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INSTRUMENT FOR RADIATION TESTING/SCREENING ELECTRONIC DEVICES OVER AN EXTENDED TEMPERATURE RANGE

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Technical Report

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EXECUTIVE SUMMARY

The DoD has the requirement that electronic devices used in many military systems be able to function over the temperature range of -55°C to 125°C . For selected systems, the electronic devices must also be able to function after being exposed to specified levels of long-term (total dose) or high-intensity (dose-rate/latch-up) ionizing radiation. Generally, however, the radiation testing and screening is only performed at room temperature. Recently, experiments have shown that the response of electronic devices irradiated at extreme temperatures can be quite different from room-temperature results.

ARACOR manufactures the Model 4100 Automatic Semiconductor Irradiation System which has come into wide-scale use for the radiation testing and screening of DoD electronic devices, including VHSIC and SDI parts. At this time, the Model 4100, which enables radiation testing at the wafer level, is only capable of room-temperature irradiations.

The primary goal of this program was to develop instrumentation, compatible with the Model 4100 design, that would enable radiation total-dose, dose-rate and latch-up measurements to be made over the temperature range of -55°C to 125°C . The overall Phase I technical objectives were:

- 1) To develop and calibrate necessary timing and dosimetry circuitry for the pulsed-laser source to permit wafer-level measurements of radiation dose-rate and latch-up effects for both conventional and heavily-doped substrates.
- 2) To evaluate and calibrate the accuracy and stability of a high-temperature system for the precise heating of electronic devices over the range 25°C to 125°C during radiation tests.
- 3) The development, evaluation and calibration of a low-temperature system that can provide precise temperature control over the range of 25°C to -55°C during radiation tests.

Dose-rate dosimetry was performed using a calibrated PIN photodiode and wide-bandwidth oscilloscope. The peak equivalent dose rate achievable at the back surface of a wafer was shown to be in excess of 2×10^{12} rad/sec. A system was designed to measure the integrated energy of the pulsed laser beam transmitted to the wafer. This dosimetry system, which will allow variation and control of the radiation dose rates, includes a Brewster window assembly and a photodiode with associated circuitry to measure the pulse energy. Timing signals, generated by the laser control circuitry, are used for triggering.

At the time the program was initiated, the ability to conduct latch-up tests at high temperatures was of special interest. Latch-up testing on the Model 4100 System, however, requires the use of a transparent (glass) wafer chuck so that the back surface of the wafer can be irradiated with the laser pulse. The use of the glass chuck, which is a dielectric material, made it impossible to directly heat the chuck. Thus, a precision gas-forcing system was selected which can provide either high- or low-temperature streams of dry nitrogen gas. In addition to being compatible with the glass chuck, the use of dry gas to cool the wafer greatly reduces the problem of frost formation during low-temperature irradiations.

High-temperature wafer experiments were conducted using a heated-N₂ stream system installed in an ARACOR Model 4100 System. Measurements were made with silicon wafers on both a standard metallic chuck and a glass chuck. The gas flow, temperature range, and temperature stability of the equipment were adequate for rapid heating of the die under test (DUT) over the required temperature range. The temperature of the DUT was inferred from electrical measurements on a wafer of "thermometer" IC's manufactured by Precision Monolithic, Inc. Although the accuracy and controllability of the gas stream temperature was very good, the die temperature was found to be strongly dependent on wafer-chuck temperature. The thermal properties of the metallic chuck used in the total-dose tests resulted in slow thermal settling time when a large temperature difference between the die and the chuck was implemented. With the glass chuck, thermal time constants were shorter, but even in this setup, the sensitivity of the die temperature to the chuck temperature made accurate chuck calibration difficult. It was concluded that it is not practical to calibrate the temperature of the DUT by sensing the temperature of the gas stream only, and that additional knowledge of the chuck temperature was

required for accurate temperature calibration. Therefore, in order to provide acceptable temperature control, the gas stream must be implemented with direct temperature control of the chuck.

A cooled-N₂ stream system was also purchased and installed and found to work well (gas-flow rate optimization was required). All experiments were performed with the glass wafer chuck and with the same temperature measurement scheme as the high temperature work. A heated-gas stream was directed over the probe card to prevent frosting on the microscope. No environmental chamber was implemented and experiments were performed at room ambient. With the dry-N₂ stream used to prevent frost formation on the wafer, temperatures to less than -40°C were possible before probe contact was interrupted, indicating that the N₂-stream inhibits the formation of frost over the wafer and other cooled components.

In summary, for both heating and cooling wafers for radiation tests, a knowledge of both the chuck temperature and the air stream temperature was found to be necessary for calibrating the die temperature. For Model 4100 Systems used only for total-dose measurements, a system combining a commercially-available temperature-controlled (metallic) chuck combined with an air stream system is proposed as the best solution for covering the entire -55° to +125° range. If tests are only to be conducted at elevated temperatures, the air stream is not required. To prevent frosting at low temperatures, the chuck temperature would be controlled to perhaps 0° to -20°C and the air stream would be used to lower die temperature to -55°C. A simple coaxial heated-gas stream combined with a semi-sealed environmental chamber should be sufficient to alleviate frosting at the lowest temperature. For low-temperature latch-up/dose-rate measurements, which require the glass chuck, accurate temperature control requires the addition of temperature sensors on the wafer. As an alternative, latch-up experiments over an extended temperature could be implemented by direct electrical measurements of test transistors/diodes on the wafer.

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SECTION 1
INTRODUCTION

Advanced Research and Applications Corporation (ARACOR) was awarded a Phase I contract by DNA under the 1985 DoD Small Business Innovation Research program. The focus of this contract was on evaluating the feasibility of and developing a breadboard apparatus for providing controlled temperatures over the range of -55°C to 125°C during the radiation testing of electronic devices at the wafer stage of production. The program also resulted in the development of timing and dosimetry circuitry for the pulsed-laser testing of devices for latch-up and dose-rate effects. The circuitry and temperature-control breadboards were designed for integration into the ARACOR Model 4100 Automatic Semiconductor Irradiation System.

Until the development of the Model 4100 System, which is described in the Appendix, radiation-hardness testing required the use of fixed-site facilities, such as linear accelerators (LINACS), flash x-ray sources, and Cobalt-60 sources. These sources are expensive to procure, maintain, and calibrate, and are also usually remote to the device fabrication and testing areas, since they involve the possibility of radiation hazard. In addition, LINACS and suitable flash x-ray sources are only available at a limited number of sites. Thus, radiation testing often imposes considerable inconvenience and cost for travel and set-up at a remote location. The complexity and expense associated with such sources is magnified if testing at precisely-controlled low and high temperatures are required.

The Model 4100 System provides unique advantages for the radiation testing of DoD electronic parts. Total-dose radiation tests are performed at the wafer level during the die probing sequence, using a collimated x-ray source in an interlocked system. A technique for non-destructive dose-rate and latch-up tests is being integrated into the system. This technique employs a pulsed infrared (IR) laser to irradiate the die under test from the backside to create a concentration of electron-hole pairs similar to those produced during LINAC or flash x-ray irradiations. Unlike tests using LINACS and flash x-ray machines, tests with the laser are non-destructive and, thus, 100% of the microcircuits on the wafer can be tested and then still be used.

The development of methods for controlling the wafer temperature during the radiation tests and circuitry to enable transient testing would provide a comprehensive radiation test capability for DoD laboratories and contractors. Since the Model 4100 provides for total-dose tests at high dose rates at the wafer stage of production, this radiation testing approach should have special value for testing VHSl circuits and for SDI-related radiation tests.

Latch-up models and experimental data show that both the susceptibility to latch-up and the latch-up/dose-rate characteristic of devices are influenced by temperature. The wafer chuck used for dose-rate and latch-up measurements must be transparent to IR radiation, therefore must be made of a dielectric material (quartz in the Model 4100) which is a poor thermal conductor. For this reason, direct heating and cooling of the chuck is not practical. After evaluating alternatives, a precision heated-gas stream, temperature-forcing system was selected for this program.

The development of a low-temperature capability (25°C to -55°C) is made complex by the necessity of preventing the development of frost or moisture on the die being tested. To achieve low temperatures, a cooled nitrogen-stream approach was implemented that is similar to that described for elevated temperatures. A reservoir of liquid nitrogen (LN₂) served as the source of gas for cooling the die being tested.

SECTION 2

DOSIMETRY AND TIMING CIRCUITRY

This task had two parts. The first part was to find a method for measuring the dose rate equivalent of the optical intensity at the backside of the wafer. The second part involved designing the circuitry which would allow automated control of the laser intensity at the backside of the wafer. The few timing signals produced by the laser control system were found adequate for synchronization needs.

2.1 DOSIMETRY.

The dose rate from Nd:YAG laser exposures in wafers was determined by measurements using calibrated PIN diodes. These diodes were previously calibrated for x-ray dosimeters as outlined in IEEE Transactions on Nuclear Science (Palkuti, Le Page, Vol. N5-29, No. 6, December 1982). By utilizing a 6-mil diode aperture and the circuit shown in Figure 1, peak photo currents ranging from 0.1 to 100 mA, could be measured above instrument noise and before diode saturation occurred. The diode sensitivity factor, F , determined from x-ray calibration exposures is

$$F = \frac{\dot{D}}{I_d} = \frac{1}{q K_g Vol} = 2.5 \times 10^8 \text{ rad(Si)/s per mA} . \quad (1)$$

where q is the electron charge, K_g is the generation rate, Vol is the sensitive volume of the diode and \dot{D}/I_d is the dose rate absorbed at the diode front surface divided by the diode current.

The dose absorbed at the diode front surface, I_d , as a ratio of the incident laser flux density, I_0 , can be determined based on reflections at the two diode surfaces and absorption in the diode bulk as follows:

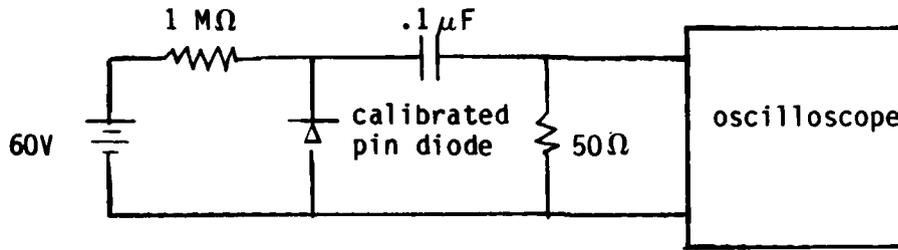


FIGURE 1. Diode dosimetry circuit.

$$\frac{I_d}{I_0} = \frac{(1-R)(1 + A_d^2 R)}{1 - A_d^2 R^2} \quad (2)$$

where

$$A_d = \exp(-\alpha_d t_d) \quad (3)$$

and α_d is the absorption coefficient of the diode material, t_d is the diode thickness and R is the reflection coefficient at the diode surfaces. The dose rate at the front surface of a wafer can be determined by a measurement of the incident, I_0 , and transmitted flux, I_t , as measured by the calibrated diode. The ratio of the incident-to-transmitted flux measured on an un-oxidized silicon test wafer can be utilized to determine the absorption coefficient of the wafer as follows:

$$\frac{I_t}{I_0} = \frac{(1-R^2) \exp(-\alpha_w t_w)}{1-R^2 \exp^2(-\alpha_w t_w)} \approx 0.5 \exp(-\alpha_w t_w) \quad (4)$$

Then, the ratio of front-surface dose rate to the diode dose rate can be determined from

$$\frac{I_f}{I_d} = 1.25 \exp(-\alpha_w t_w) \quad (5)$$

where $R = 0.3$ has been utilized for silicon at the Nd:YAG wavelength. Thus, measurement of the incident and transmitted flux with the diode yields the front-surface dose rate as follows:

$$D_f = 2.5 \left(\frac{I_t}{I_0} \right) I_d \cdot F \quad (6)$$

Since the absorption in the wafer depends on the type of wafer doping type, doping density and wafer thickness, it is necessary to determine the ratio (I_t/I_0) as the factor A_w for each type of wafer normally encountered in applications. Some typical values for this factor are listed in Table I for some common wafer types. Since the front surface absorption (proportional to $\alpha_w \exp(-\alpha_w t_w)$) is not a strong function of α_w , the variations in doping for similar wafers will not necessitate individual wafer calibrations.

Table I. Values of A_w for some typical silicon wafers used in device fabrication.

Wafer Size	$A_w = \exp(-\alpha_w t_w)$			
	n bulk	p bulk	nn ⁺ epitaxial	pp ⁺ epitaxial
3-inch	0.47	0.33	0.33	0.13
100 mm	0.35	0.20	0.20	0.06
125 mm	0.29	0.15	0.15	0.03
150 mm	0.26	0.13	0.13	0.02

2.2 CONTROL CIRCUITRY.

Control of the laser intensity of the Model 4100 occurs in two stages (Figure 2). First, a remotely-controlled rotatable polarizer assembly, called a Beam Attenuator Module (BAM), allows continuous variation of the intensity over two orders of magnitude. On the output side of the BAM, a transparent window set very near the Brewster angle reflects a small portion of the laser beam to a photodiode detector. Additional attenuation of up to four orders of magnitude is provided by a remotely controlled set of calibrated attenuators. Under this program, circuitry was designed to measure the photocharge produced in the photodiode at the output of the BAM, which allows the internal control system of the Model 4100 to set and control the intensity in a closed-loop fashion. Thus, variations in laser output due to time-dependent effects are essentially eliminated and a constant intensity is obtained.

A simplified schematic is shown in Figure 3. The photodiode is reverse biased to prevent photocurrent saturation. A simple RC network stores the charge for several microseconds before a sample and hold circuit, controlled by a signal synchronized to the laser Q-switch, acquires a voltage proportional to the charge. This voltage is sent to an A/D converter in the Model 4100 control system. A one-shot provides a 25 mS signal pulse to the control system processor as an indication that the signal is available for digitization.

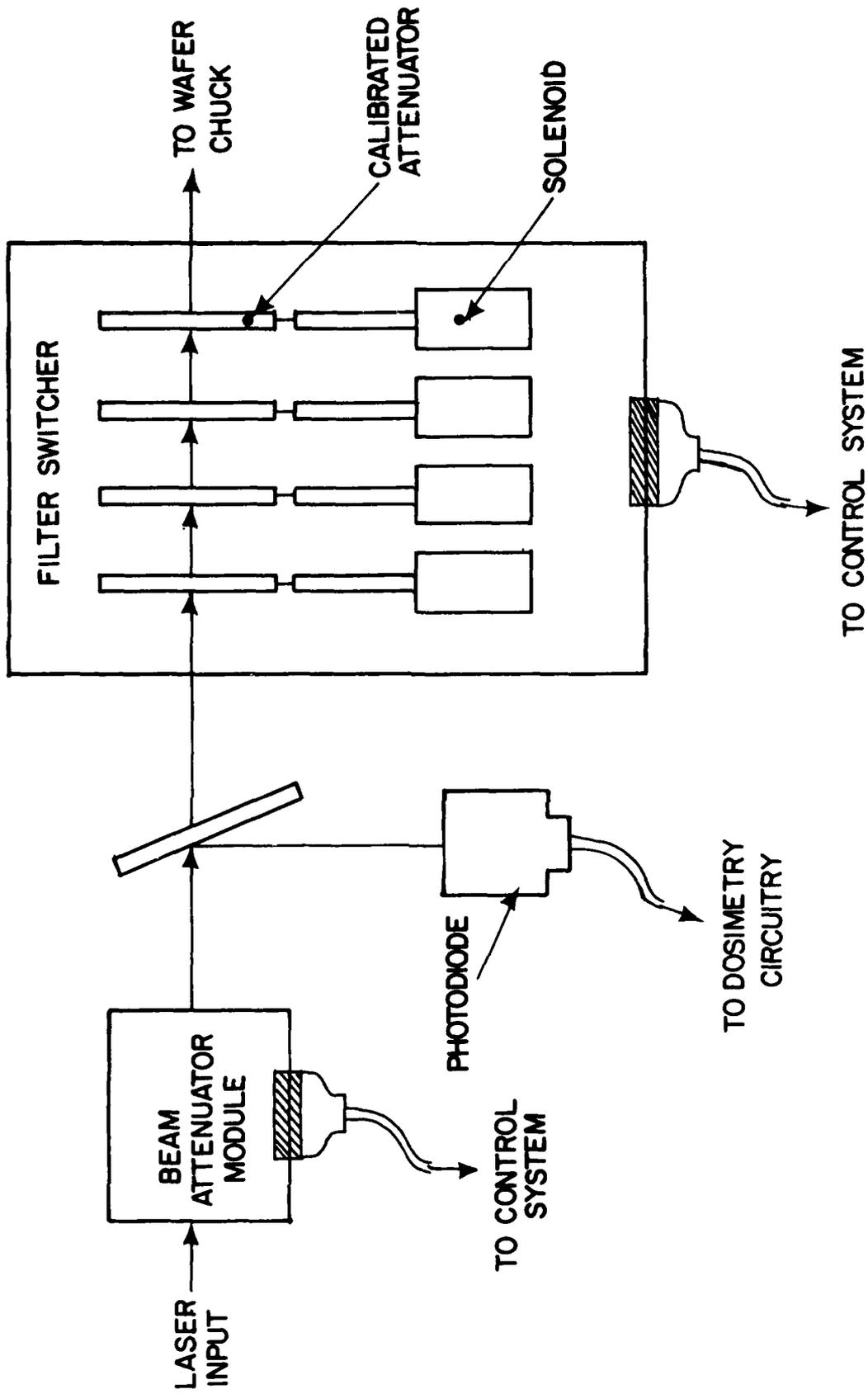


FIGURE 2: Intensity control system.

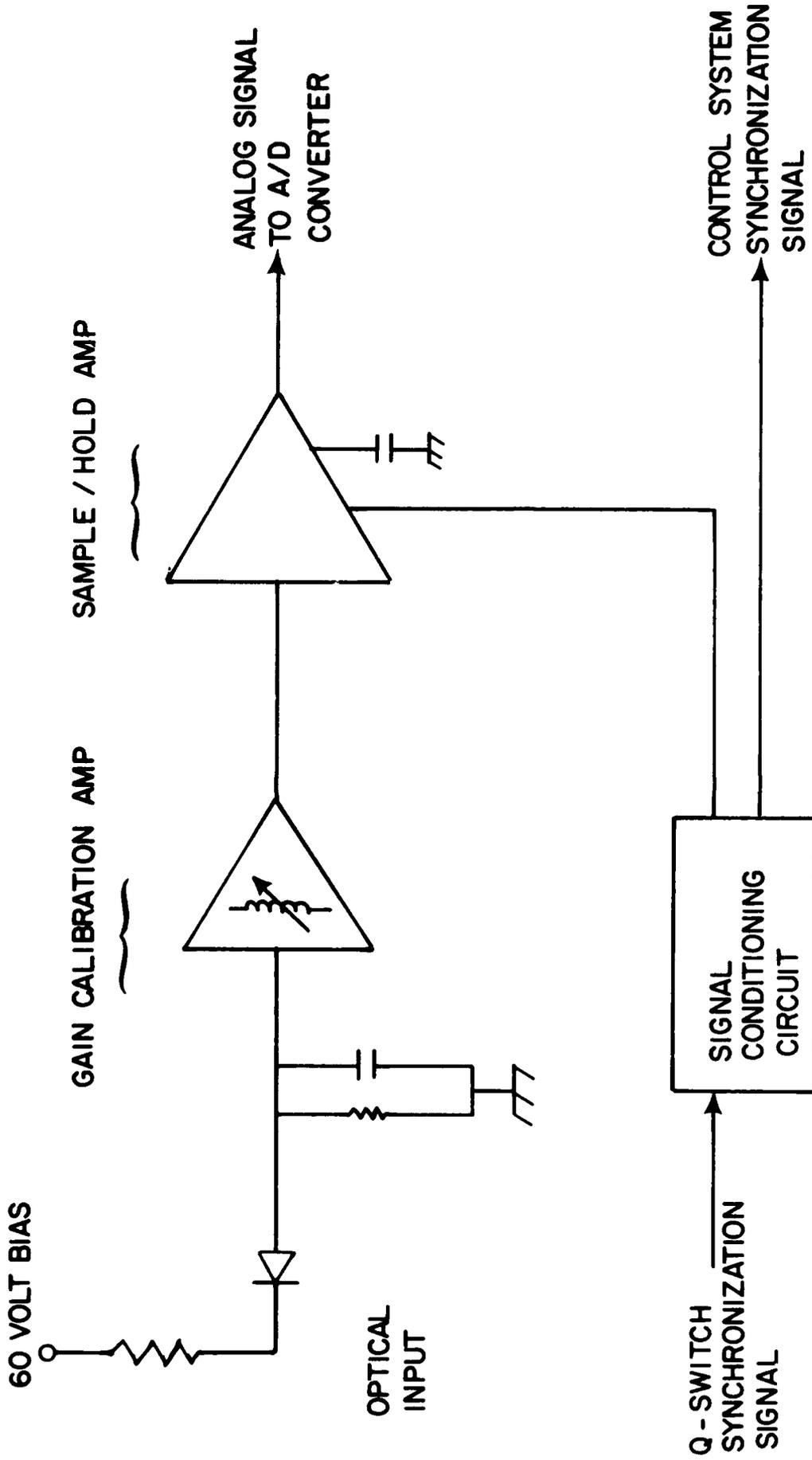


FIGURE 3. Simplified schematic, charge measurement.

SECTION 3

HIGH-TEMPERATURE TESTING

A Thermonics Model T-2100H precision temperature-forcing system (PTFS), combined with a probe-card-mounted thermal-control adaptor, was used to conduct high-temperature tests. This system produces a heated-gas (N_2) stream, which was used to control the temperature of the die under test. To achieve temperature and flow control of the gas stream, the N_2 enters the back of the PTFS and passes through a pressure regulator which controls the flow of gas to the desired level, as set by an appropriate flow knob. After the N_2 exits the pressure regulator, it passes through a venturi which is used to measure the flow of N_2 . The pressure differential created across the venturi is sensed by a solid-state pressure transducer and converted to flow and be displayed on a flow meter.

After the N_2 exits the venturi, it enters the air heater which changes the temperature of the gas to the level specified on the temperature controller. The gas, upon exiting the air heater, is directed to the entrance of the thermal-control adaptor through a flexible hose. The hot gas passes through the thermal-control adaptor and is directed to the die by a series of gas ports located about 3 mm above the wafer surface. At the exit of the gas ports, a series of solid-state temperature transducers sense the gas temperature. If the temperature is below the set level, the temperature controller will turn the heater until the desired temperature is reached. Once the desired temperature established, the temperature controller will pulse the heater, as required, to maintain the gas temperature to $\pm 1^\circ C$ of the set value.

The thermal-control adaptor was attached above the transparent chuck assembly as shown schematically in Figure 4. To heat or cool the device being tested, a stream of dry gas (i.e., nitrogen) generated by the PTFS was directed through ports in the thermal-control adaptor downward through the radiation collimator onto the portion of the wafer containing the die being tested.

After reviewing methods for measuring the stability and uniformity of the temperature at the location of the die being irradiated, a PMI Ref-02 Precision

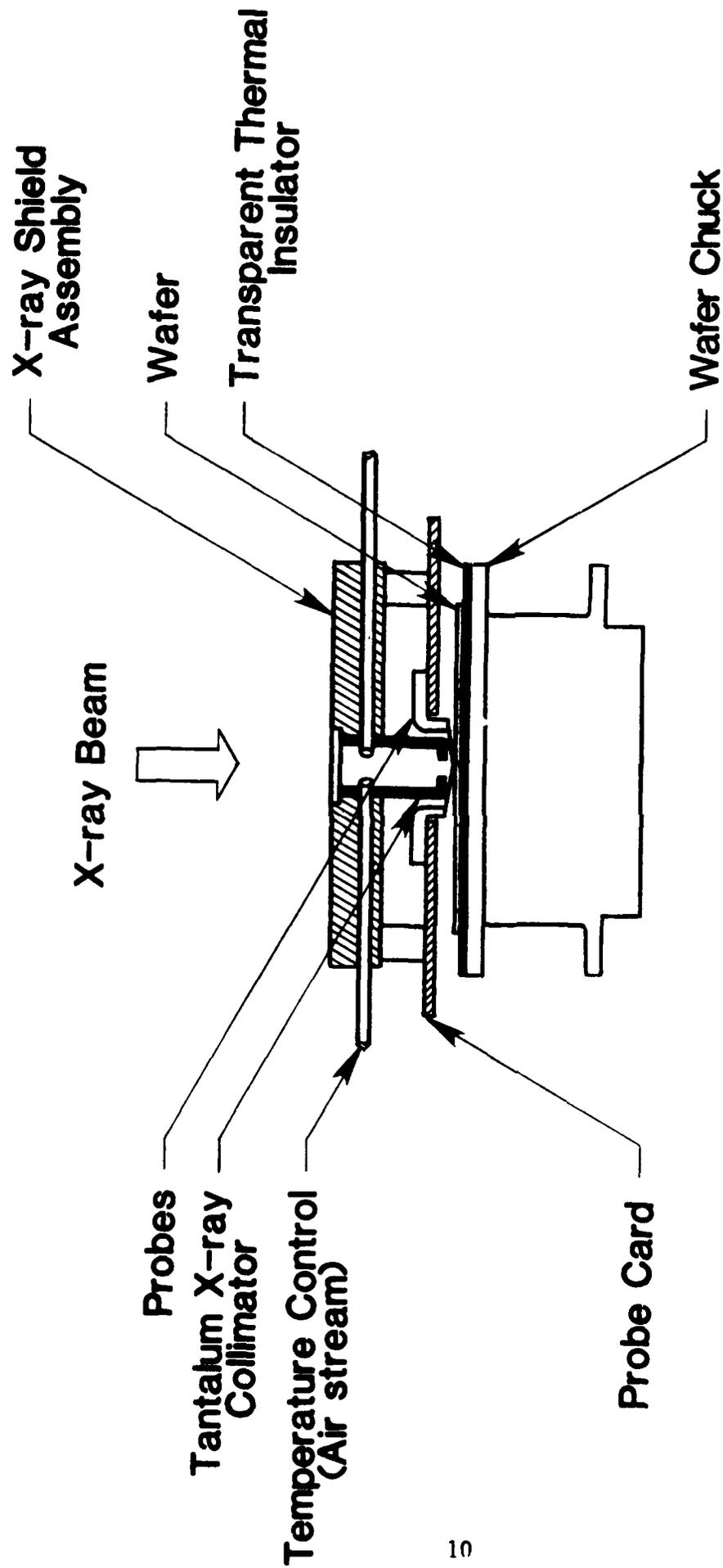


FIGURE 4: Schematic thermal-control adapter.

Voltage Reference/Temperature Transducer was selected. Typically, the Ref-02 transducer is purchased as a packaged part. However, for these experiments, ARACOR obtained a four-inch wafer containing many of these reference/temperature transducers. A probe card was used to apply bias to the circuits and to readout the temperature-proportional voltage. The Ref-02 has principal application as a precision voltage reference providing a stable +5V output. However, in a proper circuit, the Ref-02 can be used as an electronic thermometer providing a voltage output that is a direct measurement of temperature. This application uses the predictable 2.1 mV/°C output voltage temperature coefficient, which is a byproduct of a bandgap voltage reference design.

The PTFS, the thermal-control adaptor and the PMI Ref-02 unit were integrated with an ARACOR Model 4100 Automatic Semiconductor Irradiation System and experiments to insure operation over the full temperature range and to evaluate stability and reproducibility were initiated.

The experiments were designed to evaluate the thermal time response and stability of the wafer/chuck/PTFS combination. Measurements were made on a quartz chuck system. The die temperature response showed two components: a fast component attributed to wafer heating, and a slow component attributed to chuck heating. Figures 5 and 6 show the overall time response for a 400-cubic-foot-per-hour (CFH) gas flow at set temperatures of 120°C and 80°C, respectively. The first steep rise of the die temperature indicates that the die reaches an approximate equilibrium between the gas stream and chuck temperature in about 5-6 minutes. After this, the chuck temperature continues to rise at a much slower rate, raising the die temperature approximately 3-to-4°C after 40 minutes.

In order to reach the desired die temperature more quickly, a procedure was developed to "overdrive" the temperature and bring the die/chuck combination to the desired equilibrium temperature. The approximate overdrive temperature for a given equilibrium die temperature was determined empirically by heating experiments. Utilizing this approach, the gas stream is used to quickly heat the

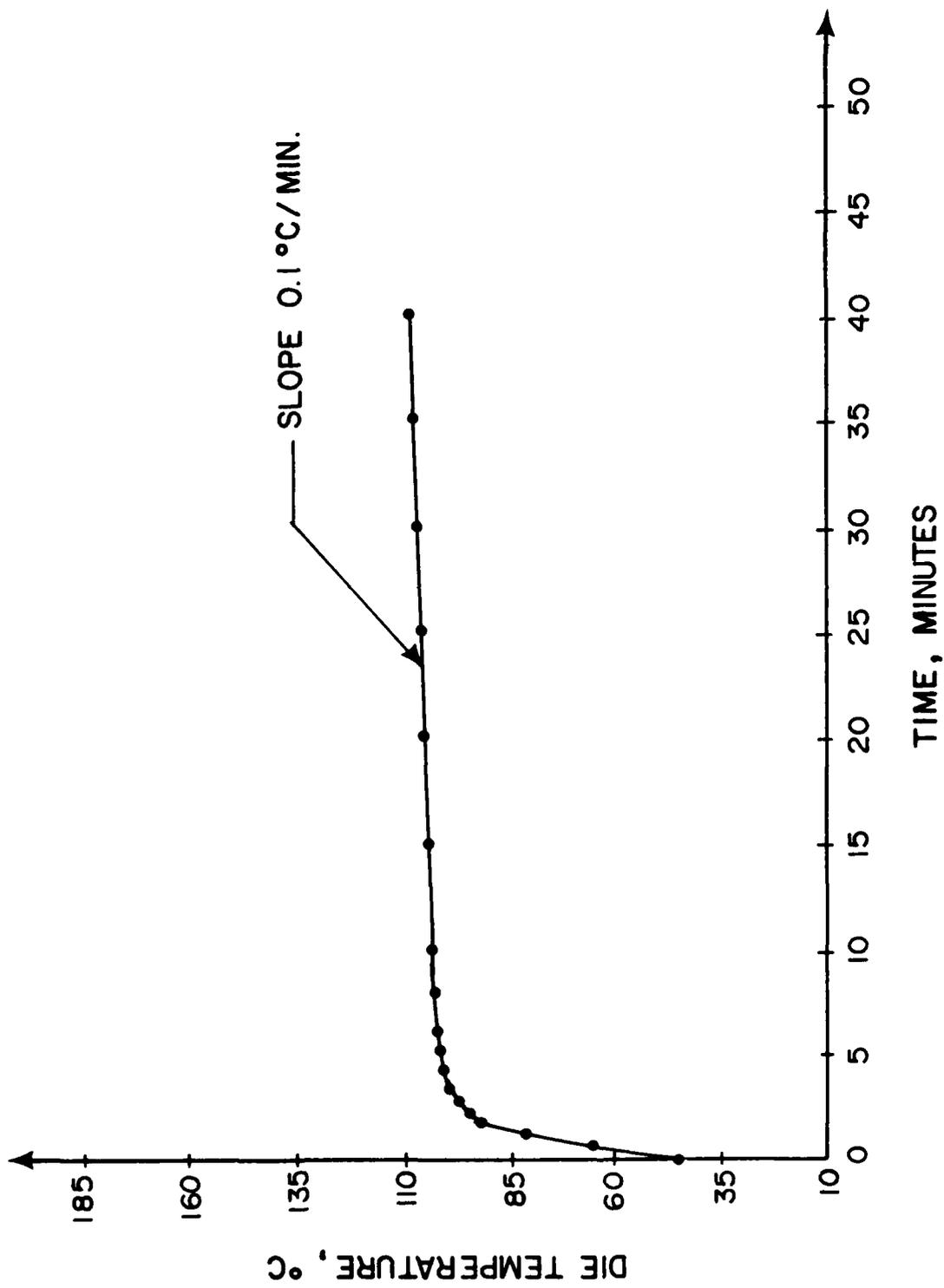


FIGURE 5. Time response 120°C gas temperature.

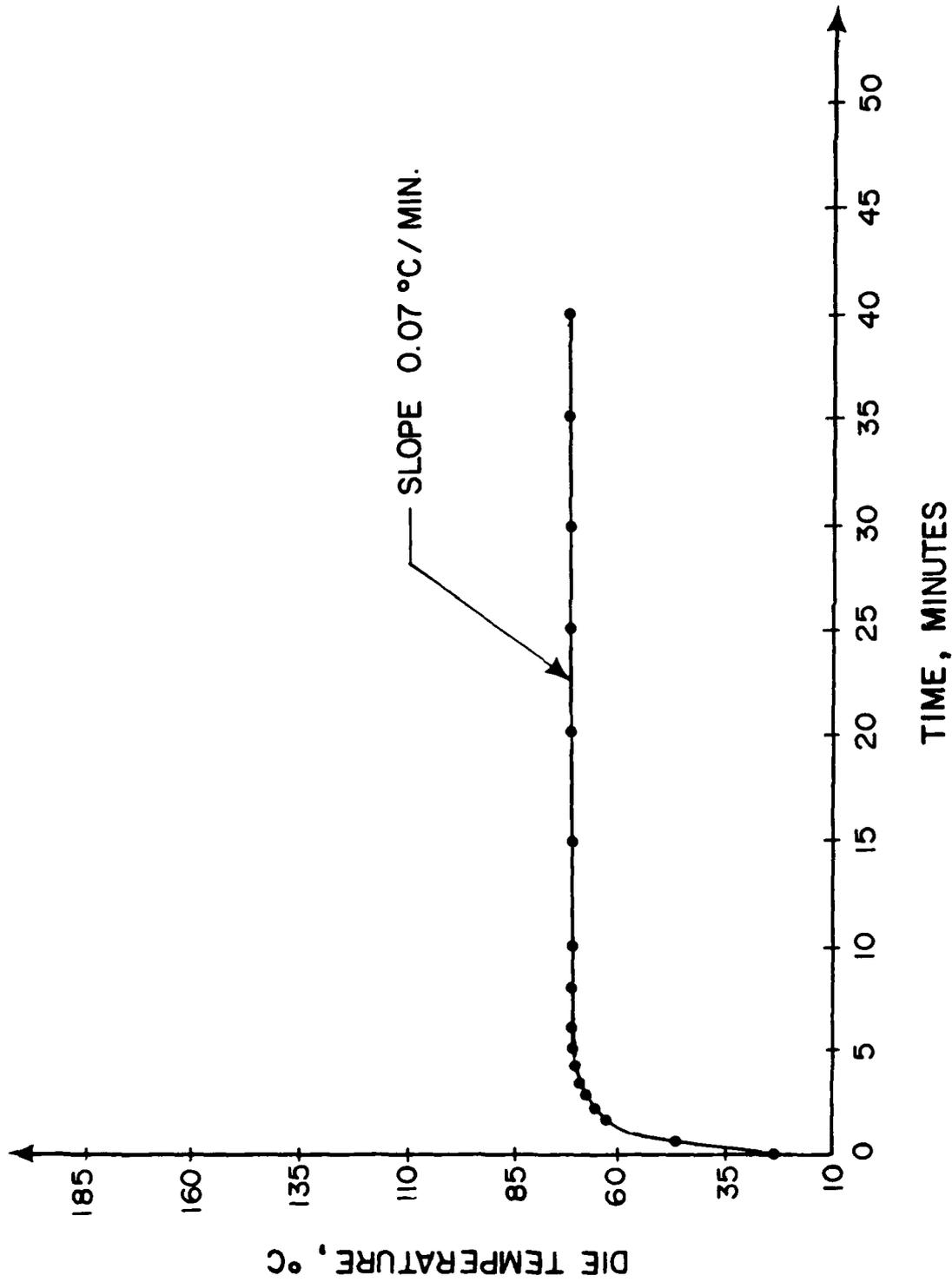


FIGURE 6. Time response, 80°C gas temperature.

die beyond the set temperature and then to allow the die to cool to the selected equilibrium temperature. In this manner, stable temperature operation was achieved without requiring the long stabilization time for the wafer chuck.

The procedure for achieving a target die temperature in roughly 6 minutes is illustrated by the graphs in Figures 7 through 11. The gas stream temperature is initially set to a high temperature to preheat the chuck quickly; after a preset time interval, the gas stream temperature is lowered and the die stabilizes at the desired temperature.

This procedure was exercised enough to indicate its usefulness for a prototype die temperature controller. However, the initial system temperatures (ambient, chuck, die) affect the end temperature and system drift. This is especially true in going up or down from one elevated temperature to another. Chuck temperature control and/or sensing would be required to accurately set the die temperature.

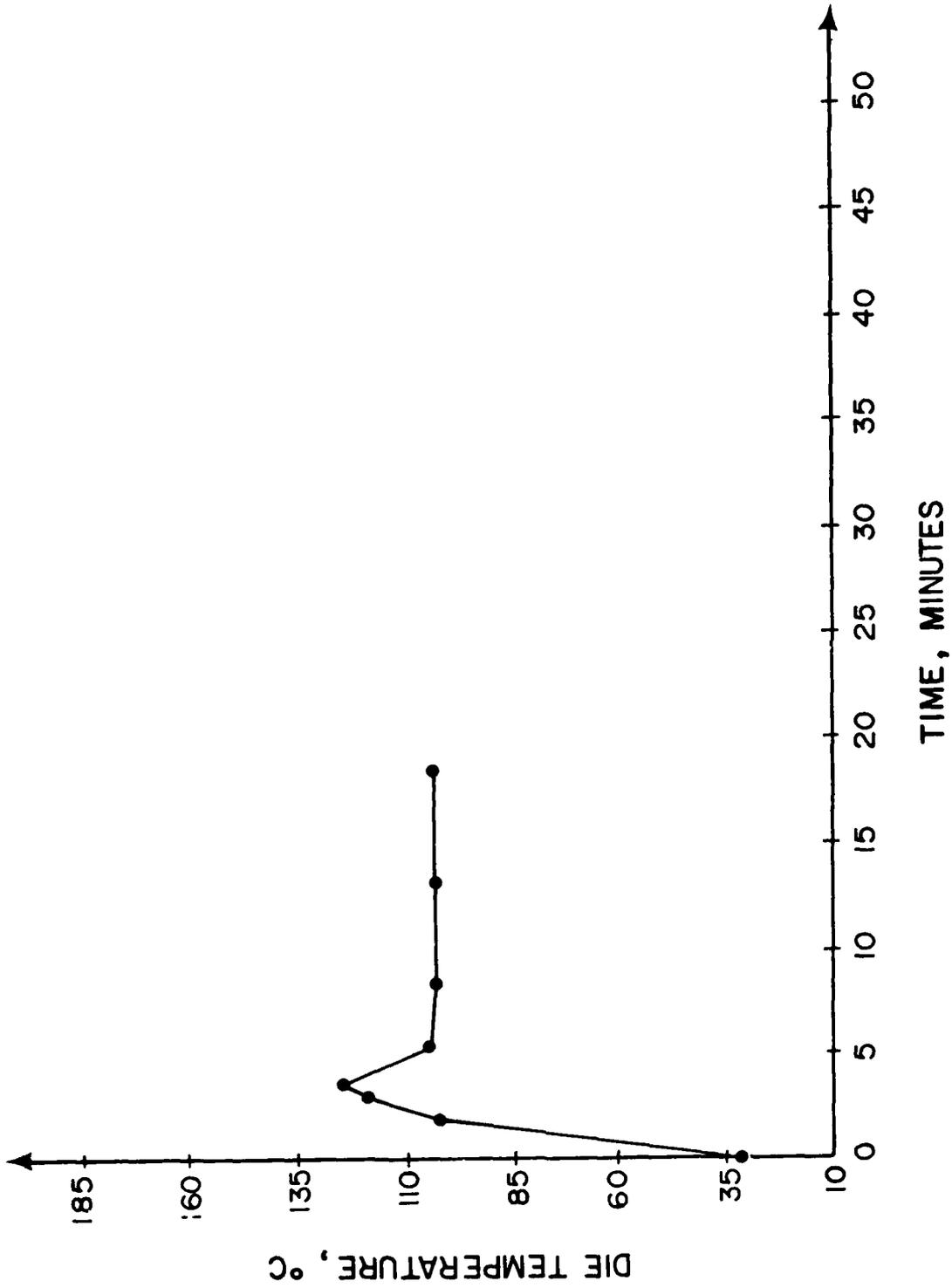


FIGURE 7. Die stability test using overshoot method (selected 100°C).

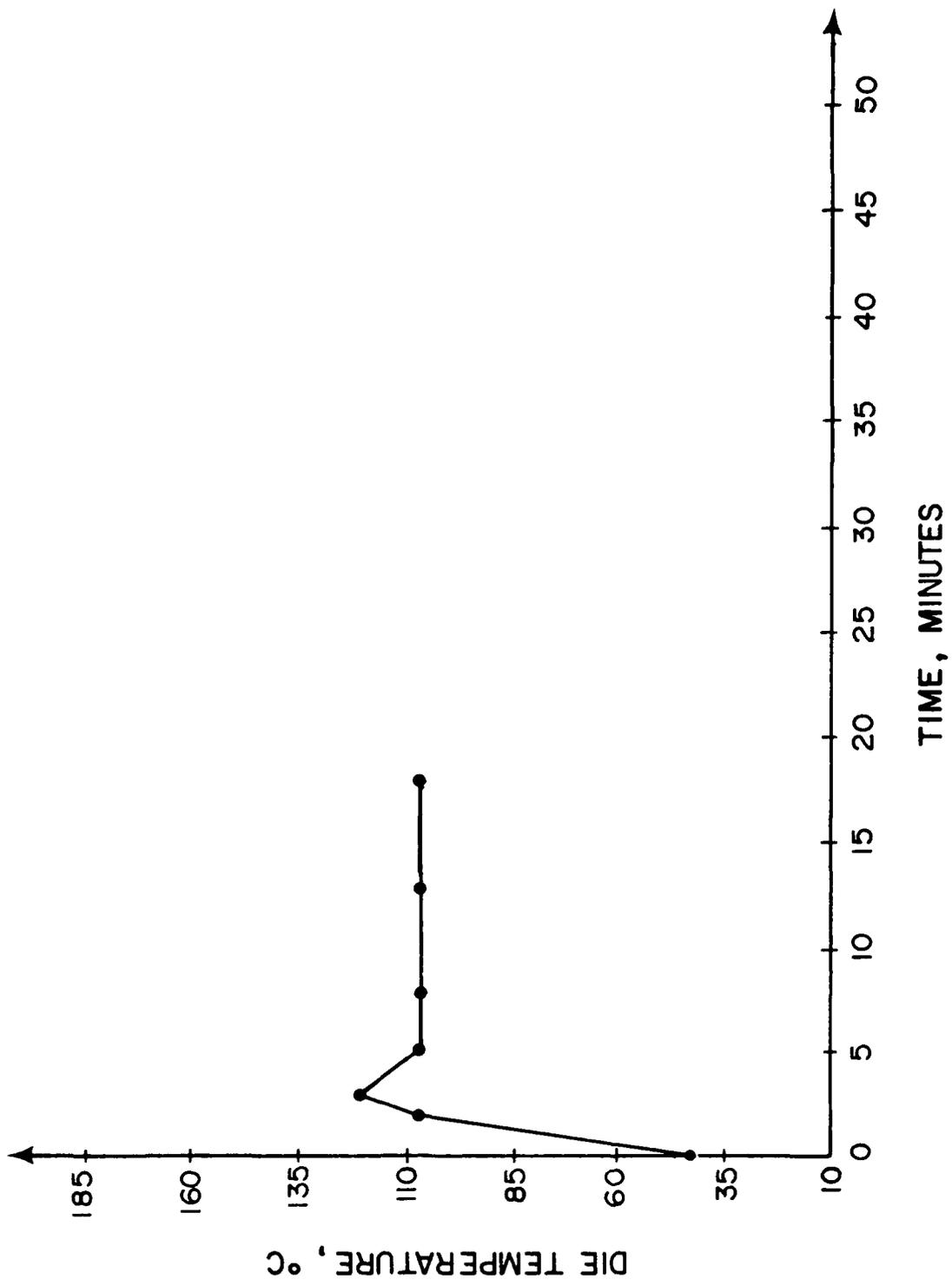


FIGURE 8. Die stability test using overshoot method (selected 105°C).

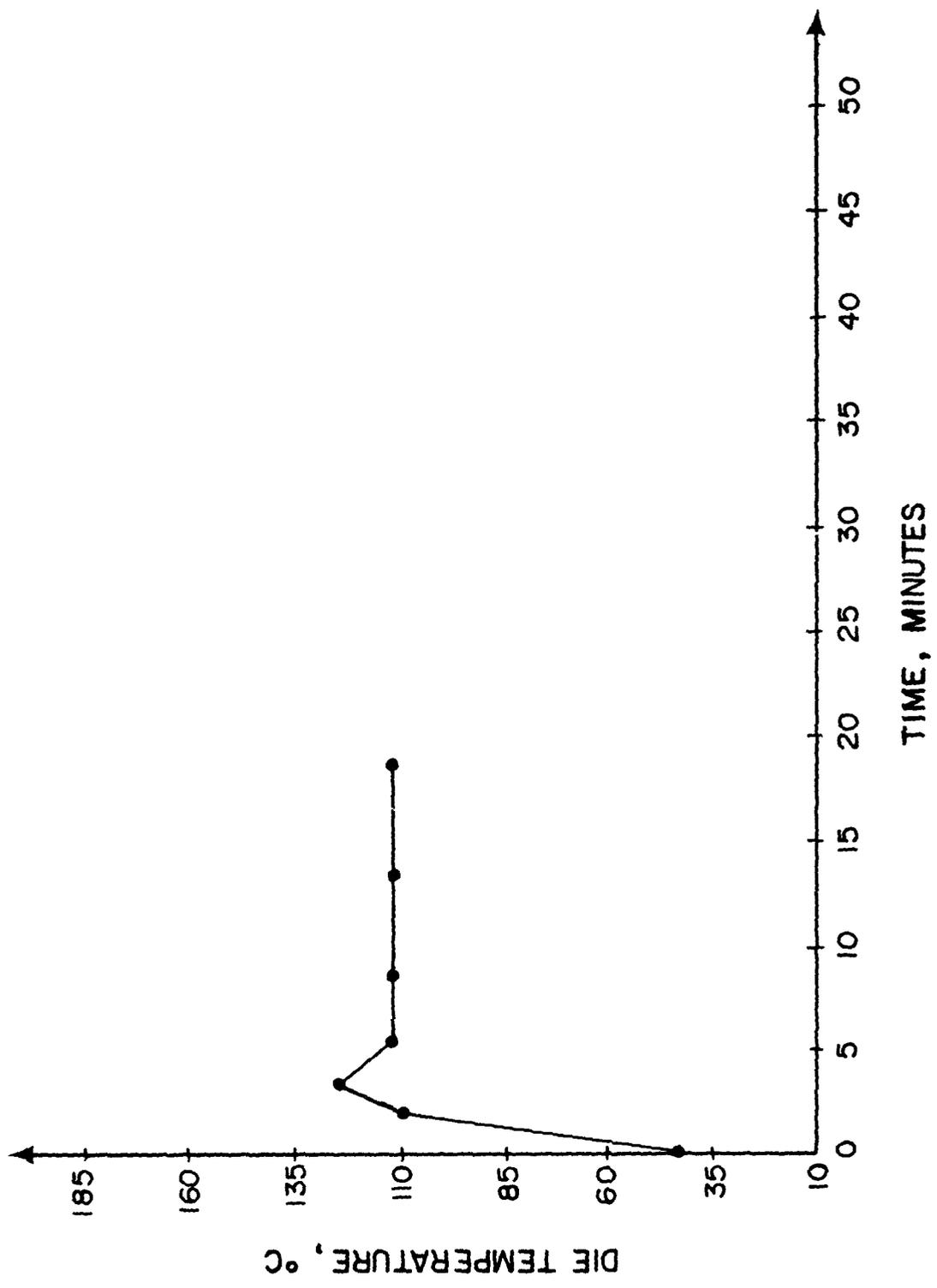


FIGURE 9. Die stability test using overshoot method (selected 110°C).

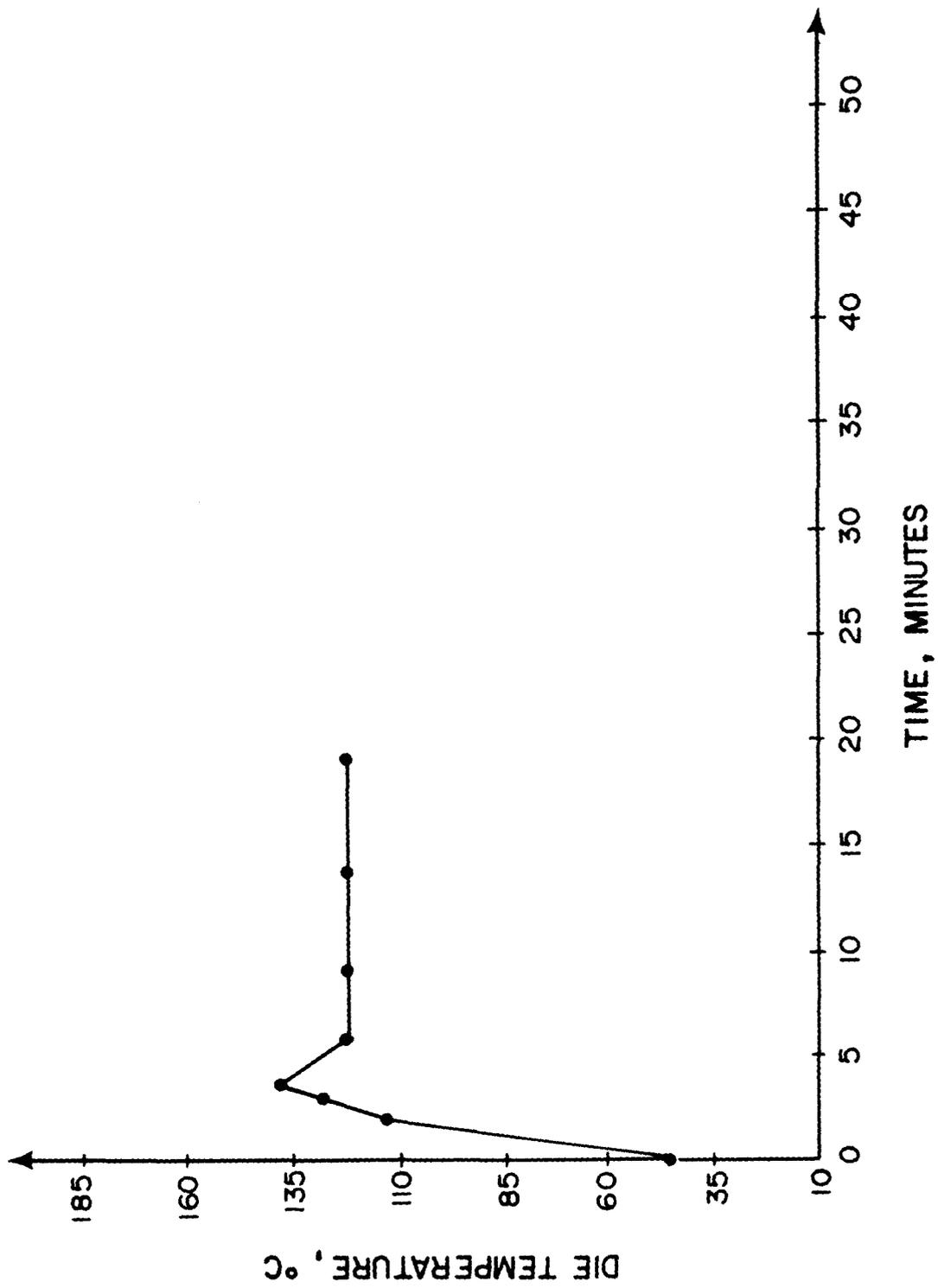


FIGURE 10. Die stability test using overshoot method (selected 120°C).

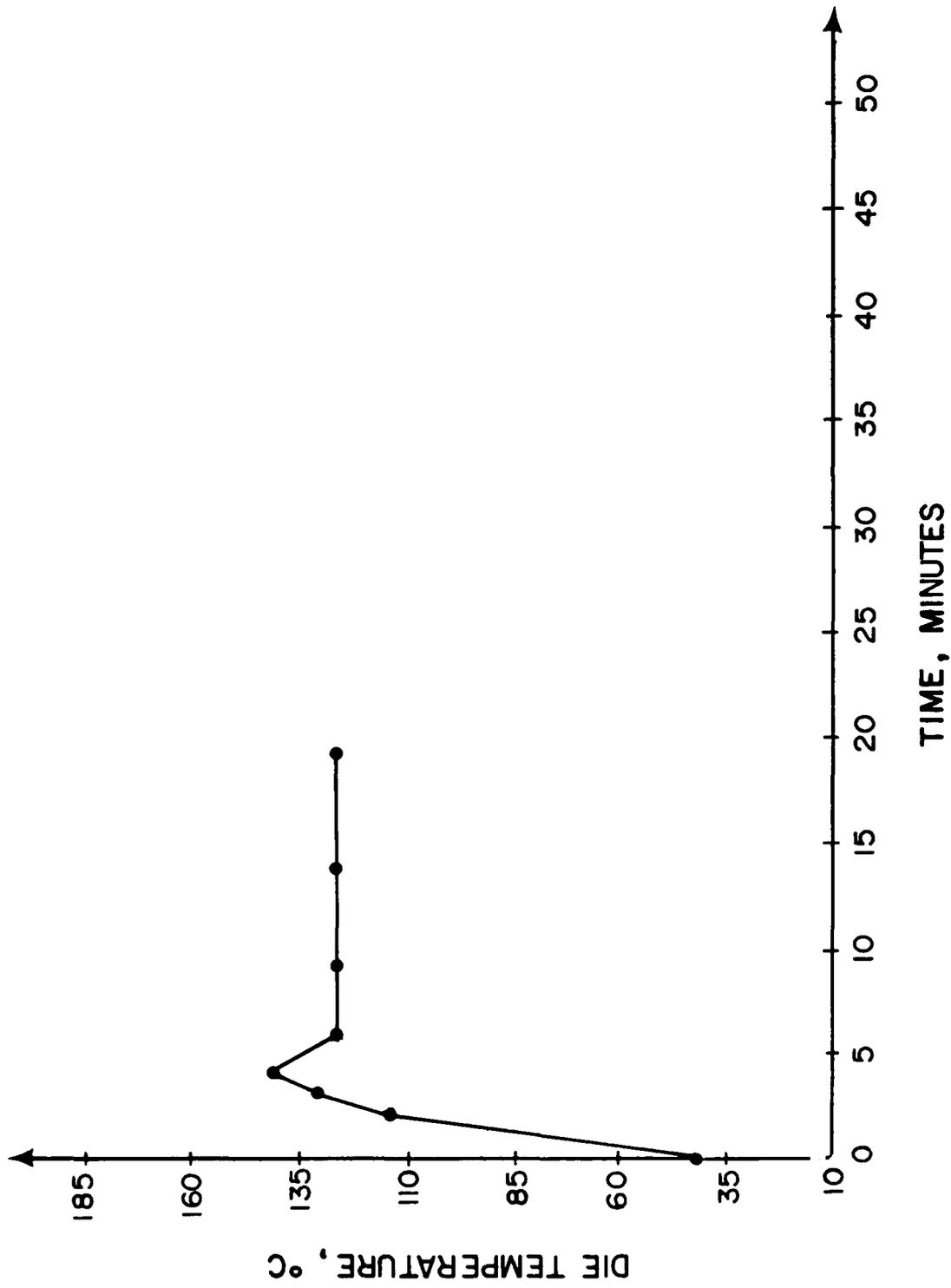


FIGURE 11. Die stability test using overshoot method (selected 125°C).

SECTION 4

LOW TEMPERATURE TESTING

A Thermonics Model T-2050 PTFS was procured and used for the low temperature testing. This system is designed to provide both high and low gas stream temperatures. For high temperatures, the system operates like the Model T2100H described above. For low temperatures, a liquid nitrogen (LN₂) source is required. LN₂ enters the system through a pressure relief and shutoff valve and enters a heated vaporizer. Nitrogen exits the vaporizer at a very low temperature (-90°C) and enters a heater where it is brought up to the desired temperature.

The experimental setup was similar to that for the high-temperature testing. The cold nitrogen was directed to the die through the thermal-control adaptor. A stream of room-temperature nitrogen was passed through a heater and directed across the microscope viewing window and probe-card components to prevent frosting. All experiments were conducted in room ambient without the use of environmental chambers or a "dry box". The wafer of PMI Ref-02s and probe card were used to determine the die temperature.

The setup provided a sufficient gas flow at low temperatures to drive the die temperature well below the required -55°C. However, the back pressure of the adaptor gas plenum restricted the flow sufficiently to prevent good regulation of temperature. The result was that the die temperature was always driven below the desired temperature.

Experiments were conducted to evaluate sensitivity to frosting. To achieve frost-free operation with a cooled chuck at a temperature of -55°C requires control of the ambient relative humidity to less than .1%. With the gas-stream, we achieved temperatures of less than -45°C without frosting and with no attempt to control ambient humidity. Data from the experiments are illustrated in Figures 12 and 13. Since the gas stream developed from liquid nitrogen is very dry, the immediate volume around the cooled die is very low in humidity. Some mixing with ambient air still occurs, however, causing frosting at the lowest range of temperatures.

COOLING DIE TEST VS. TIME

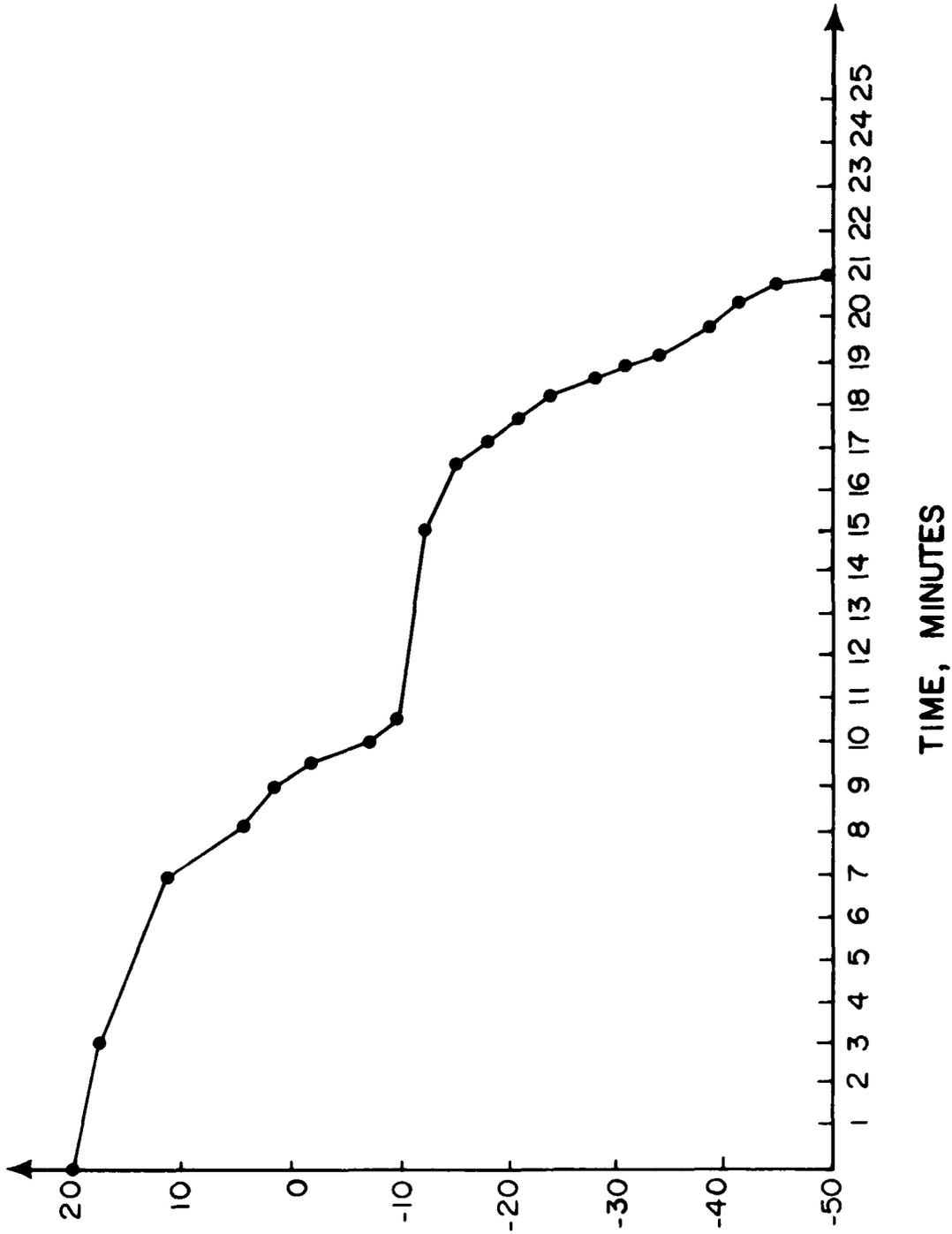


FIGURE 12. Varying temperature setting die cooling test.

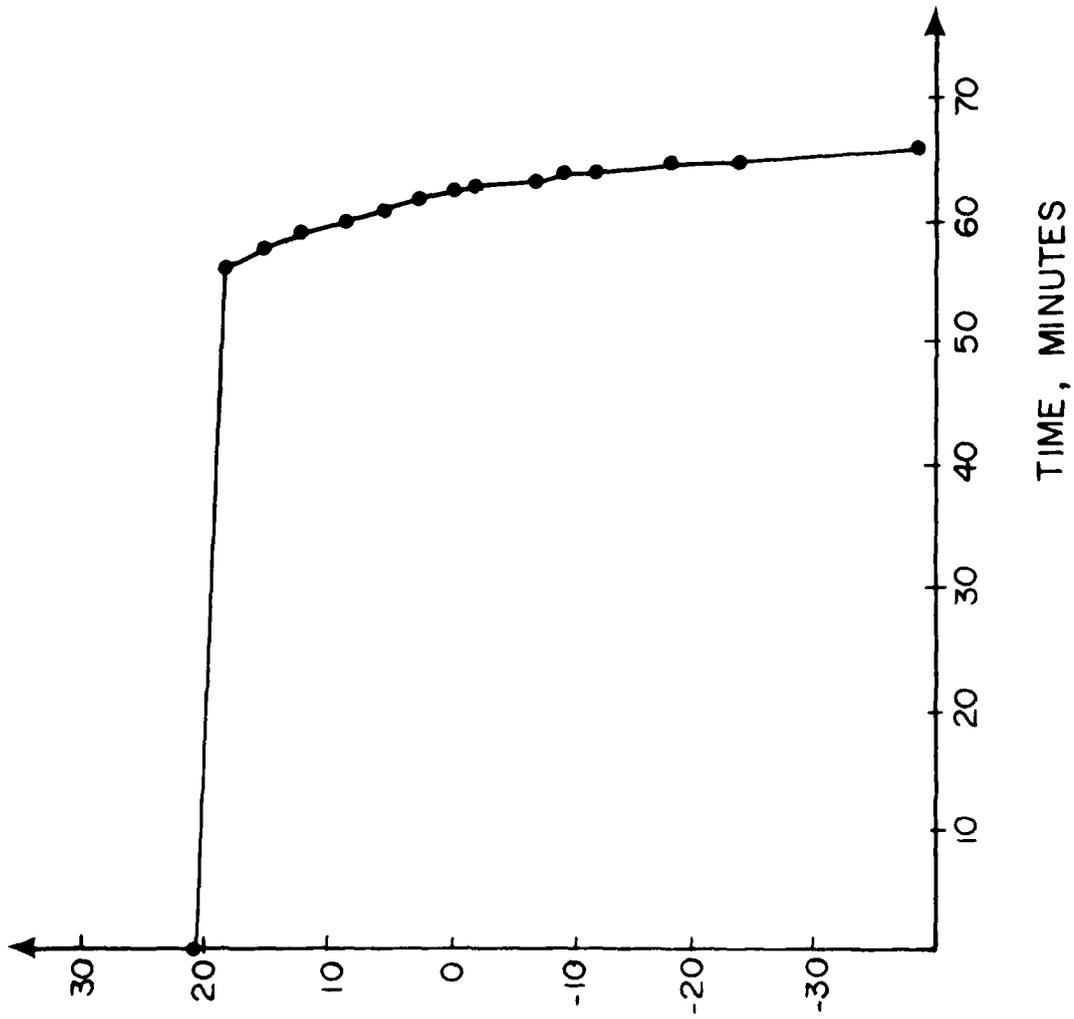


FIGURE 13. One set temperature die cooling test.

SECTION 5

SUMMARY

Dosimetry was designed to monitor the laser-pulse energy of the Nd:YAG laser used for dose-rate applications and prototype was built and tested. The design is now incorporated into the Model 4100 dose-rate testing system.

Experiments were conducted to evaluate the use of a heated-gas stream system for heating and controlling die temperature for dose rate and total dose systems. The ability to heat the die to sufficient temperatures (125°C) was demonstrated, using a gas-stream system for a quartz chuck. Experiments with a quartz chuck indicated a strong dependence of die temperature on chuck temperature. For accurate die temperature stabilization, the control of both the chuck- and gas-stream temperatures was required. Therefore, for accurate temperature stabilization, temperature-sensing structures on the die could be used as feedback elements in a temperature-control system. In systems with a metallic chuck, such as a Model 4100 used for total-dose testing, a temperature controlled chuck is a better method for temperature testing.

Experiments were conducted to evaluate the use of a cooled-gas stream system for cooling and controlling die temperature for Model 4100 dose rate applications. The ability to cool a die temperature below the -55°C limit was demonstrated. Good immunity to frosting resulting from the use of the dry gas stream was demonstrated. Since the die temperature is influenced by the chuck temperature, requires the chuck temperature must be controlled to achieve stable die temperatures.

For temperature-stabilized radiation tests involving transient and total-dose irradiations, different methods may be necessary for die temperature control. For dose-rate applications which require a transparent quartz chuck, a hot/cold gas-stream system could be used, using feedback from a temperature-sensing structure on the device under test (DUT) to control the die temperature. For total-dose testing, a combination system using a cooled-gas-stream system and a hot/cold chuck is proposed. For elevated temperatures, the heated chuck is sufficient.

For low temperatures, the chuck would be stabilized at a moderately low temperature (perhaps between 0 and -20°C), and the dry gas stream would be used to decrease the die temperature to the desired temperature. A chamber around the wafer chuck area would be required to decrease mixing of the cold gas stream with ambient air near the DUT.

APPENDIX

Model 4100

AUTOMATIC SEMICONDUCTOR IRRADIATION SYSTEM

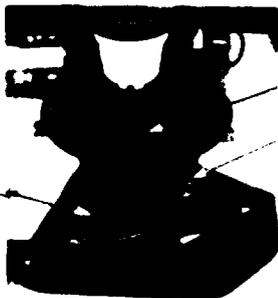
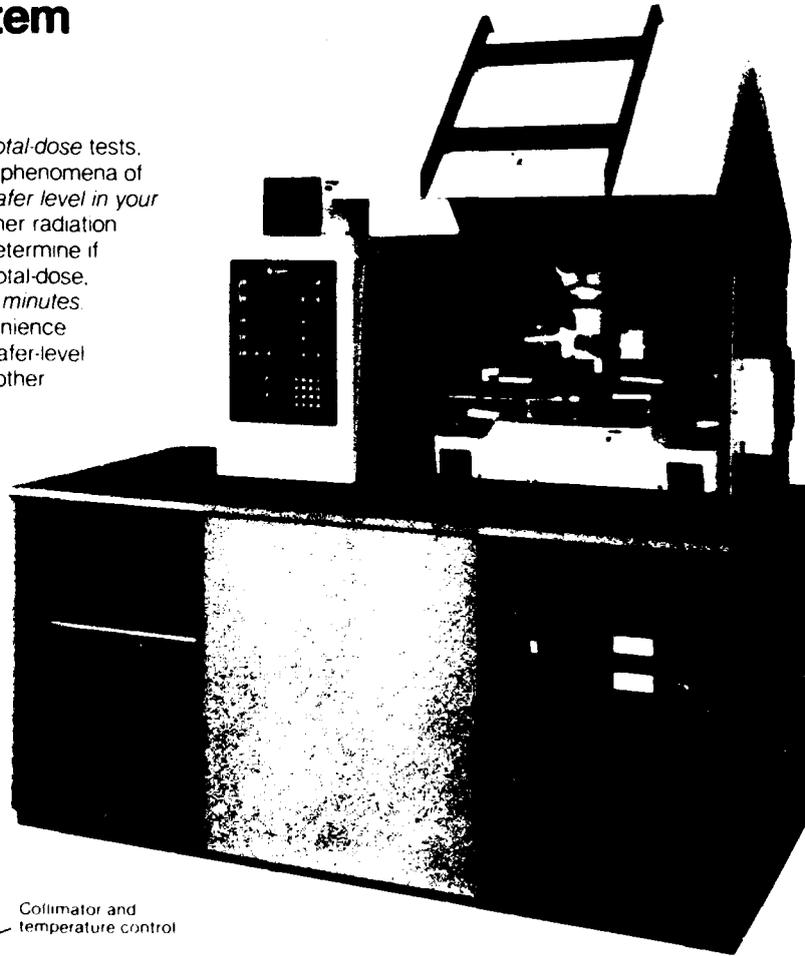
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Model 4100 Automatic Semiconductor Irradiation System

Now, for the first time, conduct *total-dose* tests, *dose-rate* tests, or study *latchup* phenomena of devices or complex ICs *at the wafer level in your laboratory or testing area*. No other radiation sources are required. You can determine if a wafer meets space and DoD total-dose, dose-rate, and latchup criteria in *minutes*. Think of the economy and convenience associated with fast, accurate wafer-level tests that correlate directly with other approaches to radiation testing. Because the dose-rate and latchup measurements impart no damage, you can test 100% of the die on the wafer.

Comprehensive Radiation Testing.

Transient tests are performed with a tungsten x-ray tube; the primary dose derives from the 10keV L-line x-rays. Dose rate and latchup tests are made with a Nd:YAG laser pulse through the bank of the wafer. Results correlate with cobalt 60 and linear accelerator exposures.



Transparent
chuck

Collimator and
temperature control

Dosimeter

Easy Interface with Modern ATE.

All Model 4100 Systems are designed to interface with either functional or parametric test systems for production-site testing of VLSI devices. Both low-current and high-speed test capabilities are provided by a controlled impedance tester interface.

Saves Time and Reduces Expenses.

On-site, wafer stage testing eliminates the lost production time required for device packaging and the high cost of off-site testing. It also permits the rejection of unsatisfactory wafers, rather than the rejection of completely fabricated production lots.

Evaluate Internal Latchup Margins.

Even if you are not interested in device radiation sensitivity or measuring radiation specific effects, you can verify internal latchup margins of complex CMOS VLSI devices. The chuck design allows latchup testing at standard and optional wafer sizes and the temperature controller provides the capability to vary the temperature of the wafer up to 150°C.

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