuum compatible flange (typically a 2.75" ConFlat®), and inserted directly into the vacuum chamber environment. The gas molecules of the vacuum chamber can flow freely into the ionization volume of the gauge thereby eliminating the pressure differential normally associated with tubulated gauges.

The basic electrode arrangement is same as in glass-tubulated BAGs so that many (but not all) modern ion gauge controllers can operate both gauge designs without any modifications. The biasing voltages and emission currents are generally identical or very similar. A connection cable replacement is usually all that is required to switch from one gauge design to the other.

Figure A-3. Nude Bayard-Alpert ionization gauge with standard (i.e. bi-filar helix anode grid) electrode design.

Nude BAGs are always more expensive than glass-tubulated designs. When connected to a suitable controller, they provide pressure readings between 10^{-3} and $4x10^{-10}$ Torr (typical X-ray limit), with extended UHV versions reaching a $2x10^{-11}$ Torr low limit. Typical sensitivities fall in the range of 8-10 $Torr^{-1}$ for standard gauges and 25 $Torr^{-1}$ for the extended UHV versions. Extended UHV versions are easily identified by the fragile closed end design (squirrel cage) of their anode grid and the thinner collector wire.

Since the elements are exposed, and easily accessible, most nude ion gauges are designed with replacement filament assemblies. This allows filaments to be replaced after a burnout without having to dispose of the gauge (an important cost saving feature!). Unless a viewport is available, it is generally not possible to see the filament once the gauge is mounted on a port, making the filament more susceptible to accidental and catastrophic overpressures.

With the exception of UHV versions (EB only), conventional nude BAGs include a double-helix anode grid design that allows for resistive, as well as electron bombardment, heating of the electrode assembly during degas.

The sensitivity of nude ion gauges is affected by the way it is mounted on the system[87]. This effect was recently demonstrated by a careful study, which showed that when the dimensions or shape of the gauge's metal envelope are changed there can be a dramatic effect (up to 2X) on the absolute magnitude of the gauge's sensitivity. There may also be a change in the relative dependence of its sensitivity on pressure. If these effects are not taken into account, the accuracy and consistency of the measurements performed with the gauge will be compromised. The envelope must be considered an integral part of the ionization gauge when specifying sensitivity. The practical consequence of these findings is that nude ion gauges must be calibrated in situ, or in an environment that exactly matches the one experienced by the gauge during its measurements. It is common practice to calibrate and operate nude ion gauges inside a nipple 38 mm ID x 100 mm long, with a screen at the input port. The input screen is necessary to eliminate the collection of ions produced somewhere else in the vacuum system, and attracted by the exposed electrodes of the ion gauge.

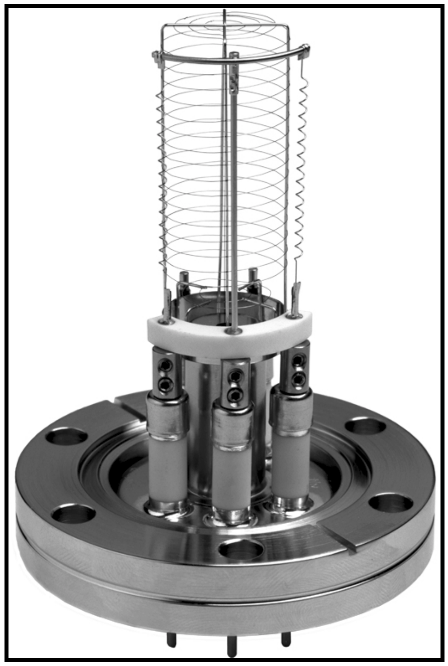

Figure A-4. Nude Bayard-Alpert ionization- UHV extended. Notice closed ends (squirrel-cage design) and fine wire design of anode grid.

Nude ions gauges are the choice of many UHV practitioners who appreciate the enhanced vacuum integrity provided by its mounting flange, the unrestricted conductance to the vacuum chamber, the reduced outgassing provided by the minimal surface area of its surroundings, and the higher bakeout temperatures that it can handle. Typical nude gauges can be baked to 450°C without any effect on performance. Nude ion gauges are the definitive solution to the gauge pumping problems experienced in tubulated gauges. The unrestricted conductance to the vacuum system also provides faster response to pressure changes in the chamber.

Extended UHV gauges provide the most cost-effective alternative for pressure measurements in the low 10^{-10} ranges typically accessed in surface science and extreme high vacuum experiments. The fine anode grid wires provide an enhanced open area, increasing the pathlength of the electrons before colliding with the grid. This effect, along with the closed ends, increases the sensitivity of the gauge by about a factor of two, relative to conventional BAG designs with open grids. The thin collector wire reduces the X-ray induced residual current by minimizing the collisional cross section with the X-rays emitted from the grid. The combination of enhanced sensitivity and reduced X-ray induced residual current is responsible for the extended X-ray limit. The effect of ESD is also relatively smaller in these gauges, since the thinner collector wire (0.125 mm vs. 0.25 mm) is very ineffective at collecting the energetic ions produced by electron stimulated desorption from the grid. The main limitation of the UHV design is the reduced linearity of the pressure gauge readings at upper pressures, starting sometimes as early as 10^{-5} Torr[88].

High-accuracy gauges

One of the most significant developments in BAG design in recent years has been the introduction of the 'high-accuracy gauge' design[89]. High-accuracy gauges operate based on the same ionization principles as nude and tubulated gauges; however, they provide highly accurate, reproducible and stable pressure readings by systematically avoiding the known problems associated with traditional gauge designs.

The long-term stability, accuracy and gauge-to-gauge reproducibility of pressure measurements in high-accuracy gauges are assured by the unique design and precise manufacturing applied to their construction.

In a commercially available design[90], dual, independent, thoria coated, ribbon filaments are carefully positioned relative to the anode axis and maintained in tension by refractory metal springs. Consequently, the filaments exhibit negligible bow, sag or twist with use, assuring stable and reproducible electron trajectories over time. Partial end-caps are employed to extend the radial electric field over a much larger area of the anode grid while at the same time short filaments are used to introduce electrons away from the end regions of the anode, assuring stable ion production conditions within the ionizer. The end-capped anode is precision assembled and stress-relieved so that it maintains its exact shape and position even after high temperature degassing. Electrode positions relative to wall are identical from gauge to gauge to assure reproducibility of measurements. A grounded conductive shield completely surrounds the anode-cathode structure to help provide a stable electrical environment for charged particle trajectories. The entire shield is designed to remain dimensionally stable over time and to have the same dimension from gauge to gauge within close tolerances. A grounded perforated high conductance shield over the port electrically isolates the electrode structures from the rest of the vacuum system.

Two different collector wire diameters of 0.005" and 0.040" are used. The thicker collector wire, precisely located at the anode axis, is so effective at collecting ions (50 $Torr^{-1}$ sensitivity) that it helps extend the upper pressure limit to 10^{-2} Torr while keeping the X-ray limit at 10^{-10} Torr. The thinner collector wire, while providing a lower sensitivity, extends the X-ray limit into the low 10^{-11} Torr range for performance compatible with ultra- and extreme-high vacuum applications.

The premise is simple, high accuracy gauges provide long-term, stable, accurate, gauge-to-gauge reproducible measurements in a way that is unmatched by any other BAG design. Current state-of-the art midrange accuracy specifications for uncalibrated high-accuracy gauges are 6%, and they get better for individually calibrated gauges.

Note

It is important to mention at this early point that no independent studies on the long term behavior of high accuracy gauges have yet been reported in the vacuum literature. All long term stability claims are based on experiments performed, and data published, by the gauge manufacturer itself. No certified independent vacuum calibration laboratory has looked at these gauges over a long period of time and compared their long term behavior to that of traditional designs.

Full enjoyment of the enhanced accuracy and stability capabilities of high-accuracy gauges requires the use of high-quality controllers such as the IGC100. Traditional (older design) controllers can contribute up to 15% uncertainty to a BAG readout[91].

High accuracy gauges are stable and reproducible enough, that it makes sense to calibrate them. Using the IGC100, it is possible to perform NIST traceable calibrations on individual gauges and store calibration information on Memory Cards that can be loaded into the controller's memory when needed. Stored values of gauge sensitivity track the actual gauge sensitivity across the entire pressure range, providing real time correction for the non-linearities that lead to errors in traditional gauge systems. Individually calibrated high accuracy gauges offer midrange reading accuracies better than 3% (close to spinning rotor gauge performance)[92].

High accuracy gauges are usually expensive, costing up to 10 times as much as a glass tubulated gauge, but they make a lot of sense in strictly controlled vacuum process environments where pressure reading inaccuracies can lead to reduced yields and increased production costs. When properly selected they can pay for themselves very quickly! The gauge-to-gauge reproducibility is a welcome feature when forced to switch to a new gauge right before trying to reproduce a production run. Calibrated high accuracy gauges are also cost-effective NIST traceable transfer standards, providing accuracies comparable to spinning rotor gauges over a larger pressure range. It is common practice for pressure calibration laboratories to use high-accuracy gauges as transfer, check and working standards. Keep in mind that whereas the gauge-to-gauge reproducibility claims for high accuracy ion gauges are generally well accepted by vacuum users, the longer term stability of these gauges has not yet been verified by any independent vacuum calibration lab.

Note

Consult Appendix C for details on the connection of high accuracy gauges to the IGC100.

Tiny Gauges

Miniaturization has not escaped BAG designs. Almost every vacuum gauge manufacturer now offers a version of 'tiny' ionization gauge[93].

Tiny gauges are a modern alternative to glass tubulated gauges and are likely to become relatively more important in the future. They eliminate glass gauge accidents by relying in all-metal construction. They offer an operational range that overlaps or sometimes exceeds that of traditional tubulated designs. The reduced size also minimizes the power requirements of the filament resulting in less heat being dissipated into the vacuum chamber and reduced outgassing.

A miniaturized, all-metal ionization gauge that retains the traditional inverted-triode design, operating voltages, good sensitivity and low X-ray limit of the conventional glass tubulated BAG has recently become commercially available[94]. This tiny gauge (5% of the conventional volume) utilizes a dual collector design to increase ion collection efficiency (20 $Torr^{-1}$ typical) while at the same time providing a wider usable pressure range that extends from $3x10^{-10}$ (X-ray limit) to $5x10^{-2}$ Torr.

Note

The IGC100 controller is compatible with most commercially available tiny-BAGs and a connector adapter is all that is required to operate them. Consult Appendix M for details.

Tiny gauges are more expensive than tubulated designs (up to 4 times) and are usually only available with dual thoriated (burn-out resistant) filaments. Filaments are not replaceable, making the gauges disposable after filament failure. Both flanged and tubular mounting options are available.

No reports on the repeatability, short- and long-term stability, and gauge-to-gauge reproducibility of tiny gauges are currently available since the gauges have only been recently introduced into the market. However, It is probably fair to assume that their accuracy specifications will be comparable to those of glass tubulated ion gauges.

Filament Considerations

Careful consideration must be dedicated to the choice of filament material.

Filaments are based on thermionic phenomena[95]- the emission of charged particles from the surface of a conductive material or compound at high temperature. The emission of charged particles depends on the *work function*[96] of the material, defined as the energy, measured in eV, required to move an electron from Fermi level outside the surface.

Filaments, in both wire and ribbon shapes, are required to

- supply a stable electron emission current with reasonable energy input and filament temperature
- have reduced chemical reactivity with the rarefied environment being measured
- have a reduced evaporation rate at the operating temperature (i.e. long life)
- have a vapor pressure at least one tenth of the lowest pressure that has to be measured
- have low levels of ionic and neutral molecule outgassing compatible with the lowest pressure measurements.

It is commonly believed that the filament in a BAG presents a reliability problem (especially when compared to Cold Cathode Gauges) and it is often true that the operating life of hot cathode ionization gauges is determined by filament lifetime. However, unless damaged by ion bombardment, high pressure operation, chemical reactions or severe contamination, filament lifetimes are usually in the thousands of hours (usually years).

The optimum choice of filament material is very application dependent, and interactions of the gas with the cathode material must be considered during filament selection.

Several attempts have been made to replace hot filaments with cold electron emitters in BAGs[97]; however, no commercially available gauges have resulted from those efforts yet.

Filament Materials

The filament materials used in BAGs can be grouped into two classes: (1) pure metals and (2) oxide-coated cathodes. This section only concentrates on the materials commonly encountered in commercially available gauges. For information on less common materials, consult the excellent primer by Gear[98] and the work by W. Kohl[99].

Among pure metals, tungsten (W) is used on a large scale in ionization gauge heads operated in medium and high vacuum environments. The operating temperature of tungsten cathodes is between 1900°C and 2200°C. At this high operating temperatures, contaminating electronegative gases, which would increase the work function and reduce emission levels, are rapidly evaporated from the filament surface. As a result, tungsten filaments provide more stable gauge operation compared to metal oxide cathodes. However, this advantage is usually at the expense of (1) large outgassing levels as a result of the elevated temperatures in the surrounding walls and (2) an increased reactivity with chemically active gases that react at the filament to produce other gases. Chemical reactions as well as a high vapor pressure (10^{-8} Torr at 2200K) make W a bad choice for

UHV measurements. Glass tubulated BAG tubes with dual W filaments are often the best choice for ion implantation applications.

The lifetime of W filaments, as determined by typical evaporation rates, is typically 10-20 hours at 10^{-3}-10^{-2} Torr, and about 1000 hours at 10^{-6} Torr (gas dependent). However, accidental exposure to air and/or mechanical mishandling will damage tungsten filaments irreversibly. Tungsten is not seriously affected by hydrocarbons and halogens during operation.

Thoria-coated iridium (ThO_2Ir) filaments are the oxide-coated cathodes most commonly encountered in BAG heads manufactured in the US[100]. These cathodes are prepared by depositing a layer of thoria (i.e. thorium oxide) on a base metal of iridium by cataphoresis. The coating is then preconditioned[101] by operation in a vacuum at about 1800°C. Iridium is the preferred substrate because it is very resistant to oxidation and does not burn out if exposed to high air pressures while hot. ThO_2Ir filaments are very resistant to poisoning and do not burn out if exposed for a short time during operation to a sudden inrush of air. In fact, BAGs with ThO_2Ir filaments are known to survive several brief exposures to atmospheric air, without any performance deterioration.

ThO_2Ir filaments operate at a 'relatively cool' temperature of ≈1400°C, resulting in reduced outgassing and chemical reactivity with active gases when compared to W filaments. These two advantages, make ThO_2Ir filaments the preferred filament choice for measurements in the ultrahigh vacuum region. Most thoriated filaments are ribbon shaped to minimize heat flow to the ends which results in reduced outgassing.

Thoria coatings are very sensitive to electron and ionic bombardment. As a consequence, electron bombardment degassing must be minimized in gauge heads with ThO_2Ir filaments. A thorough bakeout is a better alternative in this case.

The material choice is dictated by the application. Tungsten filaments are by far the least expensive and the most popular. The use of ThO_2Ir filaments is recommended for systems that are frequently brought to atmosphere (voluntarily or not!). ThO_2Ir is the only practical alternative for operation above 10^{-3} Torr. Some investigators[102] have obtained results suggesting that gauges with tungsten filaments provide better stability than do gauges with thoria coated versions. The current belief is that it is not the filament material that causes the improvement, but rather the shape of the cathode. Tungsten cathodes are typically made as tight springs stretched between rigid posts that tend to move relatively little during long term use compared to the hairpin shaped or relatively unsupported ribbon shaped thoria-coated cathodes. Whenever possible opt for spring tensioned filaments in your BAG heads, particularly those with hair pin designs.

Dual filament assemblies provide security against filament burnout if the system cannot be brought to atmosphere to change the gauge. They are the most cost-effective alternative for tubulated gauges where filament replacement is not an option. Do not expect both filaments to give identical readings in a dual filament gauge unless a high accuracy gauge is being used. Simple methods for in-house replacement of tungsten filaments in nude gauges have been described in the vacuum literature as a cost-effective alternative if high accuracy and reproducibility is not a requirement in the pressure measurements performed by the repaired gauge[103].

Filament Reactions

Chemical reactions at the hot filament can occur and usually belong to one of two groups: (1) thermal dissociation of gas or vapor at the hot cathode and further recombination of the resulting fragments with impurities in the gas or on the walls or (2) combination of gas with the filament material.

Chemical reactions involving the hot filament surface and the gas molecules can significantly affect the chemical composition and the total pressure of the gas environment in a high vacuum system[104]. There is a large dependence of these reactions on the material chosen for the cathode and the type of gas in the environment. Some of the processes triggered by these reactions include: (1) active pumping of selected gas components, (2) outgassing of impurities into the vacuum environment, (3) thinning of the filament, and (4) poisoning of the filament surface (change in work function and emissivity).

Gases and vapor usually found in measuring systems are oxygen, hydrogen and water vapor.

Oxygen

Oxygen molecules react with the hot tungsten cathode and dissociate into atomic oxygen. The atomic oxygen then reacts with the carbon impurities at the surface to yield CO and CO_2. Since carbon constantly diffuses to the surface from the bulk, CO is continuously generated by this process. Even after the carbon is consumed, atomic oxygen still combines with carbon containing impurities present on the gauge walls, yielding CO.

Oxygen atoms interact with tungsten and produce oxides (WO_2, WO_3) as surface species. These species affect the work function of the material and also make the wire very brittle. These chemical processes result in the removal of oxygen from the system, therefore an ion gauge with W filament acts as a pump for oxygen.

Hydrogen

Hydrogen molecules dissociate to atomic hydrogen in the presence of a tungsten cathode at temperatures > 800°C. The atomic hydrogen reacts with glass or metal surfaces to yield CO, H_2O, and CH_4. This fast removal of hydrogen from the gas results in anomalously high pumping speeds for hydrogen in BAG heads with W filaments.

After adsorbing a monolayer of hydrogen, the work function of a tungsten filament is significantly increased (+0.35 eV typical) and the filament must run hotter to achieve the same emission current.

Water

Water vapor reacts with hot tungsten cathodes initiating an efficient transport of tungsten molecules to the gauge walls. This process, known as the *water vapor cycle*, includes several steps: (1) water dissociates at the filament into atomic oxygen and hydrogen, (2) the atomic oxygen reacts with W to form a volatile oxide that deposits on the glass walls of the gauge head as a film, (3) atomic hydrogen reduces the film back to W thus setting free water vapor, which repeats the cycle. The cathode lifetime is severely compromised by this process. CH_4, CO and CO_2 are also formed at the filament as a result of chemical reaction with water.

Hydrocarbons

Hydrocarbons, such as methane and pump oils, backstreaming from vacuum pumps can dissociate on hot filaments to produce CO.

Emission of ions and neutrals

The emission of positive ions and neutrals from heated surfaces is a common occurrence that can affect the performance of BAGs in the UHV range.

Although the positive ions cannot normally reach the collector because of the grid potential, the emission of positive ions is accompanied by a larger flux of neutrals. These neutrals can then be ionized and reach the collector giving a pressure independent current which ultimately limits the lowest measurable pressure. The evaporation of neutrals and ions can be minimized by heating the pure metal cathodes at high temperature for prolonged periods of time while pumping the gauge head.

Accuracy and Stability

The two main variables that affect the accuracy and reproducibility of pressure measurements are (1) gauge-to-gauge reproducibility and (2) long-term stability.

Reproducibility

Gauge-to-gauge reproducibility has been examined by the High Vacuum Group at NIST (National Institute of Standards and Technology, Gaithersburg, MD). The sensitivities of a large collection of commercially available BAGs were carefully calibrated and surprisingly large sensitivity factor variations were observed even amongst seemingly identical gauge heads. The reported ranges[105] in gauge constants are summarized next:

- Glass tubulated with opposed W filaments: +20 to –10%
- Glass tubulated, with side-by-side W filaments: +25 to –5%.
- Glass tubulated, with thoria filament: +13 to –38%
- Nude UHV version, with thoria filaments: +22 to –65%

The gauge-to-gauge reproducibility and long-term stability of broad-range glass tubulated gauges was also studied at NIST[106]. A check of the sensitivity factors for the seven gauges tested found the nitrogen sensitivities to vary between 52 and 67% of their specified values. Significant non-linearities as a function of pressure were also evident. Instabilities were in the order of 10%. Some of the gauges were inoperable in hydrogen environments.

The scatter of sensitivities is easily corrected by calibration. However, many users simply accept the catalog values for sensitivity factors without correction. This practice is only acceptable for applications where a rough determination of pressure is necessary.

As a rule-of-thumb:

- gauge-to-gauge variations can be considered to be an average ±15%.
- For any one uncalibrated gauge, an accuracy of ±25% at midrange should be considered good.
- Measurement accuracies better than 1% are not achievable with BAGs.
- Calibration of the gauge is recommended whenever an accuracy better than 50% is required.

Stability

Long-term stability of measurements over long operating times is also very important for accurate measurements. Filippelli and Abbott[107] compared repeated calibrations of 20 gauges used as transfer standards in industrial applications (returned to NIST for recalibration every one to two years several times) and concluded that for tubulated gauges with W filaments the standard deviation of the maximum difference between successive calibrations was 3% (maximum 12%) while for gauges with thoria cathodes it was 6% (maximum 18%). In most cases, the sensitivity of the gauges tended to decrease. The change in gauge sensitivity did not occur in a uniform manner with time of use.

P. C. Arnold and S. C. Borichevski[108] studied the stability and gauge-to-gauge reproducibility of eleven 'conventional' BAGs with various different mechanical constructions and thoriated filaments and reported much larger sensitivity variations ranging from –57 to +72% over the first 4000 hours of operation. Gauge-to-gauge variations between –20 and +32% were observed for five virtually identical glass tubulated gauges after 48 hours of operation. The gauges were operated at 10 mA of emission current (compare to 1 mA for NIST), and were degassed daily for 20 minutes (not recommended by NIST) which might explain the poor performance of the tested gauges.

The long term stability of a BAG is highly affected by its history (see 'History Dependence' in this appendix). Gauge sensitivity factors are seen to change with time even under the carefully controlled conditions of a standards laboratory. Industrial systems with gases that contaminate the electrodes are much worse. Unfortunately, there is very little written on the effects of contamination, for, as might be expected , there are wide variations in performance, depending upon both the type of gauge and its treatment in the vacuum system. Two very useful papers[109] that deal with the causes of non-stability in BAGs are found in the references, and should be consulted for details. An excellent set of 'Recommended Operating Procedures' for better BAG stability was compiled by Tilford[110] and is highly recommended.

Partial restoration procedures for heavily contaminated glass-tubulated BAGs have been reported in the vacuum literature[111]. These procedures are only recommended for inoperable gauges, and in general only restore the sensitivity of the gauge within a factor of two of a new gauge.

Systematic differences in sensitivity are observed between the two filament positions in BAGs with dual filament assemblies and conventional design. An individual calibration for each filament is necessary for accurate measurements.

Confidence in gauge stability can be increased by periodically checking the gauge against a check gauge (work standard). This will be most effective if the check gauge is of proven stability and/or is protected from abuse or unnecessary use.

Even with inactive gases, time must be allowed for gauge equilibrium to be reached following pressure changes. Limited experimental data is available in this area. Some general rules of thumb, applicable to transient measurements, can be obtained from Tilford's work[112]:

- Tungsten (W) filament gauges accommodate to increasing nitrogen pressure faster than thoria-coated filament gauges.
- W filament gauges respond to a three fold increase in pressure to within 0.1% within a few minutes.
- The response is slower in a dirty system or with active gases.
- The response to decreasing pressure is slower by several orders of magnitude.

These effects are compounded by conductance limitations of the gauge tubulation and the time constant of the electrometer.

One of the most significant developments in BAG design in recent years has been the introduction of the 'high-accuracy gauge' design[113]. High-accuracy gauges operate based on the same ionization principles as nude and tubulated gauges; however, they provide highly accurate, reproducible and stable pressure readings by systematically avoiding the known problems associated with traditional gauge designs. The long-term stability, accuracy and gauge-to-gauge reproducibility of pressure measurements in high-accuracy gauges are assured by the unique design and precise manufacturing applied to their construction (see 'Mechanical Construction' in this appendix for details).

High accuracy gauges are stable and reproducible enough, that it makes sense to fully calibrate them. Using the IGC100 it is possible to perform NIST traceable calibrations on individual gauges and store calibration information in special Memory Cards that can be downloaded into the controller's memory when needed. Stored values of gauge sensitivity track the actual gauge sensitivity across the entire pressure range, providing real time correction for the non-linearities that lead to errors in traditional gauge systems. Individually calibrated high accuracy gauges offer midrange reading accuracies better than 3% (close to spinning rotor gauge performance) [114].

Full enjoyment of the enhanced accuracy and stability capabilities of high-accuracy gauges requires the use of high-quality controllers, with properly specified electronics, such as the IGC100. Traditional (older design) controllers can contribute up to 15% uncertainty to a BAG readout[115].

Degassing

The cleanliness of an ionization gauge has a considerable effect on its performance.

The filament is rapidly outgassed when first turned on. The radiant heat from the hot wire then causes outgassing from nearby surfaces including electrode supports and envelope walls. These effects are readily seen following the pressure indication of the BAG immediately after the filament is switched on.

The heat generated by the filament during normal operation is not enough to effectively clean the grid and collector surfaces, and effective outgassing of the envelope requires bakeout (400°C for 1 hour is typical for glass tubulated gauges).

To reduce the outgassing in a gauge to a negligible level, and minimize the effects of ESD on low pressure measurements, the outgassing technique known as *Degassing* is often employed to drive off the gas molecules adsorbed on the anode grid structure. During degas the electrodes are degassed by heating to a temperature of 900°C (nominal) for 10-20 minutes. The electrode heating is accomplished by either electron bombardment (EB Degas) or by passing a high current through the grid ($\mathbf{I}^2$R Degas) .

In conventional gauges, particularly those manufactured in the US, the anode grid is in the form of a single or double helix designed to allow a current to be passed through to provide ohmic heating. Distortion and sagging can occur here if the temperature attained during degassing is too high. Modern gauge heads use molybdenum or tungsten grids to avoid or minimize this problem. Typical powers used during resistive heating degassing are about 70 Watts (7 Vdc @ 10 A). All helix gauges can also be degassed by EB as well.

Gauges made with squirrel-cage grids (UHV nude BAGs) can accept only EB degas. During EB degas, the grid (and sometimes the collector as well) are biased at around 500 Vdc and bombarded with electrons from the filament (biased at 30 Vdc). An emission current of a few tens of milliamps is sufficient to heat the electrodes (usually molybdenum) to a dull red. The combination of heating with the electron bombardment of the electrodes provides a very effective cleaning procedure.

Degassing is best carried out, while the rest of the vacuum system is also being baked to avoid degassing products from adsorbing onto the walls of the chamber.

It is common practice for many HV users to automatically degas the gauge and/or bake the vacuum system after the gauge is exposed to ambient, or after surface contamination is suspected. BAGs will be unstable for several hours following degassing until the chemical composition and adsorbed layers on the newly cleaned surfaces reach equilibrium. This effect must be carefully considered for high accuracy determinations.

All commercially available BAGs can be degassed by electron bombardment. However, thoriated filaments can be rapidly damaged by the intense ionic bombardment that they experience when EB degassing takes place at pressures above 10^{-5} Torr. To extend filament lifetime, minimize the emission current during degas and extend the degas time to compensate. Keep the EB degas power under 40 W for all thoriated filament gauges.

Some vacuum researchers suggest bombarding the collector wire along with the anode grid during EB degassing. This approach leads to clean electrodes, but it is intrinsically dangerous in practice. Instead, it is recommended to keep the collector connected to the electrometer to get a rough estimate of the pressure during degas. EB degassing at pressures >5x10^{-5} Torr can damage the gauge, and injure the user if the system is not properly grounded (see the **Safety and Health Considerations** section for details)

The recommendation from the NIST High Vacuum Group is to eliminate degassing by high temperature heating of the grid (whether resistive or electron bombardment). For baked systems, their observation is that gauges can be effectively outgassed by simply operating them at normal emission currents while the BAG and vacuum system are baked. For unbaked systems, the gauge can be baked and outgassed by thermally insulating it with fiberglass. Degassing by electron bombardment is only recommended if (1) the gauge is heavily contaminated or (2) after exposure to surface active gases such as O_2[116]. Whenever possible minimize the emission current during degas and extend the degas time to compensate.

Note

The IGC100 offers EB degas with fully adjustable Degas power and Degas time.

Safety and Health Considerations

Electric Shock

DANGER!
The most serious hazard with BAGs and their controllers is electrical shock[117].

During normal operation the anode grid of a BAG is biased at about 180 Vdc and connected to a power supply capable of supplying 10 mA. This is enough to cause defibrillation and even death. During EB degas, the anode grid is biased to 500 Vdc at currents of up to 160 mA! Contact with this supply, with a direct current path through the body, would very likely be fatal to anybody.

A more subtle way of contacting the high voltage during EB degas was described by Morrison[118]. If EB degas is allowed at pressures above 10^{-4} Torr, a plasma might develop inside the gauge capable of providing a current path to metal portions of the system. If the system is not properly grounded, touching the charged metal section may cause a lethal shock. The effect might remain even after the filament is shut down (depending on the amount of energy stored)!

A well designed gauge system should include suitable cables, connectors and grounds. A user should never touch any connector or the gauge when the power is on. Both the controller and the vacuum system must be earth grounded with heavy gauge (12 AWG) wire.

Thoria Alpha Emission

In gauges with thoriated filaments, exposure to the alpha particles emitted by thorium is of concern to some users. The use of yttria coated iridium filaments is recommended in those cases as an alternative. Most gauge manufacturers offer this filament material as an option.

Glass breakage

With glass tubulated gauges, breakage of the glass envelope can result in implosion and the associated danger of flying glass. Whenever possible protect the gauge with a shield and provide stress relief for the cables. Do not overtighten the O-rings of the compression fittings traditionally used to connect glass tubulated gauges to vacuum systems. All-metal nude gauges should also be considered if the risk of breakage is high.

Burns

Gauge envelopes can get hot, and cause burns if touched during operation.

X-rays

The X-rays produced at the anode grid, and responsible for the X-ray limit, are not a risk since they do not have enough energy to penetrate through the gauge envelope. This is also true for the X-rays generated during EB Degas.

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[21] George Comsa, "Ion Collection in Bayard-Alpert Gauges" , J. Vac. Sci. Technol. 9 (1) (1971) 117.

[22] At pressures below 10^{-7} Torr, ions which miss the collector at their first radial trip due to excessive angular momentum with respect to the collector axis, have practically no chance to collide with atoms during their axial drift.

[23] Only a small fraction of this decrease is due to density changes caused by the rise in gas temperature.

[24] E.V.Kornelsen, Proc. 3rd Intern. Vac. Congr., 1965 , Pergamon, Oxford (1966) , Vol. 1, page 65.

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[29] George Comsa, "Ion Collection in Bayard-Alpert Gauges" , J. Vac. Sci. Technol. 9 (1) (1971) 117.

[30] C. Tilford, K. E. McCulloh and H. S. Woong, "Performance Characteristics of a broad range ionization gauge tube", J. Vac. Sci. Technology 20(4) (1982) 1140.

[31] R. Kauert et. al. ,"Numerical investigations of hot cathode ionization gauges", Vacuum 51(1)(1998) 53.

[32] A minimum negative anode bias of 5Vdc is required for this purpose.

[33] D. Alpert "New Developments in the Production and Measurement of Ultra High Vacuum", J. Apl. Phys. 24(7) (1953) 860. See fig 1(a) and text on page 862.

[34] C. Tilford, K. E. McCulloh and H. S. Woong, "Performance Characteristics of a broad range ionization gauge tube", J. Vac. Sci. Technology 20(4) (1982) 1140. See comments on page 1142, including the results of figures 3 and 4 on the same page.

[35] Standard "older design" BAG controllers can contribute as much as 15% uncertainty to readout when the root sum of the squares of the errors contributed by variations in electrode voltages, emission current, measurement of ion current and poor resolution is calculated. See, for example, brochure # 360138, 4-97, by Granville Phillips incorporated, page 12, where they describe the operation of high-accuracy gauges with their older controllers.

[36] L. T. Melfi and F. A. Kern, "Variations in Gauge Constant as a Function of Emission Current in an Unshielded Open-end Grid BAG", NASA Technical Note, NASA TN D-3811. NASA, Langley Research Center, 1967.

[37] P. J. Abbott and J. P. Looney, "Influence of the filament potential wave form on the sensitivity of glass envelope Bayard-Alpert gauges", J. Vac. Sci. Technol. A 12(5) (1994) 2911.

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[47] A. R. Filippelli, "Influence of envelope geometry on the sensitivity of nude ionization gauges", J. Vac. Sci. Technol. A 14(5) (19996) 2953.

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[50] D. G. Bills, M. D. Borenstein and P. C. Arnold, US Patent 5422573, 1995.

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[52] K. J. Close, D. Lane and J. Yarwood, Vacuum 29(1979) 249.

[53] Tentative Recommended Practice for Ionization Gauge Application to Space Simulators, ASTM E296-66T, Appendix A2. Am. Soc. Test. Mater. ,Philadelphia.

[54] The anode grid temperature in a conventional BAG can be raised to over 700K by the filament radiation at 10 mA of emission current as measured by Kendall in J. Vac. Sci. Technol A 17(4) (1999) 2041, and reported on p. 2043. The envelope of an uncoated, clean, glass-tubulated gauge usually operates at about 50°C.

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[57] P. C. Arnold and D. G. Bills, J. Vac. Sci. Technol. A2(1984) 159.

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[62] N. T. Peacock, "Measurement of X-ray currents in Bayard-Alpert type gauges", J. Vac. Sci. Technol. A 10(4) (1992) 2674.

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[64] D. Alpert, " New Developments in the Production and Measurement of Ultra High Vacuum", J. Appl. Phys. 24(7) (1953).

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[66] H. C. Heseuh and C. Lanni, "Summary Abstract: A thin Collector BAG for 10^{-12} Torr vacuum", J. Vac. Sci. Technl. A 5(5) (1987) 3244.

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[69] T. S. Chou, C. Lanni and Z. Q. Tang, "Investigation on Low pressure Limit of Bayard Alpert Gauge", NASA, Center for Aerospace information, document #84N14502, Submitted to AVS conference , Boston, MA, Nov. 1983.

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See also :
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[76] Stanford Research Systems offers a full line of state-of-the-art residual gas analyzers with 100, 200 and 300 amu range. For information visit www.thinksrs.com.

[77] J. Miertusova, "Reliability and accuracy of total and partial pressure measurements in the UHV pressure range under real experimental conditions", Vacuum 51(1) (1998) 61.

[78] P. E. Gear, Vacuum 26(1) (1975) 3. See sections 4.5 and table 3 for a dramatic demonstration of the effect.

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[84] See also the article: Gerardo A. Brucker, "Which Bayard-Alpert Gauge is Best For You?", R&D Magazine, Feb. 2000, p. 69. This includes pictures of the different gauge types and some more gauge selection criteria. Copies of this article can be obtained directly from Stanford Research Systems (while supplies last).

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[87] Albert R. Filipelli, "Influence of envelope geometry on the sensitivity of "nude" ionization gauges", J. Vac. Sci. Technol. A 14(5) (1996) 2953.

[88] R. N. Peacock and N. T. Peacock, "Sensitivity variation of Bayard-Alpert Gauges with and without closed grids from 10^{-4} to 1 Pa", J. Vac. Sci. Technol. A8 (4) (1990) 3341. An excellent comparison of open and close ended gauge designs.

[89] P.C. Arnold, D. G. Bills, M. D. Borenstein and S. C. Borichevsky, "Stable and reproducible Bayard-Alpert ionization gauge", J. Vac. Sci. Technol. A 12(2) (1994) 580.

[90] STABIL-ION gauge, model 370120 or 370121 (UHV version) , from Granville-Phillips, Helix Technology Corporation, Longmont, CO.

[91] "Series 360 Product Information. STABIL-ION Vacuum Measurement System", Sales Brochure from Granville Phillips Co. , Helix Technology Corporation, Boulder, CO, part# 360138, 4/97, page 12.

[92] Midrange accuracy is better than 2% when the calibration is performed by a primary standards lab such as NIST.

[93] Werner Grosse-Bley, "A hot cathode ionization gauge transmitter for industrial vacuum measurement", Vacuum 51(1) (1998) 31.

[94] A.R. Filipelli, "A miniature Dual-Collector Ionization Gauge", Proceedings of the 46th International Symposium, American Vacuum Society, Oct 25-29, 1999. Washington State Convention Center, Seattle Washington. Series 355 Micro-Ion® gauges, Granville-Phillips, Helix Technology Corporation, Longmont, CO.

[95] R. O. Jenkins, "A review of thermionic cathodes", Vacuum 19(8) p.359.

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[102] Charles Tilford, "Sensitivity of hot cathode ionization gauges", J. Vac. Sci. Technol. A 3(3) (1985) 546;

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[109] K. Jousten and P. Rohl, "Instability of the spatial electron current distribution in hot cathode ionization gauges as a source of sensitivity changes", J. Vac. Sci. Technol. A 13(4) (1995) 2266; D. G. Bills, "Causes of nonstability and non reproducibility in widely used Bayard-Alpert ionization gauges", J. Vac. Sci. Technol. A 12(2) (1994) 574.

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[111] P. E. Siska, "Partial Rejuvenation of Bayard-Alpert ionization gauge tubes", Rev. Sci. Instrum. 68(4) (1997) 1902.

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[113] P.C. Arnold, D. G. Bills, M. D. Borenstein and S. C. Borichevsky, "Stable and reproducible Bayard-Alpert ionization gauge", J. Vac. Sci. Technol. A 12(2) (1994) 580. The gauge described is commercially available from Granville-Phillips, HELIX TECHNOLOGY CORP, Boulder, CO under part #s 370120 and 370121(UHV Version). Both gauges are compatible with the IGC100 controller manufactured by Stanford Research Systems.

[114] Midrange accuracy is better than 2% when the calibration is performed by a primary standards lab such as NIST.

[115] "Series 360 Product Information. STABIL-ION Vacuum Measurement System", Sales Brochure from Granville Phillips Co. , Helix Technology Corporation, Boulder, CO, part # 360138, 4/97, page 12.

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Appendix B

Manufacturer Cross-Reference for Bayard-Alpert Gauges

In This Appendix

Manufacturer Cross Reference Table

Glass Tubulated									
Connection Type	**Diameter**	**Filament Material (count)**	**Pin Config**	**SRS (Stock#)**	**Granville-Phillips**	**ETI**	**Duniway Stockroom**	**Kurt J. Lesker**	**Varian**
Glass Tube (Pyrex)	0.75 in.	ThO_2/Ir (single)	Fig. B-1	GR-075P (6-552)	274002	4336P	I-075-P	G075P	K2471304
		Tungsten (dual)	Fig. B-2	GW-075P (6-548)	274012	4336TP	T-075-P	G075TP	K7360303
	1 in.	ThO_2/Ir (single)	Fig. B-1	GR-100P (6-554)	274005	4336P/1	I-100-P	G100P	K2471301
		Tungsten (dual)	Fig. B-2	GW-100P (6-551)	274015	4336TP/1	T-100-P	G100TP	K7360301
Metal Tube (Kovar)	0.75 in	ThO_2/Ir (single)	Fig. B-1	GR-075K (6-547)	274003	4336K	I-075-K	G075K	K2471305
		Tungsten (dual)	Fig. B-2	GW-075K (6-550)	274013	4336TK	T-075-K	G075TK	K7360304
	1 in.	ThO_2/Ir (single)	Fig. B-1	GR-100K (6-549)	274006	4336K/1	I-100-K	G100K	K2471302
		Tungsten (dual)	Fig. B-2	GW-100K (6-553)	274016	4336TK/1	T-100-K	G100TK	K7360302
2.75" Conflat® Flange	1 in. side tube	ThO_2/Ir (single)	Fig. B-1	GR-100F (6-556)	274008	4336F/1	I-CFF-275	G100F	K2471303
		Tungsten (dual)	Fig. B-2	GW-100F (6-555)	274018	4336TF/1	T-CFF-275	G100TF	K7360307
Nude (2.75" CF flange)									
Range	**Anode Grid**	**Filament Material (count)**	**Pin Config**	**SRS (Stock#)**	**Granville-Phillips**	**ETI**	**Duniway Stockroom**	**Kurt J. Lesker**	**Varian**
Std.	Bi-filar Helix	ThO_2/Ir (single)	Fig. B-3	NR-F (6-559)	274028	8140	I-NUDE-BAC	G8140	L5150-302
UHV	closed end cage	ThO_2/Ir (dual)	Fig. B-4	NR-F-UHV (6-557)	274023	8130	I-NUDE-F	G8130	971-5007
UHV	closed end cage	Tungsten (dual)	Fig. B-4	NW-F-UHV (6-558)	274022	8130T	T-NUDE-F	G8130T	971-5008

Note

The IGC100 is also compatible with STABIL-ION® and MICRO-ION® gauges manufactured by Granville-Phillips (Helix Corp., Longmont, CO, USA). Consult Appendices C and M for more information on using these third party gauges.

Replacement Filament Assemblies for Nude Gauges		
SRS Model #	**SRS Part #**	**Description**
O100RFA-DR	6-581	Dual ThO_2/Ir Replacement Filament Assembly for NR-F-UHV Gauge
O100RFA-DW	6-582	Dual Tungsten Replacement Filament Assembly for NW-F-UHV Gauge
O100RFA-SR	6-583	Dual ThO_2/Ir Replacement Filament Assembly for NR-F Gauge

Bayard Alpert Gauge- Pin Connector Configuration-Cable Selector

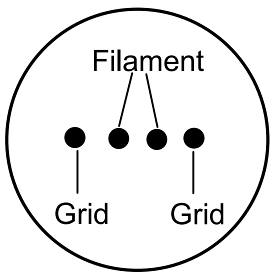


Figure B-1
Glass Tubulated Gauge
Single ThO_2/Ir filament
IGC100 Cable: **O100C1**
Default Setup: **GLASS**

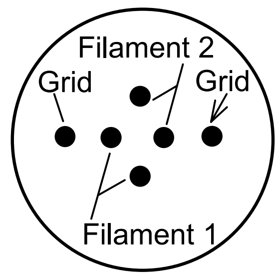


Figure B-2
Glass Tubulated Gauge
Dual Tungsten filaments
IGC100 Cable: **O100C2**
Default Setup: **GLASS**

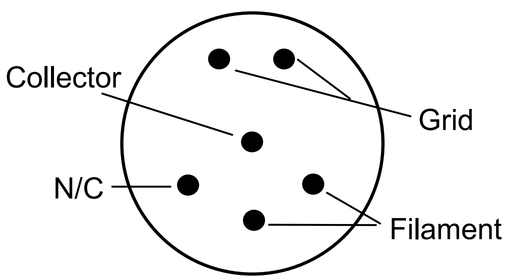


Figure B-3
Nude Gauge
Single ThO_2/Ir filament
Bi-filar helical anode grid
IGC100 Cable: **O100C3**
Default Setup: **NUDE**

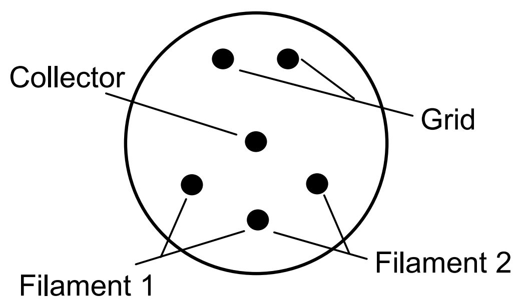
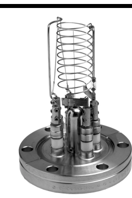
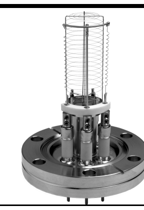


Figure B-4
Nude Gauge-UHV
Dual ThO_2/Ir or W filaments
Closed end anode grid cage
IGC100 Cable: **O100C3**
Default Setup**: NUDE-UHV**

Specifications of SRS Bayard-Alpert Ionization Gauges

	Glass Tubulated	Nude	Nude –UHV
Physical Data			
Appearance			
Connection	Side Tube or 2.75 in. Conflat® Flange	2.75 in. CF Flange	2.75 in. CF Flange
Side Tube diameter	0.75 in. (19.1 mm) or 1 in. (25.4 mm)	N.A.	N.A
Side tube material	Pyrex or Kovar[1]	N.A.	N.A.
Envelope	Nonex 7720 Glass, 2.25 in. dia. (57 mm) x 5.25 in. (133 mm) long	Nude	Nude
Mounting Position	Any, vertical preferred[2]	Any	
Collector	Tungsten, 0.005 in. diameter		
Filament	Single[6] ThO_2/Ir or dual tungsten	Single[6] ThO_2/Ir Replaceable.	Dual ThO_2/Ir or dual tungsten. Replaceable
Grid	Tungsten, bi-filar helix configuration	Tungsten, bi-filar helix configuration	Tantalum and Pt/Moly support, closed end ("squirrel cage").
Overall Length, max	6.0 in. (152 mm)	4.13 in. (105 mm)	
Insertion Length, max.	N.A.	3.30 in. (84 mm)	3.00 in. (76 mm)
Operating Data			
Operating Pressure	$2x10^{-10}$ to 10^{-3}Torr	$4x10^{-10}$ to 10^{-3}Torr	$2x10^{-11}$ to 10^{-3}Torr
Sensitivity for N2, nominal	10/Torr	10/Torr	25/Torr
X-ray limit	$2x10^{-10}$Torr	$4x10^{-10}$Torr	$2x10^{-11}$Torr
Electron Bombardment Degas, Power @500V	70 Watts, nominal 100 Watts, max	70 Watts, nominal 100 Watts, max	40 Watts, max
Resistance Heated Degas	6.3 to 7.5 volts @ 10 amps	6.3 to 7.5 volts @ 10 amps	N.A.
Bakeout Temperature	250º C	450º C	450º C
Electrical Operating Parameters[3]			
Anode Grid Bias Voltage	180 V dc		
Collector Bias Voltage	0 V dc		
Filament Bias Voltage	30 V dc		
Emission Current (nom)	10 mA	10 mA	4 mA
Filament Supply Current	4 to 6 amps		
Filament supply Voltage	3 to 5 Volts		
SRS Cable # [4]	O100C1 – one filament O100C2-dual filament	O100C3	O100C3
Default Setup File[5]	GLASS	NUDE	NUDE-UHV

Notes

[1] Glass-to-metal transition.

[2] Vertical orientation provides strain relief for electrode structures increasing long term stability performance.

[3] Direct current (dc) bias and supply voltages are recommended for all electrical connections.

[4] O100C3 cable is compatible with all Bayard Alpert Gauges in this table.

[5] Default Setup files are factory pre-loaded in the IGC100 controller and facilitate controller setup.

[6] Single filaments are hair pin shaped and spring loaded to eliminate sagging.

Appendix C

Using the IGC100 with STABIL-ION® Gauges

The IGC100 controller is compatible with STABIL-ION® gauges - model numbers 360120, 370120 and 370121- manufactured by Granville-Phillips, Helix Technology Corp (Longmont, CO, www.granville.com).

This short note discusses the wiring details, parts and gauge setup parameters required to connect and operate a STABIL-ION® gauge with an IGC100 controller.

The data included in this note is based on information available directly from Granville-Phillips[1], as well as SRS's own experience with STABIL-ION® gauges. For further information, please contact our application engineers at (408) 744-9040 or e-mail to info@thinkSRS.com.

In This Appendix

Compatibility

The ION GAUGE connector (female), located on the back panel of the IGC100, is pin-compatible with the connector (male) found on all STABIL-ION® Gauge cables manufactured by Granville-Phillips – model numbers 360112 through 360117.

1. Purchase the STABIL-ION® cable directly from Granville-Phillips[2]. For the best fit[3], choose from cable part numbers 360112 (3 m), 360114 (8m) or 360116 (user selectable length).
2. Connect the cable to the gauge and to the controller following the standard gauge connection procedure.
3. Adjust the gauge setup parameters according to the directions below.

See 'Getting Started' Chapter 1 for more complete details about connecting and configuring ionization gauges.

Gauge Setup Parameters

The IGC100 gauge setup parameters must be properly adjusted to obtain accurate pressure readings with STABIL-ION® gauges.

Select N_2 Sense Factor as the IG Cal Source for all STABIL-ION® models. The rest of the parameters are model dependent.

Tip

Default setup files are available and are based on the gauge manufacturer's recommendations.

Select 'Normal' for the Gauge Protection mode for all STABIL-ION® models.

The adjustments required for pressure measurement accuracy are:

1. IG Calibration Source.
   Select N_2 Sense Factor for all STABIL-ION® models. The rest of the parameters are model dependent.
2. N_2 Sensitivity Factor
3. Emission Current
4. Degas Power
5. Degas Time
6. Overpressure threshold.

STABIL-ION® models 360120 and 370120

These two gauge models are identical and share the same parameters.

Degas Power: 40 W
Degas Time: 10 minutes
Gauge Protection: Normal

Adjust the remaining settings depending on the vacuum system pressure range:

Pressure Range	Emission Current	N2 Sensitivity Factor	Overpressure Threshold	Default Setup File
($5x10^{-8}$ – $5x10^{-3}$ Torr) Use for P >10^{-4} Torr	0.1 mA	46/Torr	$2x10^{-2}$ Torr	Stabil-H
($2x10^{-10}$ – $5x10^{-4}$ Torr) Use for P < 10^{-7} Torr	4 mA	42/Torr	$1x10^{-3}$ Torr	Stabil-L

Use either setup for pressures between 10^{-7} and 10^{-4} Torr.

STABIL-ION® model 370121 (UHV-version)

Degas Power: 25 W
Degas Time: 10 minutes
Gauge Protection: Normal

Pressure Range	Emission Current	N2 Sensitivity Factor	Overpressure Threshold	Default Setup File
$5x10^{-11}$ to $2x10^{-5}$ Torr	4 mA	21/Torr	10^{-4} Torr	Stabil-UHV

Note

In the UHV version, the 0.040" diameter collector of the standard STABIL-ION® gauge is replaced with a 0.005" diameter ion collector. As a result, gauge sensitivity is lower, linearity range is reduced, and long term reproducibility is not as good[4].

DEGAS

The degas power may be set at a maximum of 40 Watts for models 360120 and 370120 and 25W for 370121 (UHV-version). Recommended degas times are 10 to 20 minutes. Degas powers higher than the recommended maximum can cause damaging pressure bursts in the vacuum system, and compromise filament lifetime. They can also have an effect on the long-term stability of the gauges.

Note

The IGC100 will not begin a degas process if the pressure at the gauge is above $5x10^{-5}$ Torr. A rough pressure indication is displayed during the degas process. The degas power is controlled during the entire process to minimize pressure bursts above $5x10^{-5}$ Torr.

Final Comments

Until the recent introduction of the IGC100, operation of STABIL-ION® gauges required the use of dedicated Granville-Phillips controllers (models 360 and 370) to fully enjoy accurate pressure readings. The IGC100 is a high quality instrument, built with all the electrical specifications required to control high accuracy Bayard-Alpert gauges, while at the same time providing powerful new features and significant cost savings. STABIL-ION® users looking for a gauge controller upgrade should seriously consider the IGC100 as a cost-effective and more powerful alternative to the previously available instruments.

Important!

No independent studies confirming the high accuracy and long-term stability specifications claimed by Granville-Phillips for their STABIL-ION® gauges[5] have been reported to date. Stanford Research Systems has used STABIL-ION® gauges in several applications, but no systematic study of their accuracy and long-term performance has been conducted. STABIL-ION® users should contact Granville-Phillips directly for gauge accuracy information. Long term studies and systematic comparisons against standard Bayard-Alpert designs[6] will be required to confirm the utility of these new gauges and justify their premium cost.

References

[1] Application Bulletin #360173, Granville-Phillips, Helix Technology Corporation, www.granville.com, 1996.

[2] Contact Granville-Phillips at: www.granville.com.

[3] Cables with part numbers 360113, 360115 and 360117 are also compatible with the IGC100 box but have an unnecessarily long collector current cable.

[4] P. C. Arnold, et. al. , "Stable and reproducible Bayard-Alpert ionization gauge", J. Vac. Sci. Technol. A 12 (2) (1994) 580. See Test Results section in p. 583 for details on the UHV version STABIL-ION® gauge.

[5] P. C. Arnold and S.C. Borichevsky, "Nonstable behavior of widely used ionization gauges", J. Vac. Sci. Technol. A 12(2) (1994) 568; D. G. Bills, "Causes of nonstability and nonreproducibility in widely used Bayard-Alpert ionization gauges", J. Vac. Sci. Technol. A 12 (1994) 574.

[6] C. R. Tilford, A. R. Filippelli and P. J. Abbott, "Comments on the stability of Bayard-Alpert ionization gauges", J. Vac. Sci. Technol. A 13 (2) (1995) 485.

Appendix D

Gas Correction Factors for Bayard-Alpert Ionization Gauges

The sensitivity factor, S_g, supplied by gauge manufacturers (usually in $Torr^{-1}$), *is valid only for the gas for which it is specified* and the readout of the controller provides a direct pressure reading only for that specific gas. The standard gas, used by the entire industry for gauge specification, is *nitrogen* and, unless gas correction factors are applied, all readings are considered to be 'nitrogen-equivalent pressures'.

In This Appendix

Gas Correction Factors

The sensitivity factor, S_g, supplied by gauge manufacturers (usually in $Torr^{-1}$), is only valid for the gas for which it is specified and the pressure readout of a BAG controller provides a direct reading only for that specific gas. The standard gas, used by the entire industry for gauge specification, is *nitrogen* and, unless gas correction factors are applied, all readings are considered to be 'nitrogen-equivalent pressures'.

Nominal *relative sensitivity factors*, R_g, to convert nitrogen-equivalent readings into direct pressure readouts for gases other than nitrogen, are available from most gauge manufacturers and from the public vacuum literature. A summary table and reference list, is included in this appendix. For gases where little or no data are available, it has been shown that a reasonable approximation to the relative sensitivity factor, R_g, can be obtained from the ratio of ionization cross sections at 150 eV of electron energy. Several ionization cross section tables are also available in the scientific literature.

Once the relative sensitivity factor is known, direct pressure readings are calculated from the straightforward mathematical equation:

$$P = [I_c / (S_g \cdot I_e)] \qquad \text{(eqn.1)}$$

where

$S_g = S_{N2} \cdot R_g$

S_g, sensitivity factor for gas 'g' [$Torr^{-1}$]

S_{N2}, sensitivity factor for nitrogen [$Torr^{-1}$]

R_g, gas correction or relative sensitivity factor

I_c , ion collector current [amps]

I_e, electron emission current [amps]

See Appendix A 'Bayard-Alpert Ionization Gauges' for a detailed explanation of gauge sensitivity.

Note

The IGC100 controller stores a nitrogen sensitivity factor, S_{N2} (N2 Sense Factor), and a single relative sensitivity factor, R_g (Gas Correction Factor), for every BAG connected to its back panel. The two parameters are automatically applied to the calculation of pressures according to eqn. 1 when the N_2 Sensitivity Factor is selected as Calibration Source from the Gauge Setup menu.

The Gas Correction Factor is fixed at 1.0 when 'Cal Curve' is selected as the IG Calibration Source.

Nominal Gas Correction Factors for Common Gases

(relative to N_2 = 1.00)

Gas	R_g
He	.18
Ne	.30
D_2	.35
H_2	.46
N_2	**1.00**
Air	1.0
O_2	1.01
CO	1.05
H_2O	1.12
NO	1.15
NH_3	1.23
Ar	1.29
CO_2	1.42
CH_4 (methane)	1.4
Kr	1.94
SF_6	2.2
C_2H_6 (ethane)	2.6
Xe	2.87
Hg	3.64
C_3H_8 (Propane)	4.2

IMPORTANT!

Nominal relative sensitivity factors cannot be relied upon for accurate measurements since they are known to vary significantly between seemingly identical gauges and even more for different gauge types, filament materials, and operating potentials. For general vacuum use, the discrepancy in reported measurements is not greater than 10% for the common gases, rising to a little above 20% for the less common gases, where less accurate information is available. Relative sensitivities are pressure dependent and become particularly unreliable above 10^{-5} Torr. Where greater precision is required, gauges must be calibrated individually against the specific gases and under conditions as close as possible to the operating conditions of the vacuum system.

References

Gas Correction factors

R. L. Summers, "Empirical Observations on the sensitivity of hot cathode ionization type vacuum gauges", NASA Technical Report, NASA-TN-D-5285, published 1969. *Comment: This publication is the industry standard used by BAG manufacturers to specify gas correction factors for their gauges. It includes a fairly complete compilation and review of prior literature numbers.*

R. Holanda, "Sensitivity of hot-cathode ionization vacuum gauges in several gases", NASA Technical Report, NASA-TN-D-6815 E-6759, published 1972. *Comment: Includes calibration data for 12 different gases and 4 different gauges.*

R. Holanda, "Investigation of the Sensitivity of Ionization-Type Vacuum Gauges", J. Vac. Sci. Technol. 10(6) (1973) 1133. *Comment: Demonstrates the good correlation between gas correction factor and ionization cross sections.*

F. Nakao, "Determination of the ionization gauge sensitivity using the relative ionization cross section", Vacuum 25 (1975) 431. *Comment: Includes numbers, compiled from the literature, for 44 different gases including inorganic and hydrocarbon (up to* C_{10}*) compounds.*

J. E. Bartmess and R.M. Georgiadis, "Empirical methods for determination of ionization gauge relative sensitivities for different gases", Vacuum 33(3) (1983) 149. *Comment: Includes data for 74 different gases including various organic compounds. All hydrocarbon numbers of Table I. were extracted from this report.*

C. R. Tilford, "Reliability of high vacuum measurements", J. Vac. Sci. Technol. A 1(2) (1983) 152. *Comment: A must-read paper on BAG readings and the different variables that affect them. Includes correction factors for several gases plotted as a function of pressure and a very useful discussion on the subject.*

T. A. Flaim and P. D. Ownby, "Observations on Bayard-Alpert Ion Gauge Sensitivities to Various Gases", J. Vac. Sci. Technol. 8(5) (1971) 661

M. Schulte, B. Schlosser, and W. Seidel, "Ionization gauge sensitivities of N_2, N_2O, NO, NO_2, NH_3, $CClF_3$ and CH_3OH", Fresenius Journal of Analytical Chemistry, 348(11) (1994) 778

Ionization cross sections

L. J. Kieffer and Gordon H. Dunn, "Electron Impact Ionization Cross section. Data for Atoms, Atomic Ions, and Diatomic Molecules: I. Experimental Data", Reviews of Modern Physics, 38 (1966) 1

Appendix E

Selecting a Bayard-Alpert Ionization Gauge

An immense amount of research and development work, by many talented scientists and engineers, has led to a variety of new Bayard-Alpert Gauge (BAG) designs. In fact, a high vacuum user looking for a new BAG might be surprised, and possibly overwhelmed, by the large number of new commercial options that have become available. Standardization of the BAG design has made it possible for generic ion gauge controllers, such as the IGC100, to control gauges from many different manufacturers.

This appendix provides an overview of the current state of BAG technology to help high vacuum users choose the best hot-cathode ion gauge for their application.

In This Appendix

BAG Designs

This appendix provides an overview of the current state of the BAG technology to help choose the best hot-cathode ion gauge for any application. For detailed information on the principle of operation of BAGs see Appendix A, 'Bayard-Alpert Ionization Gauges'.

Glass Tubulated Gauges

The glass tubulated BAG is the most commonly used gauge design in the world. Glass tubulated gauges are also the most inexpensive BAGs available.

The tubulated gauge has its electrodes surrounded by a glass envelope with a side tube that attaches to the vacuum system. The most common construction materials for the glass envelope are Nonex (an inexpensive glass used in old vacuum tubes) and Pyrex. Most tubulated BAGs are connected to the vacuum system through an O-ring compression fitting. Pyrex is the material selected when the side tube must be glass-blown directly on to the vacuum system. Kovar alloy is the material of choice when metallic tubulation is required for the side port. The thermal expansion coefficient of Kovar matches that of Pyrex producing strong glass-to-metal transitions. Kovar tubulation is sometimes combined with compression fittings, but most often it is welded to Klein or ConFlat® flanges for compatibility with standard vacuum ports. While slightly more expensive, flanged tubulated BAGs offer better vacuum integrity and higher bakeout temperatures than compression fitting options. Side tube diameters are set by standard compression fitting diameters to ½", ¾" and 1" OD. Whenever possible, choose the widest possible bore to assure structural integrity and maximum gas conductance between the vacuum chamber and the BAG ionization region.

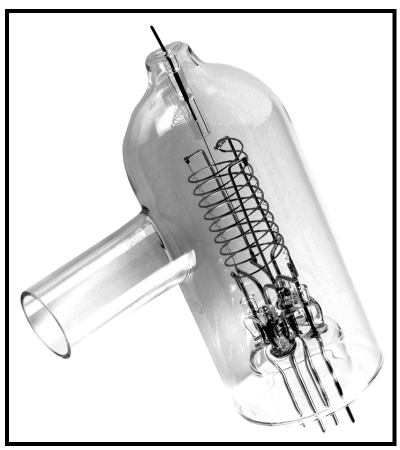


Figure E-1. Glass tubulated Bayard-Alpert ionization gauge, with glass side tube.

All glass tubulated gauges use the same bias voltages and similar emission currents, compatible with IGC100 electrical specifications, and provide pressure readings between 10^{-3} and $\approx 5\times10^{-10}$ Torr (typical X-ray limit). Specification claims beyond this range must be approached with caution!

Typical sensitivity factors fall in the range of 8-10 $Torr^{-1}$. Both I^2R and EB degas are supported by most of these gauges. A typical outgassing procedure includes heating the envelope to 250-400°C for 1 hour followed by a 15 minute degas step.

The repeatability, short and long term stability, and gauge-to-gauge reproducibility of glass tubulated gauges have been the subject of many studies. Several reports show that tubulated BAG users must be careful not to rely blindly on the accuracy of their gauge pressure readings. Gauge-to-gauge sensitivity variations are not unusual for seemingly identical gauges and 25% accuracy at midrange should be considered good for any one gauge, even with new, unused tubes. Long term stability is highly dependent on gauge construction, filament material, operation conditions and environment. Sensitivity changes are usually in the direction of decreased sensitivity. Repeatability in glass tubulated gauges is affected by accumulated electrostatic charge (electrons from the filament) on the glass walls. Several gauge manufacturers offer internal precious metal coatings (Pt) in their BAG tubes. The coating is electrically connected to the filament to reduce electrostatic charge on the glass surface and improve repeatability providing a slight advantage over standard gauges. With uncoated glass, it impossible to control the potential of the internal surfaces, which results in uncontrolled electron and ion trajectories within the gauge and reduced measurement accuracy and repeatability. Long-term stability is affected by changes in the electrode structure, particularly after repeated thermal cycling.

High stability tubulated gauges with spring tensioned (sag-free) filaments and reinforced supports that provide improved measurement stability and accuracy without adding any significant cost are available from Stanford Research .

Glass-tubulated BAGs are fragile and present a safety hazard due to implosion if not adequately shielded. Whenever possible, place them where they cannot be bumped, and be particularly careful during installation. A common problem is crushed side tubes due to excessive tightening of compression fittings. If possible, install the gauge so that the filament is visible during operation. A quick visual check might save a tungsten filament from burnout during a venting or gas loading operation. The preferred mounting orientation is with the filament and anode grid in a vertical position, with the connection pins pointing up, to minimize the electrode distortion caused by gravity pull and thermal cycles.

Tubulated gauges with single and dual filament designs are available. Both tungsten and thoriated-iridium filament materials are offered. Gauges with opposed tungsten filaments have shown better long-term stability (about a factor of two) than gauges with thoriated cathodes. Filaments are not replaceable, making single filament gauges disposable after a burnout (an added cost that must be considered!).

Glass tubulated gauges may be significant sinks of gas molecules and exhibit a certain pumping capacity that is usually time-dependent. This pumping is due to both chemical and electrical effects. The effect usually saturates after approximately three months of operation. The best way to handle gauge pumping is to provide a large conductance connection between the gauge and the vacuum system. A glass envelope gauge with 1" tubulation is recommended for applications requiring pressure measurements down to the 10^{-10} Torr scale, ¾" tubulation is adequate for routine pressure measurements above 10^{-8} Torr.

Glass, when heated, permits permeation of helium from the atmosphere. Remember this effect while leak testing your vacuum system! If helium leak testing with the ion gauge is common practice in your facility, consider an all-metal gauge instead.

BAGs require few electrical connections; however, there is no standard mating socket that will work with all gauge designs. It is the user's responsibility to assure that the correct electrical connections are made at the gauge pins. Wrong connections can cause damage to equipment and may be dangerous for the vacuum system operator. Experienced users can usually identify the different pins by visual inspection; however, the use of pre-wired cables available directly from Stanford Research Systems is recommended to connect BAGs to the IGC100 controller.

Tubulated gauges owe their popularity to their low cost, convenient measurement range, and ease of mounting. Their limited accuracy is more than adequate for most vacuum applications since very often a 'rough' pressure indication (i.e. ±50%) is all that is required by the vacuum operator to characterize the status of a vacuum system.

Broad-Range Glass Tubulated Gauges

Broad-range glass tubulated BAGs are available from many different manufacturers, and under several different trade names. These gauges are designed to operate all the way up to 10^{-1} Torr (with 0.01 mA emission current above 10^{-3} Torr) while still providing a sensitivity factor of 8 Torr^{-1}. They are easily identified because of the narrow grid design (12 mm diameter x 46 mm long), a thoria-coated filament, and a grounded platinum coating on the inside of a reduced diameter (41 mm vs the traditional 57 mm) glass tube. However, they have been shown to be susceptible to large time-dependent instabilities and non-linearities that must be carefully considered during measurements.

In several independent studies, broad-range tubulated gauges have shown large gauge-to-gauge sensitivity variations and non-linearities that make reliable measurements impossible in the absence of individual calibration over the entire pressure range.

Nude Gauges

In nude BAGs the electrodes are not enclosed in a glass envelope. Instead, the electrode structures are welded onto insulating feedthroughs mounted on a vacuum compatible flange (typically a 2.75" ConFlat®), and inserted directly into the vacuum chamber environment. The gas molecules of the vacuum chamber can flow freely into the ionization volume of the gauge thereby eliminating the pressure differential normally associated with tubulated gauges.

The electrode arrangement, biasing voltages and emission current are similar (or identical) to the glass-tubulated BAG and the IGC100 controller can operate both gauge designs without any problems. A cable replacement is usually all that is required to switch from one gauge design to another.

Figure E-2. Nude Bayard-Alpert gauge, with standard electrode design.

Nude BAGs are more expensive than glass-tubulated designs. When connected to a suitable controller, they provide pressure readings between 10^{-3} and $4x10^{-10}$ Torr (typical X-ray limit), with extended UHV versions reaching a $2x10^{-11}$ Torr low limit. Typical sensitivities fall in the range of 8-10 $Torr^{-1}$ for standard gauges and 25 $Torr^{-1}$ for the extended UHV versions. Extended UHV versions are easily identified by the fragile 'squirrel-cage' design (i.e. closed ends) of their anode grid.

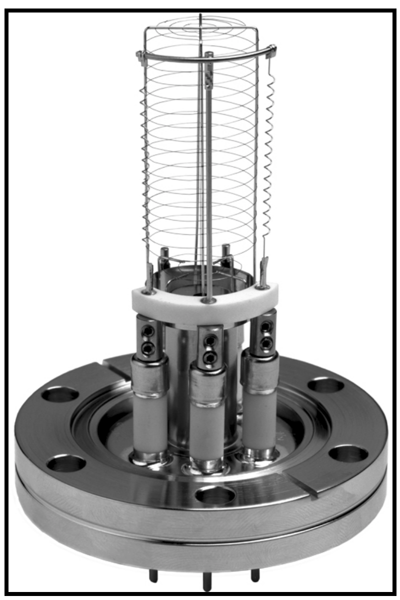


Figure E-3. Nude Bayard-Alpert Gauge, with UHV-extended design.

Gauge-to-gauge reproducibility has been shown to be worse than in tubulated gauges, particularly in UHV versions. Long term stability is comparable to that of tubulated gauges. Overall accuracies better than 30% should not be expected in general. Repeatability is improved in the absence of the insulating glass envelope.

Nude ion gauges are the definitive solution to the gauge pumping problems experienced in tubulated gauges. The unrestricted conductance to the vacuum system also provides faster response to pressure changes in the chamber.

Since the elements are exposed, and easily accessible, most nude ion gauges are designed with replacement filament assemblies. This allows filaments to be replaced after a burnout without having to dispose of the gauge (an important cost saving feature!). Unless a viewport is available, it is generally not possible to see the filament once the gauge is mounted on a port, making the filament more susceptible to accidental and catastrophic overpressures.

With the exception of extended range UHV gauges (EB only), all nude ion gauges provide both EB and I^2R degas options.

The sensitivity of nude ion gauges is affected by the way it is mounted on the system. This effect was recently demonstrated by a careful study, which showed that when the dimensions or shape of the gauge’s metal envelope are changed there can be a dramatic effect (up to 2X) on the absolute magnitude of the gauge’s sensitivity. There may also be a change in the relative dependence of its sensitivity on pressure. If these effects are not taken into account, the accuracy and consistency of the measurements performed with the gauge will be compromised. The envelope must be considered an integral part of the ionization gauge when specifying sensitivity. The practical consequence of these findings is that nude ion gauges must be calibrated in situ, or in an environment that exactly matches the one experienced by the gauge during its measurements.

Nude ions gauges are the choice of many UHV practitioners who appreciate the enhanced vacuum integrity provided by its mounting flange, the unrestricted conductance to the vacuum chamber, the reduced outgassing provided by its minimal surface area, and the higher bakeout temperatures that it can handle. Typical nude gauges can be baked to 450°C without any effect on performance.

Extended UHV gauges provide the most cost-effective alternative for pressure measurements in the low 10^{-10} Torr ranges typically seen in surface science and extreme high vacuum experiments. ThO_2Ir must be the filament material of choice for these applications.

High-Accuracy Gauges

One of the most significant developments in BAG design in recent years has been the introduction of the 'high-accuracy gauge' design. High-accuracy gauges operate based on the same ionization principles as nude and tubulated gauges; however, they provide highly accurate, reproducible and stable pressure readings by systematically avoiding the known problems associated with those gauge designs.

At the time of this writing, high-accuracy gauges are only available from one commercial source and the IGC100 controller is compatible with all available models (consult Appendix C). It is very likely that as a market is established, and the utility of the new design is demonstrated, other vacuum gauge manufacturers will follow with similar offers.

The long-term stability, accuracy and gauge-to-gauge reproducibility of pressure measurements in high-accuracy gauges are assured by the unique design and precise manufacturing applied to their construction.

In the commercially available design, dual, independent, thoria-coated, ribbon filaments are carefully positioned relative to the anode axis and maintained in tension by refractory metal springs. Consequently, the filaments exhibit negligible bow, sag or twist with use, assuring stable and reproducible electron trajectories over time. Partial end-caps are employed to extend the radial electric field over a much larger area of the anode grid, while at the same time, short filaments are used to introduce electrons away from the end regions of the anode, assuring stable ion production conditions within the ionizer. The end-capped anode is precision assembled and stress-relieved so that it maintains its exact shape and position even after high temperature degassing. Electrode positions relative to the walls are identical from gauge to gauge to ensure reproducibility of measurements. A grounded conductive shield completely surrounds the anode-cathode structure to provide a stable electrical environment for charged particle trajectories. The entire shield is designed to remain dimensionally stable over time and to have the same dimension from gauge to gauge within close tolerances. A grounded perforated high conductance shield over the port electrically isolates the electrode structures from the rest of the vacuum system.

Note

It must be noted at this point that the gauge-to-gauge reproducibility and long-term stability claims associated with high accuracy gauges have not been verified by any independent vacuum calibration laboratory. The only experiments performed and data published on these gauges come directly from the manufacturer. SRS has not directly verified any of their claims.

Two different collector wire diameters, 0.005" and 0.040", are used. The thicker collector wire, precisely located at the anode axis, is so effective at collecting ions (≈50 $Torr^{-1}$ nominal sensitivity) that it extends the upper pressure limit to 10^{-2} Torr while keeping the X-ray limit at mid-10^{-10} Torr. The thinner collector wire, while providing a lower sensitivity (≈ 25 $Torr^{-1}$), extends the X-ray limit into the low 10^{-11} Torr range for performance compatible with ultra- and extreme-high vacuum applications.

The premise is simple - high-accuracy gauges provide long-term, stable, accurate, gauge-to-gauge reproducible measurements in a way that is unmatched by any other BAG design. Current state-of-the art midrange accuracy specifications for uncalibrated gauges are ≈6%, and they get better for individually calibrated gauges. However, this increased performance comes at a price! High-accuracy gauges are expensive, costing up to 10 times as much as a glass tubulated gauge.

High-accuracy gauges are stable and reproducible enough, that it makes sense for their controllers to store gauge specific sensitivity data. In fact, it is possible to perform NIST traceable calibrations on individual gauges and store their calibration information in the IGC100 controller memory. Stored values of gauge sensitivity track the actual gauge sensitivity across the entire pressure range, providing real time correction for the non-linearities that lead to errors in traditional gauge systems. Individually calibrated high-accuracy gauges offer midrange reading accuracies better than 3% (close to spinning rotor gauge performance).

High-accuracy gauges make a lot of sense in strictly controlled vacuum process environments where pressure reading inaccuracies can lead to reduced yields and increased production costs. The gauge-to-gauge reproducibility is a welcome feature when forced to switch to a new gauge before trying to reproduce a production run. Calibrated high-accuracy gauges are also cost-effective NIST traceable transfer standards, providing accuracies comparable to spinning rotor gauges over a larger pressure range. It is common practice for pressure calibration laboratories to use high-accuracy gauges as transfer, check and working standards.

Tiny Gauges

Miniaturization has not escaped BAG designs. Almost every vacuum gauge manufacturer now offers a version of 'tiny' ionization gauge. The principle of operation remains the same, the advantages and disadvantages must be considered carefully.

Their goal is clear - replace the unreliable and fragile glass envelope gauges with much smaller and rugged designs without any compromises in performance and specifications.

The new tiny gauges accomplish most of that. They are small, occupying as little as 5% of the volume of a traditional glass envelope gauge. They eliminate glass gauge accidents by relying in all-metal construction. They offer an operational range that overlaps or sometimes exceeds that of traditional tubulated designs. The reduced size also minimizes the power requirements of the filament resulting in less heat being dissipated into the vacuum chamber.

No independent reports on the repeatability, short and long term stability, and gauge-to-gauge reproducibility of tiny gauges are currently available since the gauges have only been recently introduced into the market. However, it is probably fair to estimate that their accuracy specifications will be comparable to those of tubulated ion gauges.

Tiny gauges are more expensive than tubulated designs (up to 4 times). Tiny gauges are usually only available with thoria (burn-out resistant) filaments. Filaments are not replaceable, making the gauges disposable after filament failure. Both flanged and tubular mounting options are available.

Tiny gauges are a perfect match for applications requiring a small rugged gauge, with low power dissipation. They are often found as hidden components of portable systems including mass spectrometers, leak detectors, small sputtering systems, etc. It is possible that all-metal tiny gauges will some day become preferred over traditional glass tubulated gauges. However, in the meantime, traditional designs still offer a significant price advantage that cannot be easily overlooked. An advantage of glass envelope gauges, rarely mentioned by tiny gauge marketers, is that their use is so widespread that it is possible that your facility, or your next door neighbor, will have a spare on a shelf when you desperately need one in the middle of an experiment.

Appendix F

SRS Bayard-Alpert Gauge Calibration Service

Stanford Research Systems has established a High Vacuum Calibration Facility to generate high-accuracy, NIST-traceable, full-range calibrations for any BAG operated with an SRS IGC100 controller. Two accuracy levels are available: a 6% accuracy full-range calibration and a high-precision 3% accuracy full-range calibration.

All calibration information generated at the SRS High Vacuum Calibration Facility is returned to the user in a 'memory card' that can be used to transfer the calibration data, including all necessary instrument setup information, into any IGC100 controller. With the calibration data transferred into the controller, any IGC100 can accurately measure and display unknown pressures in real time over the entire useful range of the BAG.

In This Appendix

Introduction

The calculation of pressure with a Bayard-Alpert gauge (BAG) relies on the knowledge of the gauge sensitivity factor, S_g, which is strongly dependent on (1) gauge geometry, (2) gas type and, to a lesser extent, (3) pressure and (4) emission current[1]. Once the sensitivity factor is known, the pressure, P, is calculated from the simple mathematical expression:

$$P = [I_c / (S_g \cdot I_e)] \qquad \text{(eqn. 1)}$$

where

S_g is the sensitivity factor for gas g [$Torr^{-1}$]

I_c is the ion collector current [amps]

I_e is the electron emission current [amps]

Sensitivity Factor

A common approximation, used by most ion gauge controllers, is to treat the gauge sensitivity factor as a constant, independent of pressure and electron emission current. A single sensitivity value, known as the sensitivity constant, is used to calculate and display pressures over the entire operating range of the BAG while ignoring pressure-induced non-linearities in the gauge response.

The sensitivity value stored in most controllers is the 'nominal' sensitivity constant, as specified by the manufacturer, for the specific gauge model connected to the controller. Nominal sensitivity constants are statistical averages calculated at mid-range ($\approx 10^{-6}$ Torr, typical) for nitrogen gas. Unfortunately, relaxed manufacturing tolerances cause large spreads of individual gauge sensitivities around their nominal value - i.e. no two commercial tubes have close to the same actual sensitivity even if they seem identical to the eye. As a result, only 'rough' pressure measurements can be obtained when nominal sensitivity constants are applied to pressure calculations.

Gauge-to-gauge variation in sensitivity constants is the biggest source of errors in ionization gauge pressure measurements. In order to avoid this source of error, the sensitivity constant for the *individual*, *specific gauge* connected to the controller must be known or obtained. A simple approach, used by some high vacuum practitioners, is to calibrate the gauge response at mid-range against a certified pressure standard and store the calibrated sensitivity constant in the controller. Alternatively, high-accuracy gauges with improved gauge-to-gauge reproducibility and well-known mid-range (nominal) sensitivity constants have recently become commercially available. Calibrated sensitivity constants can provide accurate results only at pressures below the upper limit of linear response. For most commercially available gauges, this upper limit is dependent on the gauge design and starts at $\approx 10^{-5}$ Torr.

In addition to gauge-to-gauge variations and pressure dependent non-linearities, BAG measurements are also affected by several aging mechanisms responsible for changes in gauge sensitivity with operating time. Aging mechanisms affect the long term stability, accuracy and reproducibility of BAG pressure readings.

Full-range calibration

Full-range calibration of the BAG response, over the entire useful pressure range of the gauge, is the only sure way to effectively, and simultaneously, eliminate reading errors caused by (1) gauge-to-gauge variations, (2) pressure non-linearities and (3) aging-related instabilities. Full-range calibration is generated by comparison of the gauge response against a certified primary or transfer standard at many points spanning the entire useful pressure range. Typical transfer standards are NIST-traceable (1) spinning rotor gauges (SRGs) or (2) high-accuracy BAGs. The gas-dependent full-range calibration is often represented as a collection of sensitivity factors calculated at representative values of standard pressure at a known emission current. The IGC100 can store full-range calibration curves in its memory and use them for accurate, real time, pressure determinations across the entire useful pressure range of the gauge. Most other commercial controllers require the user to correct the displayed pressure readings outside the box, based on the manual interpolation of pressure-dependent correction factors derived from the full-scale calibration data.

The effect of pressure on gauge sensitivity has generally been ignored because its contribution to pressure measurement errors is small compared to the inaccuracies and instabilities caused by the electronics of conventional ion gauge controllers. This is also the reason why most calibration facilities require that the specific controller used for the actual measurements, be connected to the gauge during calibration. However, the BAG technology is rapidly evolving. High-quality controllers, such as the IGC100, can now provide stable and reproducible bias voltages, emission currents and electrometer readings that do not contribute to pressure display errors. The improved performance of these modern instruments, makes the presence of the specific controller unnecessary during the BAG calibration procedure.

The typical long term stability for the readings of a conventional BAG (as quoted by most High Vacuum Calibration Facilities) is between 1% and 6% per 1000 hours of accumulated operating time, but is strongly dependent on (1) operating environment, (2) gauge history, (3) gauge design, (4) gauge construction, and (5) filament material[2]. For a carefully treated ion gauge of high quality, a value of 3-6% over a one year period may serve as a reasonable estimate of its instability for this period[3]. The sensitivity value generally declines with time.

Note

High-accuracy gauges, with claims of improved long term stability, have only recently become commercially available[4] and no independent studies on their long term behavior have yet been reported.

Who Needs to Calibrate a BAG?

Different applications require different levels of accuracy. For many applications, the rough results provided by a pressure calculation based on the nominal sensitivity constant are sufficient. Mid-range accuracy: 25% at best, and worse above 10^{-4} Torr.

BAG accuracy can be easily improved by calibrating the mid-range gauge response against a certified transfer standard (i.e. NIST-traceable BAG or SRG) and storing a calibrated sensitivity constant in the controller. Even then, accurate readings are only possible below the upper limit of linear response - typically in the 10^{-5} Torr range. Mid-range accuracy: better than 15% under 10^{-4} Torr, but much worse at higher pressures.

In order to improve the accuracy over the *entire* useful pressure range of the gauge, full-range calibration against a certified pressure standard is required. Gauge sensitivity values calculated at several different reference pressures are then used to calibrate actual gauge response as a function of pressure. Mid-range accuracy: as good as ≈2% if calibration is performed against a primary standard, and ≈3-6% for calibrations performed against NIST-Traceable secondary standards.

Important

The accuracy of BAGs is ultimately limited by their intrinsic short-term repeatability which, for most conventional BAG designs, is between 1% - 2% (based on day-to-day random sensitivity variations).

Typical high vacuum applications requiring the accuracy of full-range calibrations include:

1. ISO 9000 applications requiring standards lab certification.
2. MIL-SPEC type applications requiring MIL-STD-45662A certification.
3. Government contracts requiring standards lab certification.
4. Transfer standards.
5. Process Control applications.
6. Basic vacuum technology research.
7. Scientific and research projects with tight pressure control requirements.
8. Measurement of fundamental physical parameters.

As a rule-of-thumb, accuracies better than 50% over the entire operating range of a BAG can only be assured through full-range calibration.

Every process engineer knows that vacuum conditions significantly affect yield. In the right process application, a calibrated BAG will generally result in increased throughput and yield and will pay for itself very quickly. For example, in semiconductor processing, an overestimated sensitivity constant could lead to high pressures that could then cause serious defects. On the other hand, an underestimated sensitivity constant could make operators waste valuable time while achieving pressures lower than necessary. Both scenarios could be very costly!

Gauge calibration will often provide the lowest total cost-of-ownership (COO), even if the added gauge cost seems hard to justify at first!

A BAG with a specific calibration traceable to a standards lab (i.e. NIST) can provide a convenient in-house reference gauge, ideal for all work requiring certification. It is the only cost effective way to meet ISO 9000 requirements and be compliant with the MIL-STD-45662A standard.

Calibration Storage in the IGC100

The IGC100 controller has the capability to store in a full-range calibration curve and a sensitivity constant (for nitrogen[5]) for each BAG connected to its back panel. An intuitive, front-panel menu selection allows the user to switch between the two calibration sources during pressure measurements.

IGC100 users can have their ionization gauges calibrated at the certified SRS High Vacuum Calibration Facility. The BAG response is calibrated below10^{-3} Torr by comparison against a NIST-traceable secondary standard and the information is stored in a Memory Card (Calibration Card) that is returned to the user with the gauge. The calibration curve, including all relevant instrument setup information, can then be easily transferred into the controller using the Memory Card Module on the front panel of the instrument.

Since all IGC100 instruments offer identical electrical performance, calibrated gauges can be operated from any IGC100 controller without any significant change in the accuracy of the results. For the same reason, the actual IGC100 controller used for real measurements does not need to be present at the SRS High Vacuum Calibration Facility during the calibration procedure.

To obtain the highest degree of accuracy, BAGs must be calibrated directly at a National (or International) Standards Laboratory against a primary high-vacuum pressure standard[6]. The Calibration Report, supplied by the standards laboratory, can be submitted to the SRS High Vacuum Calibration Facility to have the calibration data transferred into a Memory Card compatible with the IGC100 controller. A nominal fee is charged for this procedure. Consult SRS directly for additional information on this alternative calibration option.

Warning

Although BAGs calibrated against primary standards offer the highest measurement accuracy (<2%), the cost of calibration can be excessive for most applications (>$4,000 per tube), and the turn-around time is usually very long. Full-range calibration against a NIST-traceable secondary standard, as provided by the SRS High Vacuum Calibration Facility, offers a very significant cost advantage, very fast response, and sufficient accuracy for most applications.

The IGC100 uses full-range calibration data to display accurate pressure readings in real time without the need for pressure-dependent corrections outside the box. The estimated expiration date for the gauge calibration is stored in the memory card and transferred to the controller along with the rest of the calibration information.

Although in principle it should be possible to calibrate a gauge for one gas and use this calibration for another by simply multiplying by the corresponding gas correction factor, investigations have shown that this is not the case if high accuracy (<10%) is required. Specific calibration for each specific gas is recommended in that case.

SRS High Vacuum Calibration Facility

Stanford Research Systems has established a High Vacuum Calibration Facility to generate high-accuracy, NIST-traceable, full-range calibrations for any BAG operated with an IGC100 controller. Two accuracy levels are available: a 6% accuracy full-range calibration and a high-precision 3% accuracy full-range calibration.

BAGs are calibrated by the direct comparison method in a continuous flow calibration chamber[7] following the recommendations of well-established calibration standards[8] laboratories. During a calibration procedure, the test gauges and a reference gauge (NIST-calibrated secondary standard) are all exposed to a identical pressure environments in a carefully designed high-vacuum chamber[9]. The sensitivity of each test gauge is calculated, at specified pressure values of the reference gauge, using the well-known formula:

$$S = (I_c - I_{c0}) / [I_e \cdot (P - P_0)] \qquad \text{(eqn. 2)}$$

where

P_0 = pressure due to residual gases in the chamber as measured by the reference gauge.

P = pressure due to the residual gases plus the calibration pressure step generated by the gas delivery system, as measured by the reference gauge.

I_c = collector current at pressure P.

I_{c0} = residual collector current at residual pressure P_0.

I_e = emission current measured on the anode.

All calibrations start with a determination of I_{c0} and P_0 at base pressure, following an extensive overnight bakeout (>200°C) of the chamber and test gauges[10]. No return to base pressure takes place throughout the course of the calibration procedure[11].

Full-range calibration requires the determination of sensitivity constants at specified reference pressure set-points between 10^{-7} and 10^{-3} Torr. Three calibration points per decade are obtained over this range. The reference pressure readings must be constant to <0.5% for 5-10 minutes before any measurements can take place at a setpoint. The measurements are performed in a sequence of increasing pressures. The calibration information is represented as a table of calculated sensitivity factors (eqn. 2) vs. measured collector currents[12], in order of increasing reference pressure. Following the standard, the sensitivity factor is assumed a constant below the lowest calibration pressure.

The time required to complete the process, and the accuracy requirements on the test equipment used, depend on the accuracy of the calibration. This is the reason, 6%

accuracy calibrations are more affordable than the high precision (i.e. 3% accuracy) option.

Note

When the sensitivity is calculated according to eqn. 2, the residual current in the BAG caused by outgassing, ESD and X-ray limits is subtracted from the signal. When the gauge is in use, its residual current (or the equivalent pressure reading) must be subtracted from the signal as well to generate accurate results.

The standard calibration gas used at the SRS High Vacuum Calibration Facility is nitrogen. Calibration against other gases is possible by special order only. Consult Stanford Research Systems for details on this service.

All calibration information generated at the SRS High Vacuum Calibration Facility is returned to the user in a Memory Card that can be used to transfer the calibration data, including all necessary instrument setup information, into any IGC100 controller. With the calibration data transferred into the controller, an IGC100 can accurately measure and display pressures in real time over the entire useful range of the BAG. The microprocessor automatically interpolates the calibration data to find the sensitivity factor corresponding to the measured collector current, and uses eqn.1 to calculate and display the resulting pressure.

Since the BAG measures gas density but the sensitivity is defined for pressure, the temperature at which the calibration was performed must always be specified. The mean temperature of the molecules in the chamber is determined by the average temperature of the chamber walls, which is measured at several points with ±0.5°C certainty. Ion gauges are internal heat sources and, depending on their number and configuration, can add uncertainty to the gas temperature value. This effect contributes less than 1% uncertainty to the sensitivity determination even under the worse possible conditions (this does not account for thermal transpiration corrections). It is common practice for calibration facilities to correct and state sensitivity factors for a temperature T_o=23°C. If the sensitivity factor, S, was determined at a temperature T_1, it is expressed as:

$$S(T_o) = S(T_1) \cdot (T_1 / T_o) \qquad \text{(eqn. 3)}$$

Important recommendations to be followed during and after all calibration procedures include:

1. Changes in gauge envelope can result in measurement errors as large as 50% with some BAGs[13]. Thus, the envelope must be considered a proper part of an ionization gauge, and a specification of nude gauge sensitivity is not complete unless the geometry and potential of its envelope are also given. Stanford Research Systems recommends that the calibration and operation of nude ion gauges take place inside a calibration nipple – 38 mm ID x 100 mm long tube with 2.75" CF flanges at both ends and a screen at the input port. Calibration nipples are available directly from Stanford Research Systems. Consult the factory for order part numbers, pricing and availability.

2. Due to the hot cathode, the temperature inside the gauge head (T_{ga}) is higher than the temperature of the chamber (T_{ch}). As a result, gas pressure and particle density are different in the chamber and the gauge head. The difference in temperature depends

on too many factors and cannot be calculated. However, to make the calibration as useful as possible the ratio of temperatures T_{ga}/T_{ch} should be the same during calibration and actual use. This can only be accomplished if the gauge is enclosed in the same way in both cases, and is another reason to calibrate nude gauges inside calibration nipples. Additionally, the emission current (heating power) should not be changed from calibration to use.

3. The orientation of the gauge head should be identical during calibration and use, since geometrical deformations due to different orientations may affect the potential distribution and electron trajectories inside the gauge head.

4. The presence of the specific IGC100 controller used to operate the gauge is not required during gauge calibration procedures performed at the SRS High Vacuum Calibration Facility. However, the presence of the controller is usually required by Primary Laboratory Standards who routinely check the accuracy of the bias voltages and emission current before and after the gauge calibration procedure.

5. Calibrations are gas specific.

6. Gas purities for calibration gases are specified better than 0.1%.

7. Each IGC100 controller is individually tested and calibrated against NIST-traceable test and measurement instrumentation. Certificates of traceability for the controllers are available, free of charge, from Stanford Research Systems.

8. In order to obtain optimum stability, long periods of electron bombardment degas must be avoided. If it must be degassed, the gauge must be allowed to equilibrate for eight or more hours before accurate readings are obtained.

9. After exposure to air, the gauge must be thoroughly baked out at high temperature and allowed to equilibrate for 12-24 hours after bakeout.

Calibration reports are also available for those customers who require for their own records: (1) a complete description of the test procedure, (2) certification of results, including NIST-traceability information, and (3) a complete listing of the data recorded on their gauge

Calibration at a Standards Laboratory

Several laboratories, located throughout the world, offer calibration of ionization gauges against primary high-vacuum standards[14]. Calibration information obtained directly from a primary standards laboratory provides the highest level of measurement accuracy possible - typically better than 2%.

Most primary standards laboratories require the presence of the specific controller, used for actual pressure measurements, during the calibration procedure. The gauge and the controller are regarded as a unit and calibrated together for maximum accuracy of results. The bias voltages and emission current are checked before, and after, the calibration to get an estimate of the accuracy and stability of the controller's electronics.

The calibration procedures followed by most primary standards laboratories are very similar to those used at the SRS High Vacuum Calibration Facility[15]. Reference pressures are generated in carefully characterized vacuum systems consisting of (1) a high accuracy flowmeter (i.e. inlet system) of known throughput, and (2) an orifice-flow chamber, with an aperture of known conductance[16]. Reference pressure values are derived from fundamental quantities such as length, time and mass instead of being measured indirectly with a secondary standard.

The calibration results are summarized in a calibration report . A typical report describes the detailed conditions under which the tests were performed and lists the calibration data as a collection of pressure correction factors, graphed and/or tabulated as a function of the total pressure on the controller's display. When using conventional controllers, corrected pressure values are calculated as a product of the displayed pressure times the correction factor interpolated (usually by hand) from the report's graph or look-up table. This is usually slow and very inconvenient!

Calibration reports, supplied by standards laboratories, can be submitted to the SRS High Vacuum Calibration Facility to have the calibration data transferred into a memory card, compatible with the IGC100 controller. Any IGC100 can then use the calibration data to obtain accurate, real-time pressure readings from the calibrated gauge, without any need for additional correction of the results displayed on the front panel. A nominal fee is charged for this procedure. Consult SRS directly for additional information on this calibration option.

IMPORTANT

For direct transfer of the primary calibration results into a memory card, *IGC100 users must request that all collector currents, measured by the controller at the different pressure setpoints, be added to the calibration report*. A proper report must include (1) ion current, (2) pressure display and (3) derived pressure step values for all available setpoints (including values for all relevant base pressure stops).

Some of the standards laboratories offering Primary High Vacuum Calibration Services are listed in the following table.

Name	Address	Method	Country
National Institute of Standards and Technology[17] (NIST)	Center for Basic Standards National Measurement Laboratory National Institute of Standards and Technology, I-270 at Quince Orchard Road Building 220, Room A55 Gaithersburg, MD 20899-0001	Constant pressure flowmeter	USA
National Physical Laboratory-Teddington[18] (NPL-Teddington)	National Physical Laboratory Teddington, Middlesex TW11 OLW	Series expansion	UK
German Calibration Service (DKD[19]) accredited by PhysiKalisch-Technische Bundesanstalt[20] (PTB)	Physikalisch-Technische Bundesanstalt, Bundesallee 100 D-38116 Braunschweig, Postbox 3345 D-38023 Braunschweig	Constant pressure flowmeter	Germany
National Physical Laboratory-New Delhi (NPL-New Delhi)	National Physical Laboratory, New Delhi-110012	Constant pressure flowmeter and series expansion	India
National Research Council-Canada (NRC Canada)	Institute for National Measurement Standards Montreal Road, Building M-36 Ottawa, Canada K1A 0R6	series expansion	Canada

BEWARE!

Calibration information obtained directly from a primary standards laboratory offers the highest level of accuracy - typically better than 2%. However, the cost of calibration may be prohibitively high (>$4,000), and the response time is usually several months (i.e. fixed yearly calibration schedule). Full-range calibration against a NIST-traceable secondary standard, as provided by the SRS High Vacuum Calibration Facility, offers a very significant cost advantage, very fast response, and an accuracy compatible with most applications.

Important Terms

Calibration Standard
For a calibration device or instrument to qualify as a standard, its measurement performance should be predictable and thoroughly understood, and its random and systematic uncertainties should be well characterized and documented. Only if the above conditions are met can the comparison of the BAG with the standard be called a calibration.

Primary Standard
An instrument where pressure readings are derived from fundamental units such as length, time and mass. This would include measurement of a liquid column height or pressures produced by volume expansion.

Transfer Standard
An instrument that has been calibrated with traceability to a primary standard for the purpose of being used for a local calibration application. Examples of such transfer standards are calibrated high-accuracy BAGs and SRGs.

Secondary Standard
A transfer standard calibrated directly against a primary standard.

Working Standard
A working standard is a calibrated instrument used for routine calibrations of other instruments. For example this can be the transfer standard or a specific BAG.

Check Standard
A check standard is an instrument that may or may not be fully calibrated but which is known to have a stability comparable or better than the device being checked. For example, the check standard can be a specific BAG.

Static Calibration
Refers to producing known pressures by introducing a quantity of gas into the volume to which the gauge to be calibrated and the working standard are connected.

Continuous Flow (Dynamic Expansion) Calibration
Refers to producing equal pressures at the gauge under test and the working standard by establishing a steady-state gas inflow into the calibration chamber against high speed pumping through one or more orifices.

References

[1] C. R. Tilford, "Sensitivity of hot cathode ionization gauges", J. Vac. Sci. Technol. A 3(3) (1985) 546.

[2] C. R. Tilford, A. R. Filippelli, and P. J. Abbot, "Comments on the stability of Bayard-Alpert ionization gages", J. Vac. Sci. Technol. A 13(2) (1995) 485; C. R. Tilford, "Reliability of high vacuum measurements", J. Vac. Sci. Technol. A 1(2) (1983) 152; P. C. Arnold and S. C. Borichevski, "Nonstable behavior of widely used ionization gauges", J. Vac. Sci. Technol. A 12(2) (1994) 574; D. G. Bills, "Causes of nonstability and nonreproducibility in widely used Bayard-Alpert ionization gauges", J. Vac. Sci. Technol. A 12(2) (1994) 574.

[3] A. R. Filippelli and P. J. Abbott, "Long term stability of Bayard-Alpert gauge performance: Results obtained from repeated calibrations against the NIST primary vacuum standard", J. Vac. Sci. Technol. A 13(5) (1995) 2582.

[4] P. C. Arnold, D. G. Bills, M. D. Borenstein and S. C. Borichevsky, "Stable and reproducible Bayard-Alpert ionization gauge", J. Vac. Sci. Technol. A 12(2) (1994) 580.

[5] A gas correction factor is also available to correct the sensitivity factor for gases other than nitrogen.

[6] Peter Nash, "The use of hot filament ionization gauges", Vacuum 37(1987) 643. See section 7.8. titled "Calibration" on page 648.

[7] W. Steckelmacher, "The calibration of vacuum gauges", Vacuum 37(1987) 651. This is an excellent review paper on gauge calibration, including all known standards documents as of 1987.

[8] "Standard Method for Vacuum Gauge Calibration by Direct Comparison with a Reference Vacuum Gauge", DIN 28418, Beuth Verlag, Berlin, 1976. Note: other standards have been developed but none of them made it to an official state. See for example, "Calibration by Direct Comparison with a Reference gauge", ISO/DIN 3567 draft, and related ISO 3568 (calibration of ion gauges by comparison) and 5300 (calibration of thermal conductivity gauges by comparison).

[9] The vacuum system is designed following all the recommendations found in: J. M. Lafferty, "Foundations of Vacuum Science and technology", Wiley-Interscience, 1998, section 12.2. "Calibration by the comparison method", p. 673. Note; this chapter of the book was written by Karl Jousten a prominent metrologist at PhysiKalisch-Technische Bundesanstalt, Berlin, Germany, and is required reading for anybody involved in BAG calibrations.

[10] The base pressure in the chamber must be less than 2% of the lowest calibration pressure before a gauge calibration procedure can proceed.

[11] Sharrill Dittmann, "NIST High Vacuum Standard and its use", NIST Special Publication 250-34 (1988). This document describes NIST’s BAG calibration procedure in detail, and shows that no return to base pressure takes place during the primary standard calibrations. Base pressure is only established once daily in that lab.

[12] All measured collector currents included in the table are background corrected to eliminate all residual (i.e. calibration gas unrelated) contributions.

[13] Albert Filippelli, "Influence of envelope geometry on the sensitivity of "nude" ionization gauges", J. Vac. Sci. Technol. A 14(5) (1996) 2953.

[14] K. Jousten, et. al. "Comparison of the standards for high and ultrahigh vacuum at three national standards laboratories", J. Vac. Sci. Technol. A 15(4) (1997) 2395. This is a useful comparison between calibration results from three different international facilities.

[15] Sharrill Dittmann, "High Vacuum Standard and its use", NIST Special Publication, 250-34, National Institute of Standards and Technology, Gaithersburgh, Maryland.

[16] P. D. Levine and J. R. Sweda, "Development of a primary standard ultrahigh vacuum calibration station", J. Vac. Sci. Technol. A 12(4) (1994) 1727. See also: : J. M. Lafferty, "Foundations of Vacuum Science and technology", Wiley-Interscience, 1998, p. 668.

[17] C. R. Tilford, S. Dittmann and K. E. McCulloh, "The National Bureau of Standards primary high-vacuum standard", J. Vac. Sci. Technol. A 6(5) (1988) 2853.

[18] K. W. T. Elliott, D. M. Woodman and R. S. Dadson, Vacuum 17 (1967) 439. This describes part of an earlier implementation of the standard.

[19] The DKD comprises calibration laboratories in industrial firms, research institutes, technical authorities, inspection and testing institutes. They are accredited and supervised by the Physikalisch-Technische Bundesanstalt (PTB). They calibrate measuring instruments within the framework of the PTB accreditation. The DKD Calibration Certificates issued by these laboratories prove traceability to national standards as required in the ISO 9000 and EN 45 000 series of European standards.

[20] G. Grosse and G. Messer, Vacuum 20 (1970) 373; K. Jousten and G. Rupschus, Vacuum 44 (1993) 569; K. Jousten, G. Messer and D. Wandrey , Vacuum 44 (1993) 135.

Appendix G

Hot vs. Cold Ionization Gauges

Every modern high vacuum and ultrahigh vacuum system relies on some form of ionization gauge for pressure measurements under 10^{-3} Torr. There are currently two competing ionization gauge technologies to choose from - the hot cathode gauge (HCG) and the cold cathode gauge (CCG). This appendix is designed to help vacuum users choose between the two competing ionization technologies. Each gauge type has its own advantages and disadvantages. The best choice requires careful consideration of the operating characteristics of both gauges and is dependent on the application.

In This Appendix

Introduction

Every modern high vacuum and ultrahigh vacuum system relies on some form of ionization gauge for pressure measurements under 10^{-3} Torr. There are currently two competing ionization gauge technologies to choose from which are viable means for pressure measurements between 10^{-2} and 10^{-10} Torr:

1. In the hot cathode gauge (HCG) ionizing electrons from a thermionic cathode are accelerated by suitable electrodes into an ionizing space.

2. In the cold cathode gauge (CCG) ionization is caused by a circulating electron plasma trapped in crossed electric and magnetic fields.

In both cases, the electrical current resulting from the collection of the positive ions created inside the gauge is used as an indirect measure of gas density and pressure.

This appendix is designed to help vacuum users choose between the two competing ionization technologies. Each gauge type has its own advantages and disadvantages. The best choice requires careful consideration of the operating characteristics of both gauges and is dependent on the application.

For more detailed information on this subject consult the following publications:

1. J. M. Lafferty, Ed., "Foundations of Vacuum Science and Technology", p. 414, section 6.9., John Wiley and Sons, NY, 1998. Note: This is an excellent book recommended for any high vacuum question.

2. R. N. Peacock, N. T. Preacock, and D. S. Hauschulz, "Comparison of hot cathode and cold cathode ionization gauges", J. Vac. Sci. Technol. A 9(3) (1991) 1977.

3. R. F. Kendall, "Cold cathode gauges for ultrahigh vacuum measurements", J. Vac. Sci. Technol. A 15(3) (1997) 740.

4. R. F. Kendall, "Ionization Gauge Errors at Low Pressures", J. Vac. Sci. Technol. A 17(4) (1999) 2041. Note: Great paper that compares the performance of both gauges, particularly at low pressures.

5. Vic. Comello, "Should your next ion gauge run hot or cold?", R&D Magazine, p. 65, Nov. 1997.

6. Eric Bopp, "Pressure measurement in ion implanters", Solid State Technology, February 2000, p. 51. Note: The special gauging requirements of ion implant applications are nicely discussed in this article.

7. J. H. Singleton, "Practical Guide to the use of Bayard-Alpert Ionization Gauges", J. Vac. Sci. Technol. A 19(4) (2001) 1712.

Hot-Cathode Gauges (HCG)

The majority of commercially available HCGs are of the Bayard-Alpert design and are compatible with the IGC100 controller.

A Bayard-Alpert gauge (BAG) boils electrons from a hot filament and accelerates them toward a cylindrical grid cage. As the electrons traverse the space enclosed by the grid, which is fully open to the vacuum chamber, they collide with gas molecules ionizing some of them. A fine wire located at the center of the ionization volume collects the resulting cations producing a current proportional to the gas density at the gauge. At constant temperature, the collector current is linearly related to the gas pressure.

The useful operating range of a conventional BAG extends between 10^{-3} and 10^{-10} Torr, corresponding to an impressive seven decades of dynamic range. Special gauge designs are available to extend the lower limit to 10^{-11} Torr for UHV applications, or the upper end to 10^{-1} Torr for process applications.

The strict linear dependence of collector current on pressure is one of the most important advantages of HCGs over the competing ionization technology. It is generally possible to approximate the 'collector current vs. pressure' response of a BAG to a straight line and calculate pressures from a single linear proportionality factor (i.e. sensitivity factor) stored in the gauge controller. A sensitivity factor calibrated at mid-range, can be used for accurate and reproducible pressure measurements between 10^{-9} and 10^{-4} Torr. Deviations from linearity typically amount to less than ±25% over the entire useful dynamic range of the gauge, with the biggest deviations taking place at the operating limits.

BAGs are generally considered to be more accurate, stable and reproducible than CCGs. Under controlled vacuum conditions, the reproducibility of a BAG calibration can be as good as 2% through a year of uninterrupted operation. Repeatability is 1-2%, limited by uncontrollable random sensitivity variations. However, not all BAGs are created equal and gauge-to-gauge and long-term stability variations are to be expected from commercial devices used in 'real' systems. Measurement accuracies better than ±50% require calibration of the individual gauge response. High accuracy gauge designs have recently become available that guarantee better than 3% measurement accuracy following calibration against NIST standards. Calibrated, high-accuracy BAGs combined with high quality controllers, such as the IGC100, are commonly used as transfer standards in high vacuum gauge calibration laboratories.

BAG readings are gas dependent due to varying ionization efficiencies, and are usually calibrated for nitrogen gas (argon is also a popular choice in semiconductor processing). Gas correction factors, readily available from the vacuum literature, can be used to correct the gauge readings for other gases.

Any BAG, depending on its past history of operation and the precise atmosphere in the vacuum system, can act as either a source (outgassing) or sink (pumping) of gas. Its operation can cause significant changes to the gas composition in the system. The relative importance of these effects depends upon the overall vacuum system characteristics and operating conditions. For example, changes in pressure and gas composition due to pumping or outgassing will be relatively more significant in a small UHV system with low pumping speed, than in a large industrial vacuum chamber with large diffusion pumps. Similarly, any pressure gradient between the gauge and the main chamber will depend upon the conductance of the tube connecting the two, and will be zero when the gauge is inserted directly into the chamber (i.e. nude BAG).

The power requirement of a typical filament for 1 mA emission is between 10 and 15 W. This is enough to cause thermal degassing from the gauge elements and surroundings that affect the reliability of low pressure measurements. It is possible for gas composition and pressure in even a large vacuum system to be dominated by gases released from a single HCG and its immediate surroundings when such a gauge is not properly degassed.

HCGs encounter most of their problems at $\approx 10^{-10}$ Torr where the X-ray limit, electron stimulated desorption (ESD) and outgassing set a limit on the usefulness of the gauge. Degassing and bakeout of the gauge can minimize the effects of ESD and outgassing. The ultimate accuracy of a BAG may be seriously compromised in the absence of a bakeout and/or degassing. The X-ray limit provides a residual collector current comparable to the ion signal from 10^{-10} Torr of gas in conventional gauges. Special nude gauge designs, with reduced collector and grid wire diameters and closed-end grids, are required to reduce the magnitude of that residual current into the 10^{-11} Torr level.

Reactions of the gas molecules with the hot filament can seriously affect the composition of the gas, and the reliability of the pressure measurements, in a BAG. This effect must also be accounted for in high accuracy measurements at low pressures.

Gas permeation through the glass envelope, particularly of He and other light gases, must be considered in UHV systems at base pressure, and provides another good reason to use all-metal gauges in those applications.

The operating life of a HCG is frequently determined by the filament lifetime. This is, by far, the main reason why high vacuum users choose 'filament-free' Cold-Cathode Gauges (CCGs) over BAGs. However, unless damaged by ion bombardment, high pressure operation or chemical effects, filament lifetimes can be many thousands of hours, thus filament life is not an important consideration in most cases. This is especially true with ThO_2Ir filaments and when smart controllers, such as the IGC100, which protect the gauge from overpressures.

There is always a delay between turning on a HCG and obtaining a meaningful reading. It is necessary to wait for thermal equilibrium of the gauge and its surroundings. Depending on the pressure to be measured, and the history of the gauge, stabilization can last from minutes to weeks, and might require bakeout and/or degassing to reach completion.

A good quality controller, such as the IGC100, must always be part of a BAG measuring system. Controllers have been known to add as much as ±15% inaccuracies to BAG readings. The electronics required to run a BAG are generally (1) more complicated, (2) require more power, and (3) are bigger in size than those required to operate CCGs.

BAGs have safety hazards associated to them that must be considered during gauge selection and operation. Glass envelope gauges can break and/or implode violently resulting in the danger of flying glass. Gauge walls can get hot and cause burns. The risk of electrical shock is always present and can be deadly in some cases. All these risks are easily eliminated by proper system design, including glass shields, suitable connector cables and good grounds.

Cold-Cathode Gauges (CCG)

Several varieties of CCGs are used for vacuum measurements including the Penning, the magnetron, the inverted magnetron and the double inverted magnetron.

All CCGs utilize crossed electric and magnetic fields to trap electrons. The high voltage ranges from 2-6 kV and the magnetic field 1-2 kG. The electron plasma, responsible for ionization, originates from the random release of an electron at the cathode caused directly, or indirectly, by a cosmic ray, field emission, a photon, radioactivity or some other event. A discharge slowly builds inside the ionization volume to the point where the entry of new electrons into the plasma is limited by space charge repulsion. At pressures below 10^{-4} Torr, the discharge is practically a pure-electron plasma. The electrons move in cycloidal jumps, circling about the anode, and during part of each jump they have sufficient energy to ionize gas molecules through electron impact ionization. The probability of collision is proportional to the gas density. The slow ions generated, are quickly captured by the cathode. The current generated by this ion collection process is measured and used as an indirect indication of gas density and pressure.

The typical operating range of a CCG is between 10^{-2} and 10^{-9} Torr. With very special precautions, the lower end has been extended into the 10^{-11} Torr for some special gauges, but only with marginal accuracy. Claims that commercially available CCGs will measure total pressures below 10^{-9} Torr should be treated with extreme caution!

The upper pressure limit of the CCG is reached when the current becomes so large that heating and sputtering from the electrodes becomes a problem. This sets a usual limit of 10^{-4} Torr. However, several tricks are commonly implemented to extend the useful upper pressure into the 10^{-2} Torr range. At the other end of the pressure range, CCGs have been used down to 10^{-11} Torr but only under very carefully optimized conditions and with very limited accuracy.

The ion-induced current is not linearly related to the pressure in the chamber. Rather, the relationship is exponential and complicated by the presence of spurious discontinuities in the current vs. pressure characteristic. The number and size of discontinuities depends on gauge design, with the inverted magnetron being the least susceptible to this problem. Gauge-to-gauge variations among seemingly identical gauges are often observed and it is not unusual to observe discontinuities disappear between successive calibrations. Elimination of discontinuities has been a major challenge to designers of CCGs since their conception. The non-linear relationship between current and pressure is a disadvantage that complicates the reliability of pressure measurements, particularly below 10^{-9} Torr. Between 10^{-4} and 10^{-9} Torr the exponent is usually fairly constant, close to 1.0 and hidden from the user by a logarithmic detector or look-up table. Somewhere between 10^{-9} and10^{-10} Torr the exponent often shifts suddenly to higher values (1.25 or higher). This sudden *and spurious* change in exponent requires special precautions to account for the more pronounced logarithmic response, and only marginal accuracy is generally possible below 10^{-9} Torr. No standard method for dealing with currents below the magnetron knee is available as of this writing.

CCG readings are gas dependent and the gas correction factors are *not* the same as for HCGs.

There are few results in the vacuum literature on the accuracy, stability and repeatability of CCGs. In general, CCGs are considered to be less accurate than HCGs and are not recommended as high vacuum transfer standards. Repeatability is about ±5%, and sensor-to-sensor matching is within 20-25% for inverted magnetrons. Manufacturers often specify accuracies within a factor of two for new (and clean) gauges. Whenever higher accuracy is required, the specific tube/controller combination must be calibrated against a transfer standard such as a spinning rotor gauge or high-accuracy BAG. Calibration is more complicated than in HCGs because of the non-linear 'current vs. pressure' response and the presence of discontinuities in the calibration curve. Stable operation appears to be possible over periods of several years under clean, low pressure vacuum conditions. However, contamination can cause failure of a CCG just as a HCG. Pump oil is polymerized by the discharge and forms insulating films on the electrodes. Metal vapors, caused by sputtering, can cause insulator leakage. Most CCGs can be disassembled and serviced by the user in the field to restore them to normal operation when they become contaminated.

CCGs respond very quickly to pumpdowns. In general, they arrive at stable readings faster than HCGs during pressure cyclings between 10^{-3} and 10^{-7} Torr. There is also no filament to burn out. The absence of a hot filament also makes outgassing much less of a problem.

Outgassing rates are typically very much lower and more predictable than for HCGs. Degassing is not necessary since the input power is very low and there is no internal heating to cause localized outgassing. Measured pumping speeds are also low (comparable to those of HCGs) so that pressure measurement errors are generally insignificant, provided adequate tubulation to the vacuum system is provided. Residual currents are not a problem at UHV levels in CCGs which are essentially free of X-ray and ESD effects. In applications requiring frequent pumpdowns to low pressures with little or no opportunity for degassing, the readings of a CCG may be significantly closer to true chamber pressures than HCG readings. CCGs are often preferred over HCGs for critical applications such as material outgassing studies.

Sensitivity to externally produced magnetic fields is typically far lower than for unshielded HCGs and usually not a problem under normal laboratory conditions.

Concerns about stray magnetic fields from modern CCGs are mostly unfounded. Inverted and double inverted magnetron gauges reduce stray field to only a few Gauss. Addition of shielding sleeves further reduces stray fields to levels comparable with background effects in a typical laboratory. Special applications, such as electron microscopes, might still require careful experimentation with the exact location and orientation of the gauge even after shielding is in place.

On the downside, CCGs can be hard to start. The discharge in a CCG does not start (i.e. strike) the moment the high voltage is applied. The 'striking' time varies from gauge to gauge. This delay ranges from seconds at 10^{-6} Torr to hours at 10^{-10} Torr. Auxiliary 'strikers' consisting of (1) edge emitters, (2) radioactive sources or (3) UV lamps are often included in modern gauge designs to reduce this problem greatly. Striking is not a problem if the CCG can be turned on during pumpdown before the pressure reaches 10^{-5} or 10^{-6} Torr. A gauge also starts quickly if charges from any other source of ionization can reach the gauge. Once a CCG strikes, the readings are meaningful within a few seconds, faster than the time it takes a HCG to stabilize after a filament emission is established.

The circulating electron current and energy are determined by the gauge construction and its fixed operating parameters - they cannot be controlled by the user! This is a big difference from the HCG operation where most parameters can, and usually are, accessible to the user from the controller.

The electronics required to operate a CCG are usually much simpler and less expensive than those for HCGs. The CCG controller supplies only the high voltage required, and it measures the current in the same loop. Small permanent magnets are used to set the magnetic field. The amount of current in the high voltage power supply is usually limited to 0.1 mA so that danger of serious electric shock is reduced. It is generally possible to enclose the gauge assembly and low-power (i.e. <1 W) electronics into a package not much bigger in size than a tubulated BAG.

CCGs are usually of all-metal construction, and are not hot to the touch.

Conclusions

HCGs and CCGs are both capable of measuring pressures between 10^{-2} and 10^{-10} Torr. They both produce gas dependent readings. Their pumping effects are of similar magnitude and negligible in the presence of adequate (i.e. >10 Ls^{-1}) tubulation to the vacuum system.

The ultimate accuracy of the BAG is better than the CCG. However, due to increased outgassing, a bakeout and/or degassing are often required to achieve the full advantage with the HCG. In most cases, a longer delay is also required to obtain a stable reading from a HCG. For applications involving continuous pumpdowns to low pressures, without an opportunity to degas or bakeout, a CCG might be the best choice to follow chamber pressure in real time.

HCGs are more easily calibrated than CCGs because of their linear response to pressure. Spurious discontinuities in the calibration curve can also affect readings of CCGs; however, this is rarely a serious problem in modern inverted magnetrons.

The filament life often limits the useful lifespan of a HCG; however, in most applications, filament lifetime is several years of continuous operation.

Starting the CCG can be delayed, particularly at low pressures; however, this is not a serious problem if strikers are built into the gauge to shorten the delay. CCGs can also be turned on at higher pressures during a pumpdown.

Careful consideration of the effects described in this note should help you choose between the two competing ionization gauge technologies.

Appendix H

PG105 Convection Enhanced Pirani Gauge

The SRS PG105 is a convection-enhanced Pirani gauge (CEPG) manufactured by Stanford Research Systems. When used with an IGC100 controller the PG105 provides a convenient, reliable and low-cost measurement of vacuum over an wide pressure range extending from atmosphere to 10^{-4} Torr.

This appendix provides a detailed description of the principle of operation, construction, gas dependence, calibration and fundamental strengths and weaknesses of the PG105 gauge head. Application examples and a few practical tips are provided along the way. Basic maintenance and troubleshooting information are also included.

Since it is not possible to cover this complex gauge in such a short note, a comprehensive list of references is provided at the end.

In This Appendix

Principle of Operation

The PG105 Convection Enhanced Pirani Gauge (CEPG) is a variation of the traditional Pirani vacuum gauge design[1]. Pressure measurement is based on the transfer of heat from a fine wire in the sensor to the surrounding gas [2].

Figure H-1. PG105 Convection-Enhanced Pirani Gauge

A schematic representation of the basic gauge design is depicted in Fig. H-2. The hot wire sensor is located inside the vacuum and is one leg, R_{sense}, of a Wheatstone resistor bridge. The entire bridge circuit is an integral part of the gauge head. An external feedback amplifier[3] is connected to this circuit, and balances the bridge, $V_{NULL}= 0$, during normal operation. If there are no changes in ambient temperature, the value of R_{sense} at bridge 'null' is a constant, independent of pressure, and given by the product: $R_{sense} = R_{comp} \cdot R_3 / R_4$. The components R_3, R_4 and R_{comp} are located outside the vacuum and their values determine the temperature of the wire (≈120°C) during operation.

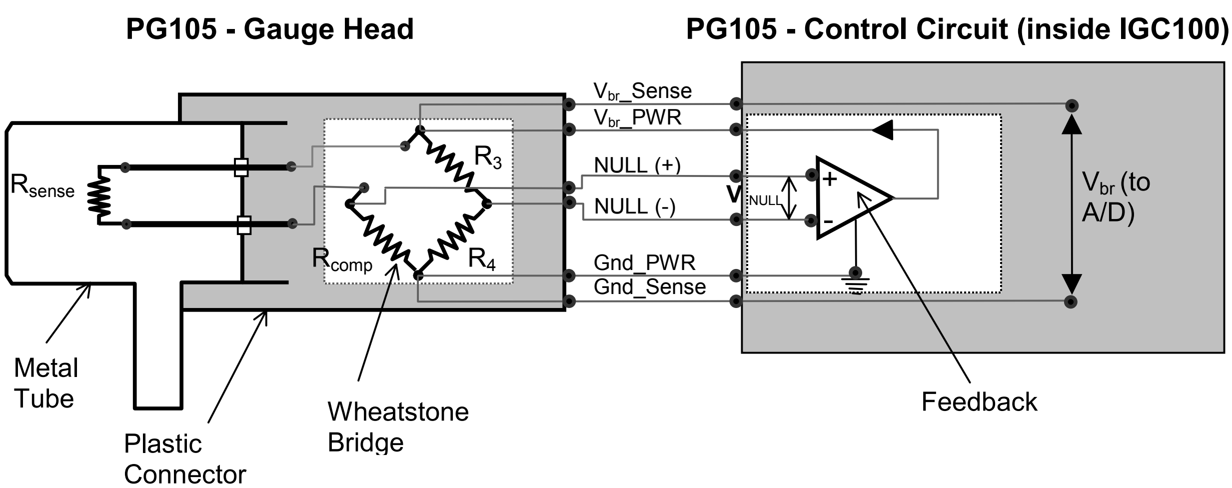


Figure H-2. Schematic representation of gauge, bridge and feedback amplifier.

In a gaseous environment the hot wire loses heat in four ways[4]: (1) radiation, (2) conduction along the wire to the end supports (3) heat conduction by the gas molecules and (4) gas convection. The energy transfer by the gas is pressure-dependent and driven by the temperature difference between the wire and the outer walls. As the vacuum system pressure is decreased, there are fewer molecules in the system to conduct heat away from the wire causing the temperature and R_{sense} to increase. The increased resistance of R_{sense} unbalances the bridge causing a voltage differential between the NULL terminals, $V_{NULL} \neq 0$. The bridge control circuit senses the NULL voltage change and decreases the voltage across the bridge, V_{br}, until V_{NULL} is again zero. Once the bridge voltage is decreased, the power dissipated by the sensor wire is decreased bringing the resistance of R_{sense} back to its original value. Obviously, the opposite set of events occurs when the pressure is increased. *The bridge voltage,* V_{br}*, is read by the controller and used as a non-linear measure of pressure*. As with all Pirani gauges, the voltage output depends on pressure as well as the thermal conductivity of the surrounding gases (i.e. indirect pressure measurement) - the gas composition must be known in order to indicate pressures correctly.

IMPORTANT

With a Pirani gauge, you need to know the gases you are pumping and calibrate the gauge for those gases before you can measure true vacuum levels.

The nominal 'V_{br} vs. P' curve for the PG105 operated in air is shown in Fig. H-3.

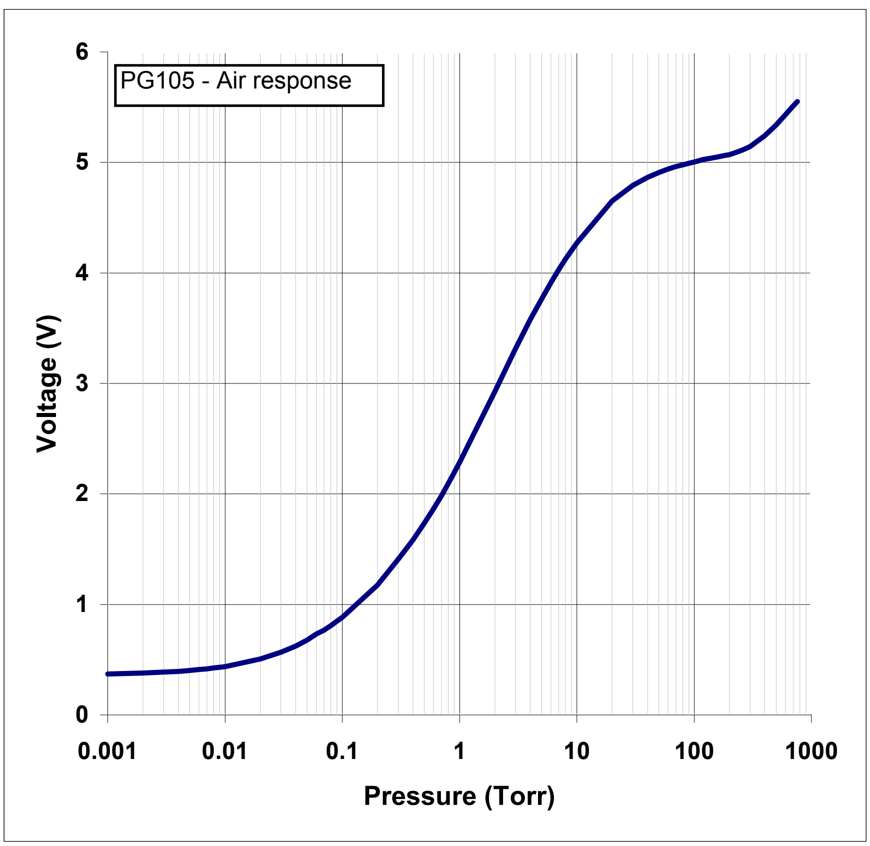


Figure H-3. PG105 Air response (gauge in horizontal orientation).

Several different heat dissipation effects contribute to the complicated shape of this curve. Below 10 Torr, the heat losses are primarily due to gas thermal conduction, and radiation. At pressures above 10 Torr, and as the mean free paths become shorter, energetic molecules departing from the wire collide with others before getting far away from its surface - a thermal insulating sheath of hot gas molecules develops around the wire as the pressure increases. This effect reduces the heat transfer efficiency of the gas as evidenced by the gradual flattening of the voltage response that takes place as the pressure increases. Above 10 Torr, convection currents also start to circulate around the wire. As the pressure increases further, they become more significant and start to slowly dominate the heat transfer. Convection currents are fully responsible for the sudden increase in gauge response that takes place above 100 Torr.

Convection-enhanced Pirani gauges, are specifically designed to optimize and take advantage of the thermal convection currents that develop around the hot wire at pressures above 10 Torr[5]. The distance from the hot wire to the tube walls in the PG105 has been carefully optimized so that convection can be quantified and reproduced well enough to give valid pressure readings up to 1000 Torr. As convection depends upon gravity, the magnitude of its effect depends upon the orientation of the wire. *The gauge tube axis must be mounted horizontally during operation to achieve efficient and reproducible natural convection above 1 Torr*. The gauge calibration above 1 Torr changes when the gauge moves from the horizontal to a vertical position, this change is most noticeable above 100 Torr.

IMPORTANT

It is important to consider the orientation of the gauge tube if accurate readings above 1 Torr are required! See 'Mounting Orientation' below for more details.

As the pressure decreases, the gas contribution to heat dissipation from the hot wire becomes smaller. The lower pressure limit of the PG105 gauge is reached when the contributions due to radiation and conduction to the mounting posts greatly exceed the thermal transfer by gas molecules. Below that limit, typically around 10^{-3} Torr, the output becomes virtually constant and the drift of the radiation component and of the ambient temperature makes long term accuracy questionable at best. The gas dependent component of the gauge response can still be followed below 10^{-3} Torr, but only under carefully monitored, short term, conditions.

IMPORTANT

Operation of the PG105 convection gauge between 10^{-4} and 10^{-3} Torr is still possible, but it requires periodic 'zero' readjustments of the controller readings to compensate against sensor drift. Only rough pressure measurement accuracy should be expected in this range! See 'Operation Below 10^{-3} Torr' below for details.

Energy transfer by the heat dissipation processes described above, is strongly dependent on the temperature of the outer walls. The power dissipated by gas molecules diminishes as the ambient temperature increases. Without proper compensation, a gauge controller cannot differentiate if a reduction in V_{br} was caused by a decrease in pressure or an increase in room temperature. The PG105 convection gauge has built-in temperature compensation that makes it possible to obtain temperature corrected pressure readings between 10°C and 40°C. A very simple but effective scheme, first described in 1965[6], is used to provide ambient temperature compensation: The R_{comp} component of the Wheatstone bridge is not a simple resistor as sketched in Fig. H-2, but rather a composite, temperature-sensitive, resistor network made up to have a temperature coefficient (R_4/R_3) times that of R_{sense}. A thin metal wire, with a high temperature coefficient of resistance, tightly wound around the outer diameter of the gauge tube, provides the temperature sensitive component of the network. The other components of the resistor network have relatively insignificant temperature coefficients and are carefully selected at the factory to trim the effective temperature coefficient of R_{comp} to the required value. Under this simple bridge configuration, a constant temperature difference is maintained between the wire and the walls at all times, and bridge voltages are relatively unaffected by ambient temperature changes. In addition to compensating for ambient temperature variations, this compensation scheme also corrects for heating of the gauge envelope due to filament dissipation at high pressures. At atmospheric pressure, the dissipation of ≈1/8 Watt from the hot filament can cause a slow temperature rise of a few degrees Celsius at the tube's outer wall. *Temperature compensation is vital if the gauge output is to have any real meaning above 100 Torr*. It also effectively reduces the time required to obtain accurate and stable pressure readings after a rapid pressure change.

Construction

The PG105 gauge head has been designed for the most demanding applications. A schematic representation of the gauge head is shown in Fig. H-4.

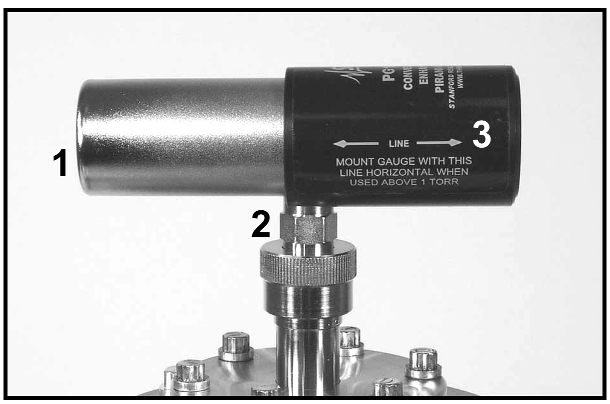


Figure H-4. PG105 Gauge components.
1. Cylindrical metal tube, 2. Side port, 3. Detachable plastic connector.

The gauge assembly is divided into three main components:

1. Cylindrical metal tube.
2. Side port (with optional vacuum fittings.)
3. Detachable plastic connector.

The cylindrical metal section consists of an inner sensor tube surrounded by an outer metal case. The vacuum-sealed inner metal tube houses the hot wire sensor, and connects to the vacuum system through the side port. The sensor wire material is gold plated tungsten, selected for the stability of its surface properties, reproducible electrical characteristics and mechanical strength. The back end of the tube, facing the plastic connector, consists of a gasket-sealed, 4-pin, electrical feedthru flange with 1/16" diameter Ni alloy conductors and glass-ceramic insulators. Two of the electrical connectors are integral parts of the filament mounting posts. The other two pins provide electrical connection points for the ends of the temperature compensation wire that is tightly wound around the waist of the inner tube. The outer shell effectively protects the sensor tube, feedthru pins and temperature compensating element from mechanical damage.

The standard PG105 convection gauge uses a high-quality Viton O-ring to seal the feedthru flange end of the tube, allowing maximum bakeout temperatures of 110°C (with the plastic connector detached). Metal gasket sealed gauge heads are also available, option PG105-UHV, that can be baked up to 250°C for more complete UHV compatibility. The metal gaskets used in all UHV enhanced gauge versions, are made out of OFHC Cu and belong to the Helicoflex Delta® family of high-performance compression metal seals, widely used for ultrahigh vacuum and ultrahigh purity applications.

IMPORTANT

Metal sealed gauge tubes, option PG105-UHV, are recommended for all ultrahigh vacuum and ultrahigh purity applications incompatible with the standard compression O-ring seal.

The stainless steel side tube provides the only connection to the vacuum system. The standard gauge head is fitted with a ½" diameter side tube terminated in a male 1/8"-NPT fitting. This allows direct attachment to a ½" ID compression fitting or into a standard 1/8" - NPR female pipe fitting. To accommodate most applications, the side tube is available with a variety of end-fittings. Some examples of available fittings include: NW16KF, NW25KF, 1.33" and 2.75" ConFlat®, Cajon® SS-4-VCR and SS-6-VCO, etc. Consult Stanford Research Systems for additional details on available fittings.

The detachable plastic connector mounts, and locks, onto the back of the metal tube and houses (1) the rest of the Wheatstone bridge components and (2) an 8-pin, RJ45 compatible socket connector (used to connect the gauge to the O105C4 connector cable). Self alignment, and a symmetric pin arrangement, prevents improper hook-up and protects the electrical pins from breakage.

As indicated before, the entire resistor bridge circuit is located inside the PG105 Pirani head. The IGC100 measures pressure-dependent bridge voltages right at the PG105 head using a four-wire (i.e. Kelvin probe) arrangement. Two wires supply electrical power to the bridge while a separate pair senses the bridge voltage right at the gauge head without drawing any additional current out of the circuit. This configuration makes the gauge calibration independent of cable length.

Strong, thick components contribute to a rugged head design that stands up to process environments and provides long-lasting reliability. Internal construction materials have been chosen to ensure compatibility with many process gases as well as UHV systems. Stainless steel construction (SS316) provides good resistance against corrosive gases. Glass-ceramic (SiOx) electrical feedthrus provide compatibility with high temperature bakeouts and UHV applications. TIG welding and assembly under cleanroom conditions, ensure compatibility with particle sensitive process applications. The inner measurement chamber offers effective RF shielding and protects the sensor wire. The temperature compensation element is located outside the vacuum to reduce outgassing and preserve UHV compatibility. Gold plated tungsten sensor construction helps minimize calibration drift (see 'Contamination' section below). A very thin and long sensor wire is used to minimize heat loss to the end supports and minimize temperature gradients along its length. This is very important for operating below 10^{-3} Torr.

The following materials are exposed to the vacuum:

1. Type 316 stainless steel
2. Carpenter glass sealing "52" alloy™ (50.5% Ni/Fe alloy)
3. Gold plated tungsten
4. Glass ceramic (SiOx ceramic)
5. Viton (standard, O-ring sealed, heads only)
6. OFHC Copper (PG105-UHV heads only)

Note

There is no brazing material in the ceramic feedthrus- the glass ceramic wets right on to the stainless steel. No solder or solder flux material is used inside the gauge tube.

Calibration

Following factory assembly, each PG105 gauge tube is *individually* calibrated for nitrogen, and temperature compensated between 10° and 40°C. After calibration, each gauge tube is then individually tested to determine if selected pressure readouts fall within narrow limits before the unit is ready for shipment. Individual factory calibration of the gauge response provides true 'plug-and-play' convenience and eliminates the need to rezero the controller each time a new gauge tube is connected[7]. PG105 gauges and IGC100 controllers are completely interchangeable without any need for instrument adjustments! In order to assure that calibration does not change with use, all gauge tubes are baked at high temperature for an extended period of time before final calibration takes place.

It is important to understand that the pressure indicated by a PG105 convection gauge depends on (1) the type of gas, (2) the orientation of the gauge axis and (3) the gas density inside the gauge tube. As mentioned before, the PG105 gauge is factory calibrated and temperature compensated for nitrogen gas. However the response of the gauge for gases other than nitrogen is very well characterized and, with the proper calibration data (i.e. V_{br} vs. P curve for the specific gas type), it is possible to obtain accurate pressure measurements for other gases.

IGC100 controllers are factory loaded with nitrogen and argon specific calibration curves compatible with all PG105 convection gauges[8]. The non-linear dependence of the bridge voltage on pressure is evident from Fig. H-3, and shows the need for detailed lookup tables to obtain accurate readings over the entire pressure range.

Note

Gas correction curves and correction factors, used to convert 'nitrogen equivalent pressure' readings into true pressure readings for some common gases, can be found in the Appendix I, 'Gas Correction Curves for PG105 Readings'. The conversion curves only apply when the pressure readings displayed by the controller are based on the nitrogen calibration curve and the gauge tube is mounted with its axis horizontal. Use the curves or correction factors (where applicable) to convert indicated (i.e. nitrogen equivalent) pressure readings into true pressures for all the gases included in the appendix.

Users should generate their own conversion curves for gases, or mixtures of gases, not listed in the appendix. A calibrated, gas-independent, capacitance manometer is recommended as a transfer standard.

WARNING!
A serious danger of explosion can arise if the calibration data for one gas is applied without correction to measure pressures for a different gas (or gases) at or above atmospheric pressure. Please consult the 'Safety Considerations' section below for information on overpressure risks.

The calibration data loaded into all IGC100 controllers is based on the response of a new gauge free of contaminants. If a tube becomes contaminated or does not seem to read correctly, the front panel readings can often be readjusted using the ZERO and ATM adjustments in the Pirani Gauge calibration menu. Consult the IGC100 instructions for details on these two adjustment procedures.

Note
The ZERO and ATM adjustments built into the IGC100 controller make it possible to accommodate considerable changes in PG105 calibration while retaining acceptable measurement accuracy.

Accuracy and Stability

Very limited information exists in the vacuum literature on the accuracy, repeatability and long term stability of measurements made with thermal conductivity vacuum gauges. This is probably because most of the users that rely on these gauges for their applications do not require high accuracy pressure reports!

The measurement accuracy of all convection gauges (including the PG105) is pressure dependent and generally between 5% to 20% of the indicated pressure[9]. Accuracies not better than 25% should be expected from convection gauges used at atmospheric pressures[10]. Highest accuracies are usually observed between 1 and 10^{-2} Torr.

Because the pressure range where gas conduction cooling is predominant does not neatly overlap the pressure range where convection cooling occurs (see Fig. H-3), all convection enhanced Pirani gauges have limited sensitivity between 20 and 200 Torr[11].

Only one relevant study on the long term performance of constant temperature Pirani gauges has appeared in the vacuum literature[12]. Over the six months of the study, the gauges tested showed reproducibilities within ±6% over the pressure range extending from 10^{-2} to 10 Torr. Similar stability should probably be expected from PG105 gauges used under controlled conditions. However, always remember that the operating environment conditions ultimately limit the long term performance of a vacuum gauge! Also remember that the ZERO and ATM adjustments built into the IGC100 controller often make it possible to accommodate slight changes in tube characteristics while still retaining acceptable reading accuracy.

Periodic comparison at several pressures against a reliable check standard is recommended to determine if gross changes in response have occurred, and to determine if readjustment, bakeout , cleaning or full replacement is necessary.

Operation Below 10^{-3} Torr

Variations in ambient temperature and wire contamination are the two major sources of instability for readings below 10^{-3} Torr, where radiation and conduction to the mounting posts dominate the heat transfer process. The emissivity of a wire might vary from 0.05 for a clean wire to unity when contaminated. Power dissipation due to radiation is a function of the fourth power of the filament temperature. As a result, operation of the PG105 convection gauge below 10^{-3} Torr (where molecular conduction contributes as little as 1% of the total heat dissipation) is still possible, but it requires periodic ZERO readjustments of the controller readings to compensate against background drift.

Only rough pressure measurement accuracy should be expected below 10^{-3} Torr!

During fast pumpdown, thermal effects will prevent the PG105 gauge from providing immediate accurate pressure readings below 10^{-3} Torr. Readings in the 10^{-4} Torr range are valid only after a 15-20 minute period of thermal stabilization. ZERO adjustments of the controller readings should not be performed until full thermal stabilization has been accomplished.

IMPORTANT

For accurate results in the 10^{-4} Torr range, ZERO readjustments of the controller readings should be performed periodically.

The peak-to-peak random noise for pressure measurements below 10^{-3} Torr is $\pm 1.5 \times 10^{-4}$ Torr (nom) for all IGC100 controllers.

Mounting Orientation

Below 1 Torr

The PG105 convection gauge will operate and report accurate pressures in any orientation.

Above 1 Torr

The PG105 convection gauge will accurately read pressures only while mounted with its axis horizontal.

In both cases, it is recommended that the gauge be installed with the port oriented vertically downward to ensure that no system condensates or other liquids collect inside the gauge tube.

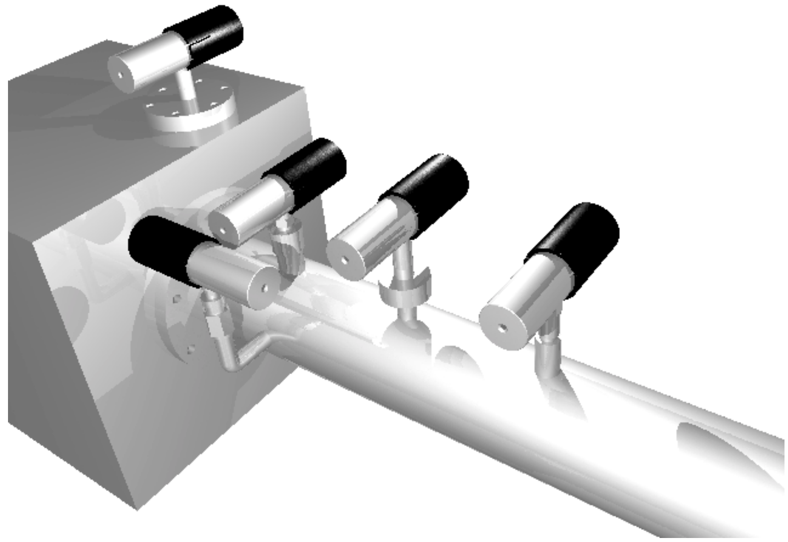


Figure H-5. PG105 Gauge mounting examples

It has been shown that for convection gauges such as the PG105, deviations as small as 5° from the horizontal can be significant above 100 Torr[13]. Erroneous readings can result in over or underpressure conditions which may damage equipment and/or injure personnel.

Mounting Recommendations

Handling

- Always use proper vacuum handling while installing the gauge.
- Keep the gauge clean- away from contamination sources!
- Use clean tools.
- Do not talk or breathe into any exposed/open vacuum ports.
- Use good quality seals and verify their integrity.
- Keep the port cover on until moments before installation.
- Do not drop or mishandle the gauge during installation causing permanent damage to the delicate sensor wire.

Location

The physical location of the gauge is critical to obtaining reliable pressure measurements. If placed near a pump, the pressure in the gauge may be considerably lower than in the rest of the system. If placed near a gas inlet or source of contamination, the pressure in the gauge may be much higher. Long tubulation or other constrictions between the gauge and the rest of the vacuum system can cause large errors in the pressure readings.

Temperature

Minimize temperature effects - locate the gauge away from internal and external heat sources. Whenever possible, choose an area where the ambient temperature is reasonably constant.

Vibration

Mount PG105 gauges where they will not experience excessive vibrations. Vibration causes convection cooling of the sensor and results in high readings at the high pressure end. Damage to the filament is also possible.

Grounding

Verify the proper electrical grounding of the vacuum port before connecting the PG105 gauge head to the vacuum system. The gauge envelope must be properly grounded during operation. If necessary, use a ground lug on a flange bolt to establish a dedicated connection to a facility ground. Alternatively, the gauge envelope may be grounded by using a metal hose clamp on the gauge connected to the system's safety ground by a #12 AWG copper wire.

Compression fittings

The standard PG105 gauge port is designed to fit any standard ½" compression fitting such as an Ultra-Torr® fitting. Do not use compression fittings for positive pressure applications!

1/8 NPT Fittings

The threads on the standard PG105 side port will fit a standard 1/8" NPT female fitting. Wrap the gauge threads with Teflon tape and screw the gauge into the female fitting. Twist the gauge body by hand until the first sign of resistance is felt. *Do not use the body of the gauge as its own wrench past this point*. Instead, finish tightening with a ½" wrench applied to the nut built into the side tube until a proper seal is achieved. Do not overtighten as that might stress the tube port!

Other Fittings

In addition to the standard tube, which provides a ½" compression port and a 1/8" NPT male thread, a variety of other mounting options are available. They include: NW16KF, NW25KF, 1.33" and 2.75" ConFlat®, Cajon® SS-4-VCR and SS-6-VCO, etc. Consult Stanford Research Systems for additional information on available fittings.

Contamination

Contamination of the sensor wire with pump oil or other films is the main source of calibration drifts in Pirani gauges.

Wire material and temperature[14] play the most important role in the long-term performance of the PG105 convection gauge.

A gold-plated tungsten wire is used in all PG105 gauge tubes. This material was selected for the stability of its surface properties, reproducible electrical characteristics and mechanical strength. Gold plating minimizes wire contamination as caused by oxidation, corrosion and surface induced decomposition reactions. A shiny gold surface offers the low emissivity levels required to extend the low limit of the gauge into the sub-mTorr pressure range.

The temperature of the wire inside the PG105 gauge tube is approximately 120°C during operation. This temperature delivers optimal gauge response[15] while, at the same time, it remains low enough to minimize contamination by surface induced decomposition of foreign materials, such as pump-oil vapors.

Care must be taken not to mount the PG105 tube in a way such that deposition of process vapor impurities may occur through direct line-of-sight access from the vacuum chamber to the interior of the gauge.

It is also recommended that the PG105 tube be installed with the side port oriented vertically downward to ensure that no system condensates or other liquids collect inside the gauge tube.

IMPORTANT

PG105 gauges should not be used in the presence of fluorine or mercury vapors. Both gases can react with the gold plated sensor and change its emissivity and/or overall diameter irreversibly.

Surface contamination strongly affects both the emissivity and accommodation coefficient[16] of the hot wire. Changes in emissivity affect the stability of the background, and effectively set the lower operating limit of a Pirani gauge during actual use. Periodic ZERO readjustments of the controller readings, to compensate against background drift, are required for operation in the millitorr and especially in the sub-millitorr range. Changes in surface properties result in changes in the efficiency of heat conduction by the gas molecules and cause calibration drifts. If, and when, contamination causes the PG105 calibration to change, the user can correct the pressure readings displayed by the IGC100 controller performing a quick ATM readjustment of the controller readings at atmospheric pressure.

The ZERO and ATM(mosphere) adjustments built into the IGC100 controller make it possible to accommodate considerable changes in tube characteristics while retaining acceptable measurement accuracy.

Periodic gauge bakeouts provide an effective way to avoid serious contamination buildup problems. Maximum bakeout temperatures are 110°C for standard (i.e. O-ring sealed) heads, and 250°C for metal-gasket sealed tubes (option PG105-UHV). The plastic connector must be disconnected from the head during bakeouts. An overnight bakeout, at ≈200°C, is the only recommended cleaning procedure for PG105-UHV gauges in direct contact with ultra high vacuum environments.

The calibration of grossly contaminated convection gauges can sometimes be partially restored using the solvent-based cleaning procedure described in the next section. This cleaning procedure is mostly recommended for gauges heavily contaminated by hydrocarbon impurities originated from vacuum pumps.

Cleaning

WARNING!

- This cleaning procedure should only be used on severely contaminated gauges, when the ZERO and ATM controller adjustments can no longer correct for drifts in the calibration.
- Stanford Research Systems does not guarantee that this procedure will remove contamination from a PG105 convection gauge.
- Use this cleaning method as a last resort only!

WARNING!
The fumes from acetone and isopropyl alcohol can be dangerous to health if inhaled and are highly flammable. Work in well ventilated areas and away from ignition sources!

Materials

1. Isopropyl alcohol or acetone, electronic grade or better.
2. Wash bottle with long thin neck.

Cleaning Procedure

Disconnect the gauge from the electrical cable and from the vacuum system port. Physically disconnect the detachable plastic connector from the back of the gauge tube and store it in a safe and clean place.

Hold the metal gauge tube in a horizontal position with the side port pointing upwards at a 45° angle. Slowly fill the volume of the gauge with solvent using the wash bottle to squirt the liquid into the side tube. Let the solvent stand inside the gauge for at least 10 minutes. Do not shake the gauge, since that might cause damage to the sensor wire. To drain the gauge, position it horizontally with the side port facing downward. Slightly warming the gauge will help dry the gauge. Allow the gauge tube to dry overnight with the port facing downward. Before reinstalling the gauge in the system, be certain no solvent odor remains.

Viton O-rings soaked in organic liquids can outgas solvent molecules for extended periods of time. Solvent outgassing rates can be significantly diminished: (a) baking the gauge tube overnight in a vacuum oven between 100-110°C before gauge installation or (b) baking out the gauge while attached to the vacuum system and before reconnecting its plastic connector.

Bakeout

WARNING!
The detachable plastic connector must be physically disconnected from the PG105 gauge head during bakeout.

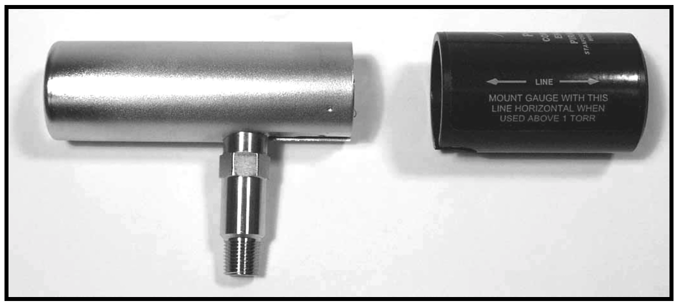


Figure H-6. Side view of the PG105 gauge tube with the detachable plastic connector disconnected.

Periodic, overnight, gauge bakeouts provide an effective way to minimize contamination buildup problems. Maximum bakeout temperatures are 110°C for standard (i.e. Viton O-ring sealed) heads, and 250°C for metal-gasket sealed tubes (option PG105-UHV) used in UHV or low contamination applications.

An overnight bakeout, at 200-250°C, is the only recommended cleaning procedure for PG105-UHV gauges in direct contact with ultra high vacuum environments.

Application Examples and Tips

Convection gauges, such as the PG105, are an accurate, fast and inexpensive means of measuring foreline and roughing line pressures, or moderate backfill pressures!

The PG105 convection enhanced Pirani gauge is the best choice for vacuum applications where conventional thermocouple and Pirani gauges are not suitable because of (1) limited range, (2) drift and (3) slow response. It is often selected as a cost effective alternative to a capacitance manometer[17].

The exceptionally wide measurement range of the PG105 makes it possible to continuously monitor the pumpdown of a vacuum system from atmospheric to the base pressure of most mechanical pumps without any blind spots. Convection gauges are found in virtually every modern semiconductor and thin film process system, for monitoring pumping system performance.

Convection gauges are the type of vacuum gauge most commonly encountered on loadlocks[18] and are often used to tell when a chamber may be safe to open to atmosphere. Yet, a convection gauge alone may not be accurate enough to tell you when there is enough internal positive pressure to ensure a gentle flow of gas out of the chamber once you open the door. For this reason, many users combine their convection gauges with differential pressure devices called atmospheric pressure switches.

A response time of a few milliseconds makes the PG105 convection gauge ideally suited for protective functions, such as determining when BAG emission should be de-activated or turned off. They are also well suited to control valves, heaters, bakeout ovens and safety interlocks.

Gas dependence makes the PG105 useful as an inexpensive leak detector. By using a tracer gas whose thermal conductivity is very different from the gases in the vacuum system, leaks as small as 10^{-4} atm cc/sec can be sensed and located. Typical gases used for leak testing include hydrogen, helium, argon and freon. This can eliminate the need for a very expensive leak detector. Several applications of Pirani gauges to leak detection have been reported in the vacuum literature[19].

The PG105 convection gauge is ideal for applications that operate between atmosphere and a few microns, and where gas composition is well known and repeatable! Convection gauges are usually found in pharmaceutical, food processing and lamp tube manufacturing process environments.

The all-metal interior construction of the PG105-UHV gauge makes it the best choice for applications requiring ultrahigh vacuum and/or ultrahigh purity compatibility. PG105-UHV gauges are often connected directly to high and ultrahigh vacuum chambers and used as cross-over gauges to protect the filaments of much more expensive ionization gauges.

PG105 gauges are not recommended for backfilling operations because of their gas dependence and risk of overpressure. For critical applications where repeatability and precision are required, a capacitance manometer gauge should be used to monitor and control the process pressure! This is particularly true if complex or changing gas mixtures are involved.

PG105 gauges are not recommended in contaminating environments because of their sensitivity to surface conditions.

Safety Considerations

Experience has proven all vacuum gauges remarkably safe. However, *incorrect use of any pressure gauge can cause accidents*. This section describes some very important safety considerations that must be taken into account during the selection, installation and operation of convection gauges[20]. The safety hazards related in this section apply to all commercially available convection enhanced Pirani gauges, and are not peculiar to the SRS PG105 convection gauge!

Consult Stanford Research Systems directly for any safety concerns related to PG105 convection gauges not addressed in this section.

Explosive Gases

WARNING!
Do not use the PG105 convection gauge to measure the pressure of combustible or flammable gases.

Thermal conductivity gauges are dangerous in applications where explosive gas mixtures may be present. This situation could exist, for example, during the fill or vent cycle of a metallurgical hydrogen furnace, or during the regeneration process of a cryopump which had frozen a quantity of organic material and oxygen. The filament temperature must remain below the ignition point of the gas mixture being measured at all times. The hot wire inside the gauge tube normally operates at a low temperature (≈120°C); however, it is possible to experience brief thermal transients during turn on or circuit failure that could raise the temperature above the safe limit. The risk of explosion, resulting in expensive equipment damage and serious personnel injuries must be carefully considered during the gauge selection process. A capacitance manometer is always a safer alternative in the presence of combustible, flammable or explosive gases.

IGC100 users can turn their PG105 convection gauges off directly from the front panel, without the need to physically disconnect the gauge tube from the controller. The filament cools down very rapidly to ambient temperature as soon as the electrical power is removed from the bridge circuit.

Compression Mounts

WARNING!
Do not use a compression fitting to attach a PG105 gauge tube to a vacuum system if positive (i.e. greater than ambient) pressures at the gauge head are possible during operation.

Positive pressures can forcefully eject the gauge head out of the fitting resulting in damaged equipment and/or injured personnel. A pressure relief valve or rupture disk should be installed in the system if the possibility of exceeding ambient pressure exists.

In general, the pressure inside the PG105 convection gauge should never exceed 1000 Torr. No reliable measurements are obtained above that limit.

Overpressure Risks

WARNING!
Using a PG105 convection gauge to backfill to atmospheric pressure should be avoided unless the gas-specific calibration curve for the backfilled gas is used to calculate and display pressures.

A serious danger can arise if the calibration data for one gas is applied without correction to measure pressures for a different gas (or gases) at or above atmospheric pressure. Argon provides an excellent example of how things can go very wrong. Applying the nitrogen calibration data to measure argon pressures provides a 'nitrogen equivalent' reading of only ≈25 Torr when the gauge is exposed to an atmosphere of Argon gas. The chamber could be seriously pressurized while the gauge controller continues to display <100Torr of 'nitrogen equivalent' pressure. An oblivious operator, looking for a 760 Torr pressure reading, might continue to increase the gas pressure leading to the possibility of a dangerous explosion. Reports of accidents caused by this effect have appeared in the vacuum literature[21]. Accidents such as these can occur only if a thermal conductivity gauge is used to measure pressures at the upper end of the range where the calibrations for different gases diverge widely. This is the one reason why many vacuum practitioners reserve their convection gauges for measuring foreline and roughing line pressures, or *moderate* backfill pressures only!

At pressures below a few Torr the danger of using the nitrogen (or argon) calibration to measure the pressures of an uncalibrated gas (or gases) disappears. The only problem left is the inaccuracy of the readings. However, it is generally possible to correct pressure readings for uncalibrated gases using lookup tables or even simple correction factors.

With systems that could be potentially backfilled to excessive pressures by failure of gauges or regulator valves the inclusion of a pressure relief valve or burst disk is the safest way to avoid over pressurization!

Grounding

WARNING!
Verify the proper electrical grounding of the vacuum port before connecting the PG105 gauge head to the vacuum system.

The gauge envelope must be properly grounded during operation. If necessary, use a ground lug on a flange bolt to establish a dedicated connection to a facility ground. Alternatively, the gauge envelope may be grounded by using a metal hose clamp on the gauge connected by a #12 AWG copper wire to the system's safety ground.

Electrical Connection

A single 8-pin, RJ45 compatible, connection socket, located on the back wall of the detachable plastic connector, provides the only electrical connection required between the PG105 gauge head and its controller cable. Fig. H-7 shows a picture of the electrical connector and lists the pin assignments in Table 1.

Pin#	Description
1	V_{br}_Sense
2	V_{br}_PWR
3	NULL(+)
4	NULL (-)
5	Not used
6	Not used
7	Ground
8	Ground

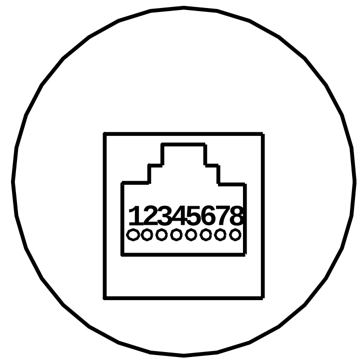


Figure H-7. PG105/RJ45 connector pin assignments.

As mentioned previously, the resistor bridge is an integral component of the PG105 gauge head (see Fig. H-2). Since pressure-dependent bridge voltages are measured right at the PG105 head using a four-wire arrangement, a total of six wires is required to establish a connection between an individual PG105 gauge head and a Pirani port of the IGC100 controller: Two wires supply the electrical power to the bridge while an independent pair senses the bridge voltage right at the gauge head without drawing any additional current out of the circuit. The last two wires connect the NULL(+) and NULL(-) voltages of the bridge to the differential input of the controller's feedback amplifier. This configuration makes the gauge calibration independent of cable length.

PG105 Gauge Test Procedure

Breakage of the small diameter sensor wire located inside the tube is a common failure mechanism for all Pirani gauges. Fortunately it is very easy to test the PG105 gauges for electrical continuity, to determine the integrity of both the sensor and temperature compensation wires.

WARNING!
Use an ohmmeter that cannot apply more than 0.1 V when the gauge is at vacuum or 2 V when at atmospheric pressure.

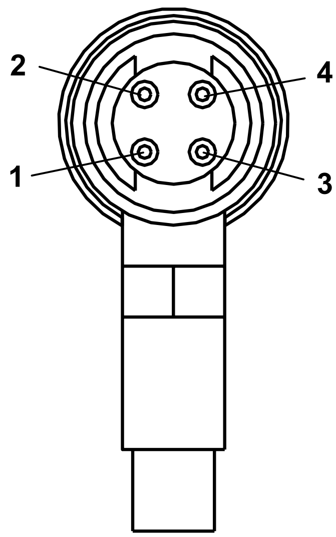


Figure H-8. Back view of the PG105 tube, with the plastic connector removed.

1. Disconnect the Detachable Plastic Connector from the PG105 gauge head. Four feedthru connector pins are now easily accessible from the back of the gauge tube as schematically represented in Fig. H-8.

2. Following the pin assignments of Fig. H-8, measure the resistance between pins 1 and 4 and between pins 2 and 3. The nominal wire resistances are:

Pins	Wire	Expected value (Ohms)
1 to 4	Sensor	20 – 22
2 to 3	Compensate	35 - 40

3. Gauge wires are not replaceable! Replace the gauge head if the wire resistance values do not fall within the ranges specified above.

References

[1] Pirani, M., Deutsche Phys. Ges. 8 (1906) 686. The first report of the Pirani gauge by its inventor.

[2] For one of the most complete discussions of Pirani Gauges consult: J.H. Leck, "Total and partial pressure measurement in vacuum systems", Chapter 2, titled "Thermal conductivity gauges", starting at page 39. Blackie & Son Ltd., Glasgow, England, 1989.

[3] Two amplifier circuits are built into every IGC100 controller, to control up to two PG105 gauges simultaneously.

[4] For theoretical derivations consult: J. M. Lafferty, "Foundations of vacuum science and technology", Wiley Interscience, 1998, NY, p. 404, section 6.8.1.

[5] L. Heijne and A. T. Vink, "A Pirani gauge for pressures up to 1000 Torr and higher", Philips Technical Rev. 30 (1969) 166; see also: J. B. Johnson, "Convection Type Manometer", The Review of Scientific Instruments, 27(5) (1956) 303; and J. A. McMillan, et. al. "Wide Range Thermal Convection Manometer", The review of Scientific Instruments , 28(11) (1957) 881.

[6] J. English, B. Fletcher and W. Steckelmacher, "A wide range constant-resistance Pirani gauge with ambient temperature compensation", J. Sci. Instrum. 42 (1965) 77; W. Steckelmacher and B. Fletcher, "Extension of range of thermal conductivity vacuum gauge to atmospheric pressure by natural convection", J. Phys. E, Sci. Instrum. 5 (1972) 405; W. Steckelmacher, "The high pressure sensitivity extension of thermal conductivity gauges", Vacuum 23 (9) (1973) 307.

[7] Zero adjustment of the gauge should not be necessary unless readout accuracy is required below 1 mTorr or the gauge has been contaminated.

[8] Consult R. E. Ellefson and A.P. Miller, "Recommended practice for calibrating vacuum gauges of the thermal conductivity type", J. Vac. Sci. Technol. A 18(5) (2000) 2568, for information on thermal gauge calibration and accuracy.

[9] R.E. Ellefson, and A. P. Miller, "Recommended Practice for Calibrating Vacuum Gauges of the Thermal Conductivity Type", J. Vac. Sci. Technol. To be published sometime during the spring of the year 2000.

[10] Vic Comello, "Simplify Rough Pumping With a Wide-Range Gauge", R&D Magazine, May 1999, p. 57.

[11] See also U.S. patent #6,227,056 for more details.

[12] K. F. Poulter, Mary-Jo Rodgers and K. W. Ascroft, "Reproducibility of the performance of Pirani Gauges", J. Vac. Sci. Technol. 17(2) (1980) 638.

[13] McMillan, J. A. and Buch, T., Rev. Sci. Instr. 28 (1957) 881.

[14] J. H. Leck, "The high temperature Pirani Gauge", J. Sci. Instr. 29 (1952) 258.

[15] Consult the book by J. H. Leck mentioned above, p. 45, section 2.3.

[16] The accommodation coefficient provides a measure of the efficiency of energy transfer from the hot wire to the gas molecules that collide with its surface. Its magnitude depends on (1) the gas, (2) the metal surface material, (3) contamination buildup on the wire surface, and (4) the temperatures involved. For more details consult: J.H. Leck, "Total and partial pressure measurement in vacuum systems", Chapter 2, titled "Thermal conductivity gauges", section 2.5., page 46. Blackie & Son Ltd., Glasgow, England.(1989).

[17] Vic. Comello, "Using Thermal Conductivity Gauges", R&D Magazine, Vol. 38, Number 8, July 1997, p. 57. Useful article with application examples, and some tips.

[18] Stephen Hansen, "Pressure measurement and control in loadlocks", Solid State Technology, October 1997, p. 151.

[19] J. Blears and J. H. Leck, J. Sci. Instrum. 28, Suppl. 1, 20 (1951); W. Steckelmacher and D. M. Tinsley, Vacuum 12 (1962) 153; J. K. N. Sharma and A. C. Gupta, Vacuum 36 (1986) 279; C. C. Minter, Rev. Sci. Instrum. 29 (1958) 793.

[20] R. N. Peacock, "Safety and health considerations related to vacuum gauging", J. Vac. Sci. Technol. A 11(4) (1993) 1627.

[21] R. Chapman and J. P. Hobson, J. Vac. Sci. Technol. 16 (1979) 965, D. G. Bills, J. Vac. Sci. Technol. 16 (1979) 2109.

Appendix I

Gas Correction Curves for PG105 Gauges

It is important to understand that the pressure indicated by a PG105 convection-enhanced Pirani gauge depends on the type of gas. All PG105 convection-enhanced Pirani gauges are factory-calibrated and temperature-compensated for nitrogen (air). However the response of the gauge to other gases is very well characterized and, with the proper calibration data, it is possible to obtain accurate pressure measurements for other gases as well.

IGC100 controllers are factory-loaded with Nitrogen and Argon specific calibration curves compatible with all PG105 gauges, and direct pressure measurements are possible for both gases.

If you must measure the pressure of gases other than Nitrogen or Argon, use Gas Correction Curves, like figures I-1 and I-2 included in this appendix, to convert “nitrogen equivalent pressure” readings into “actual pressure” readings for those gases.

Gas Correction Factors (relative to nitrogen equivalent readings) can also be used for pressure measurements below 1 Torr (See Table I-1)

PG105 users should generate their own conversion curves for gases, or mixtures of gases, not included in this appendix. A calibrated, gas-independent, capacitance manometer is recommended as a transfer standard[1].

In This Appendix

Gas Correction Curves and Factors

Important
The conversion curves and factors listed in this appendix only apply

1. when the pressure readings displayed by the controller are based on the nitrogen calibration curve (i.e. PG Cal Curve = N2 Curve)

2. the gauge tube is mounted with its axis horizontal.

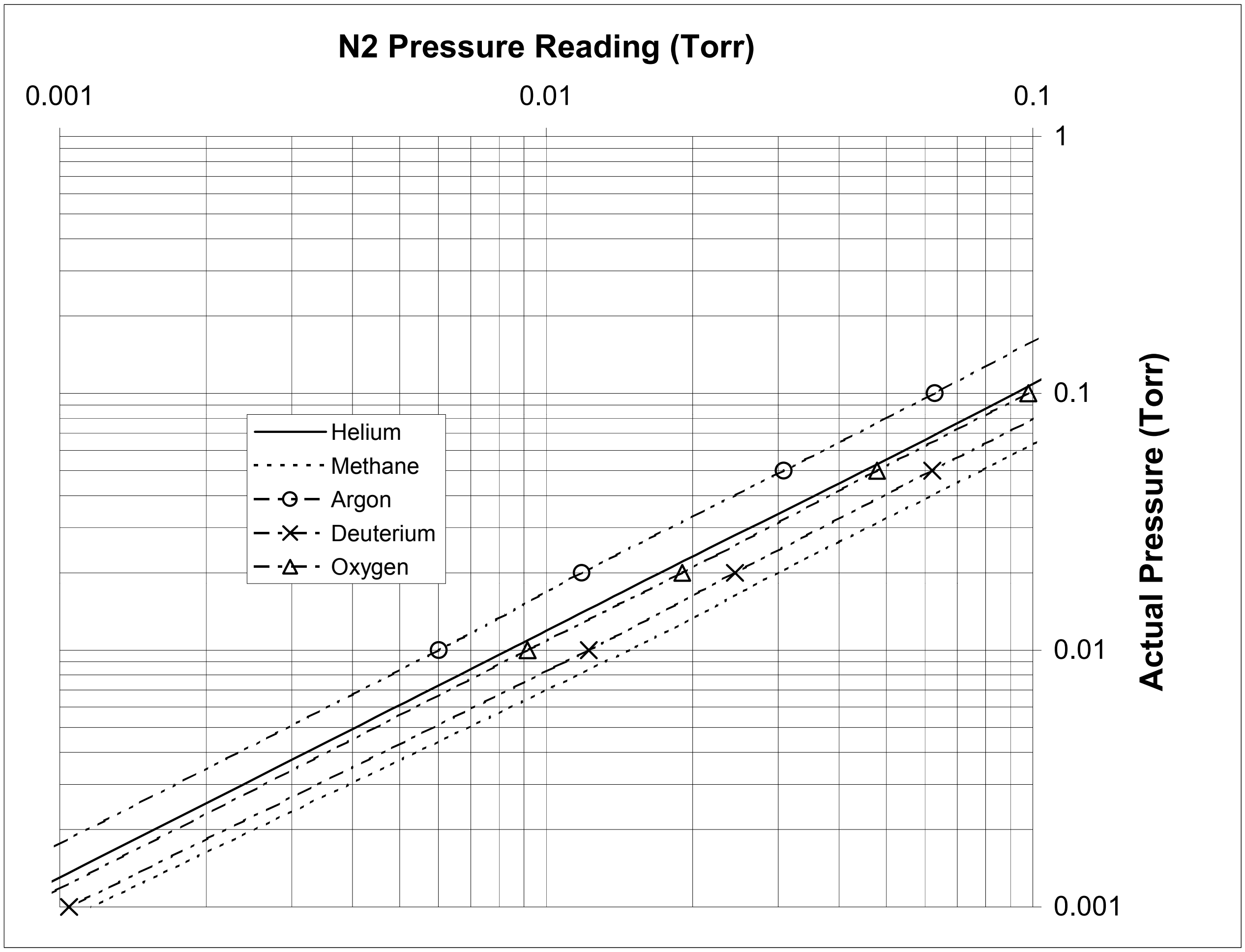


Figure I-1. PG105 Gauge Indicated Pressure (N_2 equivalent) vs. Actual Pressure Curve: 10^{-3} to 10^{-1} Torr.

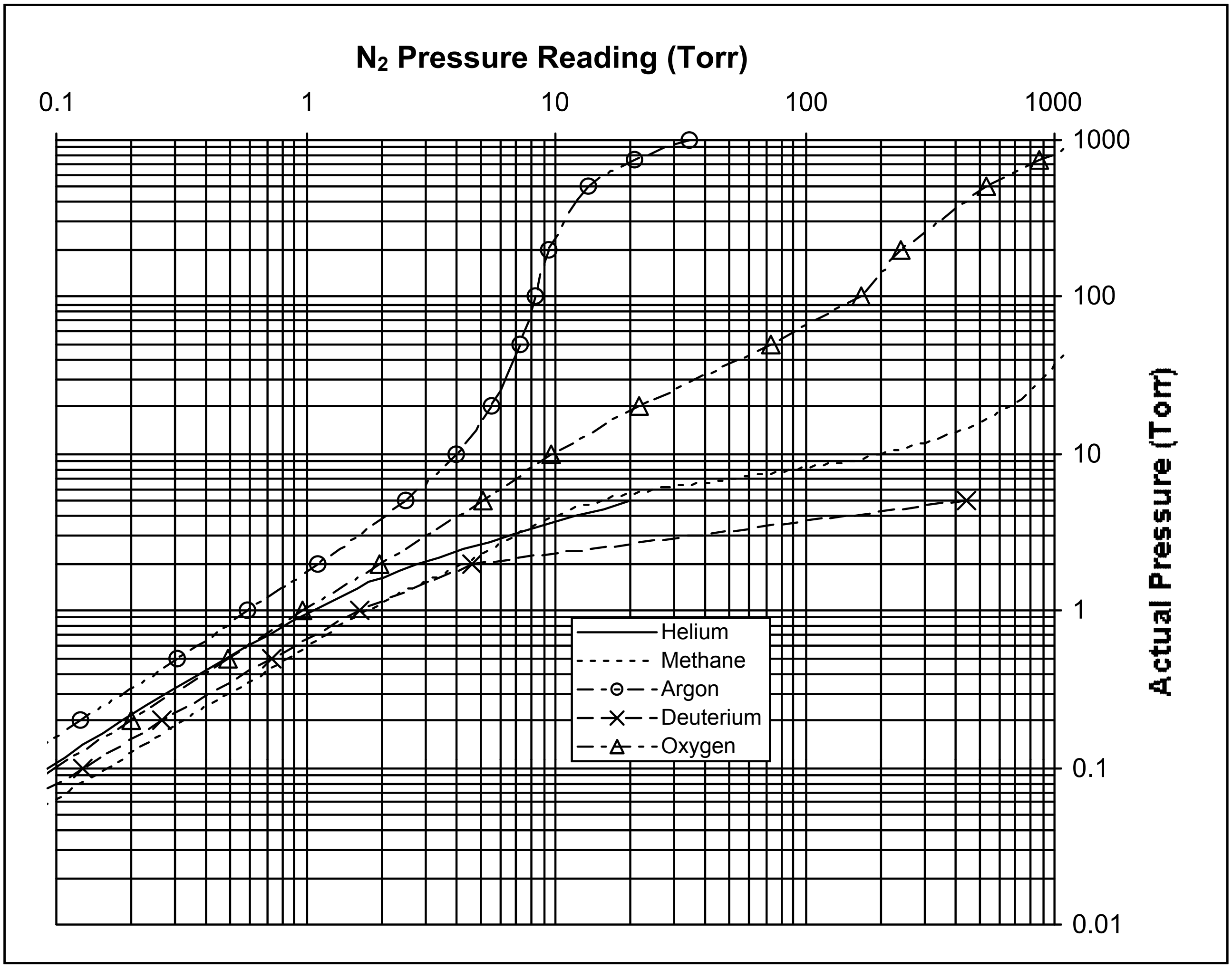


Figure I-2. PG105 Gauge Indicated Pressure (N2 equivalent) vs. Actual Pressure Curve: 10^{-1} to 1000 Torr. Use only when gauge axis is horizontal.

Nominal Gas Correction Factors for Figures I-1 and I-2.

Actual pressure = N_2 equivalent reading x K_g

(Use for pressures below 1 Torr only!)

Gas	K_g
Ar	1.59
He	1.10
Oxygen	1.03
Nitrogen	1.00
Deuterium	0.79
Methane	0.63

Overpressure risks

DANGER!

Using a PG105 convection gauge to backfill to atmospheric pressure should be avoided unless the gas-specific calibration curve for the backfilled gas is used to calculate and display pressures.

A serious danger can arise if the calibration data for one gas is applied without correction to measure pressures for a different gas (or gases) at or above atmospheric pressure. Argon provides an excellent example of how things can go very wrong. Applying the nitrogen calibration data to measure argon pressures provides a "nitrogen equivalent" reading of only ≈22 Torr when the gauge is exposed to an atmosphere of Argon gas (see Figure I-2). The chamber could be seriously pressurized while the gauge controller continues to display <100 Torr of nitrogen equivalent pressure. An oblivious operator, looking for a 760 Torr pressure reading, might continue to increase the gas pressure leading to the possibility of a dangerous explosion. Reports of accidents caused by this effect have appeared in the vacuum literature[2]. Accidents such as these can occur only if a thermal conductivity gauge is used to measure pressures at the upper end of the range where the calibrations for different gases diverge widely. This is the one reason why many vacuum practitioners reserve their convection gauges for measuring foreline and roughing line pressures, or *moderate* backfill pressures only!

At pressures below a few Torr the danger of using the nitrogen (or argon) calibration to measure the pressures of an uncalibrated gas (or gases) disappears. The only problem left is the inaccuracy of the readings. However, it is generally possible to correct pressure readings for uncalibrated gases using lookup tables, conversion curves and even simple correction factors .

TIP

With systems that could be potentially backfilled to excessive pressures by failure of gauges or regulator valves the inclusion of a pressure relief valve or burst disk is the safest way to avoid over pressurization!

References

[1] Consult R. E. Ellefson and A.P. Miller, "Recommended practice for calibrating vacuum gauges of the thermal conductivity type", J. Vac. Sci. Technol. A 18(5) (2000) 2568, for information on thermal gauge calibration and accuracy.

[2] R. Chapman and J. P. Hobson, J. Vac. Sci. Technol. 16 (1979) 965, D. G. Bills, J. Vac. Sci. Technol. 16 (1979) 2109.

Appendix J

PG105 vs. Thermocouple Gauges

The two most common thermal conductivity gauge technologies used in modern vacuum applications are Pirani gauges and thermocouple gauges.

This appendix is designed to help vacuum users choose between the two competing gauge technologies and decide when a pressure measurement setup based on TC gauges should be upgraded to PG105 convection gauges.

In This Appendix

Introduction

Pressure measurement in a thermal conductivity gauge is based on the transfer of heat from a hot wire, located inside the sensor, to the surrounding gases. Since gauge output depends on the thermal conductivity of the gases as well as their pressure, all thermal conductivity gauges provide indirect, gas-dependent, pressure readings.

The two most common thermal conductivity gauge technologies used in modern vacuum applications are:

Pirani Gauges

In the Pirani gauge (PG) the voltage required to maintain the hot wire at a constant temperature is *used as a non-linear, gas-dependent, function of pressure*. Traditional Pirani gauges provide useful pressure readings between 10^{-3} and 10 Torr. In convection-enhanced Pirani gauges, the upper range is extended upward to 1000 Torr by taking advantage of thermal convection currents created at the higher pressures.

Thermocouple Gauges

In the thermocouple gauge (TC) the pressure is indicated by measuring the small voltage of a thermocouple spot welded directly onto the hot wire. The wire is fed with a constant current and its temperature depends on the thermal conductivity and pressure of the gases present. TC gauges display useful pressures between 10^{-3} and 1 Torr.

TC gauges have long been regarded a cost-effective means to (1) monitor the foreline pressures of pumping stations and (2) as crossover gauges for vacuum systems in general. However, they are being systematically replaced in all modern vacuum systems by more accurate and reliable Pirani gauges, such as the PG105 convection-enhanced Pirani gauge manufactured by Stanford Research Systems.

This appendix is designed to (1) help vacuum users choose between the two competing gauge technologies and (2) decide when a pressure measurement setup based on TC gauges should be upgraded to PG105 convection gauges.

For additional information on this subject consult the following references:

1. J. M. Lafferty, "Foundations of Vacuum Science and Technology", section 6.8. "Thermal Conductivity Gauges", p. 403-414, Wiley-Interscience, 1998. A great book with lots of great information on almost every imaginable vacuum subject.

2. J. H. Leck, "Total and Partial Pressure Measurement in Vacuum Systems", Chapter 2., "Thermal Conductivity Gauges", p. 39, Blackie and Sons, Glasgow, 1989.

3. Stephen P. Hansen , "Pressure measurement and control in loadlocks", Solid State Technology, Oct. 1997, p. 151.

4. Simplify Rough Pumping with a Wide-Range Gauge", R&D Magazine, May 1999, p. 57.

5. J. Zettler and R. Sud, "Extension of thermocouple gauge sensitivity to atmospheric pressure", J. Vac. Sci. Technol. A6(3) (1988) 1153. Note: this is what it takes to make a TC tube extend into atmospheric pressures!

6. Vic Comello, "Using Thermal Conductivity Gauges", Back to Basics, R&D Magazine, Vol 39, Number 8, July 1997, p. 57 .

7. Vic Comello, "When to Choose a Thermocouple Gauge", Back to Basics, R&D Magazine, May 2000, p. 75.

Pressure Range Considerations

TC gauges deliver useful pressure readings between 10^{-3} and 10 Torr. Pressure readings above the upper limit are virtually useless, making it impossible, for example, to tell the difference between an overpressure condition caused by (1) a malfunctioning pump or (2) an accidental venting to ambient air by improper use of the foreline valves. While pumping down a system, a TC gauge cannot indicate if the pumps are working until pressures in the 1-10 Torr range are achieved and valid readings start to be displayed. This forces the operator to wait in front of the vacuum system until a reading of vacuum is obtained before being able to move on to something new!

PG105 convection gauges deliver useful pressure readings between 10^{-3} and 10^{3} Torr. This extended pressure range makes the PG105 convection gauge ideal for monitoring the pumpdown of vacuum systems from atmosphere to the base pressure of most mechanical pumps, without any blind pressure spots. Convection gauges are found in virtually every modern semiconductor and thin film process system, for monitoring pumping system performance. The vacuum operator gets an immediate indication of pumping action as soon as the pumpdown begins! Atmospheric pressure response is what makes convection gauges one of the most popular sensors found in loadlock systems. Most loadlocks must be open to atmosphere under a positive internal pressure of dry nitrogen or air to ensure a gentle flow of gas out of the chamber once the door is open. A convection gauge is often used to decide whether it is safe to open the gate and expose the loadlock chamber to air! Many users even combine their convection gauges with differential pressure devices called atmospheric pressure switches for added reliability. *Thermocouple gauges should definitely not be used to monitor the backfilling of loadlocks!*

WARNING!
Claims of TC Gauge readings extending to atmospheric pressures must be treated with extreme caution!

Modern oil-free high vacuum systems increasingly rely on hybrid turbo pumps backed by oil-free mechanical pumps. As the compression ratios of turbo pumps continue to increase so do the foreline pressures those systems require. Convection gauges are better suited to monitor pressures in modern turbo pumped systems. It is not uncommon to cold start a turbo pumped station from atmosphere and use a convection gauge to follow the pressure in the foreline from atmosphere to the base pressure of a diaphragm or scroll pump. The ultimate pressure of the mechanical (diaphragm) pump is one of the numbers that can be used to define if the system is properly pumped down.

With proper precautions, the PG105 lower range can also be extended further down into the 10^{-4} Torr decade, providing an amazing seven orders of magnitude of dynamic range from one gauge!

Response Times

Operation at constant wire temperature provides the PG105 convection gauge the advantage of a faster response to pressure transients. The response time is very fast (milliseconds in most cases) because components do not have to change temperature as pressure changes. Response time to a pressure step-function is pressure dependent, but it is roughly about an order of magnitude faster than in TC gauges.

Fast response time makes the PG105 convection gauge ideally suited for protective functions, as in determining when ionization gauge emission current should be deactivated or turned off. They are also well suited to control valves, heaters, bakeout ovens and safety interlocks.

Ion Gauge Auto Start

The IGC100 has a built in Auto-Start mode that makes it possible to automatically link the emission status of an ionization gauge to the pressure readings of a PG105 gauge exposed to the same vacuum environment. The ion gauge emission is immediately turned off as soon as the pressure goes above a user specified threshold value. This protects the filament from accidental burnouts. The emission is automatically reestablished as soon as the PG105 pressure readings goes below the threshold value, making it possible to automate pressure measurements from atmosphere down to UHV during pumpdown.

Remote Sensing

Compatibility with long cabling and immunity to electrical noise are important specifications for thermal conductivity gauges used in vacuum setups where the sensor must be placed far away from the controller.

The bridge circuit used to set the wire temperature is built right into the PG105 head, and the voltages are read using a Kelvin probe (4 wire) arrangement making them independent of cable length. Up to 150 m long cables can be used with PG105 gauges.

The output of the PG105 convection gauge is between 0.3 and 6 V as opposed to the much smaller, and noise sensitive, 1 – 15 mV levels that are delivered by thermocouple gauges.

Controller/Gauge Interchangeability

Thermocouple gauge tubes are made in about seven types that cannot be used interchangeably. A TC gauge controller must be matched to the gauge tubes for which it was built to assure accurate pressure measurements. Many manufacturers make tubes with compatible specifications.

TC Gauges are often differentiated by the filament current they require for their operation, and it is not unusual to need to fine tune the current delivered by the controller to the gauge to obtain accurate readings. Some TC tubes include a label with the recommended heater current required to obtain accurate pressure readings. Re-zeroing of the controller is recommended every time a new TC gauge tube is connected.

Following factory assembly, each PG105 gauge tube is individually calibrated for nitrogen, and temperature compensated between 10 and 40°C. After calibration each gauge tube is then individually tested to determine if selected pressure readouts fall within narrow limits before the unit is ready for shipment. Individual factory calibration of the gauge response provides true 'plug-and-play' convenience and eliminates the need to rezero the controller each time a new gauge tube is connected. PG105 gauges and IGC100 controllers are completely interchangeable without any need for instrument adjustments! In order to assure that calibration does not change with use, all gauge tubes are baked at high temperature for an extended period of time before final calibration takes place.

Contamination Resistance

Some widely used TC gauges utilize sensor wire temperatures of 250°C or higher at vacuum. Such high temperatures can cause pump oil to crack and leave carbon residues on the sensor which can then cause calibration shifts.

The temperature of the wire inside the PG105 gauge tube is approximately 120°C during operation. This temperature delivers optimal gauge response while, at the same time, remains low enough to minimize contamination by surface induced decomposition of foreign materials, such as pump-oil vapors. Contamination resistance provides enhanced accuracy, repeatability and long term stability compared to TC gauges.

UHV Compatibility

TC gauges are not compatible with UHV environments. Most of them include plastic feedthru headers and cannot be baked out.

The standard PG105 convection gauge uses a high-quality Viton® O-ring to seal the feedthru flange end of the tube, allowing maximum bakeout temperatures of 110°C (with the plastic connector detached). Metal gasket sealed gauge heads are also available, option PG105-UHV, that can be baked up to 250°C for more complete UHV compatibility. The metal gaskets used in all UHV enhanced gauge versions, are made out of OFHC Cu and belong to the Helicoflex Delta® family of high-performance compression metal seals, widely used for ultrahigh vacuum and ultrahigh purity applications. (Note: Helicoflex Delta® Seal is a registered trademark of Garlock Helicoflex, Columbia, SC)

Metal sealed gauge tubes, option PG105-UHV, are recommended for all ultrahigh vacuum and ultrahigh purity applications incompatible with the standard compression O-ring seal.

The all-metal interior construction of the PG105-UHV gauge makes it the best choice for applications requiring ultrahigh vacuum and/or ultrahigh purity compatibility. PG105-UHV gauges are often connected directly to high and ultrahigh vacuum chambers and used as cross-over gauges to protect the filaments of much more expensive ionization gauges.

Price/Performance Ratio

In relative terms, convection gauges are more expensive than most thermocouple gauges (about twice the price). However, in absolute numbers, the difference amounts to a very small extra cost that is usually insignificant relative to other recurring costs associated to the design and operation of a standard vacuum system.

Cost only plays a role in heavily contaminated systems, which require constant gauge replacements and do not rely on high accuracy pressure reports. A TC gauge might be the way to go in those applications. TC gauges are often preferred for dirty or corrosive processes because they are inexpensive enough to be thrown away when they become contaminated.

Freeze-Drying Processes

TCs are the gauge of choice in freeze drying operations because of the high water contents present during the drying processes. Pirani gauges do not fare as well in high humidity environments.

Leak Testing

Gas dependence makes the PG105 useful as an inexpensive leak detector. By using a tracer gas whose thermal conductivity is very different from the gases in the vacuum system, leaks as small as 10^{-4} atm cc/sec can be sensed and located. Typical gases used for leak testing include hydrogen, helium, argon and freon. This can eliminate the need for a very expensive leak detector. Several applications of Pirani gauges to leak detection have been reported in the vacuum literature.

Appendix K

Conversion Factors for Pressure Units

	Pascal	bar	mbar	μbar	Torr (mm Hg)	micron (mTorr)	atm	psi
Pascal	1	10^{-5}	10^{-2}	10	$7.5006 \cdot 10^{-3}$	7.5006	$9.8692 \cdot 10^{-6}$	$1.4504 \cdot 10^{-4}$
bar	10^{5}	1	10^{3}	10^{6}	750.06	$7.5006 \cdot 10^{5}$	0.98692	14.504
mbar	10^{2}	10^{-3}	1	1000	0.75006	750.06	$9.8692 \cdot 10^{-4}$	$1.4504 \cdot 10^{-2}$
μbar	10^{-1}	10^{-6}	10^{-3}	1	$7.5006 \cdot 10^{-4}$	0.75006	$9.8692 \cdot 10^{-7}$	$1.4504 \cdot 10^{-5}$
Torr (mm Hg)	$1.3332 \cdot 10^{2}$	$1.3332 \cdot 10^{-3}$	1.3332	1333.2	1	10^{3}	$1.3158 \cdot 10^{-3}$	$1.9337 \cdot 10^{-2}$
micron (mTorr)	0.13332	$1.3332 \cdot 10^{-6}$	$1.3332 \cdot 10^{-3}$	1.3332	10^{-3}	1	$1.3158 \cdot 10^{-6}$	$1.9337 \cdot 10^{-5}$
atm	$1.0133 \cdot 10^{5}$	1.0133	1013.3	$1.0133 \cdot 10^{6}$	760	$7.6 \cdot 10^{5}$	1	14.696
psi	$6.8948 \cdot 10^{3}$	$6.8948 \cdot 10^{-2}$	68.948	$6.8948 \cdot 10^{4}$	51.715	$5.1715 \cdot 10^{4}$	$6.8046 \cdot 10^{-2}$	1

How do you use this conversion table?

Example

Convert a pressure reading of 2.1 Torr into mbar units.

Start on the left side of the table and move down vertically until you reach the row labeled **Torr**. Move horizontally to the right along that row until you reach the 'Torr-to-mbar' conversion factor at the intersection with the **mbar** column. The conversion factor is 1.3332 (mbar/Torr). Multiply the pressure value expressed in Torr by this conversion factor to obtain the corresponding pressure value in mbar units –
2.1 Torr x 1.3332 mbar/Torr = 2.7997 mbar.

Appendix L

Dual Ionization Gauge Connector Box Option O100IG

The standard IGC100 controller can connect to, and display pressures from, only one ionization gauge. The Dual Ionization Gauge Connector Box (SRS Model # O100IG) is an optional component that, when attached to an IGC100, makes it possible to simultaneously connect two ionization gauges to the IGC100. An IGC100 properly fitted with the O100IG optional box can switch operation between two independent ionization gauges (i.e. sequential operation) from the front panel, and measure pressure at a first or second location (IG1 or IG2) at a small fraction of the cost of a second instrument.

The O100IG option is easily installed in the field making it easy to extend the capabilities of the IGC100 controller as needed.

In This Appendix

What does the Kit include?

The O100IG Option Kit includes all the components required to add a second ionization gauge connection port to your IGC100 controller. The basic package includes…

1. Dual Gauge Connector Box.
2. Connection Cable (connects O100IG box to IGC100 controller)
3. Mounting pins (for side mounting)
4. Fastening screw (for side mounting).
5. Instructions sheet.

Installation

IMPORTANT

For the most compact design and safest operation, SRS recommends you mount the O100IG box on the left side of the IGC100 controller as shown below in Fig. L-1. However, side mounting is not a requisite for the proper operation of the O100IG option (i.e. steps 1 –4 of the following installation procedure are optional).

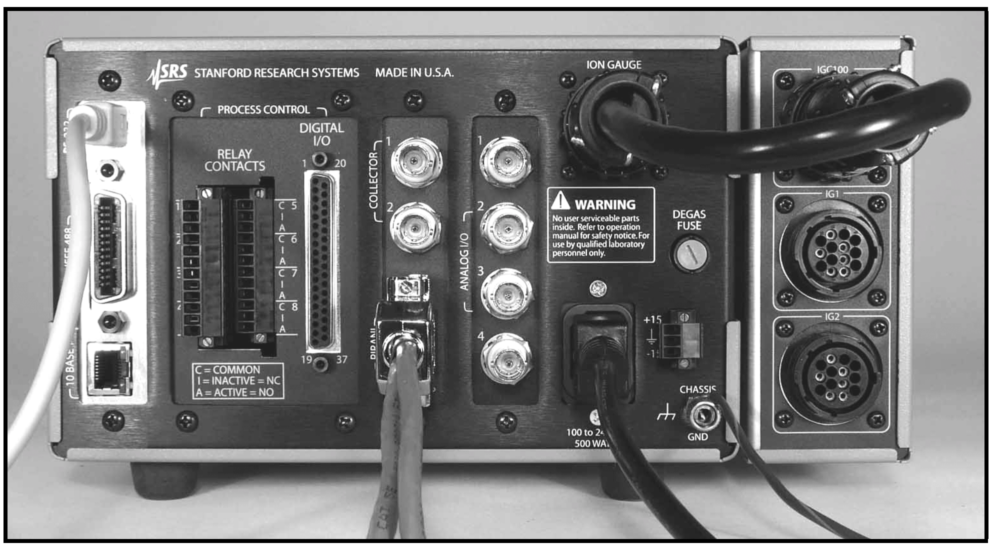


Figure L-1. Side Mounting configuration.

A few steps are required to complete a side mount installation…

Step 1

Working on the back end of the left side of the controller box, remove the top and bottom cover screws as shown in Fig. L-2. A #2 Phillips screwdriver is required.

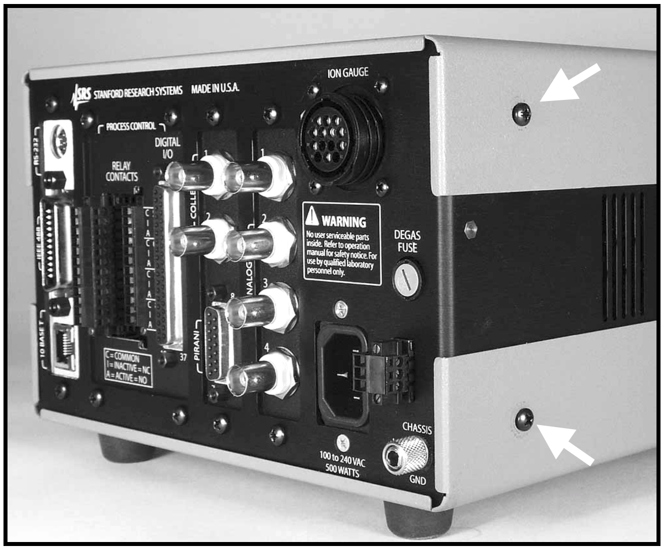


Figure L-2. Remove of the top and bottom cover screws from the back end of the left side of the IGC100.

Step 2

Replace the screws with the Mounting Pins included in the O100IGC Kit.

Figure L-3. Mounting pins in place.

Step 3

Mount the O100IG box on the left side of the IGC100. Insert the side pins into the round holes of the keyhole shaped slots located at the bottom of the O100IG box, and pull the box forward, towards the front of the controller, so that the box locks in place (i.e. the pins slide into the keyhole slots).

Step 4

Fasten the O100IG box to the side of the IGC100 controller using the Phillips screw included in the kit, as shown in Figure L-4.

Figure L-4. O100IG box must be fastened to the side of the IGC100 controller.

Step 5

Electrically connect the O100IG box to the IGC100 using the Connection Cable included in the kit. The male cable connector end attaches to the ION GAUGE port on the back of the IGC100, while the female cable connector end attaches to the IGC100 port on the O100IG Box. Figure L-5 shows a completed connection.

Figure L-5. Connect the IGC100 Ionization Gauge port to the O100IG Box.

Step 6

Connect the ionization gauges to the IG1 and IG2 ports of the O100IG box, using signal cables purchased directly from Stanford Research Systems. Connect the collector cable BNC connectors to the Collector ports labeled 1 (for IG1) and 2 (for IG2) on the back of the IGC100.The system is now fully configured for dual gauge operation and ready to go.

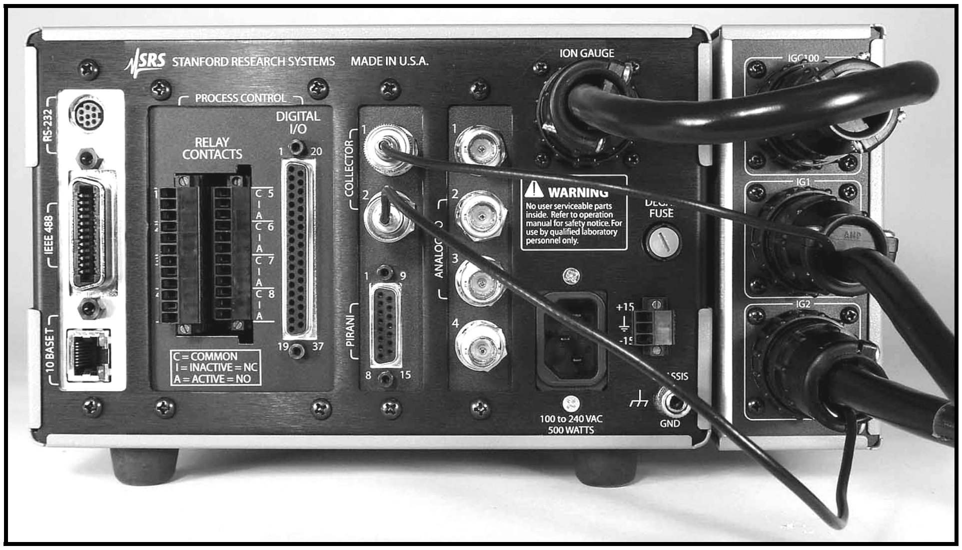


Figure L-6. An IGC100 with an O100IG option installed and two Ion gauges connected to its back panel. Decide up front which gauge you want to connect to the IG1 port and which one to the IG2 port.

Appendix M

Using MICRO-ION® Gauges

The IGC100 controller is compatible with Series 355 MICRO-ION® gauges manufactured exclusively by Granville-Phillips, Helix Technology Corp (Longmont, CO, USA, www.granville.com).

This appendix discusses the wiring details, parts and gauge setup parameters required to connect and operate a MICRO-ION® gauge (G-P Catalog 355001) with an IGC100 controller.

The data included here is based on information available directly from Granville-Phillips[1], as well as SRS's own experience with MICRO-ION® gauges. For further information, please contact Stanford Research Systems.

In This Appendix

Wiring Requirements

IMPORTANT

The ION GAUGE connector (female), located on the back of the IGC100, is **NOT** pin-compatible with the connector (male) found in all MICRO-ION® Gauge cables manufactured by Granville-Phillips. A cable adapter, SRS# O100CA1, is required to complete the connection.

1. Purchase the MICRO-ION® gauge (G-P Catalog 355001) and signal cable (G-P Catalog 358008, 358009 or 358010) directly from Granville-Phillips[2].
2. Purchase a MICRO-ION® cable adapter, SRS# O100CA1, directly from Stanford Research Systems.
3. Mount the MICRO-ION® gauge on your vacuum system following the manufacturer's recommendations.
4. Connect the O100CA1 cable adapter to the ION GAUGE connector[3] on the back plane of the IGC100 controller.
5. Connect the O100CA1 cable adapter to the MICRO-ION® signal cable.
6. Connect the collector cable BNC connector of the signal cable to the proper collector port (1 for IG1, and 2 for IG2) on the back of the IGC100.
7. Connect the gauge end of the MICRO-ION® signal cable to the gauge head.
8. Adjust the gauge setup parameters according to the directions of the next section.

Gauge Setup Parameters

The IGC100 Gauge Setup parameters must be properly adjusted to obtain accurate pressure readings with MICRO-ION® gauges.

The adjustments required for pressure measurement accuracy are

1. IG Calibration Source
2. N_2 Sensitivity Factor
3. Emission Current
4. Degas Power
5. Degas Time
6. Overpressure Threshold
7. Gauge Protection

The following settings are strictly based on manufacturer's recommendations[4] :

IG Calibration Source	N2 Sense Factor(1/Torr)
N2 Sense Factor	20/Torr (nominal)
Degas Power	3 Watts (max)
Degas Time	2 minutes (max)
Gauge Protection	Micro-Ion

Adjust the emission current and overpressure threshold settings taking into account the vacuum system pressure range:

Pressure Range	Emission Current	Overpressure Threshold	Default Setup File
1E-9 to 2E-4 Torr (1)	4 mA	2E-4 Torr	N.A.
1E-7 to 8E-4 Torr	1 mA	8E-4 Torr	N.A.
1E-6 to 5E-2 Torr	.02 mA	5E-2	MICRO

(1) X-ray limit is specified at $3x10^{-10}$ Torr.

Degas

Recommendation

Granville-Phillips recommends the use of both filaments during degas. The "Both" filament selection setting cleans up the tube more satisfactorily allowing for a lower ultimate pressure reading.

Warning

Do not touch the MICRO-ION® Gauge during degas operation. Burns can occur.

The IGC100 controller will not allow a degas process to start if the pressure at the gauge head is above $2x10^{-5}$ Torr. A rough pressure indication is displayed during the degas process. Degas power is carefully regulated during the entire process to minimize pressure bursts. Degas is completely shutdown if a pressure burst exceeding $5x10^{-5}$ Torr is detected at any time during the process.

The following recommendations should be observed while degassing MICRO-ION® gauges:

P > 10^{-5} Torr

If the pressure in the chamber (as measured at the MICRO-ION® gauge head) is above 10^{-5} Torr, perform a gauge and vacuum system bakeout instead of attempting an electron-bombardment degassing procedure. Degassing above 10^{-5} Torr is of little value and may (1) damage the filament and (2) cause pressure bursts that can cause an electrical discharge which can couple high voltage to the vacuum system hardware.

$5x10^{-7}$Torr < P < 10^{-5} Torr

Do not use the controller's Degas function while in this pressure range. Instead, outgas the MICRO-ION® gauge by operating the gauge in its normal operating mode with 4 mA of emission current for 2 minutes. Repeat this procedure as required until the desired base pressure is achieved. Degassing the gauge in this manner avoids the high electrode voltages used during a standard EB Degas. Due to its reduced size, the MICRO-ION gauge is very susceptible to high voltage electrical discharges during pressure bursts.

The normal operation of MICRO-ION® gauges with emission currents >4 mA is discouraged by its manufacturer[5].

P < $5x10^{-7}$Torr

Degas the MICRO-ION® gauge using the controller's built-in Degas function with a maximum of 3 W Degas Power and 2 minutes Degas Time settings. Do not exceed the recommended settings, since that may damage your gauge.

Bakeout

It is recommended to bake the gauge (and entire vacuum system if possible) in order to achieve an ultra-clean state. Recommended bakeout temperatures between 150ºC and 200ºC are usually adequate.

IMPORTANT

The gauge must not be baked above 200ºC. Remove the MICRO-ION® gauge cable from the gauge head when baking over 150ºC.

Gauge Protection

MICRO-ION® gauges are very compact, but still manage to include a dual filament assembly in their electrode structure. The dual ThO_2/Ir filament wires used for electron emission are very thin and require significantly less electrical power during operation (2V/2A normal, 2.3V/3A max) than standard ionization gauge filaments. As a result, the risk of overpowering is always present when MICRO-ION® gauges are connected to an ion gauge controller designed to operate standard ionization gauges.[6] Electrical overpowering will, in most cases, cause permanent damage to the filament wire.

The IGC100 controller includes a Gauge Protection function in its design which allows the user to limit the amount of power that can be safely delivered to a filament during operation. This Gauge Protection feature is gauge specific and intended to reduce the chances of filament burnouts when using gauges with delicate filaments, such as MICRO-ION® gauges.

To activate this protection for MICRO-ION® gauges, set the Gauge Protection (in the Advanced Gauge Setup menu) to Micro-Ion before operating a MICRO-ION® gauge. The MICRO-ION® protection is also set when the MICRO-ION® Default Setup is loaded.

IMPORTANT
Set the Gauge Protection to Micro-Ion when operating MICRO-ION® gauges with the IGC100 controller.

Accuracy

No independent studies on the accuracy and long-term stability specifications of MICRO-ION® gauges have been reported to date. Stanford Research Systems has used MICRO-ION® gauges in several applications, but no systematic study of their accuracy, gauge-to-gauge reproducibility and long-term performance has been conducted. MICRO-ION® users should contact Granville-Phillips directly for gauge accuracy information. Long term studies and systematic comparisons against standard Bayard-Alpert designs will be required to confirm the utility of these new gauges.

References

[1] Technical Notes #013606 and 355004, and Series 358 Vacuum Gauge Controller Instruction Manual (G-P Catalog#358013), Granville-Phillips, Helix Technology Corporation, Longmont, CO, USA, 1998, U.S. patent 6,198,105.

[2] Contact Granville-Phillips at: www.granville.com.

[3] Connect the cable adapter to the IG1 or IG2 port of the Dual Ion Gauge Connector Box, when connecting to an IGC100 with an O100IG option.

[4] Stanford Research Systems is not responsible for changes in design or specifications of third-party products that might render them incompatible with these recommendations and/or the IGC100 controller.

[5] Private communication from Granville-Phillips, Helix Technology Corporation, Longmont, CO, USA.

[6] For example, the gauge manufacturer (Helix Corporation, Longmont, CO) offers a cable adapter module (G-P part# 355002) to connect MICRO-ION® gauges to its standard ionization gauge controllers that limits the filament current to 3A.

Appendix N

Circuitry and Parts Lists

In This Chapter

Warnings

- **Read and follow all 'Safety and Preparation for Use' warnings before handling this product (see front of this manual).**
- Dangerous voltages, capable of causing injury or death, are present in this instrument. Use extreme caution whenever troubleshooting any of its parts.
- Do not substitute parts or modify the instrument. Do not use the product if it has unauthorized modifications. Return the product to Stanford Research Systems for service and repair to ensure that safety features are maintained.
- Use only SRS supplied replacement/accessory parts.
- The IGC100 controller does not have any serviceable parts other than the Degas Fuse.
- Consult the 'Damage Requiring Service' section at the end of this chapter for instructions on how to return the instrument for authorized service and adjustment.

Circuit Board Locations

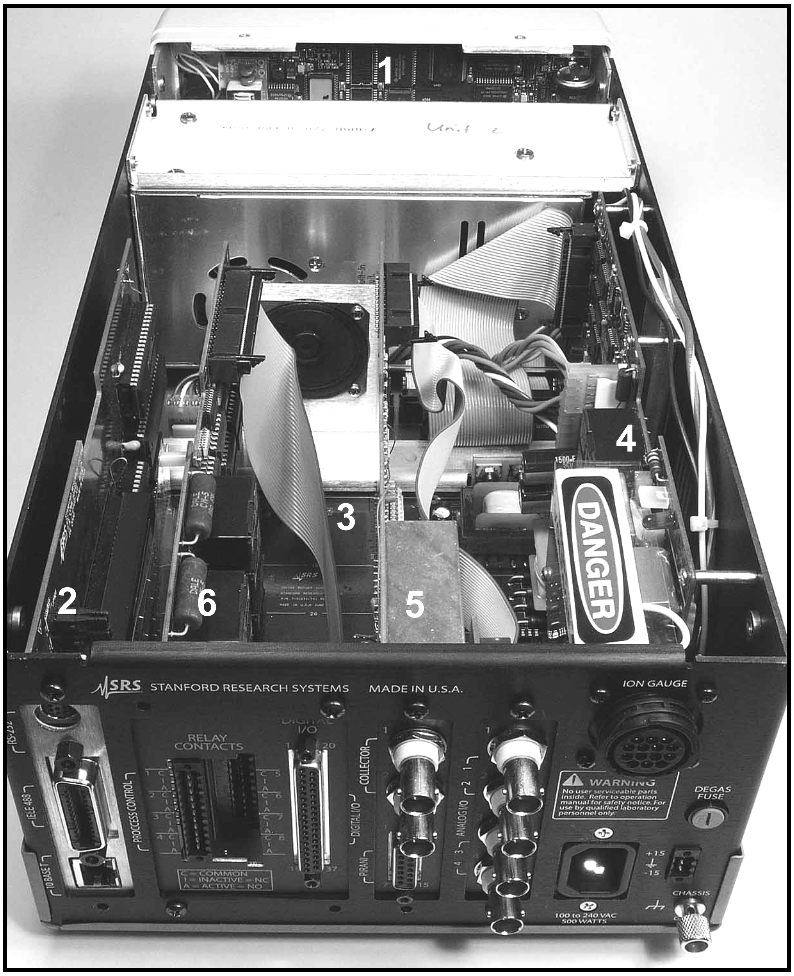


Figure N-1. Circuit board locations inside the IGC100 (rear view).

Circuit Boards

The IGC100 has six main printed circuit boards shown above.

1. CPU board
2. Communications board
3. Motherboard
4. High Voltage Power Supply board
5. Gauge Board
6. Process Control board (optional)

Circuit Descriptions

CPU Board

Overview

The CPU board contains the main microprocessor system. CPU memory, front panel and serial interfaces are on this board. An off-board data bus is driven from this board via connectors J601 and J602. This bus connects to the Motherboard via ribbon cables. These cables also bring Vcc power to the CPU board.

Microprocessor System

The microprocessor, U101, is an 80C186XL (or 80C186EA) microcontroller which integrates a fast 16-bit processor, counter-timers, interrupt controller, DMA controller and I/O decoding into a single component.

The 80C186 is clocked at 40.00 MHz by crystal oscillator U102. The external clock period is 2 oscillator cycles or 20.0 MHz. The data and lower 16 bits of address are multiplexed on processor lines AD0-AD15. U201, U202, U203 latch the address A0-A19 at the beginning of each memory or I/O cycle. U204 and U205 are bi-directional data bus drivers which are active during the data read/write portion of each memory or I/O cycle. U201-U205 provide the on-board System bus.

Memory Map

The 80C186 can address 1 Mbyte of memory and 64k of I/O space. U301 is a 512 kbyte flash EPROM mapped from 80000H to FFFFFH. U302-U303 are 128 kbyte CMOS static RAMs mapped from 00000H to 3FFFFH (256 kbytes). Locations U305 and U306 are not used.

I/O Map

U206, U207 and U213 are the bus drivers for the off-board I/O bus. U208 enables the correct bus drivers depending upon the I/O address space being accessed. All memory accesses and on-board I/O use the System bus.

The 80C186 generates 7 peripheral chip select strobes, each covering 128 byte I/O addresses. -PCS0 enables the LCD controller U401. -PCS1 enables the UART U501. -PCS2 through –PCS6 enable individual boards plugged into the Motherboard.

U208 and U212 decode on-board I/O and memory.

Interrupts generated by the UART and the Communications board are routed directly to the microprocessor.

U507 is the clock/calendar.

Front Panel

U401 is the LCD controller. U401 generates the timing signals for the front panel LCD. U402 and U403 are 32 kbyte static RAMs which contain the screen information. This memory is mapped to processor memory starting at location 40000H.

U405 is a switching power supply to generate the LCD bias voltage. U406 is an inverter to power the LCD backlight.

U404 is the touchscreen controller. U404 senses the location of a touch and reports the X and Y location to the microprocessor.

Latches U503-U508 are used to read the front panel buttons, turn on the front panel LEDs and control various on-board peripherals.

Communications Board

Serial Port

The Communications board passes the connections from the UART on the CPU board to the serial DIN connector (JP103) on the back panel.

GPIB Port

If the GPIB option is installed, a NAT9914 (U101) provides the GPIB interface.

Web Server

If the Web Server option is installed, a web controller module (U109) provides the ethernet interface as well as the web server. U109 communicates with the IGC100 via 2 serial ports provided by dual UART U105.

Jumpers identify which options are available in the unit.

Mother Board

The Motherboard provides the necessary CPU power, regulated 5 V (Vcc) and unregulated ±20 V, for the entire IGC100 while accommodating the Gauge Board, Process Control Board and the Communication Board.

In the power generation section, the primary of transformer T22 is operated from the +24 Vdc supply and is driven differentially by a pair of IRF530 MOSFETs (Q211 and Q212). An SG3525 switching controller, U21, is used to drive the FET gates. Since a reference voltage of 5.1 V (from pin 16) is supplied to the COMP pin (pin 9) the controller is set to run freely at a switching frequency of 120 kHz. The voltage developed at the sense resistor R214 is fed to the shutdown pin (pin 10) on U21 as a hardware safety precaution. When the voltage on this pin goes higher than 1 V U21 is shut off on by pulse-by-pulse basis. A snubber circuit (R221 and C222) is used to damp the transient, which occurs when a FET is turned off.

On the secondary side of the transformer there are two secondary windings to generate Vcc (5 V) and ±20 V. Two full wave bridge rectifiers (with Schottky diodes D221 through D228) are used to generate final 5 Vdc and ±20 Vdc. U23 is used to generate the regulated 5 Vdc as the Vcc supply for the entire gauge controller.

High Voltage Power Supply Board

Overview

The High Voltage Power Supply (HVPS) board provides the high voltages and high currents necessary to operate ion gauges. In the normal mode of operation, ion gauges require steady grid voltages and filament heater power. In addition, the IGC100 is capable of supplying 1.5 W to power capacitance manometers (AUX Power). The HVPS board contains the circuitry for the filament heater power, grid voltage, emission current control, analog power for the board, and a digital interface.

Filament Power Supply

Stable filament power is one of the key factors required to operate an ion gauge reliably. The filament emission current is controlled by regulating the filament temperature via the filament heater current's duty cycle. A 120 kHz switching power supply is used to power the filament heater. The transformer T12, driven by PWM U11, produces 8 Vmax output stepping down from 24 V. This transformer is capable of supplying 64 W (max) power to the filament heater depending upon the emission current setting. The output of the transformer is rectified by two Schottky diodes D121.

The primary of the transformer is operated from the +24 Vdc supply and is driven differentially by the pair of IRF530 MOSFETs (Q111 and Q112). An SG3525 switching controller, U11, is used to drive the FET gates. The duty cycle of the gate drive depends on the voltage at the COMP pin (pin 9). A voltage of about 0.9 V or below will set the duty cycle to zero. A snubber circuit (R122 and C122) is used to damp the transient, which occurs when a FET is turned off.

The voltage at the (COMP pin 9) on U11 is controlled according to the required emission current via opamp U14. The values of the closed loop compensating network components C131, R132 and C132 have been set to establish the best loop stabilization during both normal and degas operations. The analog switch U15A is used as an On/Off switch to turn on and off the ion gauge. Closing the switch (5 V at pin 1 of U15) is equivalent to switching off the gauge since the output of U14 drops to zero volts.

The primary side current is passed through a 0.01Ω sense resistor (R126). The voltage (with reference to 24 Vdc return) across this resistor is amplified by a differential amplifier, U13A, and read by the CPU via mux U51 and the 8-bit analog to digital converter, U52. The duty cycle of the gate drivers are measured at C127 in terms of voltage and is read by the CPU via U51 and U52. By reading the duty cycle and the primary current, the CPU can detect if there is any malfunction in the ion gauge filament.

On the secondary side of transformer T12 there is a snubber circuit (R121 and C123) to suppress the transient, which occurs when a FET is turned off. The components L122, C124, and C125 act as a LC filter for the DC output which drives the filament heater.

Grid Power Supply

The grid power operates very similarly to the heater power supply with the major difference being the generation of high voltages instead of high currents. During degas, ion gauges require 500 Vdc to be applied to the grid. During normal operation, the grid should have a steady 180 Vdc. In addition, the grid power supply should be able to supply sufficient current as the emission current in various settings. The highest emission current that the IGC100 can deliver is approximately 160 mA during degas. Therefore the grid power supply should be able handle up to 80 W of power.

The primary of the transformer, T24, is operated from the +24 Vdc supply and is driven differentially by a pair of IRF530 MOSFETs (Q231 and Q232). An SG3525 switching controller (U23), running at 120 kHz, is used to drive the FET gates. The duty cycle of the gate drive depends on the voltage at the COMP pin (pin 9). A voltage of about 0.9 V or below will set the duty cycle to zero.

The voltage at the (COMP pin 9) on U23 is controlled according to the required grid voltage. During normal operations the grid voltage is 180 V and during degas it is 500 V. The voltage divider resistors R242 and R244 generate the feedback voltage and is fed to the input of the opamp U22B via R227. In addition, the feedback voltage is read by the CPU via U51 and U52 periodically to make sure the grid the voltage has the expected value. The output of opamp U22B is switched between two values during normal and degas conditions depending on voltages set by GRID_SET_1, GRID_SET_2 and the output of the opamp U22A. The analog switch U15B is used to switch the output of the opamp U22A between –2.5 V and –6.94 V (normal and degas settings). The values of the closed loop compensating network components C221, R225 and C222 have been set to establish the best loop stabilization during both normal and degas operations.

The grid power supply circuit has two on/off switches, U25A and U27A. Similar to filament heater power supply, U15B is an analog switch, which will be in the closed position (HIGH on pin 6) to ensure that the output of opamp 22B (and COMP pin on U23) is at zero volts. The second switch, U27, is a D-flip flop which will pull pin 5 up (HIGH) or down (LOW) depending on PR signal on pin 4 and CL signal on pin 1. Pin 5 (D) on U27 is connected to the shutdown pin (pin 10) on the switching controller U23. When the voltage on this pin goes higher than 1 V U23 is shut off on a pulse-by-pulse basis. As long as this pin is pulled high (by pin 5 on U27) the grid power supply is switched off. LED D271 shows the status of shutoff pin on U23.

The primary current is passed through the 0.01Ω sense resistor R245. The voltage (with reference to 24 Vdc return) across this resistor is compared (using U26) with a preset value at the voltage divider (R262 and R263) and generates a clock signal at the output of the comparator. If the primary current exceeds a predetermined value defined by the voltage divider, a high clock signal is generated and the grid power supply will be switched off.

On the secondary side of transformer T24 there is a full wave bridge rectifier with four Schottky diodes (D214, 242, 243 and 244). R241 and C242 act as an output filter for the grid supply voltage. LED D245 shows the status of the grid voltage even if the fuse F241 is blown out.

Emission Control Circuit

One of the most sensitive circuits in the HVPS board is the emission control circuit. The IGC100 emission current has a tolerance of ±0.03% or better. The emission control circuit has two sections.

In the first section the 30 V bias voltage (to bias the filament) is generated by regulating down from 180 V/500 V. A MOSFET IRF530 (Q311), opamp U31, voltage divider R312 and R316 are used to generate the bias voltage. The grid voltage is sensed at the voltage divider and compared with a preset value at the inputs of U31. The FET Q311 and its feedback network maintain the bias voltage at 30 V within the required tolerance. The filament is kept at this bias voltage by connecting the filament return to the drain of the FET Q311.

In the second section, the emission current which is generated at the grid and coming to the HVPS board via the filament return, is fed into the emission current control circuit via Q311. Under normal operation the switch U32 is off and the incoming emission current goes through an I-V converter (U31, R336, R318 and R341). The resulting voltage is compared with a preset value generated by a 20-bit DAC U35 and is fedback to the filament heater control circuit at the output of opamp U34 to supply heater power.

The emission control circuit has three different gain settings. The three resistors in the I to V converter (R336, R314 and R318) and analog switches are used to select the required gain setting. The opamp U13D, resistors R1393, R1395, R1392, R1394 and D132 give a diagnostic voltage output for the emission current. This voltage may be read by the CPU for further processing.

Power Supplies

The HVPS board is operated from ±20 V and Vcc (+5 V) supplied from the motherboard through J72. The on board ± 15 V regulators (U76 and U66) generate most of the power used on this board. In addition, other miscellaneous power such as ±15 V (AUX) and ±2.5 V reference are generated from U74, U75, and U78. Required Vcc is directly supplied from the motherboard via the J72 connector.

Digital Interface

In the digital interface circuitry there are two CMOS decoders (U61 and U62), one octal latch with 3-state output (U63) and three octal 3-state non-inverting D flip-flops (U64, U65, U66). U61 and U62 are mainly used to generate Out Enable signals for the octal latch and the D-flip flops. The board ID is generated on U63 and latched out to the CPU when it is requested. Similarly all the other data are latched into the HVPS board from the CPU board via octal 3-state non-inverting D flip-flops (U64, U65 and U66).

Gauge Board

Overview

The Gauge Board is the most important circuit board when it comes to measuring pressures. The pressure measurement is done by two different circuits depending on the type of gauge used. The Gauge Board consists of five different sections, namely the I to V converter, Pirani Gauge electronics, Analog to Digital I/O circuitry, Digital Interface Circuitry, and Board Power Supplies.

When measuring pressure using an ion gauge, a minute ion current, which is a function of pressure, is generated by the ion gauge and fed into the gauge board. The first section of the Gauge Board is a very sensitive electrometer that measures the incoming ion current through an I to V converter. The I to V converter has three different gain stages to handle pressures ranging from 10^{-2} to 10^{-11} Torr. The resulting voltage is then converted to a digital signal by a 24-bit analog to digital converter. The digitized signal is sent to the CPU board for further processing and displayed as pressure on the LCD Display.

In the Pirani gauge circuit, the gauge bridge voltage, which is a function of pressure in the range of 1000 to 10^{-4} Torr, is measured and converted to a digital signal by a 14-bit analog to digital converter. The digitized signal is sent to the CPU board for processing and displaying on the LCD screen.

In addition to measuring pressure, the gauge board has circuitry for four analog I/O channels. The low voltage power required for the Gauge Board is produced by on board power circuitry.

Ion Current

The front end of the Gauge Board has two separate input BNCs to convert ion current from two different ion gauges (sequentially) to a voltage signal. Both these inputs share one electrometer unit. The most sensitive part of the entire instrument is the I to V converter of the electrometer unit. The electrometer has circuitry for four different gain stages including an Ultra-Low Input Current op amp LMC6001. Depending on the ion current, each stage is selected by applying a HIGH signal from the CPU to three different solid-state relays U17, U13, and U14. The relays U11 and U12 act as on and off switches to select ion current between two gauges sequentially. Switches U111 and U121 are used to ground the input signal during auto zero cycles. The resulting positive voltage at the output of U16 (high precision op amp) is converted to a digital signal by a 24-bit A to D (U31) and is sent to the CPU board via U54. The hex inverter U18 is used as to buffer the SCK and F0 inputs of the LTC 2400 24-bit A to D converter. JP181 selects the filtering of the 50/60 Hz line frequency. The LTC 2400 internal oscillator provides better than 110 dB normal mode rejection at the line frequency and all its harmonics for 50 and 60 Hz (within 2%). For 60 Hz rejection pin 8 should be at ground and for 50 Hz rejection pin 8 should be at +5 V.

Pirani Bridge Voltage

The Pirani gauge section consists of two identical circuits to drive two gauges simultaneously. The bridge circuit inside the gauge is connected to the pin 3,4,7 and 8 of

DB15 connector (P21). The bridge is balanced and driven by U21A and the gauge power can be switched off or on by U23. The bridge voltage is measured by U21B via a 4-wire connection through pin 3 and 8 of P21 connector. The resistor R244 measures the bridge current and the resulting voltage is digitized via mux U34. Once the power is gently applied through R217 to the gauge the U21A opamp will begin to control the power through Q232 properly. The output of U21B, the bridge voltage which represents the pressure, is sent to U32 (14 bit A to D) via mux U34.

Analog I/O

The Gauge Board also has four Analog Inputs/Output BNCs. The analog outputs are generated by a four channel 12 bit DAC (U42). The DAC output from each channel is amplified with a gain of 5.2 to produce the required analog output up to 12 V. Similarly, the analog input is attenuated by U43 and is fed into a 14-bit analog to digital converter (U32) via MUX U34. The analog inputs and outputs are able to share the same BNCs by using a CMOS analog switch U44.

Digital Interface

In the digital interface circuitry there are two CMOS decoders (U51 and U52), one octal latch with 3-state output (U54) and three Octal 3-state non-inverting D flip flops (U53, U55, U56). U51 and U52 are used mainly to generate Out Enable signals for U53, U54, U55 and U56. The board ID generated on U54 is latched out the CPU when it is requested. Similarly all the other data are latched into the gauge board from the CPU board via Octal 3-state non-inverting D flip flops (U53, U55 and U56).

Power Supplies

The gauge board is operated from ±20 V and Vcc (+5 V) supplied from the motherboard through the J51 Euro card 96 pin connector. The on board ± 15 V regulators (U61 and U62) generate most of the power used on this board. In addition, other miscellaneous power such ±7.5 V and ±5 V are regulated from U63, U64, U65 and U66. Required Vcc is supplied directly from the motherboard via J51 connector.

Process Controller Board

The Process Control Board has electronics for 12 remote TTL inputs, 8 process control inputs, 8 TTL outputs and 8 relay outputs. All TTL inputs and outputs are optically isolated with a photo coupler LTV847S.

The status of each TTL input is latched out to the CPU via with 3-state output (U53, U54 and U55). Each TTL output is buffered with an inverting octal buffer U33. In the relay output section, the status byte of the each relay is generated at the DPDT relay (using the 2nd pole). The status of the relay is latched out to the CPU via U56 and U57. The activation signal (from the CPU) for each relay is latched into the process controller board via octal 3-state non-inverting D flip-flop U58. The board ID generated on U54 and latched out to the CPU when requested.

Parts Lists

Parts lists for all of the circuit boards are listed in the following sections. Schematic diagrams follow the parts lists.

CPU Board

CPU Board			
Ref No.	SRS Part No.	Value	Component Description
BT201	6-00534-612	CR2032/1GV	Battery
C 101	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 102	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 103	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 104	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 401	5-00369-552	33P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 402	5-00369-552	33P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 410	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 411	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 412	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 413	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 430	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 431	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 432	5-00518-569	15U/T35	Cap, Tantalum, SMT (all case sizes)
C 433	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 434	5-00520-569	4.7U/T35	Cap, Tantalum, SMT (all case sizes)
C 435	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 450	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 501	5-00368-552	27P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 502	5-00368-552	27P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 510	5-00543-568	.33UF 25V	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 511	5-00407-552	.047U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 512	5-00543-568	.33UF 25V	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 513	5-00543-568	.33UF 25V	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 514	5-00543-568	.33UF 25V	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 650	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 651	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 652	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 653	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 654	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 655	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 656	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 657	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 658	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 659	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 661	5-00393-552	3300P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 662	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 664	5-00522-569	47U/T10	Cap, Tantalum, SMT (all case sizes)
C 670	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 671	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 672	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 673	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 690	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
D 201	3-00806-360	BAV170LT1	Integrated Circuit (Surface Mount Pkg)
D 430	3-00926-360	MBR0540T1	Integrated Circuit (Surface Mount Pkg)
D 501	3-00010-303	GREEN	LED, T1 Package
D 502	3-00010-303	GREEN	LED, T1 Package
D 503	3-00010-303	GREEN	LED, T1 Package
D 504	3-00010-303	GREEN	LED, T1 Package

CPU Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
D 505	3-00010-303	GREEN	LED, T1 Package
D 506	3-00010-303	GREEN	LED, T1 Package
D 507	3-00010-303	GREEN	LED, T1 Package
D 508	3-00010-303	GREEN	LED, T1 Package
D 509	3-00009-303	YELLOW	LED, T1 Package
D 510	3-00010-303	GREEN	LED, T1 Package
D 511	3-00011-303	RED	LED, T1 Package
D 513	3-00010-303	GREEN	LED, T1 Package
D 514	3-00010-303	GREEN	LED, T1 Package
D 515	3-00011-303	RED	LED, T1 Package
D 520	3-00806-360	BAV170LT1	DUAL DIODE COMMON CATHODE
J 401	1-00078-130	4 PIN SI	Connector, Male
J 402	1-00522-179	FFC 12CKT	Connector Housing, Receptacle
J 403	1-00515-130	2 PIN HEADER	Connector, Male
J 502	1-00531-100	MICRO-MATK RECP	Connector, Misc.
J 601	1-00529-130	50 PIN ELH VERT	Connector, Male
J 602	1-00530-130	40 PIN ELH VERT	Connector, Male
L 430	6-00519-609	22UH - SMT	Inductor, Fixed, SMT
N 101	4-01616-463	3.3KX8D	Resistor network, SMT, Leadless
N 102	4-01616-463	3.3KX8D	Resistor network, SMT, Leadless
N 201	4-01617-463	82X8D	Resistor network, SMT, Leadless
N 202	4-01617-463	82X8D	Resistor network, SMT, Leadless
N 203	4-01617-463	82X8D	Resistor network, SMT, Leadless
N 205	4-01617-463	82X8D	Resistor network, SMT, Leadless
N 501	4-01616-463	3.3KX8D	Resistor network, SMT, Leadless
N 503	4-01618-463	330X8D	Resistor network, SMT, Leadless
PC1	7-00858-701	IGC CPU	Printed Circuit Board
Q 201	3-00580-360	MMBT3906LT1	Integrated Circuit (Surface Mount Pkg)
Q 401	3-00580-360	MMBT3906LT1	Integrated Circuit (Surface Mount Pkg)
Q 402	3-00966-360	IRF7103	Integrated Circuit (Surface Mount Pkg)
R 201	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 202	4-01453-461	82	Thick Film, 5%, 200 ppm, Chip Resistor
R 203	4-01453-461	82	Thick Film, 5%, 200 ppm, Chip Resistor
R 301	4-01491-461	3.3K	Thick Film, 5%, 200 ppm, Chip Resistor
R 401	4-01551-461	1.0M	Thick Film, 5%, 200 ppm, Chip Resistor
R 410	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 411	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 412	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 413	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 414	4-01527-461	100K	Thick Film, 5%, 200 ppm, Chip Resistor
R 420	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 421	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 431	4-01527-461	100K	Thick Film, 5%, 200 ppm, Chip Resistor
R 432	4-01527-461	100K	Thick Film, 5%, 200 ppm, Chip Resistor
R 433	4-01521-461	56K	Thick Film, 5%, 200 ppm, Chip Resistor
R 434	4-01521-461	56K	Thick Film, 5%, 200 ppm, Chip Resistor
R 435	4-01551-461	1.0M	Thick Film, 5%, 200 ppm, Chip Resistor
R 436	4-01524-461	75K	Thick Film, 5%, 200 ppm, Chip Resistor
R 437	4-01355-462	301K	Thin Film, 1%, 50 ppm, MELF Resistor
R 450	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 501	4-01551-461	1.0M	Thick Film, 5%, 200 ppm, Chip Resistor
R 511	4-00065-401	3.3K	Resistor, Carbon Film, 1/4W, 5%
R 512	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 520	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 521	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 522	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 523	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 524	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 530	4-01467-461	330	Thick Film, 5%, 200 ppm, Chip Resistor

CPU Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
R 531	4-01467-461	330	Thick Film, 5%, 200 ppm, Chip Resistor
R 532	4-01467-461	330	Thick Film, 5%, 200 ppm, Chip Resistor
R 533	4-01467-461	330	Thick Film, 5%, 200 ppm, Chip Resistor
R 534	4-01467-461	330	Thick Film, 5%, 200 ppm, Chip Resistor
R 535	4-01467-461	330	Thick Film, 5%, 200 ppm, Chip Resistor
R 601	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 602	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 610	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 611	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
SO101	1-00108-150	PLCC 68 TH	Socket, THRU-HOLE
SW500	2-00050-201	E-SWITCH BLCK	Switch, Momentary Push Button
SW501	2-00050-201	E-SWITCH BLCK	Switch, Momentary Push Button
SW502	2-00050-201	E-SWITCH BLCK	Switch, Momentary Push Button
SW503	2-00050-201	E-SWITCH BLCK	Switch, Momentary Push Button
SW504	2-00051-201	E-SWITCH RED	Switch, Momentary Push Button
U 101	3-01439-360	80C186XL-25	Integrated Circuit (Surface Mount Pkg)
U 102	6-00586-626	50.0MHZ 100PPM	Crystal, SMT
U 201	3-00790-360	74ACT573	Integrated Circuit (Surface Mount Pkg)
U 202	3-00790-360	74ACT573	Integrated Circuit (Surface Mount Pkg)
U 203	3-00790-360	74ACT573	Integrated Circuit (Surface Mount Pkg)
U 204	3-00928-360	74ACT245	Integrated Circuit (Surface Mount Pkg)
U 205	3-00928-360	74ACT245	Integrated Circuit (Surface Mount Pkg)
U 206	3-00928-360	74ACT245	Integrated Circuit (Surface Mount Pkg)
U 207	3-00790-360	74ACT573	Integrated Circuit (Surface Mount Pkg)
U 208	3-00460-343	22V10-25	GAL/PAL, I.C.
U 209	3-00930-360	MAX693ACSE	Integrated Circuit (Surface Mount Pkg)
U 210	3-00929-360	74ACT32	Integrated Circuit (Surface Mount Pkg)
U 211	3-00790-360	74ACT573	Integrated Circuit (Surface Mount Pkg)
U 212	3-00405-343	16V8-15	GAL/PAL, I.C.
U 213	3-00928-360	74ACT245	Integrated Circuit (Surface Mount Pkg)
U 301	3-00931-360	29F400B	Integrated Circuit (Surface Mount Pkg)
U 302	3-00932-360	128KX8	Integrated Circuit (Surface Mount Pkg)
U 303	3-00932-360	128KX8	Integrated Circuit (Surface Mount Pkg)
U 401	3-00933-360	SED1352FOB	Integrated Circuit (Surface Mount Pkg)
U 402	3-00934-360	32KX8	Integrated Circuit (Surface Mount Pkg)
U 403	3-00934-360	32KX8	Integrated Circuit (Surface Mount Pkg)
U 404	3-00958-360	ADS7843E	Integrated Circuit (Surface Mount Pkg)
U 405	3-00959-360	MAX686EEE	Integrated Circuit (Surface Mount Pkg)
U 406	8-00069-800	INVERTER	Miscellaneous
U 501	3-00935-360	ST16C550CQ48	Integrated Circuit (Surface Mount Pkg)
U 502	3-00936-360	MAX3232CSE	Integrated Circuit (Surface Mount Pkg)
U 503	3-00750-360	74HC573	Integrated Circuit (Surface Mount Pkg)
U 504	3-00750-360	74HC573	Integrated Circuit (Surface Mount Pkg)
U 505	3-00751-360	74HC574	Integrated Circuit (Surface Mount Pkg)
U 506	3-00751-360	74HC574	Integrated Circuit (Surface Mount Pkg)
U 507	3-00937-360	DS1307Z	Integrated Circuit (Surface Mount Pkg)
U 508	3-00751-360	74HC574	Integrated Circuit (Surface Mount Pkg)
U 601	3-00938-360	AD7528JR	Integrated Circuit (Surface Mount Pkg)
U 602	3-00581-360	AD822	Integrated Circuit (Surface Mount Pkg)
U 603	3-00939-360	LM4882M	Integrated Circuit (Surface Mount Pkg)
W 601	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 602	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 603	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 604	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 605	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 606	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 607	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 608	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 609	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R

CPU Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
W 610	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 611	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 612	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 613	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 614	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 615	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 616	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 617	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 618	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 619	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 620	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 621	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 622	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 623	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 624	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 625	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 626	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
W 627	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
X 401	6-00514-626	6 MHZ 32PF SMD	Crystal, SMT
X 501	6-00515-626	3.68MHZ 20PF	Crystal, SMT
X 502	6-00516-626	32.768KHZ SMD	Crystal, SMT

Communications Board

Communications Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
C 101	5-00100-517	2.2U	Capacitor, Tantalum, 35V, 20%, Rad
C 102	5-00100-517	2.2U	Capacitor, Tantalum, 35V, 20%, Rad
C 103	5-00100-517	2.2U	Capacitor, Tantalum, 35V, 20%, Rad
C 104	5-00225-548	.1U AXIAL	Capacitor, Ceramic, 50V,+80/-20% Z5U AX
C 105	5-00225-548	.1U AXIAL	Capacitor, Ceramic, 50V,+80/-20% Z5U AX
C 106	5-00225-548	.1U AXIAL	Capacitor, Ceramic, 50V,+80/-20% Z5U AX
C 107	5-00225-548	.1U AXIAL	Capacitor, Ceramic, 50V,+80/-20% Z5U AX
C 108	5-00225-548	.1U AXIAL	Capacitor, Ceramic, 50V,+80/-20% Z5U AX
C 110	5-00011-501	27P	Capacitor, Ceramic Disc, 50V, 10%, SL
C 111	5-00011-501	27P	Capacitor, Ceramic Disc, 50V, 10%, SL
J 200	1-00234-109	96 PIN RT ANGLE	DIN Connector, Male
JP102	1-00238-161	GPIB SHIELDED	Connector, IEEE488, Reverse, R/A, Female
JP103	1-00580-136	8 MINI-DIN RTA	Connector, Other
JP112	0-00985-000	ENETLED (G/Y)	Hardware, Misc.
JP114	1-00285-130	4 PIN DI MTLW	Connector, Male
PC1	7-01108-701	IGC COMM BD	Printed Circuit Board
R 100	4-00031-401	100	Resistor, Carbon Film, 1/4W, 5%
R 101	4-00031-401	100	Resistor, Carbon Film, 1/4W, 5%
R 102	4-00031-401	100	Resistor, Carbon Film, 1/4W, 5%
R 103	4-00031-401	100	Resistor, Carbon Film, 1/4W, 5%
R 104	4-00065-401	3.3K	Resistor, Carbon Film, 1/4W, 5%
R 105	4-00065-401	3.3K	Resistor, Carbon Film, 1/4W, 5%
R 106	4-00065-401	3.3K	Resistor, Carbon Film, 1/4W, 5%
R 107	4-00065-401	3.3K	Resistor, Carbon Film, 1/4W, 5%
R 110	4-00022-401	1.0M	Resistor, Carbon Film, 1/4W, 5%
R 120	4-00072-401	330	Resistor, Carbon Film, 1/4W, 5%
R 121	4-00072-401	330	Resistor, Carbon Film, 1/4W, 5%
S0104	1-00024-150	20 PIN 300 MIL	Socket, THRU-HOLE
U 101	3-00645-340	NAT9914BPD	Integrated Circuit (Thru-hole Pkg)
U 103	3-00440-340	74HC573	Integrated Circuit (Thru-hole Pkg)
U 104	3-00405-343	16V8-15	GAL/PAL, I.C.
U 105	3-00960-340	ST16C2550CP40	Integrated Circuit (Thru-hole Pkg)
U 106	3-00078-340	DS75160A	Integrated Circuit (Thru-hole Pkg)
U 107	3-00079-340	DS75161A	Integrated Circuit (Thru-hole Pkg)
U 108	3-00155-340	74HC04	Integrated Circuit (Thru-hole Pkg)
U 109	3-01059-340	XEAWC86	Integrated Circuit (Thru-hole Pkg)
X 101	6-00037-620	3.6864 MHZ	Crystal
Z 0	0-00043-011	4-40 KEP	Nut, Kep
Z 0	0-00187-021	4-40X1/4PP	Screw, Panhead Phillips
Z 0	0-00209-021	4-40X3/8PP	Screw, Panhead Phillips
Z 0	0-00500-000	554808-1	Hardware, Misc.
Z 0	7-01008-720	I/O PCB BRK	Fabricated Part
Z 0	7-01297-715	BRKT	Bracket
Z 0	7-01298-715	BRKT	Bracket
Z 0	7-01299-715	BRKT	Bracket
Z 0	7-01300-715	BRKT	Bracket

Motherboard

Motherboard			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
C 211	5-00395-552	4700P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 212	5-00472-569	4.7U/T35	Cap, Tantalum, SMT (all case sizes)
C 221	5-00329-526	120U	Capacitor, Electrolytic, 35V, 20%, Rad
C 222	5-00384-552	560P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 2110	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2120	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2210	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 2220	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 2310	5-00471-569	10U/T16	Cap, Tantalum, SMT (all case sizes)
C 2320	5-00522-569	47U/T10	Cap, Tantalum, SMT (all case sizes)
C 2330	5-00522-569	47U/T10	Cap, Tantalum, SMT (all case sizes)
C 2340	5-00522-569	47U/T10	Cap, Tantalum, SMT (all case sizes)
C 2510	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
D 211	3-00380-301	1N5248	Diode
D 221	3-00479-301	MUR410	Diode
D 222	3-00479-301	MUR410	Diode
D 223	3-00479-301	MUR410	Diode
D 224	3-00479-301	MUR410	Diode
D 225	3-00479-301	MUR410	Diode
D 226	3-00479-301	MUR410	Diode
D 227	3-00479-301	MUR410	Diode
D 228	3-00479-301	MUR410	Diode
J 11	1-00235-108	96 PIN VERTICAL	DIN Connector, Female
J 12	1-00235-108	96 PIN VERTICAL	DIN Connector, Female
J 13	1-00235-108	96 PIN VERTICAL	DIN Connector, Female
J 18	1-00533-110	34 PIN CNCTR	Pins & Connectors, AMP
J 26	1-00036-116	7 PIN, WHITE	Header, Amp, MTA-156
J 151	1-00529-130	50 PIN ELH VERT	Connector, Male
J 152	1-00530-130	40 PIN ELH VERT	Connector, Male
L 221	6-00055-630	FB43-1801	Ferrite Beads
PC1	7-01031-701	IGC MOTHER BD	Printed Circuit Board
Q 211	3-00283-340	IRF530/IRF532	Integrated Circuit (Thru-hole Pkg)
Q 212	3-00283-340	IRF530/IRF532	Integrated Circuit (Thru-hole Pkg)
R 211	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 212	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 213	4-01158-462	2.67K	Thin Film, 1%, 50 ppm, MELF Resistor
R 214	4-00436-409	.1	Resistor, Wire Wound
R 221	4-01001-462	61.9	Thin Film, 1%, 50 ppm, MELF Resistor
R 251	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 254	4-01013-462	82.5	Thin Film, 1%, 50 ppm, MELF Resistor
R 255	4-01013-462	82.5	Thin Film, 1%, 50 ppm, MELF Resistor
R 256	4-01013-462	82.5	Thin Film, 1%, 50 ppm, MELF Resistor
R 261	4-01588-453	10.0 - 2W	Resistor, 2W, 1%
R 262	4-01588-453	10.0 - 2W	Resistor, 2W, 1%
R 2110	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 2120	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
T 22	6-00535-610	Q8283C-04	Transformer
U 21	3-00919-360	3525A	Integrated Circuit (Surface Mount Pkg)
U 23	3-00549-329	LT1085CT-5	Voltage Reg., TO-220 (TAB) Package
Z 0	0-00043-011	4-40 KEP	Nut, Kep
Z 0	0-00048-011	6-32 KEP	Nut, Kep
Z 0	0-00128-053	4" #24	Wire #24 UL1007 Strip 1/4x1/4 Tin
Z 0	0-00187-021	4-40X1/4PP	Screw, Panhead Phillips
Z 0	0-00209-021	4-40X3/8PP	Screw, Panhead Phillips
Z 0	0-00222-021	6-32X1/4PP	Screw, Panhead Phillips
Z 0	0-00231-043	#4 SHOULDER	Washer, nylon

Motherboard			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
Z 0	0-00316-003	PLTFM-28	Insulators
Z 0	0-00390-024	1-72X1/4	Screw, Slotted
Z 0	0-00391-010	1-72X5/32X3/64	Nut, Hex
Z 0	0-00772-000	1.5" WIRE	Hardware, Misc.
Z 0	6-00076-600	2" SPKR	Misc. Components
Z 0	7-01171-720	BCKT, MOTHER BD	Fabricated Part

High Voltage Power Supply Board

High Voltage Power Supply Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
C 111	5-00363-552	10P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 112	5-00395-552	4700P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 121	5-00329-526	120U	Capacitor, Electrolytic, 35V, 20%, Rad
C 122	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 123	5-00375-552	100P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 124	5-00515-526	1500U HIGH RIPL	Capacitor, Electrolytic, 35V, 20%, Rad
C 125	5-00515-526	1500U HIGH RIPL	Capacitor, Electrolytic, 35V, 20%, Rad
C 126	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 127	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 128	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 131	5-00527-568	.47U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 132	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 133	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 221	5-00403-552	.022U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 222	5-00526-569	22U-T16	Cap, Tantalum, SMT (all case sizes)
C 223	5-00403-552	.022U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 224	5-00471-569	10U/T16	Cap, Tantalum, SMT (all case sizes)
C 231	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 232	5-00395-552	4700P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 241	5-00329-526	120U	Capacitor, Electrolytic, 35V, 20%, Rad
C 242	5-00529-500	0.022UF/630V	Capacitor, Misc.
C 243	5-00530-500	0.47UF/630V	Capacitor, Misc.
C 262	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 271	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 272	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 311	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 312	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 313	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 314	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 315	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 351	5-00393-552	3300P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 352	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 461	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 462	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 463	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 511	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
C 521	5-00387-552	1000P	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 611	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 641	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1110	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1120	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1310	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1320	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1410	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1420	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1510	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1520	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1530	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2210	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2220	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2310	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2320	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2510	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2520	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2610	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2710	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R

High Voltage Power Supply Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
C 3110	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3120	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3410	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3420	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3510	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3520	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 3530	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3540	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 5110	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 5210	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 5310	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6110	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6210	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 6310	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 6410	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 6510	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6610	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 7110	5-00329-526	120U	Capacitor, Electrolytic, 35V, 20%, Rad
C 7120	5-00329-526	120U	Capacitor, Electrolytic, 35V, 20%, Rad
C 7410	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 7420	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 7430	5-00471-569	10U/T16	Cap, Tantalum, SMT (all case sizes)
C 7510	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 7520	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 7530	5-00471-569	10U/T16	Cap, Tantalum, SMT (all case sizes)
C 7610	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 7620	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 7630	5-00471-569	10U/T16	Cap, Tantalum, SMT (all case sizes)
C 7710	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 7720	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 7730	5-00471-569	10U/T16	Cap, Tantalum, SMT (all case sizes)
C 7810	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 7820	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
D 121	3-00625-302	MBR1535CT	Diode, Dual Schottky
D 241	3-00626-301	MUR1100E	Diode
D 242	3-00626-301	MUR1100E	Diode
D 243	3-00626-301	MUR1100E	Diode
D 244	3-00626-301	MUR1100E	Diode
D 245	3-00957-303	RED HLMP-D150	LED, T1 Package
D 251	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
D 252	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
D 271	3-00885-306	YELLOW	LED, Rectangular
D 311	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
D 411	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
D 441	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
D 611	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
D 641	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
F 241	0-00957-000	FUSE HOLDER	Hardware, Misc.
G 311	6-00088-613	NE-2H	Lamp
J 43	1-00541-110	206043-1	Pins & Connectors, AMP
J 61	1-00533-110	34 PIN CNCTR	Pins & Connectors, AMP
J 71	1-00260-116	4 PIN, WHITE	Header, Amp, MTA-156
J 72	1-00036-116	7 PIN, WHITE	Header, Amp, MTA-156
J 73	1-00528-130	3 PIN 3.5MM RT	Connector, Male
K 41	3-00964-335	845HN1CS24	Relay
K 42	3-00964-335	845HN1CS24	Relay
L 121	6-00055-630	FB43-1801	Ferrite Beads
L 122	6-00509-601	47.7UH	Inductor
L 241	6-00055-630	FB43-1801	Ferrite Beads

High Voltage Power Supply Board			
Ref No.	SRS Part No.	Value	Component Description
L 711	6-00055-630	FB43-1801	Ferrite Beads
PC1	7-01030-701	IGC HV BOARD	Printed Circuit Board
Q 111	3-00283-340	IRF530/IRF532	Integrated Circuit (Thru-hole Pkg)
Q 112	3-00283-340	IRF530/IRF532	Integrated Circuit (Thru-hole Pkg)
Q 231	3-00283-340	IRF530/IRF532	Integrated Circuit (Thru-hole Pkg)
Q 232	3-00283-340	IRF530/IRF532	Integrated Circuit (Thru-hole Pkg)
Q 311	3-01441-340	IRF820	Integrated Circuit (Thru-hole Pkg)
R 111	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 112	4-01479-461	1.0K	Thick Film, 5%, 200 ppm, Chip Resistor
R 113	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 114	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 116	4-01158-462	2.67K	Thin Film, 1%, 50 ppm, MELF Resistor
R 117	4-01519-461	47K	Thick Film, 5%, 200 ppm, Chip Resistor
R 121	4-01443-461	33	Thick Film, 5%, 200 ppm, Chip Resistor
R 122	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 123	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 124	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 125	4-01173-462	3.83K	Thin Film, 1%, 50 ppm, MELF Resistor
R 126	4-01613-400	.01 CURRENT SNS	Resistor, Misc.
R 127	4-00111-402	390	Resistor, Carbon Comp, 1/2W, 5%
R 128	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 131	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 132	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 133	4-01271-462	40.2K	Thin Film, 1%, 50 ppm, MELF Resistor
R 134	4-01203-462	7.87K	Thin Film, 1%, 50 ppm, MELF Resistor
R 135	4-01300-462	80.6K	Thin Film, 1%, 50 ppm, MELF Resistor
R 136	4-01203-462	7.87K	Thin Film, 1%, 50 ppm, MELF Resistor
R 137	4-01300-462	80.6K	Thin Film, 1%, 50 ppm, MELF Resistor
R 138	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 139	4-01251-462	24.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 151	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 221	4-01197-462	6.81K	Thin Film, 1%, 50 ppm, MELF Resistor
R 222	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 223	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 224	4-01261-462	31.6K	Thin Film, 1%, 50 ppm, MELF Resistor
R 225	4-01070-462	324	Thin Film, 1%, 50 ppm, MELF Resistor
R 226	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 227	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 228	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 229	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 231	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 232	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 233	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 234	4-01158-462	2.67K	Thin Film, 1%, 50 ppm, MELF Resistor
R 235	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 236	4-01519-461	47K	Thick Film, 5%, 200 ppm, Chip Resistor
R 241	4-01626-409	40	Resistor, Wire Wound
R 242	4-01627-453	350K	Resistor, 2W, 1%
R 243	4-01627-453	350K	Resistor, 2W, 1%
R 244	4-01133-462	1.47K	Thin Film, 1%, 50 ppm, MELF Resistor
R 245	4-01628-400	0.01/0.5W	Resistor, Misc.
R 251	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 261	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 262	4-01242-462	20.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 263	4-01105-462	750	Thin Film, 1%, 50 ppm, MELF Resistor
R 271	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 272	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 273	4-01456-461	110	Thick Film, 5%, 200 ppm, Chip Resistor
R 311	4-01623-448	10M	Resistor, Metal Film, 1W, 1%,

High Voltage Power Supply Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
R 312	4-01309-462	100K	Thin Film, 1%, 50 ppm, MELF Resistor
R 313	4-01273-462	42.2K	Thin Film, 1%, 50 ppm, MELF Resistor
R 314	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 315	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 316	4-01335-462	187K	Thin Film, 1%, 50 ppm, MELF Resistor
R 318	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 319	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 333	4-01630-409	50.0 1W	Resistor, Wire Wound
R 334	4-01088-462	499	Thin Film, 1%, 50 ppm, MELF Resistor
R 336	4-01088-462	499	Thin Film, 1%, 50 ppm, MELF Resistor
R 341	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 342	4-01242-462	20.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 343	4-01242-462	20.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 345	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 411	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 421	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 431	4-01050-462	200	Thin Film, 1%, 50 ppm, MELF Resistor
R 432	4-01146-462	2.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 441	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 442	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 451	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 452	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 512	4-01503-461	10K	Thick Film, 5%, 200 ppm, Chip Resistor
R 513	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 521	4-01491-461	3.3K	Thick Film, 5%, 200 ppm, Chip Resistor
R 522	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 611	4-01448-461	51	Thick Film, 5%, 200 ppm, Chip Resistor
R 641	4-01515-461	33K	Thick Film, 5%, 200 ppm, Chip Resistor
R 661	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 741	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 742	4-01327-462	154K	Thin Film, 1%, 50 ppm, MELF Resistor
R 751	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 752	4-01301-462	82.5K	Thin Film, 1%, 50 ppm, MELF Resistor
R 1110	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 1120	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 1310	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 1320	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 1391	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 1394	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 1395	4-01105-462	750	Thin Film, 1%, 50 ppm, MELF Resistor
R 1410	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 1420	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 1510	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 1520	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 1530	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 2210	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 2220	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 2310	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 2320	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 2610	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 3110	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 3112	4-01660-462	2.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 3120	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 3410	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 3420	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 3510	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 3520	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 5110	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
T 12	6-00532-610	Q8283D-01	Transformer

High Voltage Power Supply Board

Ref No.	SRS Part No.	Value	Component Description
T 24	6-00533-610	Q8283A-04	Transformer
U 11	3-00919-360	3525A	Integrated Circuit (Surface Mount Pkg)
U 13	3-00723-360	LF347	Integrated Circuit (Surface Mount Pkg)
U 14	3-00967-360	OPA177GS	Integrated Circuit (Surface Mount Pkg)
U 15	3-00956-360	MAX4602CWE	Integrated Circuit (Surface Mount Pkg)
U 22	3-00952-360	OPA2277UA	Integrated Circuit (Surface Mount Pkg)
U 23	3-00919-360	3525A	Integrated Circuit (Surface Mount Pkg)
U 25	3-01371-360	DG417DY	Integrated Circuit (Surface Mount Pkg)
U 26	3-00965-360	LM2903M	Integrated Circuit (Surface Mount Pkg)
U 27	3-00742-360	74HC74	Integrated Circuit (Surface Mount Pkg)
U 31	3-00581-360	AD822	Integrated Circuit (Surface Mount Pkg)
U 32	3-00966-360	IRF7103	Integrated Circuit (Surface Mount Pkg)
U 34	3-00967-360	OPA177GS	Integrated Circuit (Surface Mount Pkg)
U 35	3-00969-360	DAC1220E	Integrated Circuit (Surface Mount Pkg)
U 44	3-00540-360	MMBT5087	Integrated Circuit (Surface Mount Pkg)
U 45	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
U 51	3-00661-360	74HC4051	Integrated Circuit (Surface Mount Pkg)
U 52	3-01442-340	LTC1096	Integrated Circuit (Thru-hole Pkg)
U 53	3-00655-360	TLC5628	Integrated Circuit (Surface Mount Pkg)
U 61	3-00743-360	SN74HC138D	Integrated Circuit (Surface Mount Pkg)
U 62	3-00743-360	SN74HC138D	Integrated Circuit (Surface Mount Pkg)
U 63	3-00750-360	74HC573	Integrated Circuit (Surface Mount Pkg)
U 64	3-00751-360	74HC574	Integrated Circuit (Surface Mount Pkg)
U 65	3-00751-360	74HC574	Integrated Circuit (Surface Mount Pkg)
U 66	3-00751-360	74HC574	Integrated Circuit (Surface Mount Pkg)
U 74	3-00118-325	78L15	Transistor, TO-92 Package
U 75	3-00124-325	79L15	Transistor, TO-92 Package
U 76	3-00118-325	78L15	Transistor, TO-92 Package
U 77	3-00124-325	79L15	Transistor, TO-92 Package
U 78	3-00970-360	MAX6225BCSA	Integrated Circuit (Surface Mount Pkg)
U 411	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
U 421	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
Z 0	0-00039-006	66101-4	NIM (Nuclear Instrumentation Module)
Z 0	0-00096-041	#4 SPLIT	Washer, Split
Z 0	0-00130-050	5-5/8" #18	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-00187-021	4-40X1/4PP	Screw, Panhead Phillips
Z 0	0-00209-021	4-40X3/8PP	Screw, Panhead Phillips
Z 0	0-00231-043	#4 SHOULDER	Washer, nylon
Z 0	0-00243-003	TO-220	Insulators
Z 0	0-00330-050	5-1/2" #18	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-00594-050	4-1/2" #18 BLUE	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-00595-050	4-1/2" #18 ORAN	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-00617-031	4-40X1-3/16 F/F	Standoff
Z 0	0-00772-000	1.5" WIRE	Hardware, Misc.
Z 0	0-00810-020	4-40X1/2PF SS	Screw, Flathead Phillips
Z 0	0-00988-050	5" #18	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-00989-050	5" #18	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-00990-050	5" #18	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-00991-050	4" #18	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-01000-048	4" #18 UL1015	Wire, #18 UL1015 Strip 3/8 x 3/8 No Tin
Z 0	0-01022-019	4-40	Lock Nut
Z 0	1-00542-110	66181-1	Pins & Connectors, AMP
Z 0	1-00612-176	1238	Terminal, Male
Z 0	6-00042-611	1.25A 3AG	Fuse
Z 0	7-01009-721	2-POS FET BRKT	Machined Part
Z 0	7-01010-721	6 POS FET BRKT	Machined Part

Gauge Board

Gauge Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
C 1	5-00023-529	.1U	Cap, Monolythic Ceramic, 50V, 20%, Z5U
C 2	5-00023-529	.1U	Cap, Monolythic Ceramic, 50V, 20%, Z5U
C 3	5-00023-529	.1U	Cap, Monolythic Ceramic, 50V, 20%, Z5U
C 4	5-00023-529	.1U	Cap, Monolythic Ceramic, 50V, 20%, Z5U
C 5	5-00023-529	.1U	Cap, Monolythic Ceramic, 50V, 20%, Z5U
C 6	5-00023-529	.1U	Cap, Monolythic Ceramic, 50V, 20%, Z5U
C 7	5-00023-529	.1U	Cap, Monolythic Ceramic, 50V, 20%, Z5U
C 8	5-00023-529	.1U	Cap, Monolythic Ceramic, 50V, 20%, Z5U
C 121	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 151	5-00078-516	10P	Capacitor, Silver Mica, 500V, 5%,
C 152	5-00139-516	910P	Capacitor, Silver Mica, 500V, 5%,
C 153	5-00460-572	.033U	SMT Film Capacitors, 50V, 5%, All Sizes
C 154	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 155	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 211	5-00472-569	4.7U/T35	Cap, Tantalum, SMT (all case sizes)
C 212	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 213	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 214	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 215	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 216	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 217	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 218	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 221	5-00472-569	4.7U/T35	Cap, Tantalum, SMT (all case sizes)
C 222	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 223	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 224	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 225	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 226	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 227	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 228	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 421	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 422	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 423	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 424	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 431	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 432	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 433	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 434	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 435	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 436	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 437	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 438	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 531	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1510	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1520	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1610	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 1620	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2110	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2120	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2210	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2220	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2310	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2320	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 2330	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3110	5-00525-578	1U	SMT Ceramic Cap, all sizes
C 3120	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R

Gauge Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
C 3210	5-00471-569	10U/T16	Cap, Tantalum, SMT (all case sizes)
C 3220	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3230	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3240	5-00471-569	10U/T16	Cap, Tantalum, SMT (all case sizes)
C 3250	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3260	5-00526-569	22U-T16	Cap, Tantalum, SMT (all case sizes)
C 3270	5-00470-569	2.2U/T16	Cap, Tantalum, SMT (all case sizes)
C 3410	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3420	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3610	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 3620	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 4110	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 4120	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 4210	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 4220	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 4310	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 4320	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 4410	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 4420	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 4430	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 5110	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 5210	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 5310	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 5410	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 5510	5-00299-568	.1U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 5610	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6110	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6120	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6130	5-00471-569	10U/T16	Cap, Tantalum, SMT (all case sizes)
C 6210	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6220	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6230	5-00471-569	10U/T16	Cap, Tantalum, SMT (all case sizes)
C 6310	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6320	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6410	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6420	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6510	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6520	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6610	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 6620	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
D 45	3-00896-301	BAV99	Diode
D 46	3-00896-301	BAV99	Diode
D 47	3-00896-301	BAV99	Diode
D 48	3-00896-301	BAV99	Diode
D 231	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
D 241	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
D 531	3-00544-360	BAV70LT1	Integrated Circuit (Surface Mount Pkg)
G 111	6-00531-613	CG90L	Lamp
G 121	6-00531-613	CG90L	Lamp
J 1	1-00233-120	RT ANGLE	Connector, BNC
J 2	1-00233-120	RT ANGLE	Connector, BNC
J 3	1-00233-120	RT ANGLE	Connector, BNC
J 4	1-00233-120	RT ANGLE	Connector, BNC
J 5	1-00336-130	26 PIN ELH VERT	Connector, Male
J 51	1-00234-109	96 PIN RT ANGLE	DIN Connector, Male
J 111	1-00233-120	RT ANGLE	Connector, BNC
J 121	1-00233-120	RT ANGLE	Connector, BNC
JP52	1-00336-130	26 PIN ELH VERT	Connector, Male
P 21	1-00370-160	15 PIN D	Connector, D-Sub, Right Angle PC, Female

Gauge Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
PC1	7-01029-701	IGC GAUGE BOARD	Printed Circuit Board
Q 231	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
Q 232	3-00378-329	TIP102	Voltage Reg., TO-220 (TAB) Package
Q 241	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
Q 242	3-00378-329	TIP102	Voltage Reg., TO-220 (TAB) Package
R 111	4-01471-461	470	Thick Film, 5%, 200 ppm, Chip Resistor
R 112	4-01471-461	470	Thick Film, 5%, 200 ppm, Chip Resistor
R 121	4-01471-461	470	Thick Film, 5%, 200 ppm, Chip Resistor
R 122	4-01471-461	470	Thick Film, 5%, 200 ppm, Chip Resistor
R 131	4-01471-461	470	Thick Film, 5%, 200 ppm, Chip Resistor
R 141	4-01471-461	470	Thick Film, 5%, 200 ppm, Chip Resistor
R 151	4-00398-407	499K	Resistor, Metal Film, 1/8W, 1%, 50PPM
R 152	4-00864-458	500M 3/4-WATT	Resistor, Metal Oxide
R 153	4-00139-407	10.0M	Resistor, Metal Film, 1/8W, 1%, 50PPM
R 154	4-00170-407	249K	Resistor, Metal Film, 1/8W, 1%, 50PPM
R 155	4-00161-407	2.49K	Resistor, Metal Film, 1/8W, 1%, 50PPM
R 156	4-00925-462	10.0	Thin Film, 1%, 50 ppm, MELF Resistor
R 163	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 164	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 165	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 166	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 171	4-01471-461	470	Thick Film, 5%, 200 ppm, Chip Resistor
R 182	4-01146-462	2.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 211	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 212	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 213	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 214	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 215	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 216	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 217	4-01167-462	3.32K	Thin Film, 1%, 50 ppm, MELF Resistor
R 218	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 219	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 221	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 222	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 223	4-01230-462	15.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 224	4-01184-462	4.99K	Thin Film, 1%, 50 ppm, MELF Resistor
R 225	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 226	4-01280-462	49.9K	Thin Film, 1%, 50 ppm, MELF Resistor
R 227	4-01167-462	3.32K	Thin Film, 1%, 50 ppm, MELF Resistor
R 228	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 229	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 231	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 232	4-01146-462	2.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 233	4-00925-462	10.0	Thin Film, 1%, 50 ppm, MELF Resistor
R 234	4-01632-462	10.0 1/4W	Thin Film, 1%, 50 ppm, MELF Resistor
R 235	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 241	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 242	4-01146-462	2.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 243	4-00925-462	10.0	Thin Film, 1%, 50 ppm, MELF Resistor
R 244	4-01632-462	10.0 1/4W	Thin Film, 1%, 50 ppm, MELF Resistor
R 245	4-01575-461	10M	Thick Film, 5%, 200 ppm, Chip Resistor
R 311	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 341	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 342	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 343	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 344	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 345	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 346	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor
R 347	4-01117-462	1.00K	Thin Film, 1%, 50 ppm, MELF Resistor

Gauge Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
R 361	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 362	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 411	4-01273-462	42.2K	Thin Film, 1%, 50 ppm, MELF Resistor
R 412	4-01273-462	42.2K	Thin Film, 1%, 50 ppm, MELF Resistor
R 413	4-01273-462	42.2K	Thin Film, 1%, 50 ppm, MELF Resistor
R 414	4-01273-462	42.2K	Thin Film, 1%, 50 ppm, MELF Resistor
R 415	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 416	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 417	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 418	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 423	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 424	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 425	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 426	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 431	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 432	4-01335-462	187K	Thin Film, 1%, 50 ppm, MELF Resistor
R 433	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 434	4-01335-462	187K	Thin Film, 1%, 50 ppm, MELF Resistor
R 435	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 436	4-01335-462	187K	Thin Film, 1%, 50 ppm, MELF Resistor
R 437	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 438	4-01335-462	187K	Thin Film, 1%, 50 ppm, MELF Resistor
R 451	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 452	4-00925-462	10.0	Thin Film, 1%, 50 ppm, MELF Resistor
R 461	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 462	4-00925-462	10.0	Thin Film, 1%, 50 ppm, MELF Resistor
R 471	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 472	4-00925-462	10.0	Thin Film, 1%, 50 ppm, MELF Resistor
R 481	4-01021-462	100	Thin Film, 1%, 50 ppm, MELF Resistor
R 482	4-00925-462	10.0	Thin Film, 1%, 50 ppm, MELF Resistor
R 491	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 492	4-01335-462	187K	Thin Film, 1%, 50 ppm, MELF Resistor
R 493	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 494	4-01335-462	187K	Thin Film, 1%, 50 ppm, MELF Resistor
R 495	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 496	4-01335-462	187K	Thin Film, 1%, 50 ppm, MELF Resistor
R 497	4-01405-462	1.00M	Thin Film, 1%, 50 ppm, MELF Resistor
R 498	4-01335-462	187K	Thin Film, 1%, 50 ppm, MELF Resistor
R 531	4-01515-461	33K	Thick Film, 5%, 200 ppm, Chip Resistor
R 541	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 542	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 543	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 544	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 551	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 1510	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 1520	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 1610	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 1620	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 1810	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 2110	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 2120	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 2210	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 2220	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 2310	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 2320	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 2330	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 2331	4-00954-462	20.0	Thin Film, 1%, 50 ppm, MELF Resistor
R 2431	4-00954-462	20.0	Thin Film, 1%, 50 ppm, MELF Resistor
R 3110	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor

Gauge Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
R 3410	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 3420	4-01455-461	100	Thick Film, 5%, 200 ppm, Chip Resistor
R 3610	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 3620	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 4110	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 4120	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 4310	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 4320	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 4410	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 4420	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 4430	4-01431-461	10	Thick Film, 5%, 200 ppm, Chip Resistor
R 6310	4-01058-462	243	Thin Film, 1%, 50 ppm, MELF Resistor
R 6320	4-01125-462	1.21K	Thin Film, 1%, 50 ppm, MELF Resistor
R 6410	4-01058-462	243	Thin Film, 1%, 50 ppm, MELF Resistor
R 6420	4-01125-462	1.21K	Thin Film, 1%, 50 ppm, MELF Resistor
U 11	3-00950-335	LH1541AT1	Relay
U 12	3-00950-335	LH1541AT1	Relay
U 13	3-00950-335	LH1541AT1	Relay
U 14	3-00950-335	LH1541AT1	Relay
U 15	3-00951-340	LMC6001CIN	Integrated Circuit (Thru-hole Pkg)
U 16	3-01370-360	OPA277UA	Integrated Circuit (Surface Mount Pkg)
U 17	3-00950-335	LH1541AT1	Relay
U 18	3-00662-360	74HC14	Integrated Circuit (Surface Mount Pkg)
U 21	3-00952-360	OPA2277UA	Integrated Circuit (Surface Mount Pkg)
U 22	3-00952-360	OPA2277UA	Integrated Circuit (Surface Mount Pkg)
U 23	3-00643-360	DG211BDY	Integrated Circuit (Surface Mount Pkg)
U 31	3-00953-360	LTC2400CS8	Integrated Circuit (Surface Mount Pkg)
U 32	3-00954-360	LTC1416IG	Integrated Circuit (Surface Mount Pkg)
U 34	3-00661-360	74HC4051	Integrated Circuit (Surface Mount Pkg)
U 36	3-00952-360	OPA2277UA	Integrated Circuit (Surface Mount Pkg)
U 41	3-01364-360	OPA4277UA	Integrated Circuit (Surface Mount Pkg)
U 42	3-00955-360	DAC7624U	Integrated Circuit (Surface Mount Pkg)
U 43	3-01364-360	OPA4277UA	Integrated Circuit (Surface Mount Pkg)
U 44	3-00956-360	MAX4602CWE	Integrated Circuit (Surface Mount Pkg)
U 51	3-00743-360	SN74HC138D	Integrated Circuit (Surface Mount Pkg)
U 52	3-00743-360	SN74HC138D	Integrated Circuit (Surface Mount Pkg)
U 53	3-00751-360	74HC574	Integrated Circuit (Surface Mount Pkg)
U 54	3-00750-360	74HC573	Integrated Circuit (Surface Mount Pkg)
U 55	3-00751-360	74HC574	Integrated Circuit (Surface Mount Pkg)
U 56	3-00751-360	74HC574	Integrated Circuit (Surface Mount Pkg)
U 61	3-00114-329	7815	Voltage Reg., TO-220 (TAB) Package
U 62	3-00120-329	7915	Voltage Reg., TO-220 (TAB) Package
U 63	3-00971-360	LM317LM	Integrated Circuit (Surface Mount Pkg)
U 64	3-00972-360	LM337L/SO	Integrated Circuit (Surface Mount Pkg)
U 65	3-00122-325	79L05	Transistor, TO-92 Package
U 66	3-00709-360	78L05	Integrated Circuit (Surface Mount Pkg)
U 111	3-00950-335	LH1541AT1	Relay
U 121	3-00950-335	LH1541AT1	Relay
Z 0	0-00043-011	4-40 KEP	Nut, Kep
Z 0	0-00079-031	4-40X3/16 M/F	Standoff
Z 0	0-00187-021	4-40X1/4PP	Screw, Panhead Phillips
Z 0	0-00472-018	1-329631-2	Jam Nut
Z 0	0-00501-042	1-329632-2	Washer, lock
Z 0	0-01030-007	592502B03400	Heat Sinks
Z 0	1-00611-171	26 PIN, 8.5"	Cable Assembly, Ribbon
Z 0	7-01006-720	A/D PCB BRACKET	Fabricated Part
Z 0	7-01007-720	BCKT, GAUGE PWB	Fabricated Part
Z 0	7-01292-709	IGC	Lexan Overlay
Z 0	7-01305-720	IGC	Fabricated Part

Process Control Board

Process Control Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
C 581	5-00298-568	.01U	Cap, Ceramic 50V SMT (1206) +/-10% X7R
C 5110	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 5210	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 5310	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 5410	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
C 5510	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 5610	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 5710	5-00399-552	.01U	Capacitor, Chip (SMT1206), 50V, 5%, NPO
C 5810	5-00318-569	2.2U/T35	Cap, Tantalum, SMT (all case sizes)
D 411	3-00806-360	BAV170LT1	Integrated Circuit (Surface Mount Pkg)
D 431	3-00806-360	BAV170LT1	Integrated Circuit (Surface Mount Pkg)
D 451	3-00806-360	BAV170LT1	Integrated Circuit (Surface Mount Pkg)
D 471	3-00806-360	BAV170LT1	Integrated Circuit (Surface Mount Pkg)
J 51	1-00234-109	96 PIN RT ANGLE	DIN Connector, Male
J 61	1-00530-130	40 PIN ELH VERT	Connector, Male
J 62	1-00577-130	24 PIN RT.ANGLE	Connector, Male
K 41	3-01056-335	24VDC DPDT	Relay
K 42	3-01056-335	24VDC DPDT	Relay
K 43	3-01056-335	24VDC DPDT	Relay
K 44	3-01056-335	24VDC DPDT	Relay
K 45	3-01056-335	24VDC DPDT	Relay
K 46	3-01056-335	24VDC DPDT	Relay
K 47	3-01056-335	24VDC DPDT	Relay
K 48	3-01056-335	24VDC DPDT	Relay
PC1	7-01084-701	IGC PROCESS CNT	Printed Circuit Board
Q 411	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
Q 421	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
Q 431	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
Q 441	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
Q 451	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
Q 461	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
Q 471	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
Q 481	3-00601-360	MMBT3904LT1	Integrated Circuit (Surface Mount Pkg)
R 11	4-01616-463	3.3KX8D	Resistor network, SMT, Leadless
R 12	4-01659-463	100KX8D	Resistor network, SMT, Leadless
R 13	4-01616-463	3.3KX8D	Resistor network, SMT, Leadless
R 14	4-01659-463	100KX8D	Resistor network, SMT, Leadless
R 21	4-01616-463	3.3KX8D	Resistor network, SMT, Leadless
R 22	4-01659-463	100KX8D	Resistor network, SMT, Leadless
R 31	4-01616-463	3.3KX8D	Resistor network, SMT, Leadless
R 32	4-01659-463	100KX8D	Resistor network, SMT, Leadless
R 41	4-01644-463	10KX8D	Resistor network, SMT, Leadless
R 42	4-01644-463	10KX8D	Resistor network, SMT, Leadless
R 43	4-01616-463	3.3KX8D	Resistor network, SMT, Leadless
R 61	4-00320-409	18	Resistor, Wire Wound
R 62	4-00320-409	18	Resistor, Wire Wound
R 331	4-00992-462	49.9	Thin Film, 1%, 50 ppm, MELF Resistor
R 332	4-00992-462	49.9	Thin Film, 1%, 50 ppm, MELF Resistor
R 333	4-00992-462	49.9	Thin Film, 1%, 50 ppm, MELF Resistor
R 334	4-00992-462	49.9	Thin Film, 1%, 50 ppm, MELF Resistor
R 335	4-00992-462	49.9	Thin Film, 1%, 50 ppm, MELF Resistor
R 336	4-00992-462	49.9	Thin Film, 1%, 50 ppm, MELF Resistor
R 337	4-00992-462	49.9	Thin Film, 1%, 50 ppm, MELF Resistor
R 338	4-00992-462	49.9	Thin Film, 1%, 50 ppm, MELF Resistor
R 541	4-01213-462	10.0K	Thin Film, 1%, 50 ppm, MELF Resistor
R 581	4-01125-462	1.21K	Thin Film, 1%, 50 ppm, MELF Resistor

Process Control Board			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
U 11	3-01057-360	LTV847S	Integrated Circuit (Surface Mount Pkg)
U 12	3-01057-360	LTV847S	Integrated Circuit (Surface Mount Pkg)
U 13	3-01057-360	LTV847S	Integrated Circuit (Surface Mount Pkg)
U 21	3-01057-360	LTV847S	Integrated Circuit (Surface Mount Pkg)
U 22	3-01057-360	LTV847S	Integrated Circuit (Surface Mount Pkg)
U 31	3-01057-360	LTV847S	Integrated Circuit (Surface Mount Pkg)
U 32	3-01057-360	LTV847S	Integrated Circuit (Surface Mount Pkg)
U 33	3-01465-360	74C240	Integrated Circuit (Surface Mount Pkg)
U 51	3-00743-360	SN74HC138D	Integrated Circuit (Surface Mount Pkg)
U 52	3-00743-360	SN74HC138D	Integrated Circuit (Surface Mount Pkg)
U 53	3-00750-360	74HC573	Integrated Circuit (Surface Mount Pkg)
U 54	3-00750-360	74HC573	Integrated Circuit (Surface Mount Pkg)
U 55	3-00750-360	74HC573	Integrated Circuit (Surface Mount Pkg)
U 56	3-00750-360	74HC573	Integrated Circuit (Surface Mount Pkg)
U 57	3-00750-360	74HC573	Integrated Circuit (Surface Mount Pkg)
U 58	3-00747-360	74HC273	Integrated Circuit (Surface Mount Pkg)
Z 0	0-00043-011	4-40 KEP	Nut, Kep
Z 0	0-00048-011	6-32 KEP	Nut, Kep
Z 0	0-00079-031	4-40X3/16 M/F	Standoff
Z 0	0-00222-021	6-32X1/4PP	Screw, Panhead Phillips
Z 0	0-00577-024	2-56X1/8 PAN	Screw, Slotted
Z 0	0-00796-024	2-56X3/16SP	Screw, Slotted
Z 0	0-00998-032	2-56 X 3/16 F/F	Termination
Z 0	1-00586-131	24 PIN	Connector, Female
Z 0	1-00592-169	9" 40 PIN DB37	Cable Assembly, Custom
Z 0	7-01157-720	PLATE, PROC CNT	Fabricated Part
Z 0	7-01158-720	BCKT, PROC CNT	Fabricated Part
Z 0	7-01290-709	IGC	Lexan Overlay
Z 0	7-01303-709	IGC	Lexan Overlay

Dual Ion Gauge Box

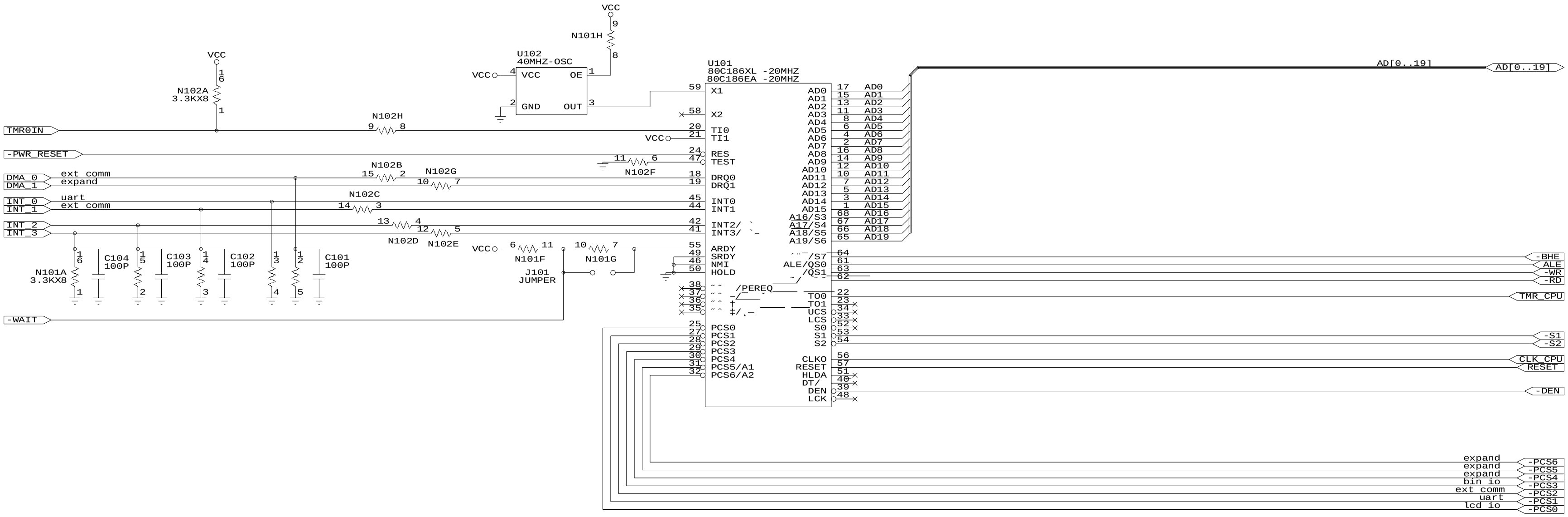
Dual Ion Gauge Box			
Ref No.	**SRS Part No.**	**Value**	**Component Description**
K 1	3-01395-335	SCL-1-DPDT-24V	Relay
K 2	3-01395-335	SCL-1-DPDT-24V	Relay
K 3	3-01394-335	241CX*1K2CAB	Relay
PC1	7-01265-701	IGC RELAY BOX	Printed Circuit Board
Z 0	0-00038-006	66099-4	NIM (Nuclear Instrumentation Module)
Z 0	0-00039-006	66101-4	NIM (Nuclear Instrumentation Module)
Z 0	0-00043-011	4-40 KEP	Nut, Kep
Z 0	0-00089-033	4"	Tie
Z 0	0-00209-021	4-40X3/8PP	Screw, Panhead Phillips
Z 0	0-00306-026	4-40X3/16PP	Screw, Black, All Types
Z 0	0-00894-026	4-40X1/2PP	Screw, Black, All Types
Z 0	0-01001-048	6" #18 UL1015	Wire, #18 UL1015 Strip 3/8 x 3/8 No Tin
Z 0	0-01002-050	6" BROWN	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-01003-050	6" BLUE	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-01004-050	6" ORANGE	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-01005-050	6" BLACK	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-01006-050	6" VIOLET	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-01007-050	6" GREY	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-01008-050	6" WHITE	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-01009-050	6" GREEN	Wire #18 UL1007 Stripped 3/8x3/8 No Tin
Z 0	0-01010-000	RUBBER GROMMET	Hardware, Misc.
Z 0	1-00541-110	206043-1	Pins & Connectors, AMP
Z 0	1-00612-176	1238	Terminal, Male
Z 0	1-00615-169	DUAL IG BOX	Cable Assembly, Custom
Z 0	7-00581-721	SR625-6	Machined Part
Z 0	7-01281-720	IGC	Fabricated Part
Z 0	7-01282-720	IGC	Fabricated Part
Z 0	7-01283-720	IGC	Fabricated Part
Z 0	7-01291-709	IGC	Lexan Overlay

VCPU.E

RevD:

Buffer SYSCLK and TMR0OUT with U211
Move N102H from TI1 to TI0
Change R511 to 3.3k

RevE:
Change Flash to 48pin TSOP
Add D520
Add grounding caps C69X



LINK
VCPU2.
VCPU3.
VCPU4.
VCPU5.
VCPU6.

STANFORD RESEARCH SYSTEMS, Inc.
1290-D Reamwood Avenue
Sunnyvale, CA 94089
(408) 744-9040

Title		
	CPU	
Size	Document Number	REV
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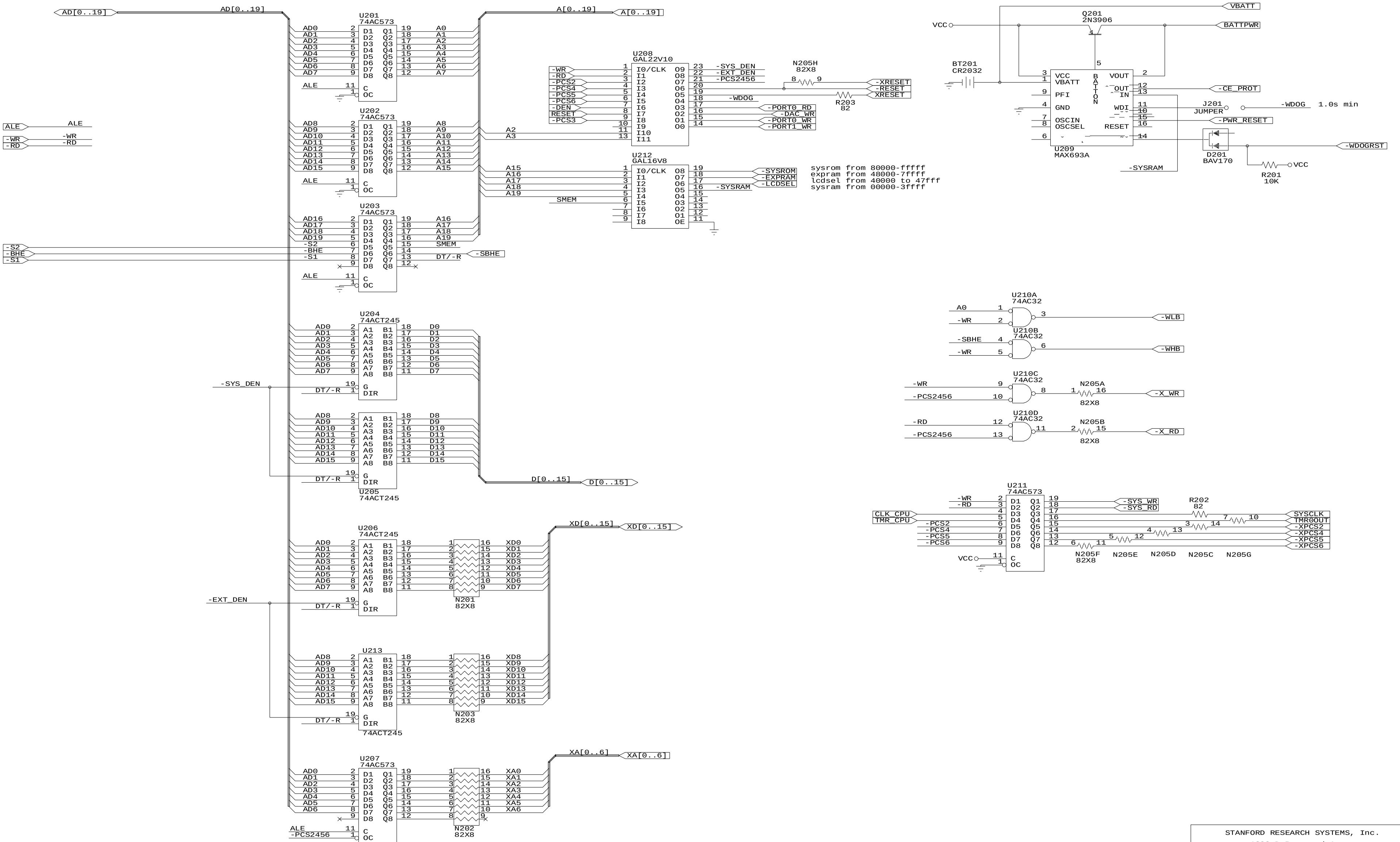
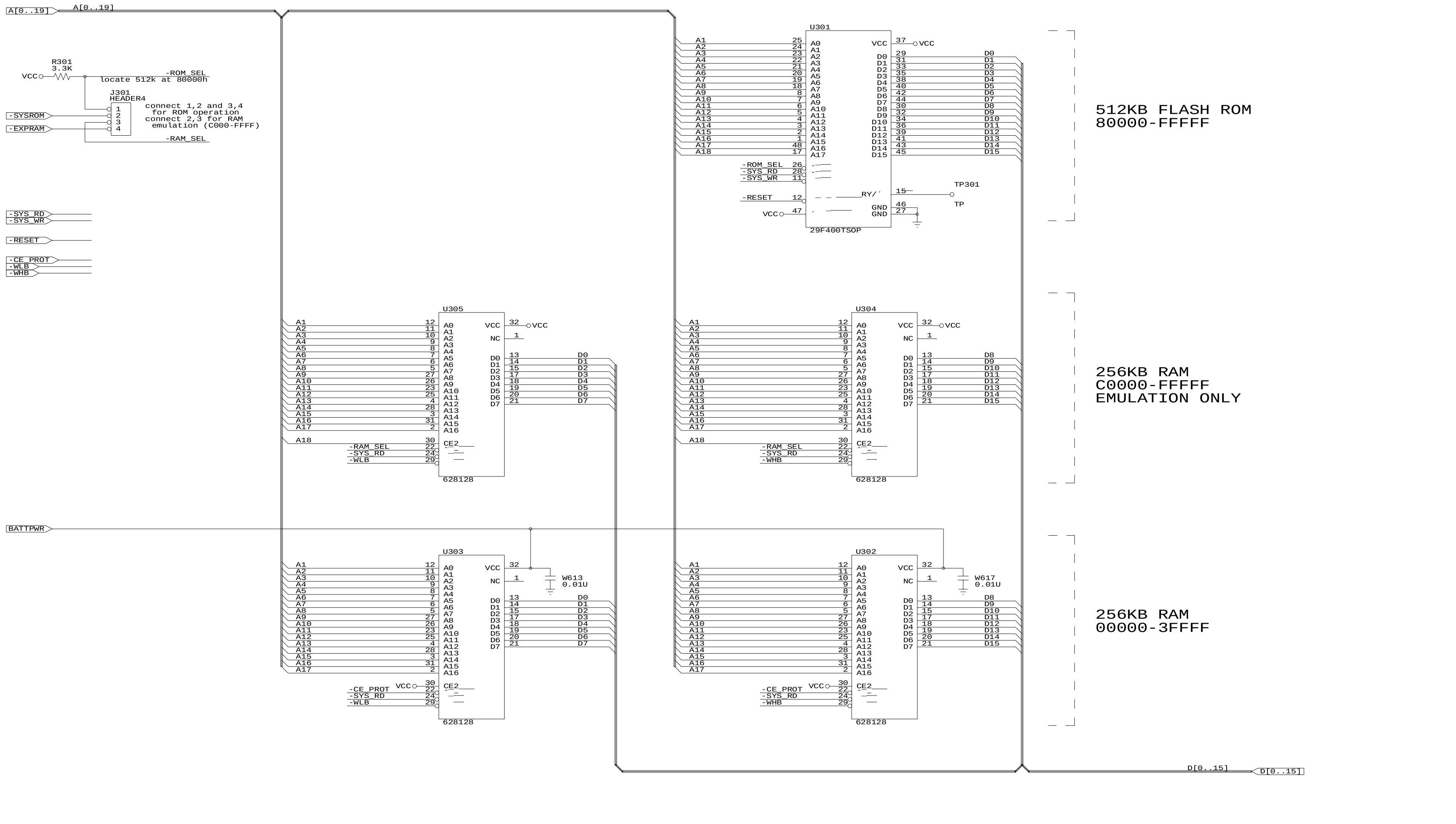
Date: April 22, 2002	Sheet 1 of 6	



STANFORD RESEARCH SYSTEMS, Inc. 1290-D Reamwood Avenue Sunnyvale, CA 94089 (408) 744-9040			
Title	ADDRESS AND DATA BUFFERS		
Size C	Document Number VCPU-2		REV E
Date: December 5, 2001	Sheet 2 of 6		



STANFORD RESEARCH SYSTEMS, Inc. 1290-D Reamwood Avenue Sunnyvale, CA 94089 (408) 744-9040		
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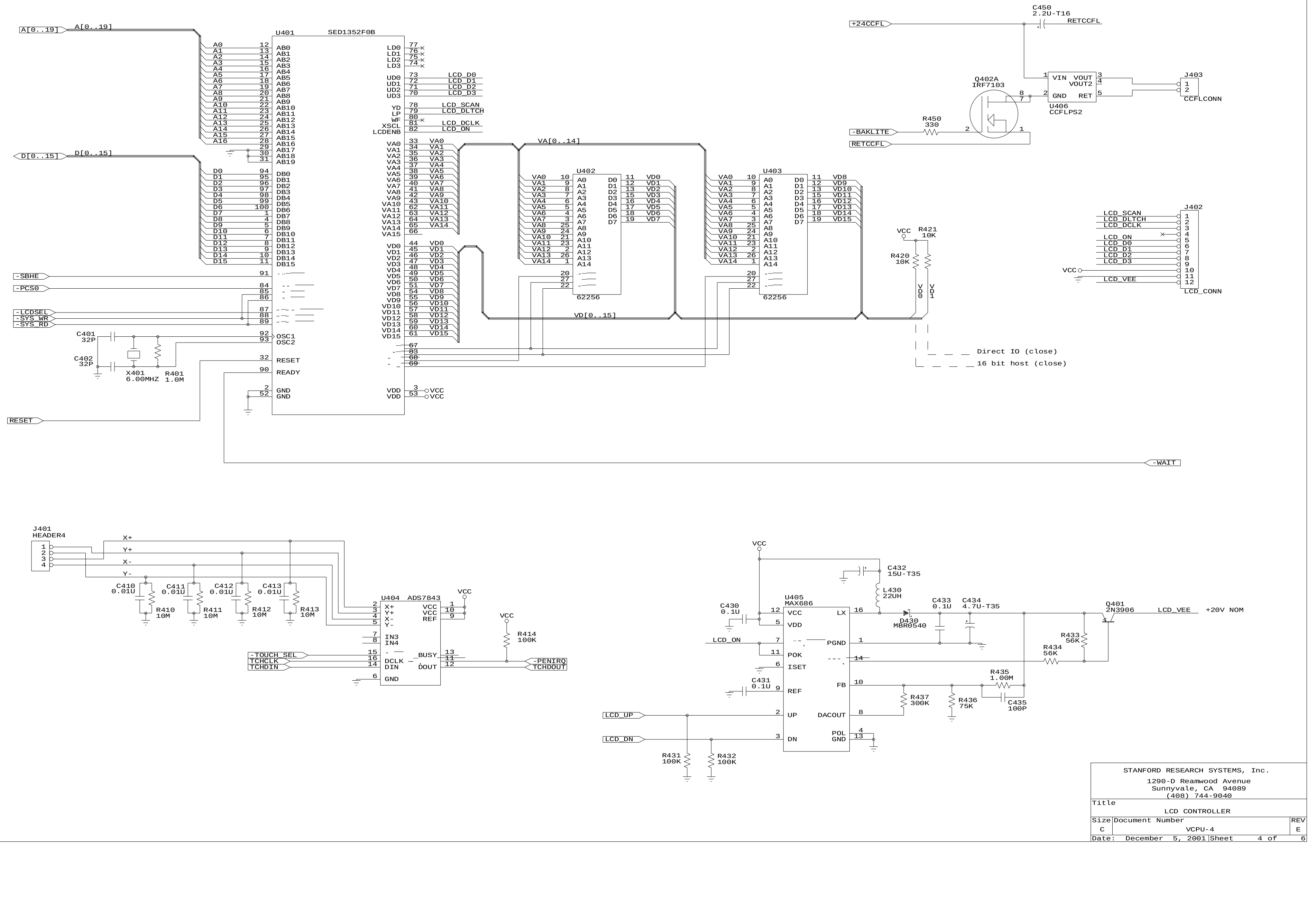
Size: C	Document Number: VCPU-3	REV: E
Date: December 5, 2001	Sheet 3 of 6	



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Size: C	Document Number: VCPU-4 — REV: E
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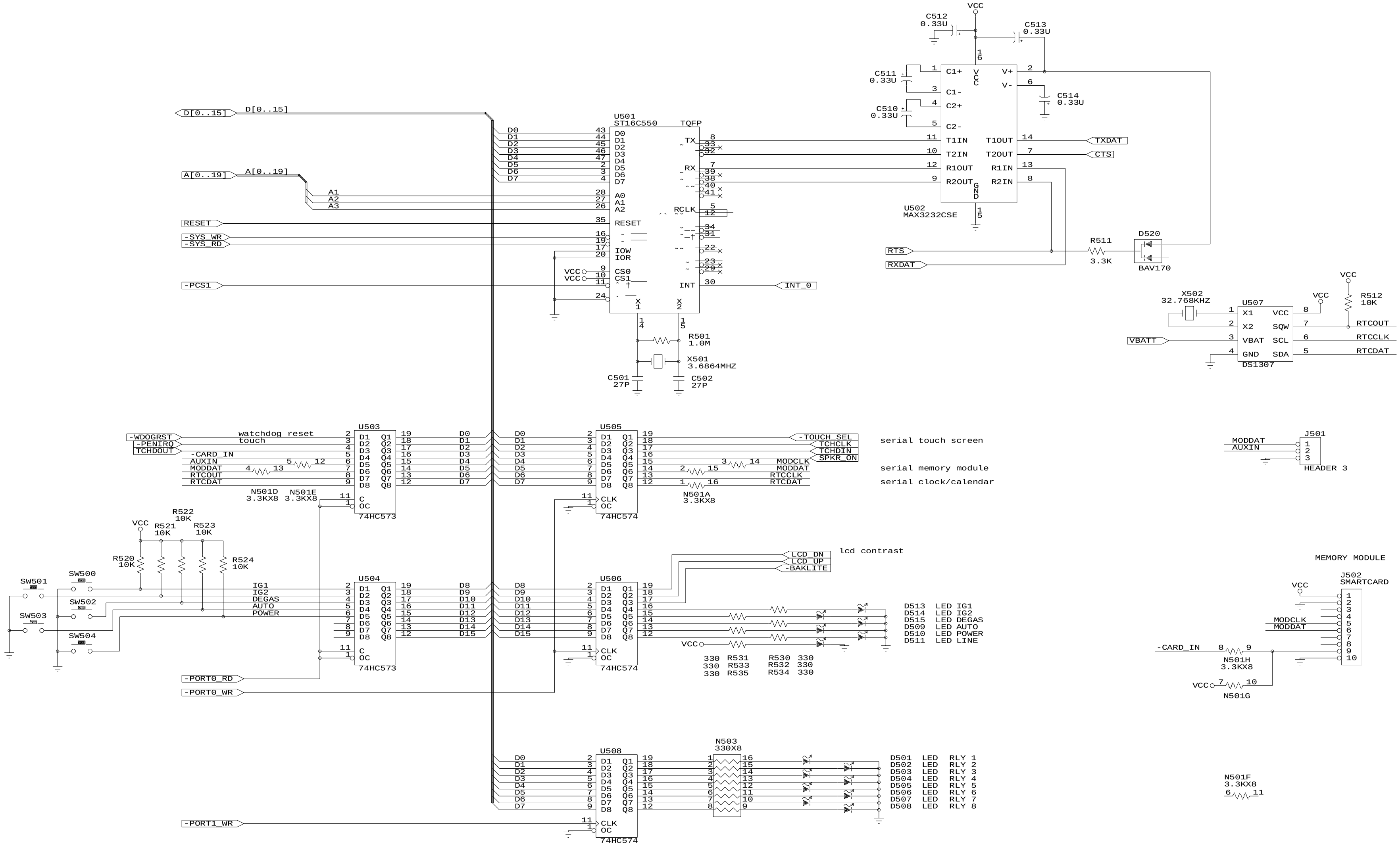

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1290-D Reamwood Avenue
Sunnyvale, CA 94089
(408) 744-9040

Title			
	SERIAL/CLOCK/TOUCH		
Size	Document Number		REV
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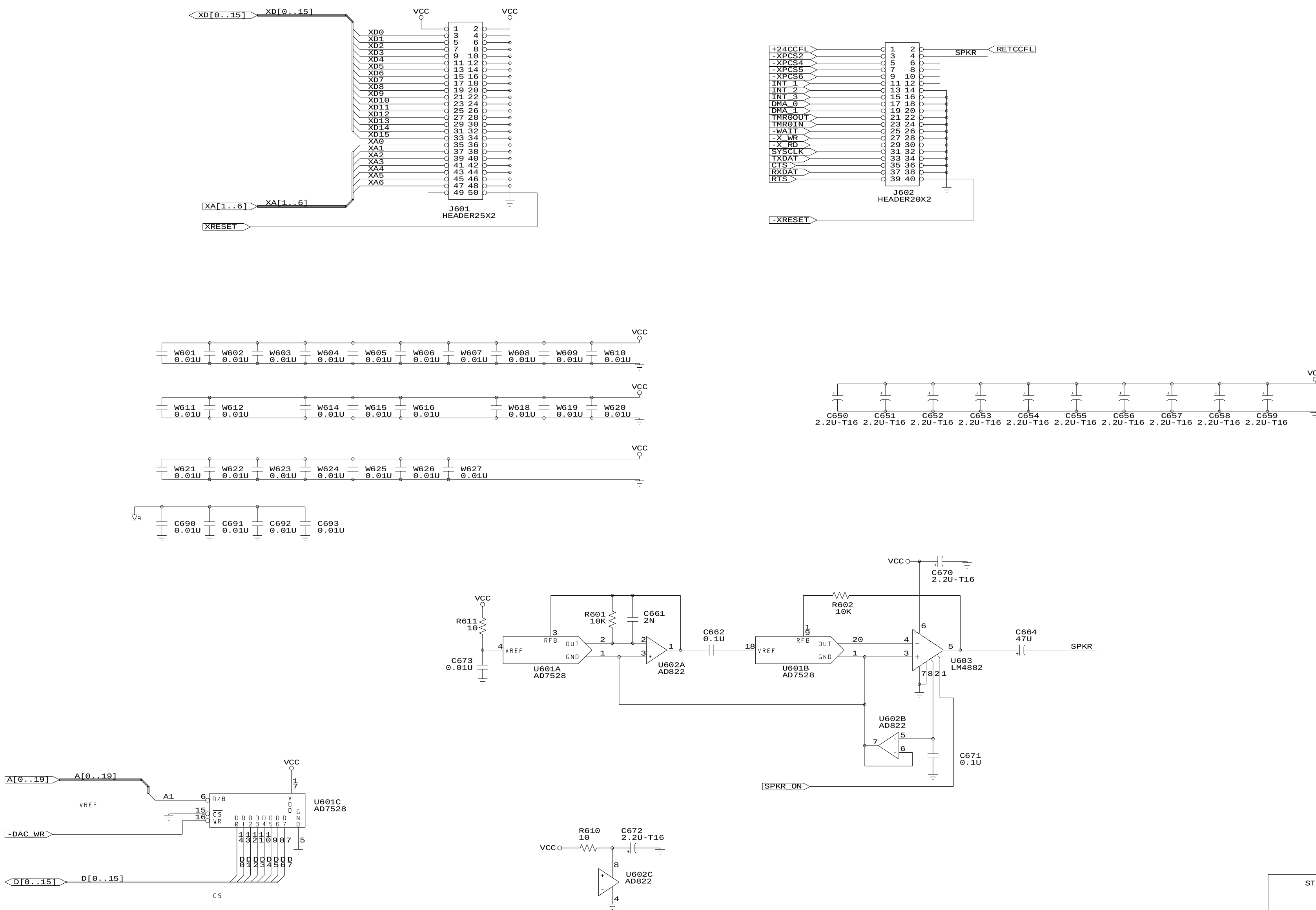
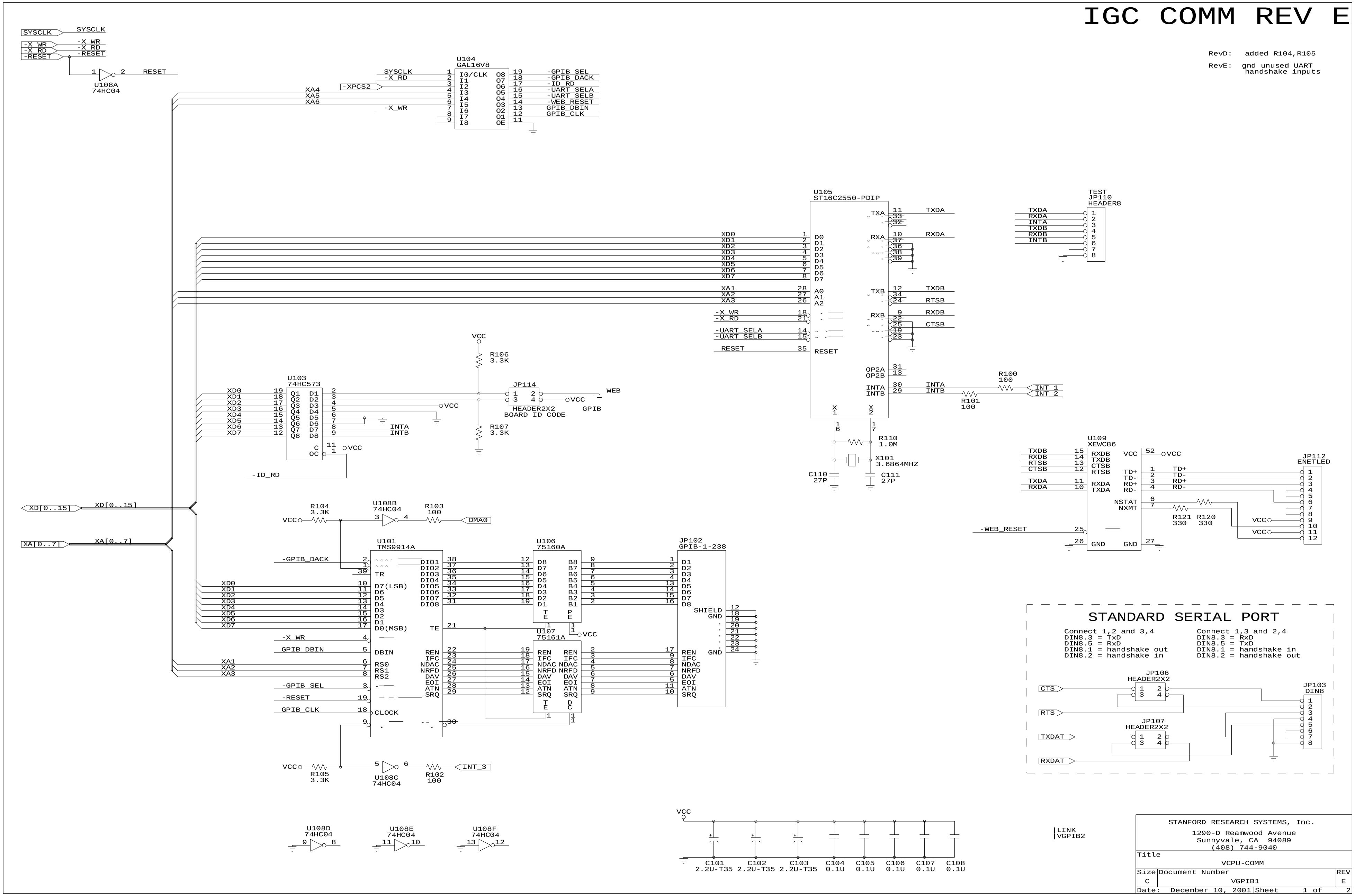
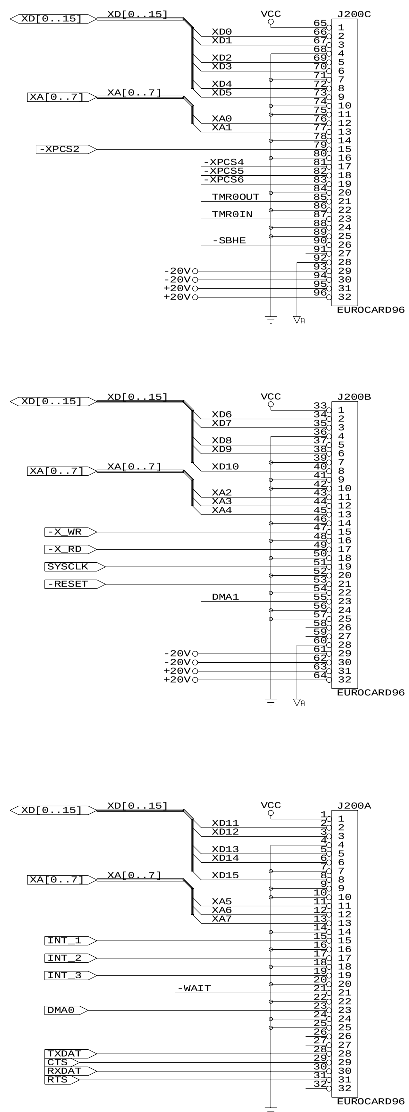
Date: December 5, 2001	Sheet	5 of	6

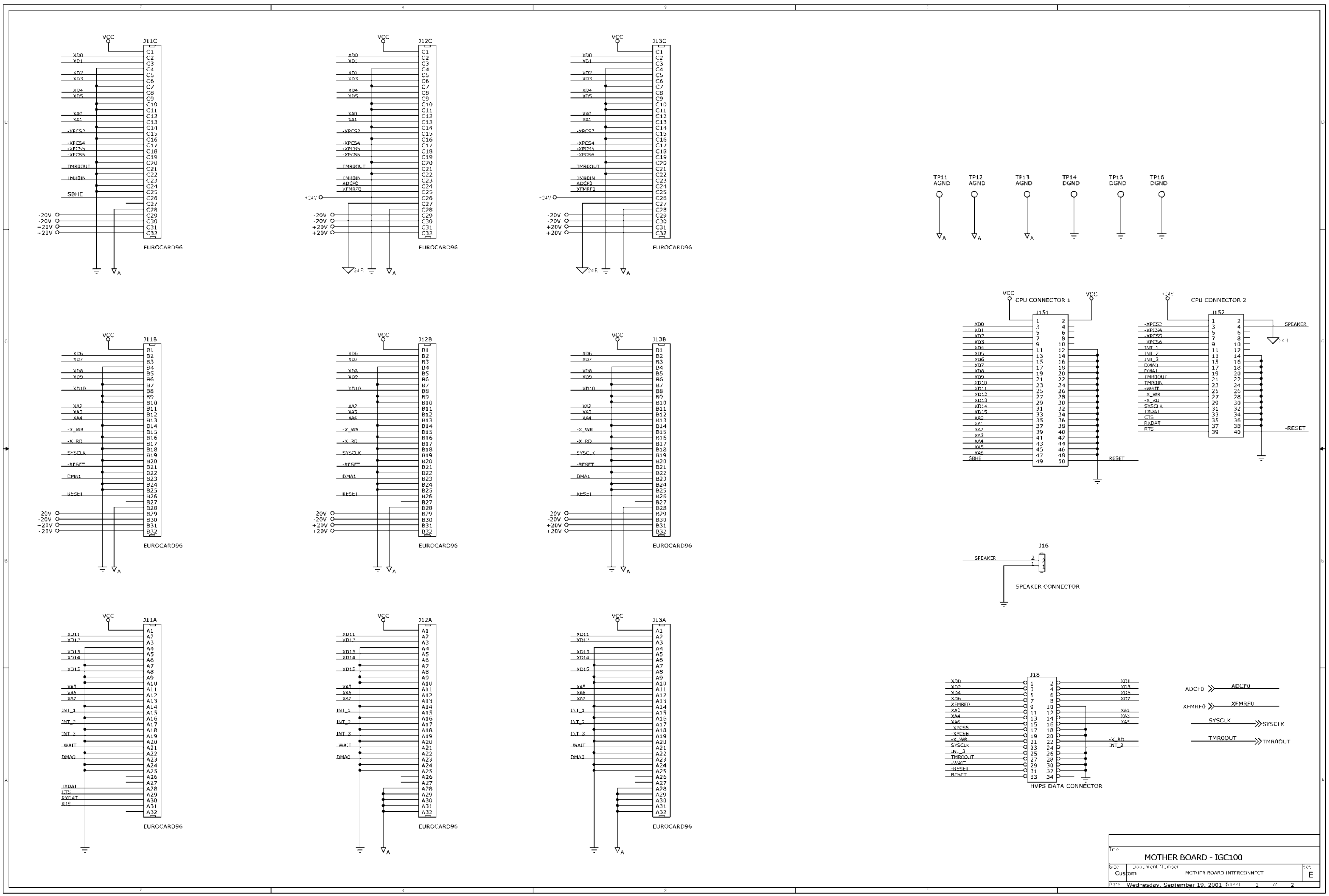


STANFORD RESEARCH SYSTEMS, Inc. 1290-D Reamwood Avenue Sunnyvale, CA 94089 (408) 744-9040		
Title: INTERCONNECT		
Size: C	Document Number: VCPU-6	REV: E
Date: April 22, 2002	Sheet 6 of 6	

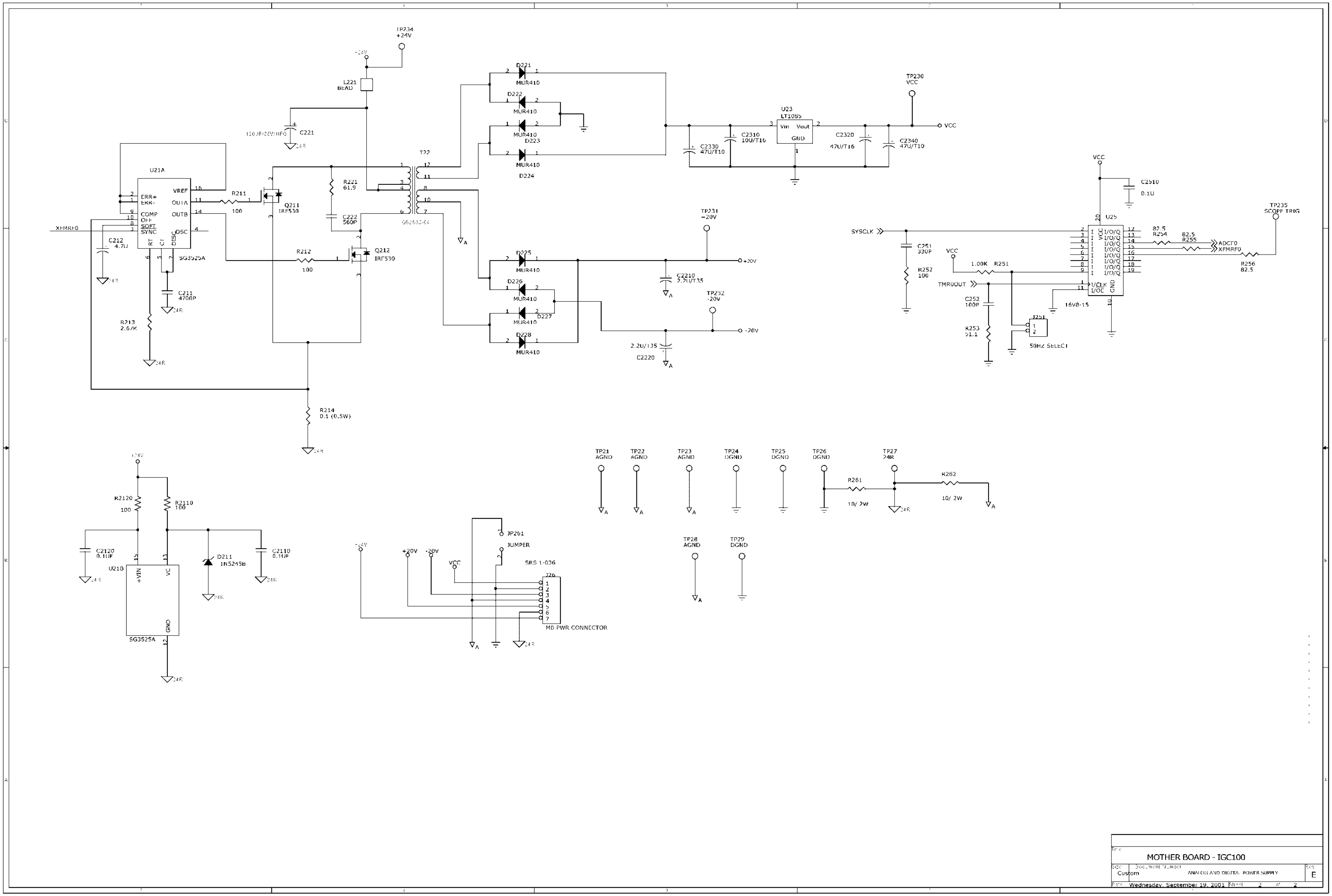

IGC COMM REV E
RevD: added R104,R105
RevE: gnd unused UART handshake inputs
SYSCLK
-X_WR
-X_RD
-RESET
U108A 74HC04
RESET
U104 GAL16V8
-XPCS2
-GPIB_SEL
-GPIB_DACK
-ID_RD
-UART_SELA
-UART_SELB
-WEB_RESET
GPIB_DBIN
GPIB_CLK
U105 ST16C2550-PDIP
TXDA
RXDA
TXDB
RTSB
RXDB
CTSB
INTA
INTB
R100 100
R101 100
INT_1
INT_2
R110 1.0M
X101 3.6864MHZ
C110 27P
C111 27P
TEST JP110 HEADER8
U103 74HC573
R106 3.3K
R107 3.3K
JP114 HEADER2X2 BOARD ID CODE
WEB
GPIB
XD[0..15]
XA[0..7]
R104 3.3K
U108B 74HC04
R103 100
DMA0
U101 TMS9914A
U106 75160A
U107 75161A
JP102 GPIB-1-238
R105 3.3K
U108C 74HC04
R102 100
INT_3
U108D 74HC04
U108E 74HC04
U108F 74HC04
U109 XEWC86
JP112 ENETLED
R121 330
R120 330
-WEB_RESET
STANDARD SERIAL PORT
Connect 1,2 and 3,4
DIN8.3 = TxD
DIN8.5 = RxD
DIN8.1 = handshake out
DIN8.2 = handshake in
Connect 1,3 and 2,4
DIN8.3 = RxD
DIN8.5 = TxD
DIN8.1 = handshake in
DIN8.2 = handshake out
JP106 HEADER2X2
JP107 HEADER2X2
JP103 DIN8
CTS
RTS
TXDAT
RXDAT
C101 2.2U-T35
C102 2.2U-T35
C103 2.2U-T35
C104 0.1U
C105 0.1U
C106 0.1U
C107 0.1U
C108 0.1U
LINK VGPIB2
STANFORD RESEARCH SYSTEMS, Inc.
1290-D Reamwood Avenue
Sunnyvale, CA 94089
(408) 744-9040
Title VCPU-COMM
Size C
Document Number VGPIB1
REV E
Date: December 10, 2001
Sheet 1 of 2



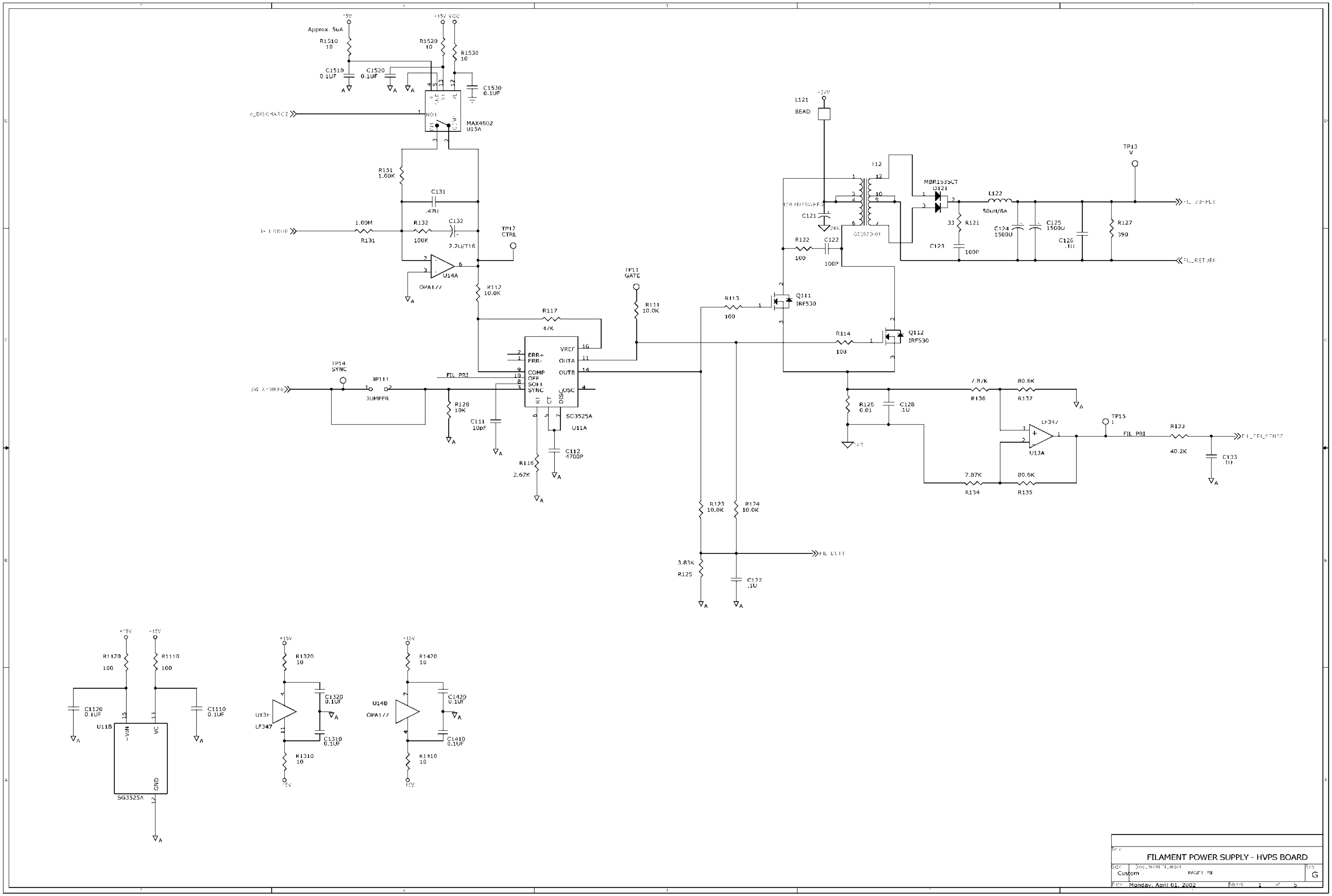
Stanford Research Systems 1290 D Reamwood Ave Sunnyvale, CA 94089 (408) 744-9047		
Title VCPU-GPIB CARD		
Size C	Document Number VGPIB2	REV E
Date: December 10, 2001	Sheet 2 of 2	



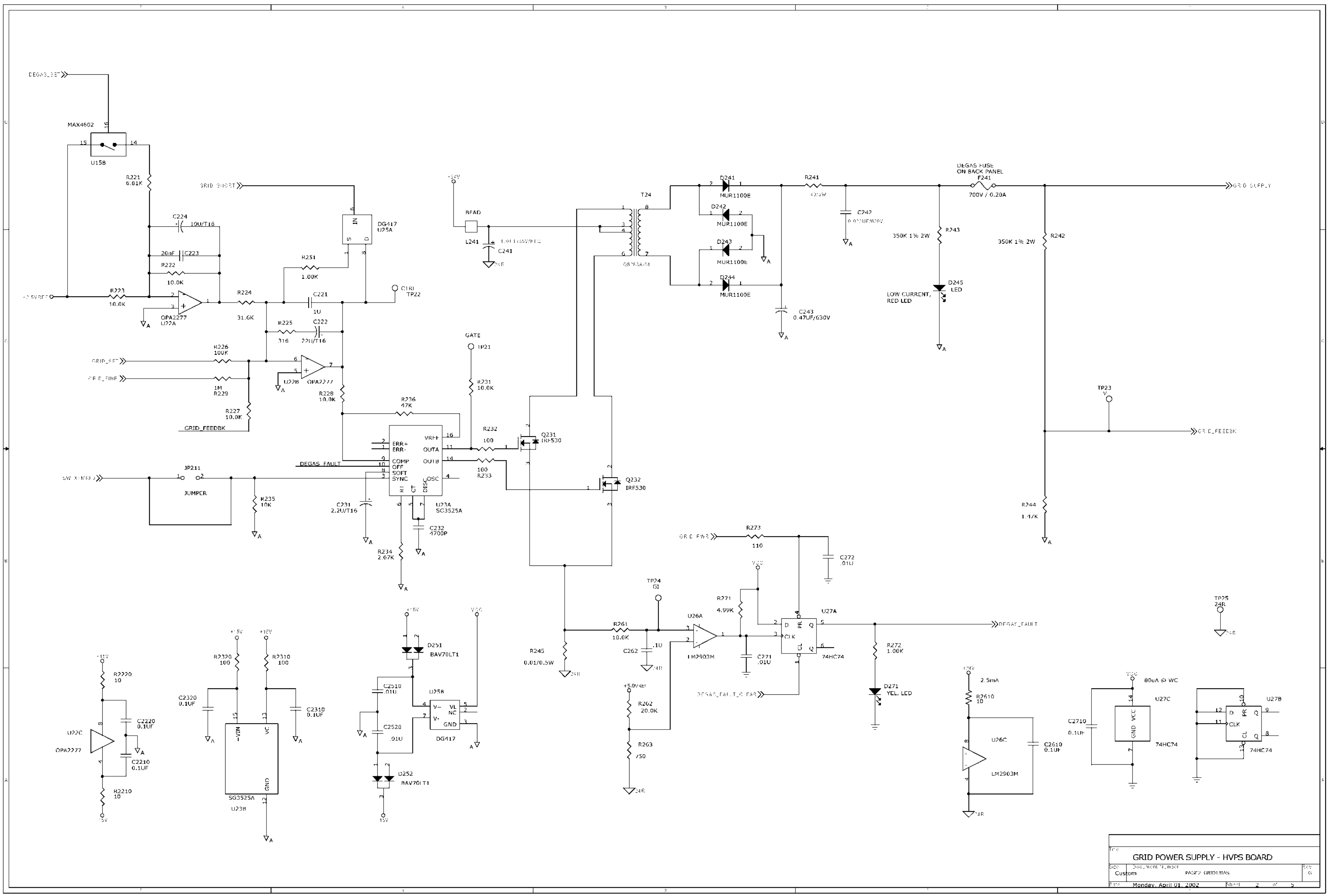
J11C
J12C
J13C
J11B
J12B
J13B
J11A
J12A
J13A
EUROCARD96
VCC
TP11 AGND
TP12 AGND
TP13 AGND
TP14 DGND
TP15 DGND
TP16 DGND
CPU CONNECTOR 1
J151
CPU CONNECTOR 2
J152
SPEAKER
-RESET
J16
SPEAKER CONNECTOR
J18
HVPS DATA CONNECTOR
ADCF0
XFMRF0
SYSCLK
TMR0OUT
MOTHER BOARD - IGC100
Custom
MOTHER BOARD INTERCONNECT
E
Wednesday, September 19, 2001
1
2



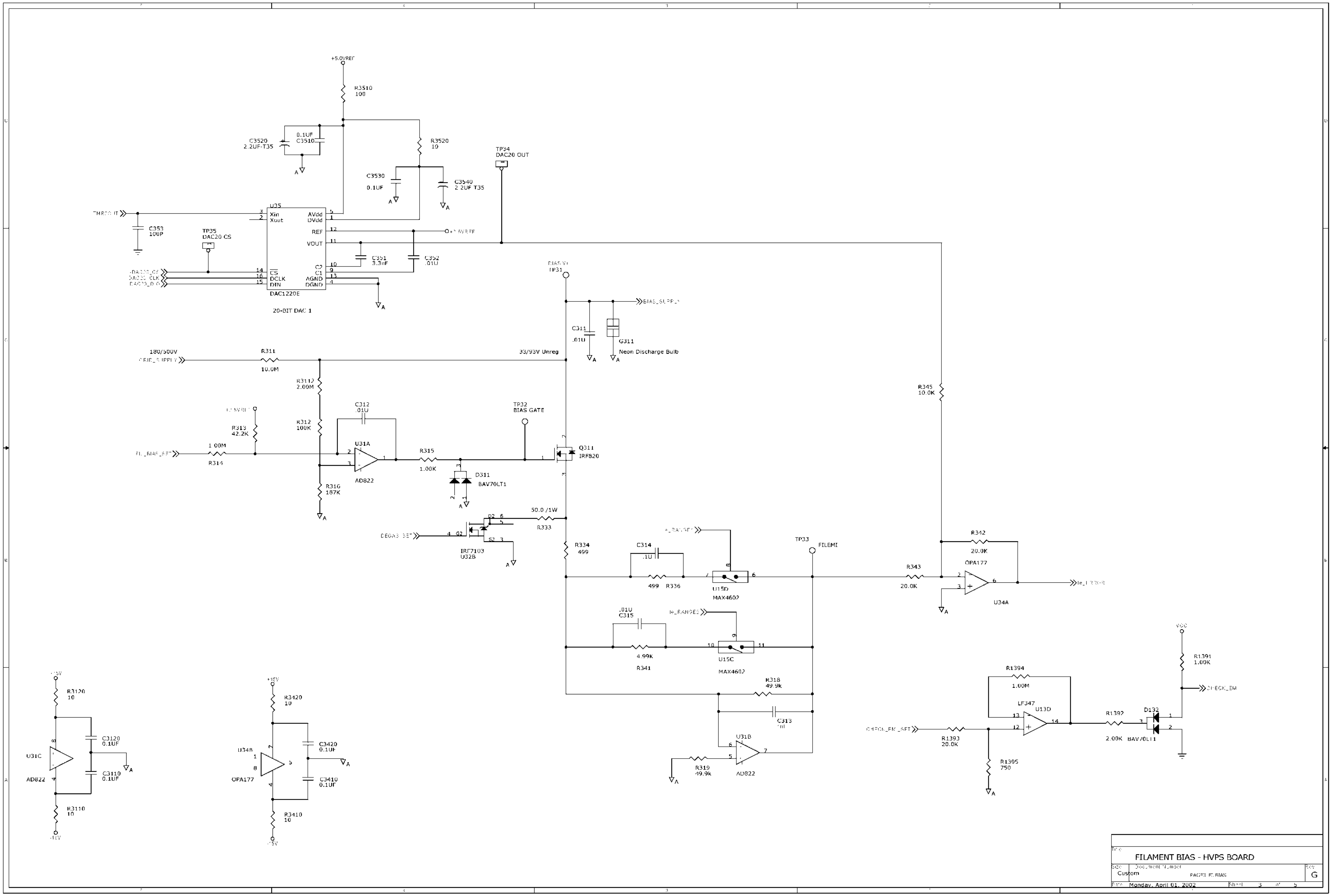
TP234
+24V
L221
BEAD
C221
U21A
VREF
OUTA
OUTB
OSC
ERR+
ERR-
COMP
OFF
SOFT
SYNC
RT
CT
DISC
SG3525A
XFMRF0
C212
4.7U
C211
4700P
R213
2.67K
R211
100
Q211
IRF530
R212
100
Q212
IRF530
R221
61.9
C222
560P
T22
R214
0.1 (0.5W)
D221
D222
D223
D224
D225
D226
D227
D228
MUR410
U23
LT1085
Vin
Vout
GND
C2330
47U/T10
C2310
10U/T16
C2320
47U/T16
C2340
47U/T10
TP230
VCC
TP231
+20V
TP232
-20V
C2210
2.2U/T35
2.2U/T35
C2220
VCC
C2510
0.1U
U25
I/O/Q
I/CLK
I/OE
GND
16V8-15
SYSCLK
C251
330P
R252
100
1.00K
R251
TMROUT
C252
100P
R253
51.1
J251
50HZ SELECT
R254
82.5
R255
82.5
ADCF0
XFMRF0
R256
82.5
TP235
SCOPE TRIG
U21B
+VIN
VC
GND
SG3525A
R2120
100
R2110
100
C2120
0.1UF
C2110
0.1UF
D211
1N5245B
JP261
JUMPER
SRS 1-036
J26
MB PWR CONNECTOR
+20V
-20V
VCC
TP21
AGND
TP22
AGND
TP23
AGND
TP24
DGND
TP25
DGND
TP26
DGND
TP27
24R
R261
10/ 2W
R262
10/ 2W
TP28
AGND
TP29
DGND
MOTHER BOARD - IGC100
Custom
ANALOG AND DIGITAL POWER SUPPLY
E
Wednesday, September 19, 2001

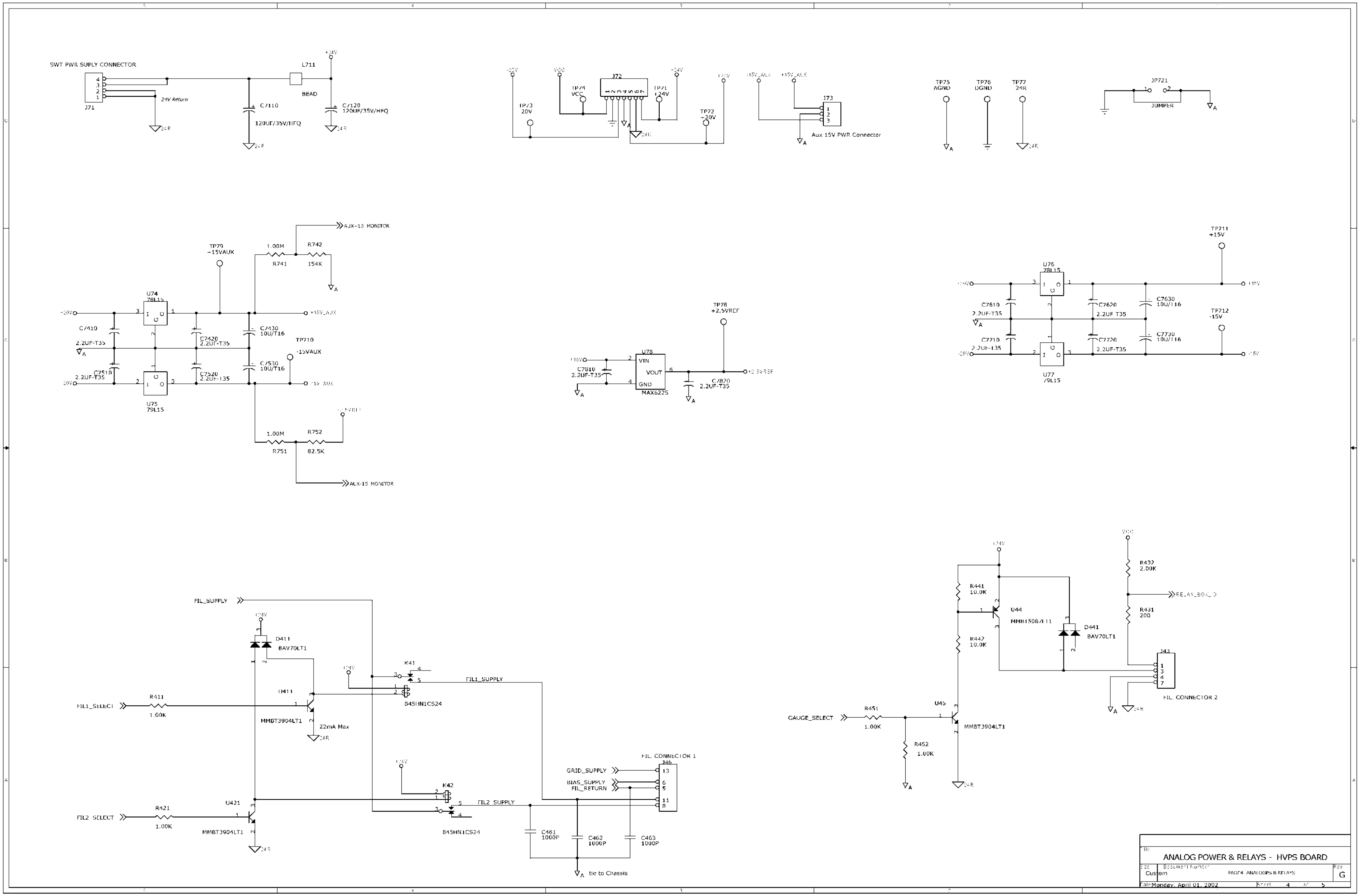


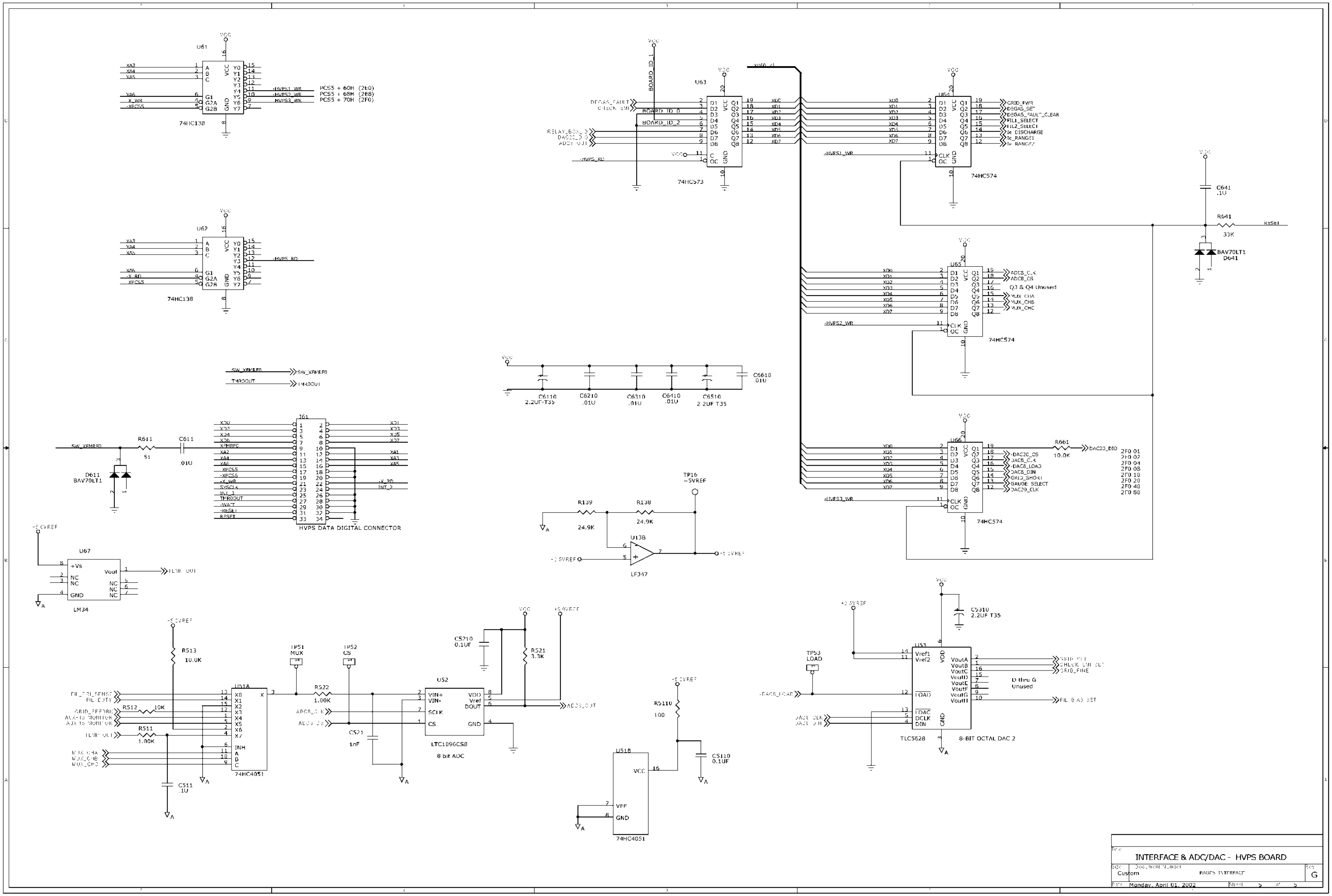
FILAMENT POWER SUPPLY - HVPS BOARD
Custom
PAGE1 FB
G
Monday, April 01, 2002
Sheet 1 of 5
MAX4602
U15A
OPA177
U14A
SG3525A
U11A
IRF530
Q111
Q112
MBR1535CT
D121
L121
BEAD
L122
50uH/8A
LF347
U13A
FIL_PRI
TP11
GATE
TP12
CTRL
TP13
TP14
SYNC
TP15
JUMPER
U11B
U13F
U14B

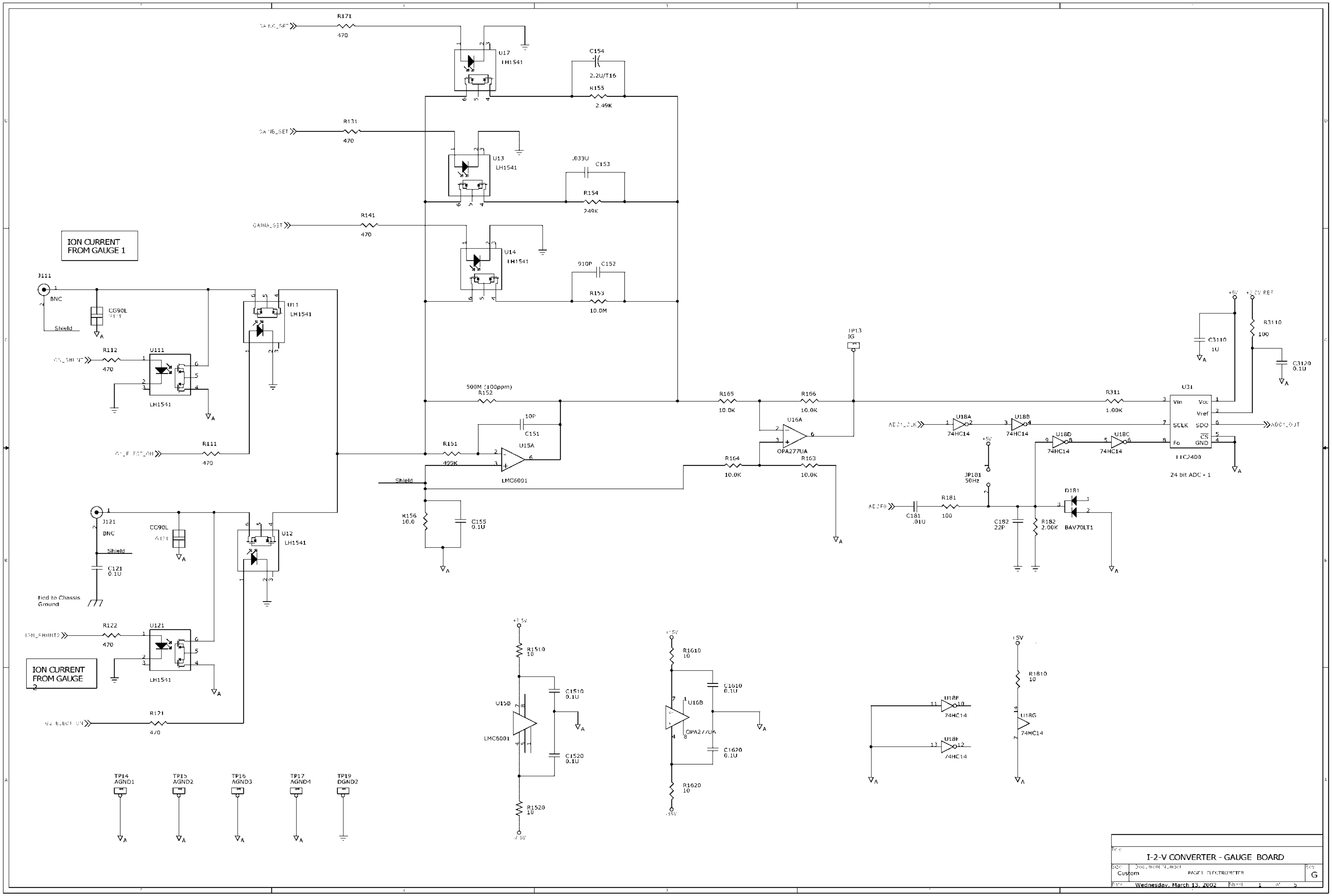


DEGAS_SET
MAX4602
U158
R221
6.81K
GRID_SHORT
DG417
U25A
C224
10U/T16
C223
20nF
R222
10.0K
R251
1.00K
R223
10.0K
OPA2277
U22A
R224
31.6K
C221
1U
CTRL
TP22
R225
316
C222
22U/T16
GATE
TP21
GRID_SET
R226
100K
1M
R229
OPA2277
U22B
R228
10.0K
R231
10.0K
R227
10.0K
GRID_FEEDBK
R236
47K
ERR+
ERR-
COMP
OFF
SOFT
SYNC
VREF
OUTA
OUTB
OSC
RT
CT
DISC
R232
100
R233
100
Q231
IRF530
Q232
IRF530
DEGAS_FAULT
JP211
JUMPER
R235
10K
C231
2.2U/T16
U23A
SG3525A
C232
4700P
R234
2.67K
BEAD
L241
C241
T24
D241
MUR1100E
D242
MUR1100E
D243
MUR1100E
D244
MUR1100E
R241
C242
C243
0.47UF/630V
DEGAS FUSE
ON BACK PANEL
F241
700V / 0.20A
GRID SUPPLY
350K 1% 2W
R243
R242
D245
LED
LOW CURRENT,
RED LED
TP23
V
GRID_FEEDBK
R244
GRID_PWR
R273
110
C272
.01U
TP24
GI
R271
4.99K
U26A
U27A
R245
0.01/0.5W
R261
10.0K
C262
.1U
LM2903M
C271
.01U
74HC74
DEGAS_FAULT
R272
1.00K
D271
YEL. LED
+5.0VREF
R262
20.0K
R263
750
TP25
24R
U22C
OPA2277
R2220
10
C2220
0.1UF
C2210
0.1UF
R2210
10
R2320
100
R2310
100
C2320
0.1UF
C2310
0.1UF
SG3525A
U23B
-VIN
VC
GND
D251
BAV70LT1
D252
BAV70LT1
C2510
.01U
C2520
.01U
U25B
DG417
2.5mA
R2610
10
U26C
LM2903M
C2610
0.1UF
C2710
0.1UF
80uA @ WC
U27C
74HC74
U27B
74HC74
GRID POWER SUPPLY - HVPS BOARD
Custom
PAGE2 GRIDBIAS
Monday, April 01, 2002

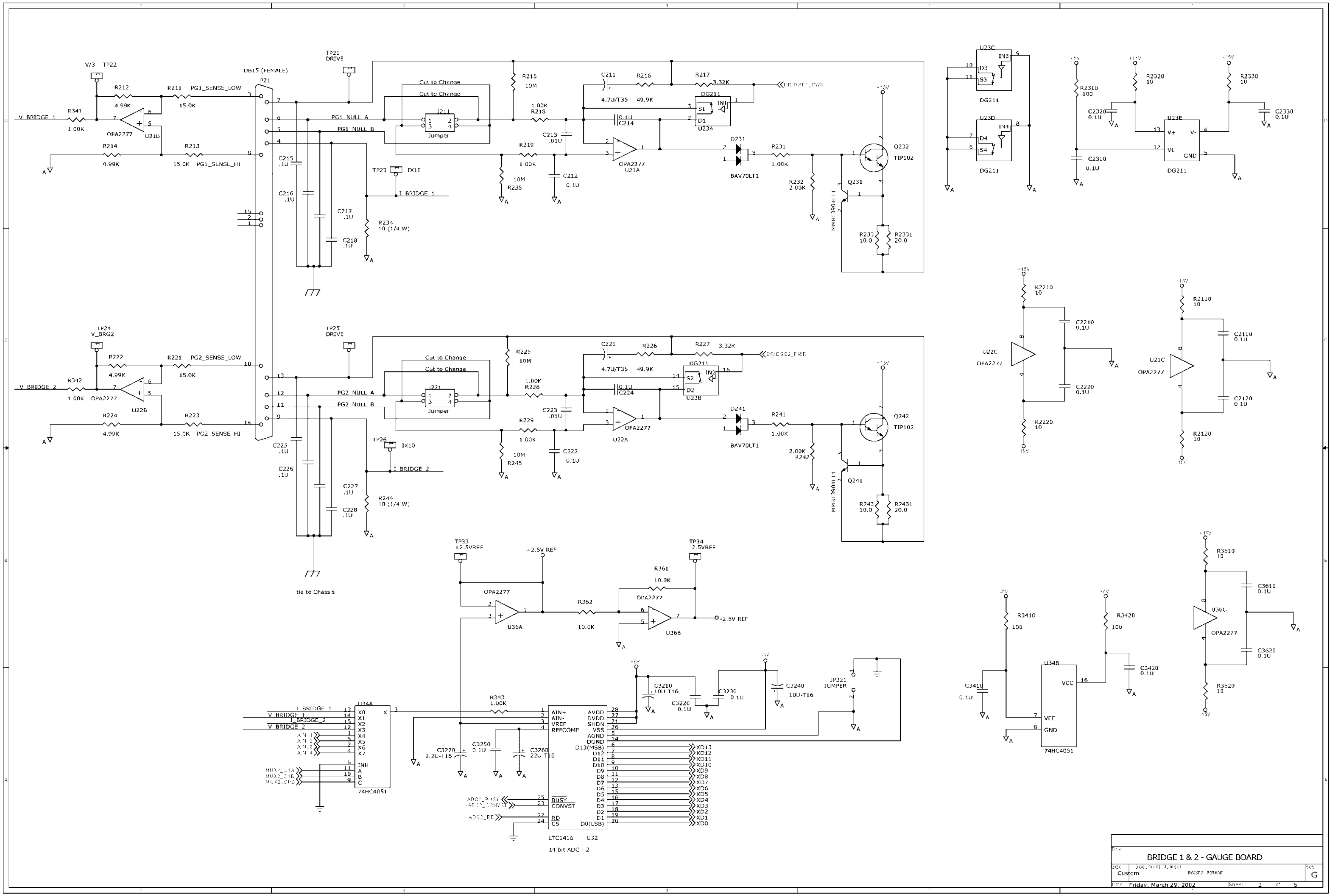

+5.0VREF
R3510
100
C3520
2.2UF-T35
0.1UF
C3510
R3520
10
C3530
0.1UF
C3540
2.2UF T35
TP34
DAC20 OUT
U35
Xin
Xout
AVdd
DVdd
REF
VOUT
C2
C1
AGND
DGND
CS
DCLK
DIN
DAC1220E
20-BIT DAC 1
C353
100P
TP35
DAC20 CS
C351
3.3nF
C352
.01U
BIAS V+
TP31
C311
.01U
G311
Neon Discharge Bulb
180/500V
R311
10.0M
33/93V Unreg
R3112
2.00M
R312
100K
C312
.01U
TP32
BIAS GATE
R313
42.2K
1.00M
R314
U31A
AD822
R315
1.00K
Q311
IRF820
D311
BAV70LT1
R316
187K
50.0 /1W
R333
IRF7103
U32B
R334
499
C314
.1U
499
R336
U15D
MAX4602
TP33
FILEMI
R343
20.0K
R345
10.0K
R342
20.0K
OPA177
U34A
.01U
C315
4.99K
R341
U15C
MAX4602
R318
49.9k
C313
U31B
R319
49.9k
AD822
R1394
1.00M
LF347
U13D
R1393
20.0K
R1395
750
R1392
2.00K
D132
BAV70LT1
R1391
1.00K
VCC
R3120
10
C3120
0.1UF
U31C
AD822
C3110
0.1UF
R3110
10
R3420
10
U34B
OPA177
C3420
0.1UF
C3410
0.1UF
R3410
10
FILAMENT BIAS - HVPS BOARD
Custom
G
Monday, April 01, 2002

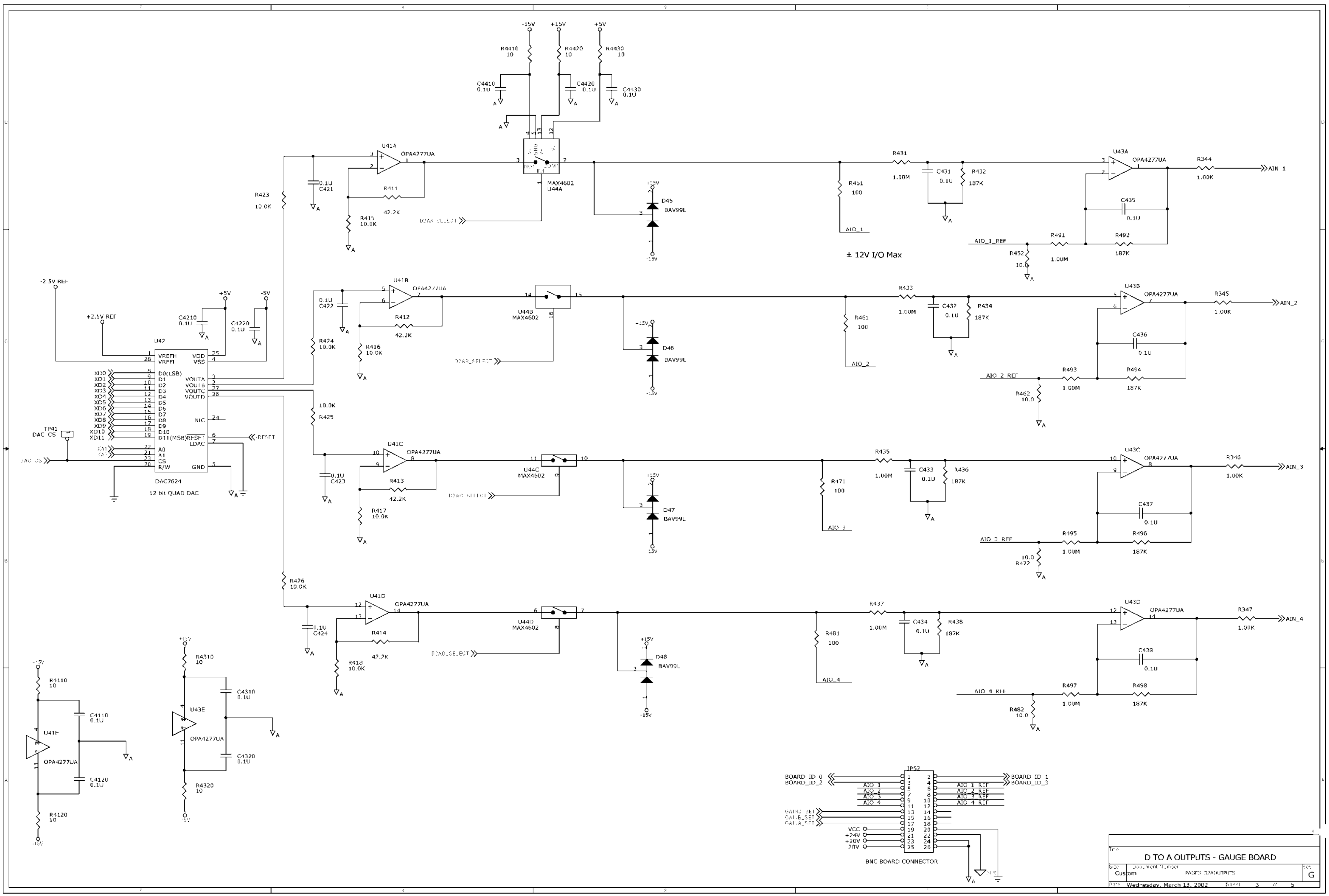

SWT PWR SUPLY CONNECTOR
J71
24V Return
L711
BEAD
C7110
120UF/35V/HFQ
C7120
120UF/35V/HFQ
J72
TP73
20V
TP74
VCC
TP71
+24V
TP72
-20V
J73
Aux 15V PWR Connector
TP75
AGND
TP76
DGND
TP77
24R
JP721
JUMPER
AUX-15 MONITOR
TP79
-15VAUX
R741
1.00M
R742
154K
U74
78L15
C7410
2.2UF-T35
C7420
2.2UF-T35
C7430
10U/T16
C7510
2.2UF-T35
C7520
2.2UF-T35
C7530
10U/T16
TP710
-15VAUX
U75
79L15
R751
1.00M
R752
82.5K
AUX-15 MONITOR
TP78
+2.5VREF
U78
VIN
VOUT
GND
MAX6225
C7810
2.2UF-T35
C7820
2.2UF-T35
TP711
+15V
U76
78L15
C7610
2.2UF-T35
C7620
2.2UF T35
C7630
10U/T16
TP712
-15V
C7710
2.2UF-T35
C7720
2.2UF-T35
C7730
10U/T16
U77
79L15
FIL_SUPPLY
D411
BAV70LT1
U411
MMBT3904LT1
FIL1_SELECT
R411
1.00K
22mA Max
K41
FIL1_SUPPLY
845HN1CS24
K42
FIL2_SUPPLY
845HN1CS24
FIL2_SELECT
R421
1.00K
U421
MMBT3904LT1
FIL. CONNECTOR 1
J46
GRID_SUPPLY
BIAS_SUPPLY
FIL_RETURN
C461
1000P
C462
1000P
C463
1000P
tie to Chassis
R441
10.0K
U44
MMBT5087LT1
R442
10.0K
D441
BAV70LT1
R432
2.00K
R431
200
RELAY_BOX_D
J43
FIL. CONNECTOR 2
GAUGE_SELECT
R451
1.00K
R452
1.00K
U45
MMBT3904LT1
ANALOG POWER & RELAYS - HVPS BOARD
Custom
PAGE4 ANALOGPS & RELAYS
G
Monday, April 01, 2002
4
5

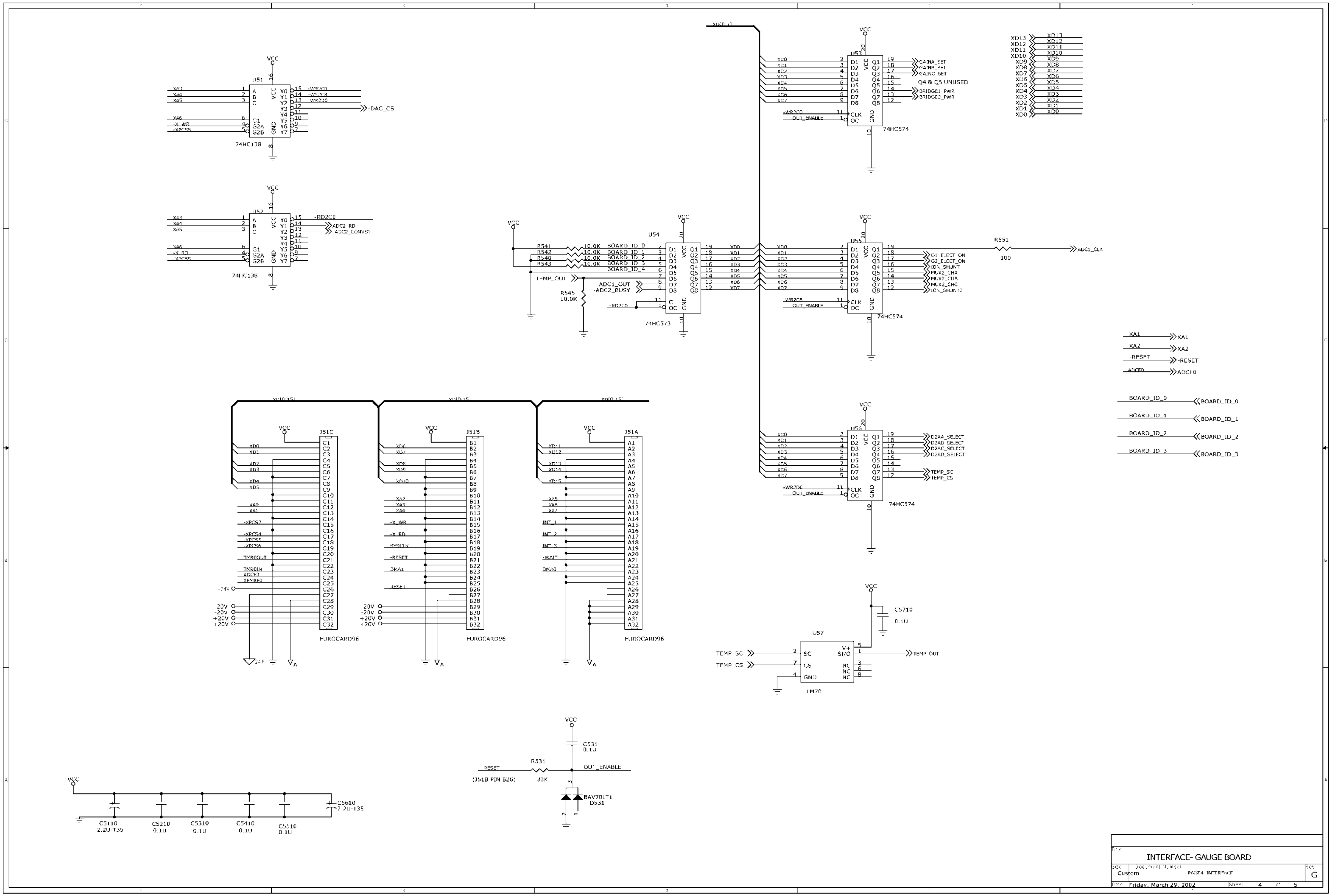

INTERFACE & ADC/DAC - HVPS BOARD
Custom
PAGE5 INTERFACE
G
Monday, April 01, 2002
5 of 5

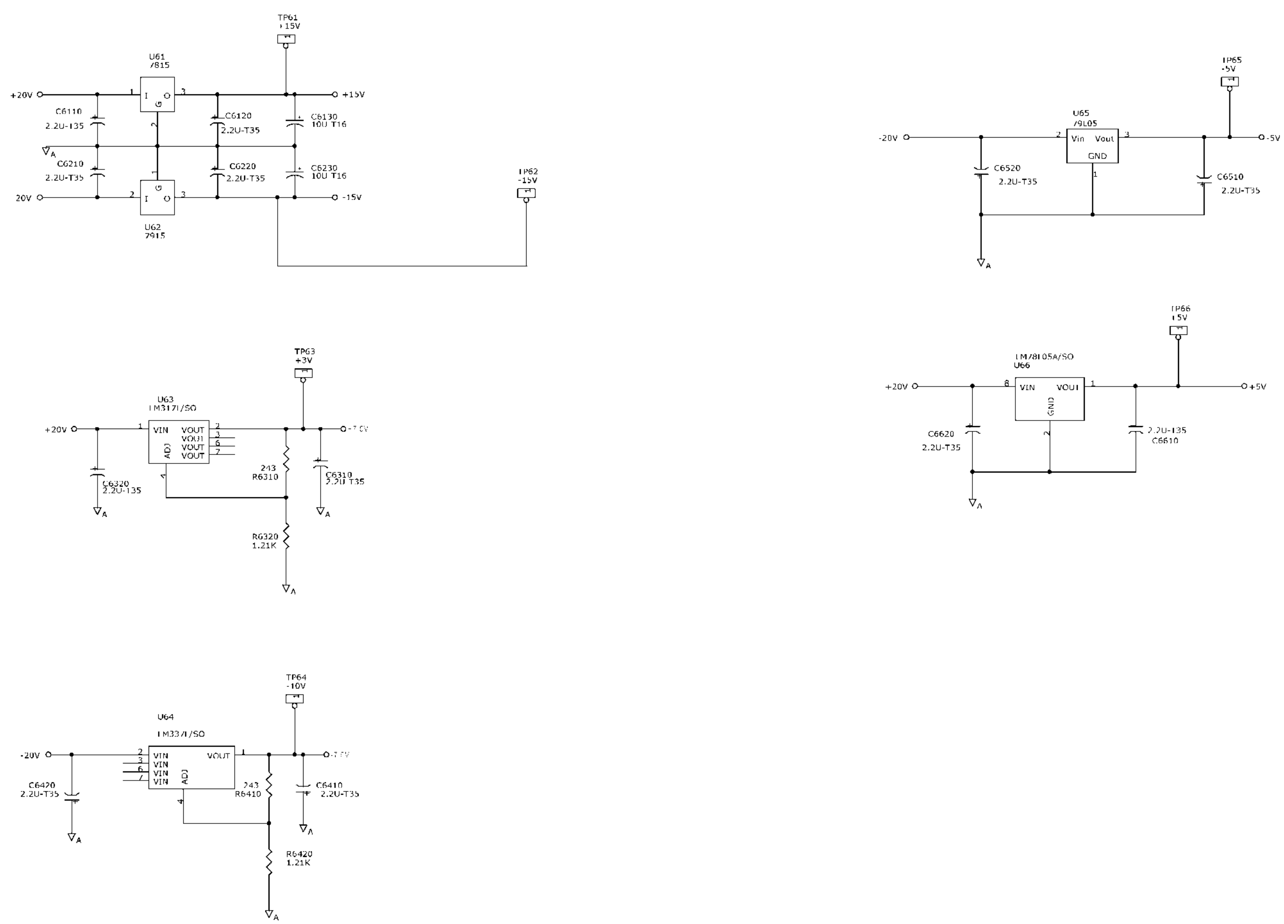


ION CURRENT FROM GAUGE 1
ION CURRENT FROM GAUGE 2
J111 BNC
J121 BNC
Shield
Tied to Chassis Ground
CG90L
C121 0.1U
R171 470
R131 470
R141 470
R111 470
R112 470
R122 470
R121 470
U17 LH1541
U13 LH1541
U14 LH1541
U11 LH1541
U12 LH1541
U111 LH1541
U121 LH1541
C154 2.2U/T16
R155 2.49K
.033U C153
R154 249K
910P C152
R153 10.0M
500M (100ppm) R152
10P C151
R151 499K
U15A LMC6001
R156 10.0
C155 0.1U
R165 10.0K
R166 10.0K
R164 10.0K
R163 10.0K
U16A OPA277UA
TP13 IG
R311 1.00K
U31 LTC2400
Vin Vcc Vref SCLK SDO CS GND Fo
24 bit ADC - 1
ADC1_OUT
R3110 100
C3110 1U
C3120 0.1U
+5V
U18A 74HC14
U18B 74HC14
U18C 74HC14
U18D 74HC14
U18E 74HC14
U18F 74HC14
U18G 74HC14
JP181 50Hz
C181 .01U
R181 100
C182 22P
R182 2.00K
D181 BAV70LT1
U15B LMC6001
R1510 10
R1520 10
C1510 0.1U
C1520 0.1U
U16B OPA277UA
R1610 10
R1620 10
C1610 0.1U
C1620 0.1U
R1810 10
TP14 AGND1
TP15 AGND2
TP16 AGND3
TP17 AGND4
TP19 DGND2
I-2-V CONVERTER - GAUGE BOARD
Custom
G
Wednesday, March 13, 2002
1 5


BRIDGE 1 & 2 - GAUGE BOARD
Custom
G
Friday, March 29, 2002
14 bit ADC - 2
tie to Chassis


D TO A OUTPUTS - GAUGE BOARD
Custom
G
Wednesday, March 13, 2002
± 12V I/O Max
DAC7624
12 bit QUAD DAC
BNC BOARD CONNECTOR
AIN_1
AIN_2
AIN_3
AIN_4
AIO_1
AIO_2
AIO_3
AIO_4
AIO_1_REF
AIO_2_REF
AIO_3_REF
AIO_4_REF
BOARD_ID_0
BOARD_ID_1
BOARD_ID_2
BOARD_ID_3
OPA4277UA
MAX4602
BAV99L
+2.5V REF
-2.5V REF
TP41
DAC CS

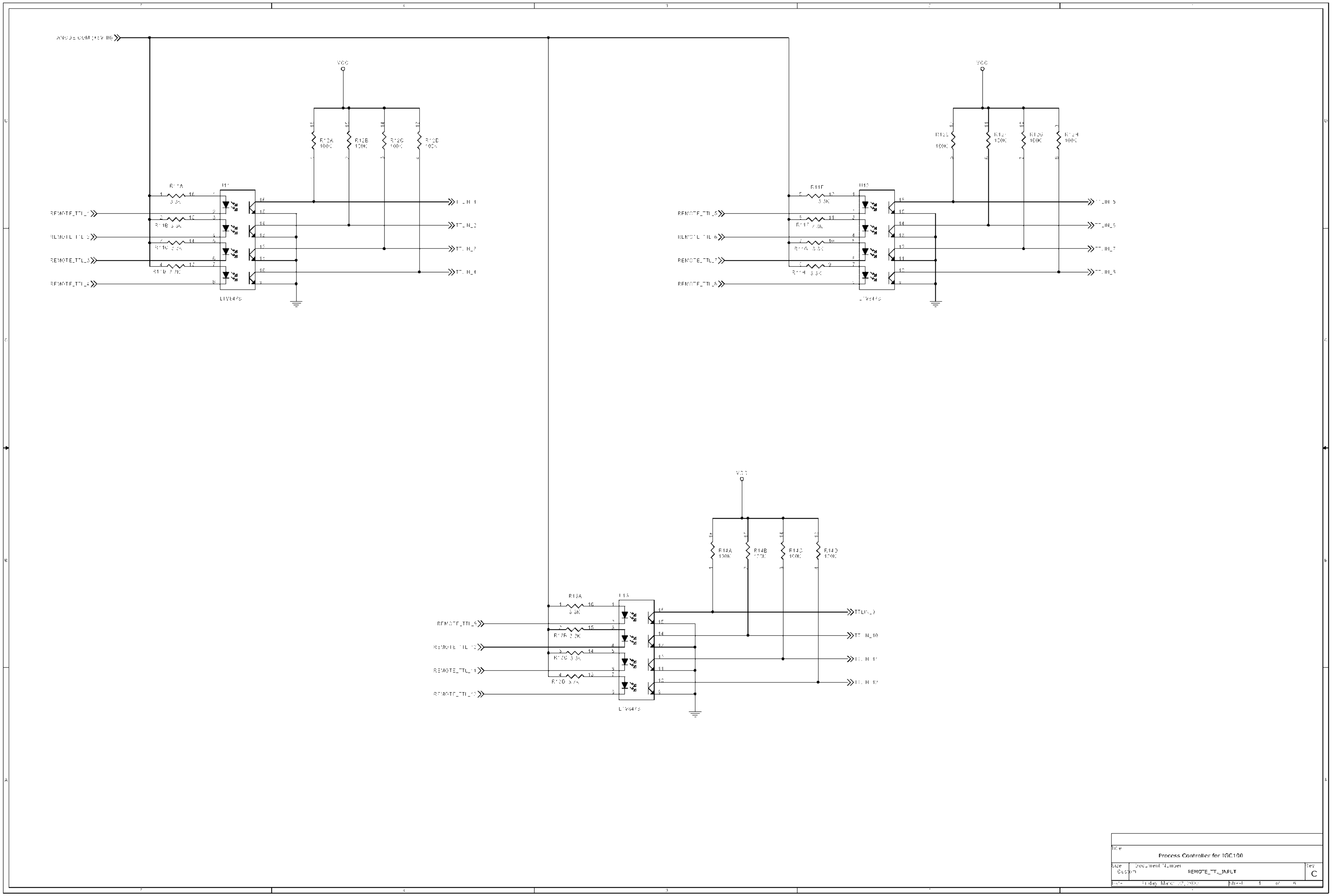

INTERFACE- GAUGE BOARD
Custom
PAGE4 INTERFACE
G
Friday, March 29, 2002
4
5

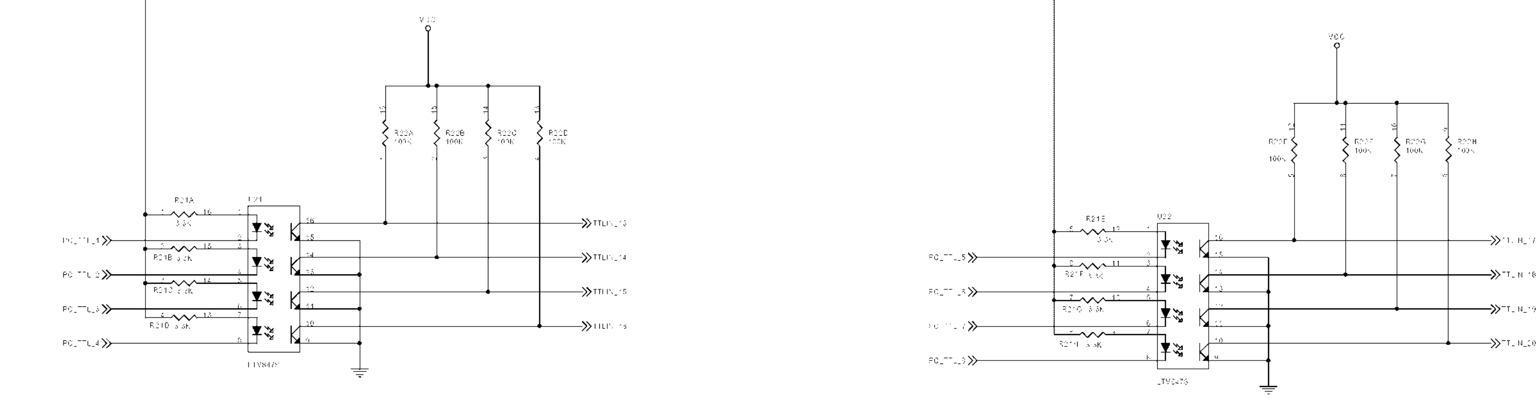


CIRCUIT POWER - GAUGE BOARD

Size: Custom | PAGE5 POWER | Rev: G

Wednesday, March 13, 2002 | Sheet 5 of 5


ANODE COM
VCC
REMOTE_TTL_1
REMOTE_TTL_3
REMOTE_TTL_4
REMOTE_TTL_5
REMOTE_TTL_6
REMOTE_TTL_8
REMOTE_TTL_9
REMOTE_TTL_11
LTV847S
Process Controller for IGC100
REMOTE_TTL_INPUT
C



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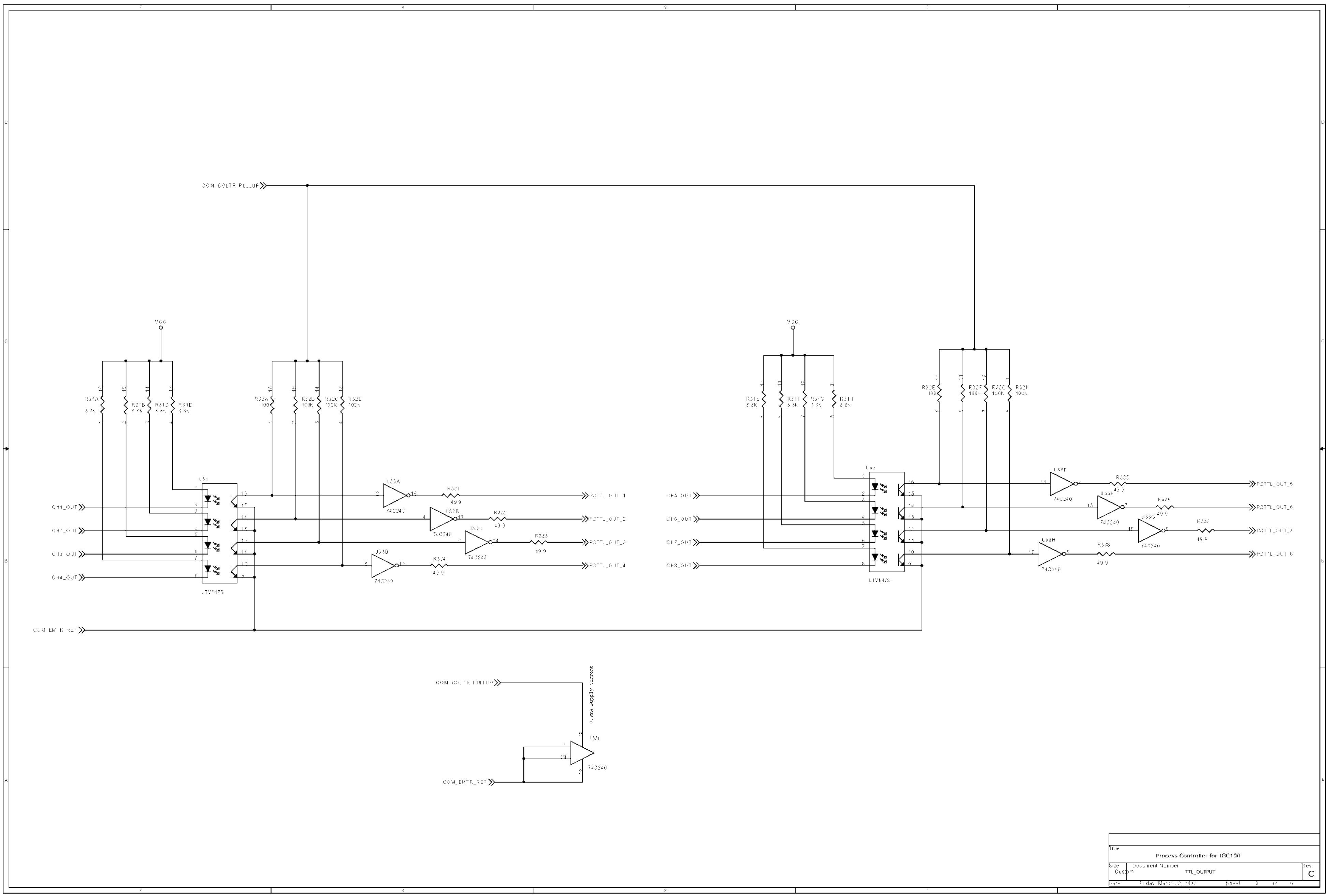
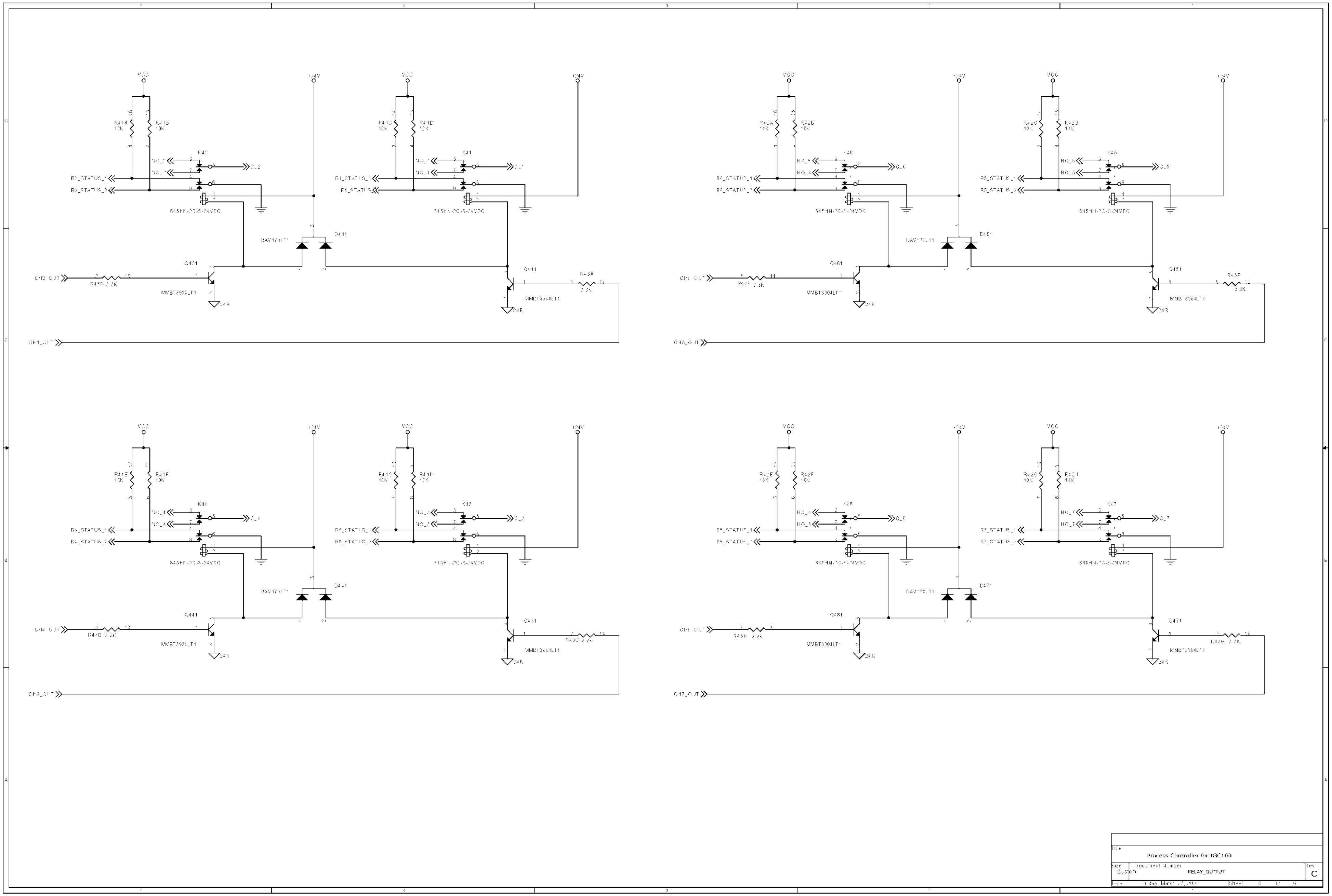
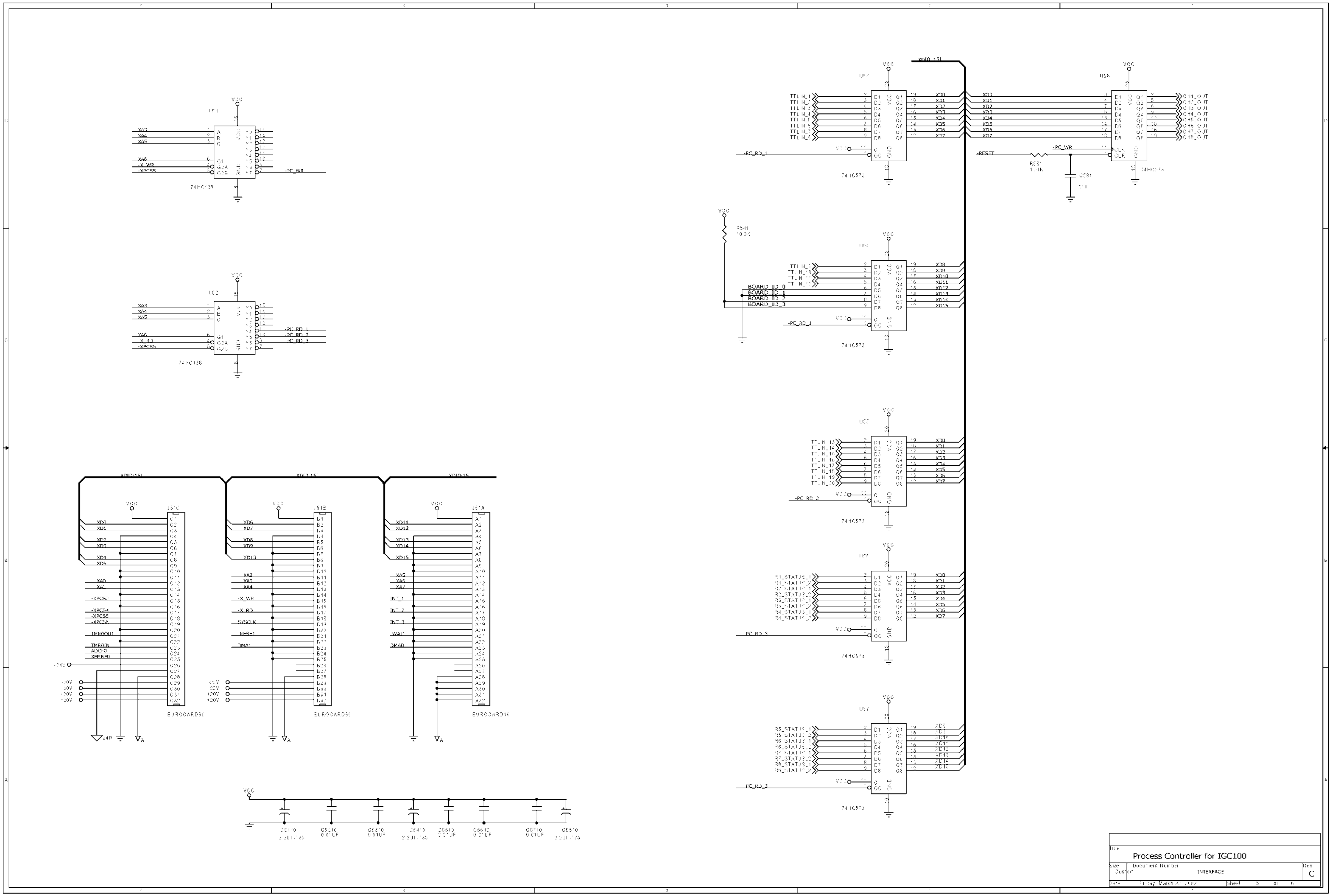
Process Controller for IGC100		
Size: Custom	Document Number: PC_TTL_INPUT	Rev: C
Date: Friday, March 22, 2002	Sheet 2 of 6	

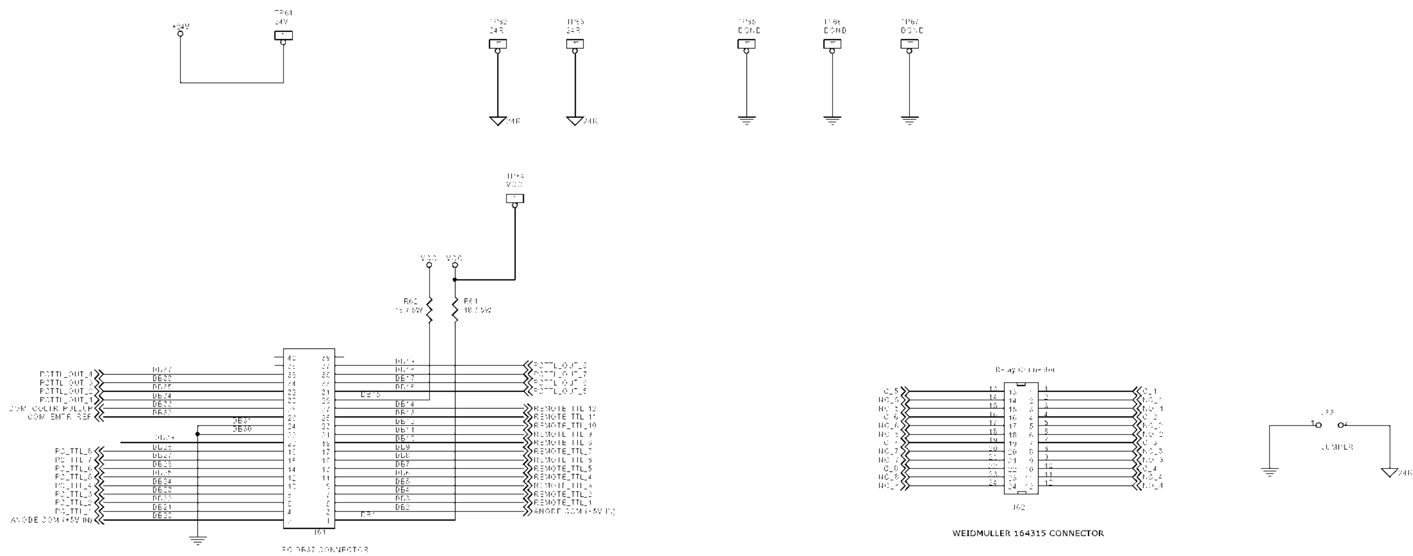

COM_COLTR_PULLUP
VCC
U31
LTV847S
U32
CH1_OUT
CH2_OUT
CH3_OUT
CH4_OUT
CH5_OUT
CH6_OUT
CH7_OUT
CH8_OUT
COM_EMTR_REF
POTTL_OUT_1
POTTL_OUT_2
POTTL_OUT_3
POTTL_OUT_4
POTTL_OUT_5
POTTL_OUT_6
POTTL_OUT_7
POTTL_OUT_8
74C240
COM_EMTR_REF
Title
Process Controller for IGC100
Size
Custom
Document Number
TTL_OUTPUT
Rev
C
Sheet 3 of 6



Process Controller for IGC100
RELAY_OUTPUT
C



Title
Process Controller for IGC100
Size
Custom
Document Number
INTERFACE
Rev
C
Sheet 5 of 6



REMOTE TTL INPUTS:

1 = IG1_ON
2 = IG2_ON
3 = IG_DEGAS
4 = IG_TTL_LOCKOUT
5 = IG_KEY_DIABLE
6 = IG1_OFF
7 = IG2_OFF
8 = PRESSURE_LOG_RESET
9 = IG_REMOTE_SETUP_ENABLE
10 = IG_REMOTE_SELECT_FIL2
11 = IG_REMOTE_SELECT_FIL_BOTH
12 = TOUCH_SCREEN_DISABLE

Title: Process Controller for IGC100

Size: Custom | Document Number: CONNECTORS | Rev: C

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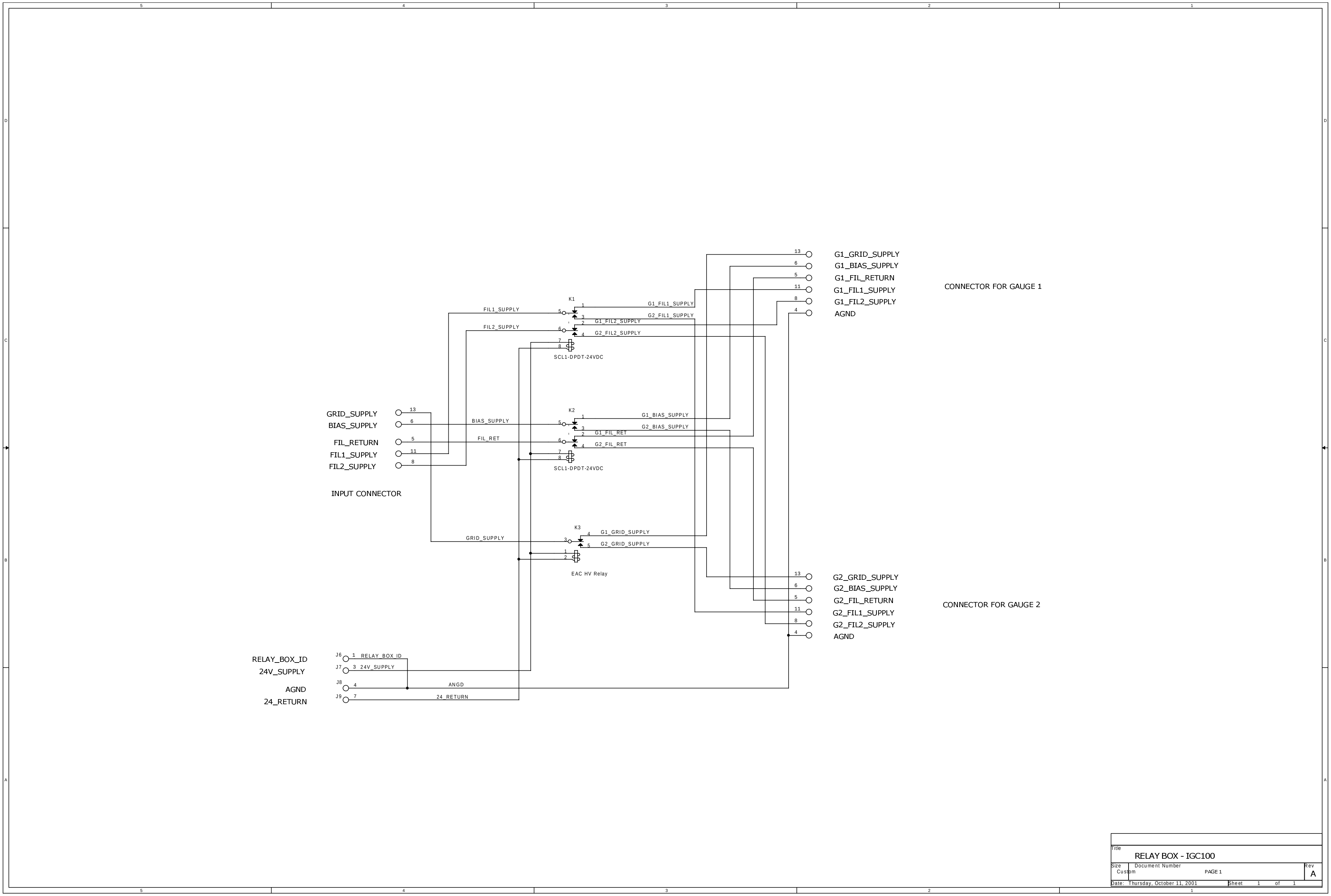
G1_GRID_SUPPLY
G1_BIAS_SUPPLY
G1_FIL_RETURN
G1_FIL1_SUPPLY
G1_FIL2_SUPPLY
AGND
CONNECTOR FOR GAUGE 1
K1
FIL1_SUPPLY
FIL2_SUPPLY
G1_FIL1_SUPPLY
G2_FIL1_SUPPLY
G1_FIL2_SUPPLY
G2_FIL2_SUPPLY
SCL1-DPDT-24VDC
GRID_SUPPLY
BIAS_SUPPLY
FIL_RETURN
FIL1_SUPPLY
FIL2_SUPPLY
INPUT CONNECTOR
K2
BIAS_SUPPLY
FIL_RET
G1_BIAS_SUPPLY
G2_BIAS_SUPPLY
G1_FIL_RET
G2_FIL_RET
SCL1-DPDT-24VDC
K3
GRID_SUPPLY
G1_GRID_SUPPLY
G2_GRID_SUPPLY
EAC HV Relay
G2_GRID_SUPPLY
G2_BIAS_SUPPLY
G2_FIL_RETURN
G2_FIL1_SUPPLY
G2_FIL2_SUPPLY
AGND
CONNECTOR FOR GAUGE 2
RELAY_BOX_ID
24V_SUPPLY
AGND
24_RETURN
J6
J7
J8
J9
RELAY_BOX_ID
24V_SUPPLY
ANGD
24_RETURN
Title
RELAY BOX - IGC100
Size
Custom
Document Number
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A
Date: Thursday, October 11, 2001
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