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MARTIN MARIETTA

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OPTICAL IMAGING OF CHARGED PARTICLE TRACKS IN A GAS

J. E. Turner and R. N. Hamn
Oak Ridge National Laboratory

S. R. Hunter, W. A. Gibson, and G. S. Hurst
Pellissippi International, Inc.

H. A. Wright
Consultec Scientific, Inc.

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MARTIN MARIETTA ENERGY SYSTEMS, INC.

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November 28, 1994

Mr. Peter D. Dayton
Director, Procurement and Contracts
Department of Energy, Oak Ridge Operations
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Dear Mr. Dayton:

Final Report for CRADA No. ORNL90-0034 with Pellissippi International

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S.R. Hunter, W.A. Gibson, G.S. Hurst, J.E. Turner, R.N. Hamm, and H.A. Wright

ABSTRACT

The development of a new detector designed to optically image the track of a charged particle in a gas is outlined. In the detector, a pulsed high-voltage (up to $\approx$ 30-40 kV), high-frequency (f = 27.125 MHz) RF field is temporarily applied (pulse duration $\approx$ 1-3 μs) across a pair of electrodes, immediately following, or alternatively, just prior to the passage of a charged particle through the chamber. The pulsed RF field excites the subexcitation electrons left along the particle's path leading to excitation and ionization of the surrounding gas and the emission of light. The track is then imaged by a fast intensified digital camera (shutter speed $\approx$ 0.1-5 μs). The image is recorded in a two-dimensional pixel array (512 x 512 pixels) within the camera, and transferred to a computer for later analysis. The detector has been operated over the total gas pressure range 2.5-100 kPa (20-750 torr) using a gas mixture of 2-10% N_2 in Ar. Images of both α and β tracks obtained with this detector are discussed to demonstrate the usefulness of the present technique in charged-particle track analysis for dosimetry and microdosimetry applications.

FINAL REPORT

OPTICAL IMAGING OF CHARGED PARTICLE TRACKS IN A GAS

S.R.HUNTER, W.A.GIBSON, and G.S.HURST

Pellissippi International, Inc.

110 Ridgeway Center, Oak Ridge, TN 37830, USA

J.E.TURNER and R.N.HAMM

Oak Ridge National Laboratory

Oak Ridge, TN 37831, USA

H.A.WRIGHT

Consultec Scientific, Inc.

725 Pellissippi Parkway, Knoxville, TN 37932, USA

INTRODUCTION

In this paper we report the progress that has made in the development of a new type of ionizing radiation detector which is based on the digital, as opposed to the more conventional analog, measurement of the ionization signal produced in a radiation detector[1-5]. As originally envisioned, the digital characterization of the charged particle tracks in a gas has several advantages over presently used analog gaseous ionization chambers in such applications as neutron dosimetry and microdosimetry[1,2]. Whereas present analog techniques utilize tissue-equivalent instruments and measurements of the ionization signal pulse height and shape to infer neutron dose and dose-equivalent[6], the digital technique registers a charged particle track by measuring the number of electrons it produces in given subvolumes of a chamber gas[2]. The track is thus characterized by a set of integers in each volume element. A digital detector of this type can measure both the track length and the energy of the secondary electrons in the path of a neutron recoil ion for instance. This information enables the identity of the recoil ion, as well as its energy and LET, to be established, from which the dose equivalent can be calculated.

In the field of microdosimetry, the study of the fluctuations in the energy deposition by the particle track on the order of molecular to cellular (i.e. nanometers to microns) dimensions is important in the understanding of the chemical and biological effects of ionizing radiation. An important aspect of microdosimetry is the calculation of the charged particle track structure in

gaseous and liquid media from which the effects of the ionizing radiation on biological samples at these spatial dimensions can be inferred[1,6]. By necessity, this has been the only technique available for directly accessing the statistical fluctuations in the energy deposition processes on the micron and submicron distance scales. Other techniques, such as the measurement of LET distributions using spherical Rossi proportional ionization counters[6] are available to estimate microdosimetric parameters and have been used to obtain particle energy spectra at tissue equivalent spatial dimensions on the order of 10 nm[7]. Generally however, these techniques are not able to resolve the microscopic details of the track structure of individual particle tracks. The instrument that we have been developing has the potential for directly measuring the energy deposition processes in tissue equivalent gases at gas pressures and with sufficient spatial resolution to simulate the energy deposition processes in unit density materials with submicron resolution. This device can be used to make direct comparisons between the experimentally observed energy deposition processes in a gas and the track structure calculations in that gas, allowing the various assumptions and approximations implicit in the calculations to be checked and quantified[1,2]. In this paper we outline the principles behind the present track detection technique, discuss the recent improvements we have made to the chamber[4,5], and show examples of the α and β particle tracks that have been obtained with the detector.

DETECTOR DESIGN

A schematic diagram of the detector concept is given in Figure 1. The basic operating

principles of this detector have been discussed previously[3-5] and will only be briefly outlined. An ionizing radiation source produces a track of subexcitation electrons in the gas of an ionization chamber. In the present studies, the source was either an ^{241}Am source from a smoke detector emitting a 5.5 MeV α particle, or a ^{232}Th source from a Coleman lantern mantle emitting several α particles, with energies over the range 4.0-8.8 MeV, and several β particles with maximum energies up to 2.3 MeV. A pulsed, high-voltage (peak voltages up to 30-40 kV), high frequency RF field (f = 27.125 MHz stabilized by a crystal controlled oscillator - Henry Electronics Model 3000D, 2000 watt oscillator-amplifier) is temporarily applied to the chamber electrodes, immediately following the passage of the ionizing particle through the chamber. For the present measurements, the chamber was filled with a 5-10 % mixture of N_2 in Ar with total gas pressures in the range 2.5-100 kPa, corresponding to an E/N range of 10-50 V-cm^2.

The detector has been operated in one of two modes. Firstly, the prompt fluorescence from the gas due to the ionizing particle is detected by two fast photomultipliers operating in coincidence mode. The output pulse from the coincidence detector is then used to trigger the RF field circuit and a short burst of RF voltage (pulse duration $\approx$ 1-3 μs) is applied to the chamber electrodes. Alternatively, the RF field circuit is operated in a pulsed duty cycle mode (the duty cycle for these measurements was usually 0.1% - 10%) with a pulse duration of typically 0.1-10 ms. Although both techniques were successfully used to obtain images of the particle tracks in the gas, the latter technique has been used to obtain the images presented in this paper due to the minimization of the electron diffusion before the application of the high

voltage RF field.

The pulsed RF field excites the subexcitation electrons left along the particle's path leading to ionization of the surrounding gas and the emission of light in the immediate vicinity of the particle track. Under low electron amplification, the amount of light given off by a given subvolume of the gas will be directly proportional to the initial number of electrons in that subvolume due to the particle track. The detection of the light emission by one or both of the photomultipliers is used to turn off the RF field in the pulsed duty cycle mode before gas breakdown occurs in the chamber. The emitted light is imaged by a fast microchannel plate intensified digital camera (shutter speed $\approx$ 0.1-5 μs) and recorded on a 512 x 512 CCD pixel array within the camera (Photometrics Series 200 camera). The image is digitized and transferred to a computer (PC 486 clone) for later analysis.

DETECTOR PERFORMANCE

The present detector contains several significant improvements since our last report on this project[4,5]. The major changes include the following. (1): The use of a high speed, intensified, digital camera instead of a conventional 35 mm camera to record the track image. (2): The particle track detection circuitry (i.e., the RF field and camera shutter circuits) is triggered either by the ionization event in the chamber, or the track detection circuitry is switched off when the light level in the chamber, as measured by one of the photomultipliers, has reached a predetermined value. Previously, the high voltage RF field was randomly triggered in

relation to the passage of an ionizing particle in the chamber. (3): The RF field is generated by a crystal controlled oscillator and high-voltage RF amplifier, rather than a damped tuned oscillator circuit which was shock excited by a spark gap. As a result, the detector can now operated at a higher frequency (f = 27.125 MHz) and higher voltages (up to $\approx$ 40 kV) than previously (i.e. compared with f $\approx$ 10 MHz and V $\approx$ 10-20 kV) along with improved shot to shot reproducibility. (4): The use of the higher RF voltages and improved peak voltage stability has enabled us to operate the chamber over a wider range of gas pressures (p $\approx$ 2.5-100 kPa) than before (p $\approx$ 40-55 kPa), effectively improving the resolution with which the track structure can be imaged. (5): Improved vacuum techniques (i.e., the use of a turbomolecular vacuum pump along with stainless steel vacuum components, copper gaskets, a UV grade quartz chamber, etc) have enabled us to improve the base pressure of the chamber from $\approx 10^{-2}$ to $\approx 2 \times 10^{-6}$Pa ($\approx 10^{-4}$ torr to $\approx 10^{-8}$ torr). This has led to a corresponding reduction in the impurity levels within the chamber during operation, and more reproducible excitation and light output measurements from one gas fill to the next. The present version of the detector has been operating successfully for some time and is continually being upgraded to improve system performance in terms of track resolution, operating gas pressure range and reliability, reproducibility of the measurements.

TRACK IMAGING RESULTS

Images of four α particle events are shown in Figure 2a-2d. Figure 2a shows the track produced by an α particle from a ^{241}Am source located at the bottom of the image. The α

particle track was produced in a gas mixture of 5% N_2 in Ar at a total gas pressure of 55 kPa and the α particle experienced a scattering event about 2/3 the way along the total track length. The total track length was $\approx$ 5 cm and the apparent half width of the track is $\approx$ 2-3 mm. The vertical structures apparent in the image to the left and right of the track are the walls and electrodes of the chamber which are imaged by reflected light from the particle track.

The other three α particle tracks shown in Figure 2 were produced from a ^{232}Th source. In the image shown in Figure 2a, the source was also located at the bottom of the figure, while the source for the α particle tracks shown in Figures 2c and 2d was located near the bottom of the image. These three images show the three general types of α particle tracks that we have detected with this chamber; i.e. conventional tracks with a high degree of ionization near the stopping point of the track (Figure 2c), essentially linear tracks with a relatively uniform degree of ionization from beginning to end (Figure 2b), and more unexpectedly, double ended tracks with a high degree of ionization at both the beginning and end of the track (Figure 2d). No analysis of these tracks has been performed to date to model or understand the energy deposition processes shown in these images. The track image shown in Figure 2d is an example of a recently recorded track with a half width of $\approx$ 0.7-1.0 mm, giving a corresponding unit density resolution of $\approx$ 0.6-0.9 μm.

Images have also been obtained of β particle tracks from the ^{232}Th source, and two of these are shown in Figure 3a and 3b. The source for these images is located at right of the figures, and these images show that, in contrast to the α particle tracks, the β particle undergoes many

large angle scattering collisions during its energy decay. The energy deposition for β particles is considerably more irregular than that for the α particles showing regions of dense electron production (and hence high energy deposition and correspondingly high LET) and other regions with very little ionization of the gas (and hence low LET). These track images show remarkable agreement with previous Monte-Carlo calculations of the particle tracks for proton tracks in methane[1] and α particle tracks in water[5], and β particle tracks in water[8].

To indicate the sensitivity of the experimental technique, Figure 4 shows the image obtained from a single electron located near the top of the figure, and a four electron α particle track. The image is of an "old" track in which virtually all of the electrons in the track have either recombined, been converted to negative ions, or diffused to the walls of the chamber. These results show that the present device is capable of the ultimate track detection sensitivity, namely single electron detection and resolution, provided that the electron density in the track is not too high. Finally, we have been exploring methods for obtaining three dimensional information on the track structure in the detector. Presently, images from the chamber are recorded using a single camera and a second camera could be used to obtain three dimensional track structure information. Alteratively, imaging the radiation from the chamber with a mirror located at 45° to the camera imaging plane, and having the camera image both the chamber and the mirror allows two images of a single track to be recorded at 90° from each other. The three dimensional spatial coordinates of the particle track can then be reconstructed from the image. Preliminary measurements using this technique indicate that we will be successful in this endeavor.

SUMMARY AND CONCLUSIONS

We have shown in this work that we can use the experimental technique outlined in this paper to image the track structure produced by the energy decay of both α and β particles in a gas over the pressure range 0.25-100 kPa. The best resolution we have obtained to date is approximately 0.7 mm for the α particle tracks in 50 kPa of a N_2/Ar gas mixture, corresponding to a resolution of $\approx$ 0.6 μm in unit density material. Further work is in progress to improve the detector resolution by operating the RF circuit at higher frequencies and reducing the delay between the formation of the track and the production of the light from the chamber[3]. These improvements will ultimately allow this device to probe the energy deposition processes of ionizing radiation in three dimensions in unit density materials on submicron dimensions.

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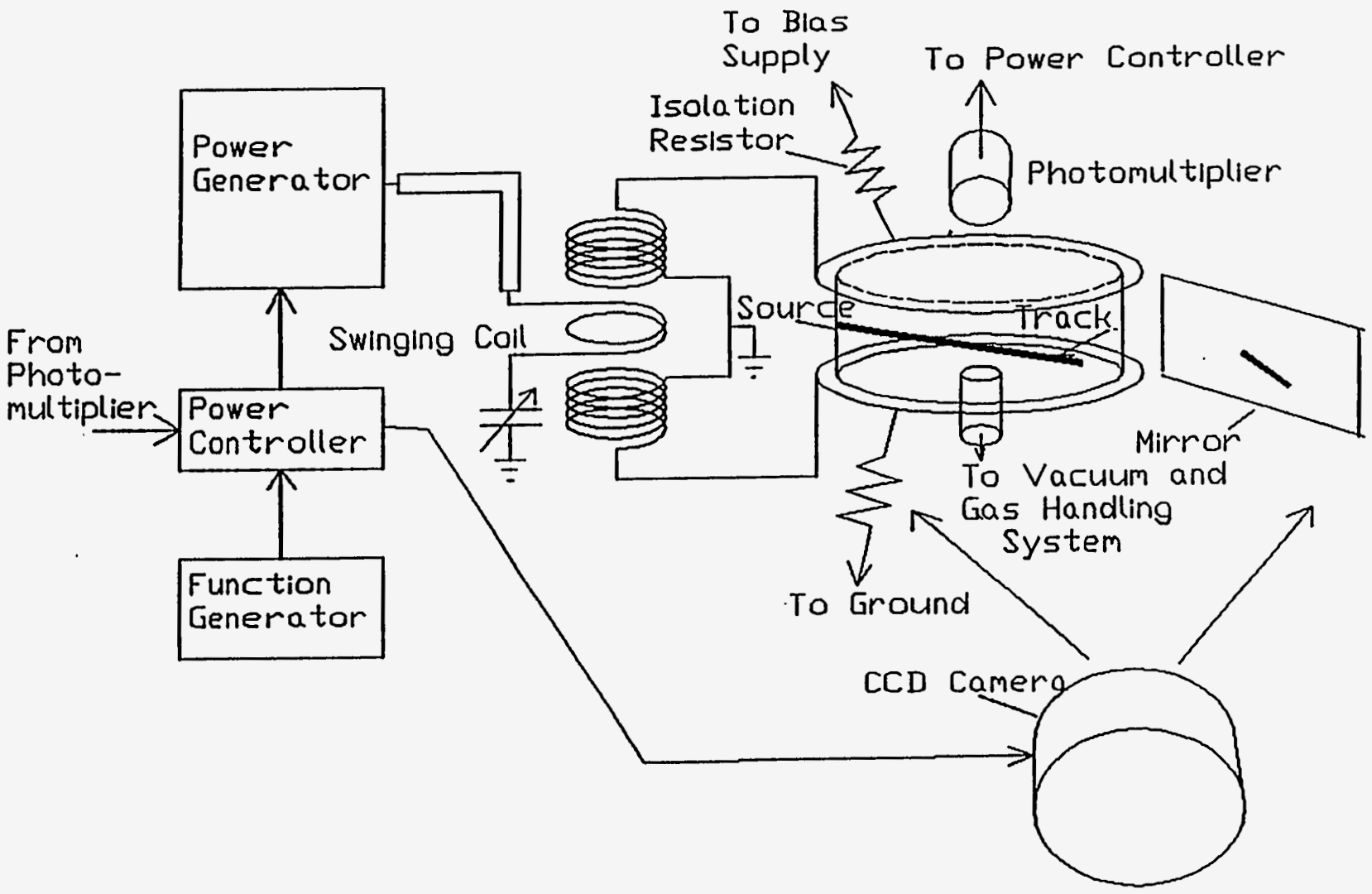
FIGURE CAPTIONS

Figure 1. Schematic diagram of the optical ionizing radiation detector.

Figure 2. Images of four α particle tracks obtained in a gas mixture of 5% N_2 in Ar at a total gas pressures in the range 50-60 kPa.

Figure 3. Images of two β particle tracks obtained from a ^{232}Th source located within the ionization chamber.

Figure 4. Image of a single electron and that obtained by an "old" α particle track containing only four electrons.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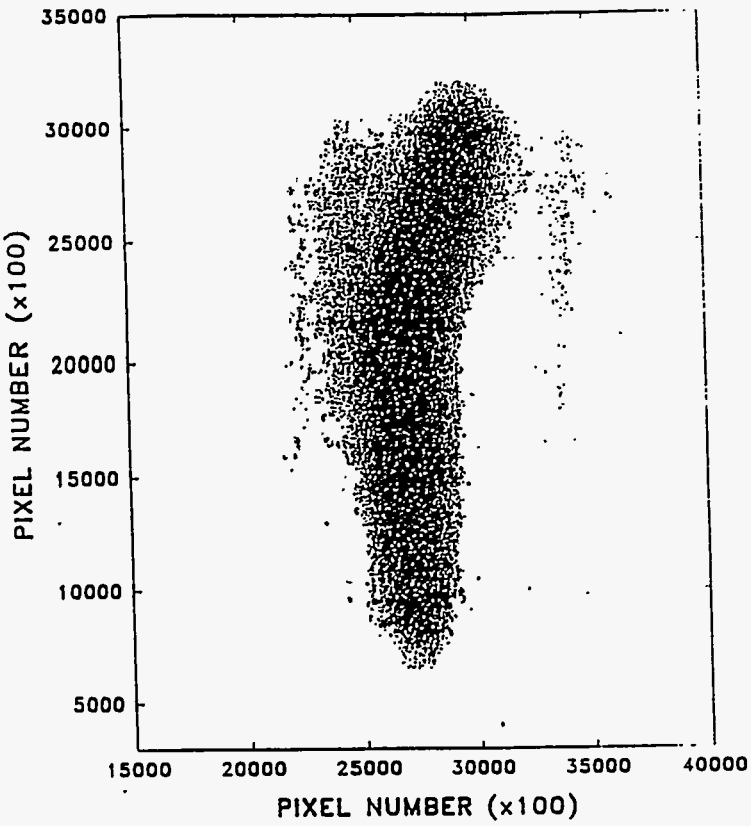
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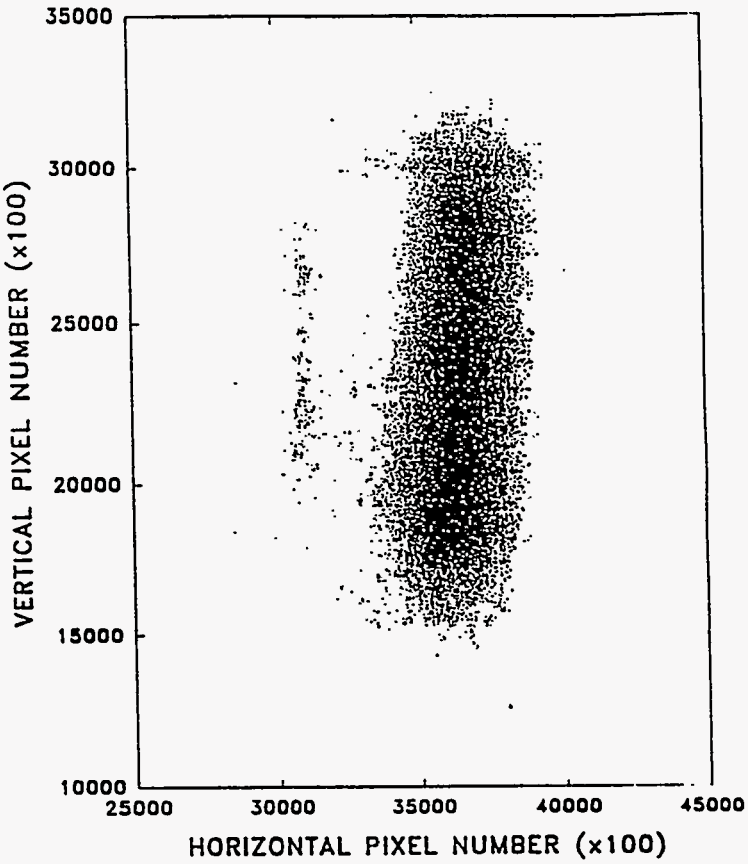
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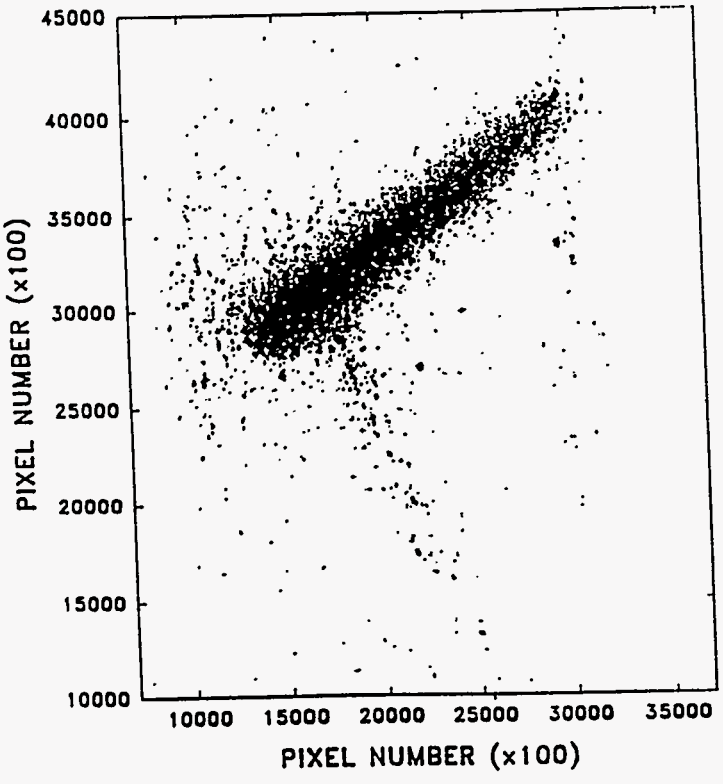
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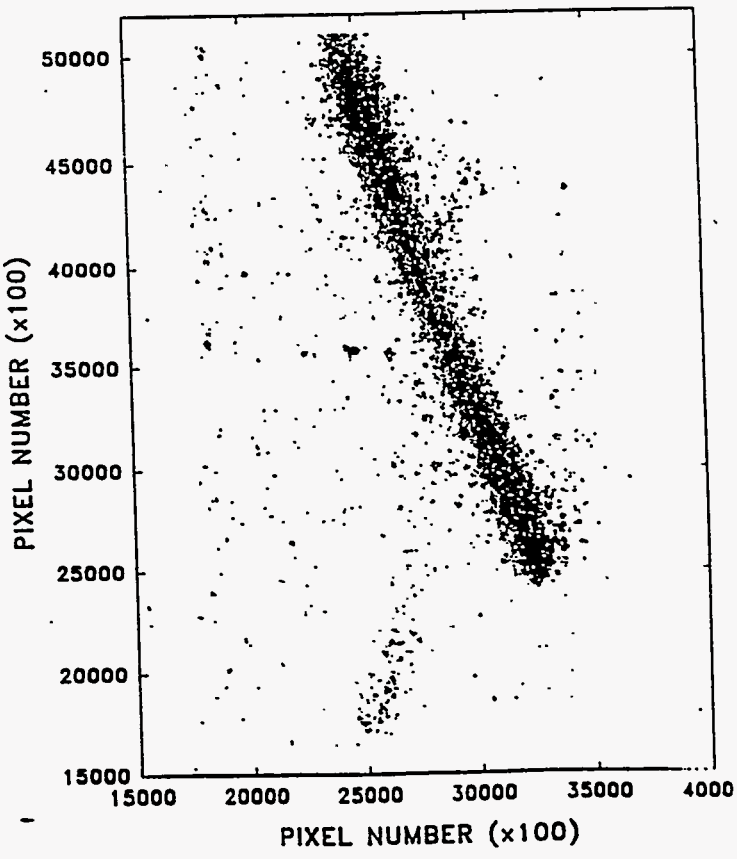
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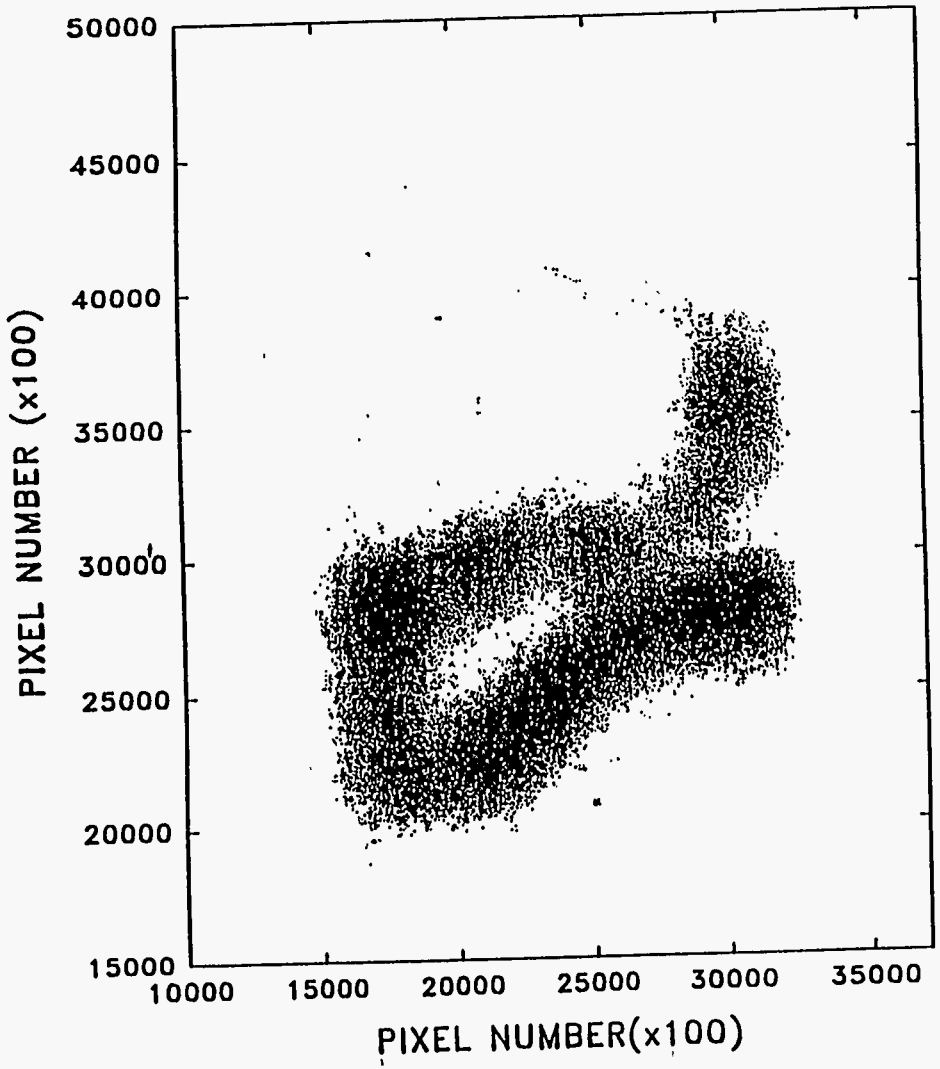
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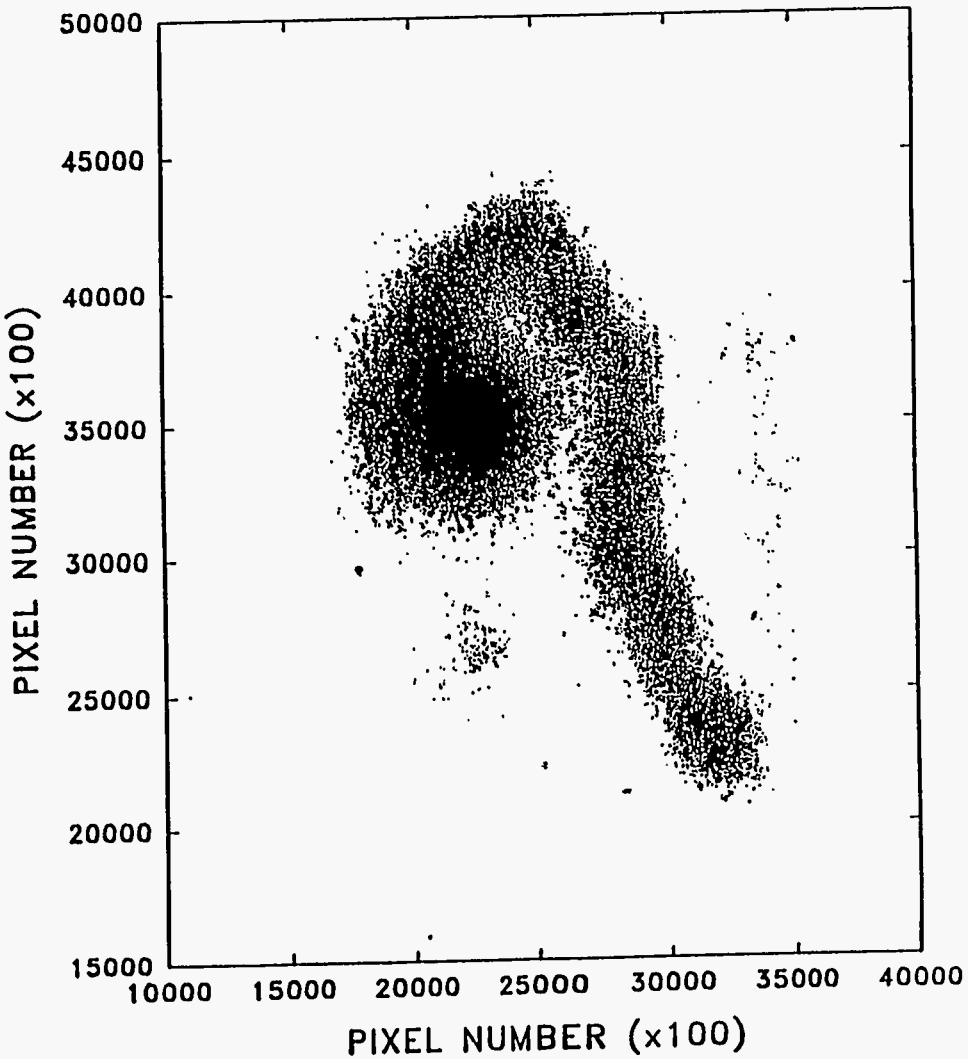
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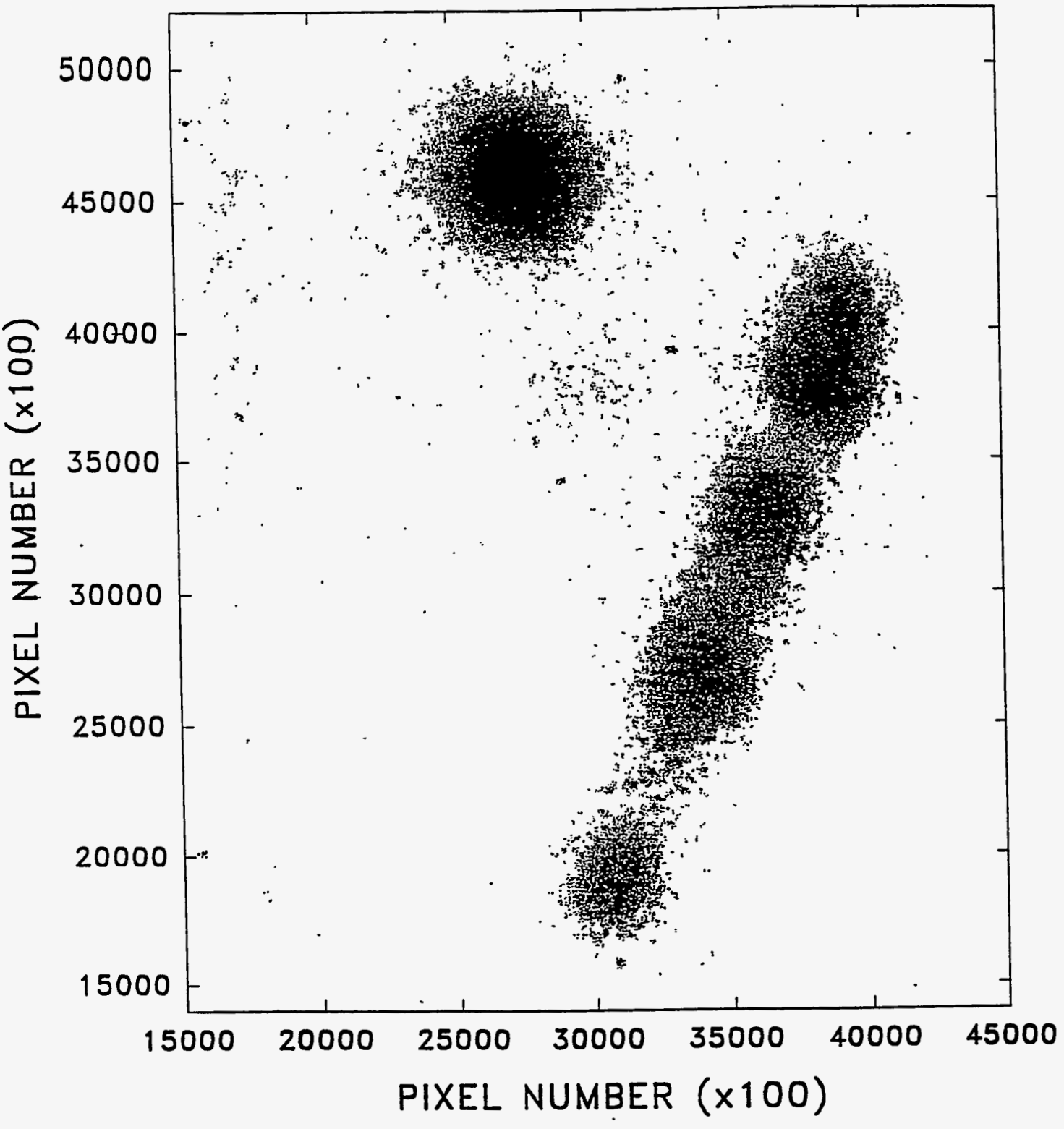
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