BARGAIN BASEMENT BAKEOUT*

William Manwaring, Shannon Noe, Terry Sloan
Indiana University Cyclotron Facility
2401 Milo B. Sampson Lane
Bloomington, Indiana 47401

Abstract: The design goal of this project was to develop a modestly priced system capable of reliably baking the 87 meter IUCF Cooler Ring vacuum chamber to 250°C. Digital-to-analog converters provide the seek command to proportional controllers; these controllers drive solid-state relays which in turn drive 110 VAC coaxial heating coils. Thermistors (not thermocouples) provide feedback to the controllers and read-outs to the PC through a commercial 200-channel ADC interface. Insulation is provided by a combination of ceramic paper and ceramic wool. Average vacuum achieved to date is 2.0 nanoTorr. Total system cost: approx. $35k.

General Comments

Several decisions were made early-on that shaped the evolution of this project. One was to use commercially available coaxial heater cable and to avoid the use of fiberglass heating tapes. Another was to save cost by avoiding expensive custom insulation/heater units. Thirdly we chose high-temperature thermistors rather than the commonly employed thermocouples. Finally, an IBM PC was selected as a stand-alone controller/monitor, with a strictly limited control function.

Heating and Insulation

The vacuum system is constructed entirely of stainless steel with copper gasket knife-edge seals. Bellows are used to allow for thermal expansion. The ring is equipped with commercially available hardware and all valves, pumps, and flanges are bakeable to a minimum of 350°C.

Economic considerations made it necessary to minimize the gap available in the ring magnetic elements, resulting in only 1 cm between the outside of the vacuum chamber and the magnet steel return yokes. Heating elements and adequate insulation had to be squeezed into the available space. Consequently there is a large heat loss to the magnet steel return yokes.

Five major problems were addressed in the design of the heat source and insulation:

1. Possible failure of a temperature sensor in such a manner as to apply full power to a heating element.
2. Possible failure of a heating element.
3. Uneven heating of flanges causing leaks due to differential thermal expansion.
4. A maximum heating rate of many ring components of 50°C per hour.
5. Reliability of heater elements.

Coaxial electric heating cable with an inner nichrome conductor, MgO insulation, and an outer stainless steel sheath 1.5 mm in diameter was chosen. The heater cable can be operated at temperatures up to 800°C and power densities up to 150 watts per square inch of sheath area. The heater cable has a resistance of 1.6 ohms per foot. A control circuit described later in this paper applies a maximum of 10 amps at 110 VAC to each heater circuit. The 10 amp maximum current determines the minimum length of heater cable for a heater circuit.

For several reasons a section of vacuum chamber may be divided into more than one heater circuit. The power required may exceed that available from a single heater cable. The ends of a heater cable should be accessible for connection to the AC wiring. And finally the vacuum chamber should be removable at flanges for repair or modification. The length of cable applied to a section of vacuum chamber is chosen so that 110 VAC will provide 120% of the power required to hold the chamber at 250°C.Although matching the maximum power available to the load requirement will not prevent excessive heating rates, it does prevent dangerous maximum temperatures from being reached.

Once the correct length of heater cable has been estimated, it is wound around the vacuum chamber in a spiral and fastened at the ends. The heating element is located so that it contacts only thin-walled sections of the vacuum chamber. This prevents applying enough power in a non-uniform distribution to cause thermal distortion in critical, large cross section, massive ring elements such as flanges and valves. Since there is a shortage of space inside the magnet gaps, the locations where the vacuum chamber is thin walled and the heat is applied occurs where the heat loss is greatest. In the event of a heating element failure the magnet vacuum can cools rapidly but cannot conduct heat away from a flange or valve fast enough to exceed the allowed rate of temperature change. The disadvantages of this are increased mechanical stress on welds and increased baking times to adequately heat all parts of the vacuum chamber.

In critical locations a spare heating element was wound alongside the primary element. After fastening the heating elements, the vacuum chamber was wrapped in several layers of aluminum foil. The foil helps conduct the heat over the entire surface of the vacuum chamber and also prevents local hot spots in the heating elements. Next, several layers of insulation are applied and the entire assembly is wrapped in aluminum foil to contain the insulation. Experience has shown this system to be very reliable.

We have never developed a detectable vacuum leak in the Cooler Ring vacuum system. We have had one thermistor failure leading to heating element run away. We have also had

*Work supported by U.S. National Science Foundation

CH2669-0/89/0000-0580$01.00©1989 IEEE

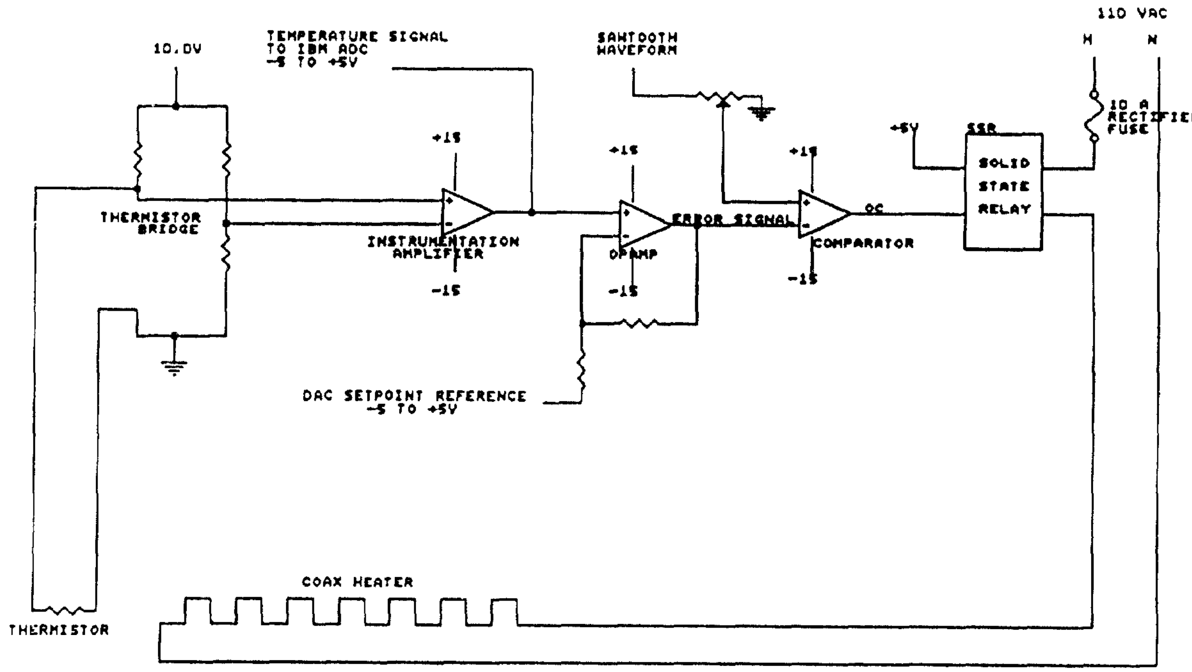

FIG. 1 BAKEOUT PROPORTIONAL CONTROL CIRCUIT

heater element failures during a bake. Nearly all of these failures have been at the end termination of the heater elements. The many different lengths of heating elements required to match the power available to the load, forced us to develop an in-house method for terminating the high temperature heating element to the standard AC wiring. We still experience about a 10% failure rate of terminations on initial bake. Consequently, we try to leave these leads accessible and long enough for repair.

Controls

The controls can be divided into four main parts:

1. An IBM personal computer with hard disk and printer.
2. A Keithley IBM interface box with 200 ADC channels.
3. Six distributed relay enclosures (20 solid-state relays each).
4. Four wire-wrap bins for interlocks and proportional control.

The IBM is used for temperature ramp programming, status display, and hardcopy. The hexagonal ring is divided into six bakeout sectors (20 relays, 20 heaters); the IBM can drive six Digital-to-Analog Converters (DACs) which act as a setpoint for the proportional controllers in the corresponding sector. If only one DAC is driven, only one sector will ramp through a bakeout cycle. The IBM monitors the feedback thermistors, checks for excessive temperature differentials between heater sections, displays bar graphs of temperatures, and performs other functions described below in more detail. Aside from providing the DAC setpoint, the IBM plays no role in temperature regulation. If the IBM locks up, the bakeout ramp will stop at the last DAC value written and will continue to regulate around that value.

The IBM "talks to" the bakeout electronics through a Keithley Series 500 data acquisition and control system. This system was chosen over a number others because it could provide 200 channels of 12-bit Analog-to-Digital Conversion at a reasonable price per channel, all packaged in a separate box with power supply. In addition it provides four bytes of digital I/O which are used to drive the six DACs and pass interlock information.

The four wire-wrap bins contain the six DACs, interlock circuitry, thermistor amplifiers, proportional control electronics, and relay drivers. A printed circuit card was developed in-house to perform the last three functions (fig. 1). This 4"x6" card amplifies four thermistors via a bridge circuit and instrumentation amplifier, and provides proportional control to four solid-state relays. We had considered using simple "bang-bang" control, but it took relatively little effort to make the control proportional with markedly better performance.

The circuit works by comparing the IBM-written DAC reference with the actual temperature (amplified thermistor signal) and generating an error signal (fig. 1). This error signal is compared to a 1 Hz sawtooth waveform provided to all cards from a master oscillator. When the sawtooth voltage exceeds the error signal, the relay is on; when the error signal is zero, the relay is never on. As the error increases, the 'on' time of the relay increases linearly. With a large enough error the relay is always on and we are now out of the proportional band.

This system would soon wear out mechanical relays because the relays cycle every second. By using solid state relays with a "zero-crossing turnon", there are no serious EMI problems or wear problems. We did not wish to use SCR phase-angle control because of its negative effects on the building power system.

The relays chosen were 10 A, 120 VAC units (Crydom D1210). Twenty of these units were mounted on a large aluminum plate (to provide heat-sinking) along with fuses and connections. When using relays of this type it is important to provide a fast semiconductor fuse in each circuit. This protects the relay in the event of a load fault and can also prevent fire in the relay enclosure. A breaker is NOT sufficient.

The front cover of each relay enclosure has 20 LEDs to monitor relay drive from the control circuit, and 20 neon lights to monitor load drive. These lights flash at 1 Hz during normal operation, with the duty cycle gradually increasing as the programmed temperature increases.

Control Computer Software

The IBM PC runs a program titled BakeOut. BakeOut enables the user to generate time vs. temperature ramps which vary the proportional controller setpoint as a function of time on the computer clock. Once a ramp has been generated a bakeout can be initiated. BakeOut checks vacuum interlock switches to be sure the selected ring segments are under vacuum before beginning the temperature ramp. Once BakeOut is running the following menu appears on the screen.

Halt System - This immediately sets the proportional controller setpoint to zero.

Pause System - Temperature will be maintained at the level at the time of the pause and error checking will be disabled.

Display Thermistor Deviations - A histogram display of the thermistor variations from the temperature requested by the ramp at the current time.

Display Ramp - A graph of both the requested temperature vs. time for the complete ramp and the average temperature of the thermistors up to the current time.

Set MAX Deviation - Sets the maximum allowed deviation between the temperature measured by any active thermistor and the temperature requested by the ramp at the current time. If a deviation exceeds the maximum the program sounds an alarm and pauses the ramp until the operator takes corrective action.

Modify Thermistor - Allows the operator to change the status of a thermistor from control to monitor. A monitor thermistor is still displayed on a thermistor deviation graph but will no longer pause the bakeout if it exceeds the MAX deviation limit.

The computer has various print options which allow the operator to document system performance and faults.

Interlocks

Four interlocks will shut the system down by shunt-tripping the main AC breaker. The first is a big red "panic button", to be used in case of fire, arcing, boredom, whatever. The second is a vacuum thermocouple in each of the six bakeout sections. The third is computer failure for longer than ten minutes, and the fourth is a computer initiated shutdown due to one or more thermistors being outside of the acceptable temperature band.

Acknowledgments

John Collins and Kevin MacKenzie contributed software direction and support; David Frame, Andy Qualls, and David Shuee were instrumental in installing the system. Bob Palmer, Ron Stillabower, and Moira Wedekind assisted in the development, installation, and testing of the system.