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APOLLO HELMET DOSIMETRY EXPERIMENTS

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FINAL REPORT

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APOLLO HELMET DOSIMETRY EXPERIMENTS

1. RESULTS

The purpose of this experiment was to measure the dose of heavy cosmic ray particles experienced by astronauts on the Apollo 8 and 12 missions by means of the particle tracks created in the space helmets. The results of the study are embodied in two written papers that are attached as Appendix I and II. Table I of Appendix I contains the basic information sought, that the Apollo 8 helmet has approximately ½ track/cm^2 and Apollo 12 helmets ~3/2 track/cm, a variation which we interpret as caused by two factors -- the increased duration of the Apollo 12 mission over that of Apollo 8 and the decreased solar modulation of the galactic cosmic ray flux at the time of the Apollo 12 mission. The absolute number of tracks is consistent with the known fluxes, abundances, and energy spectra of primary cosmic rays and with the known detection properties of the Lexan polycarbonate material of which the helmets are constructed.

In the process of carrying out this study we recognized and developed a new method of particle identification with solid state track detectors. In this procedure the variation in ionization along a particle track is read out by means of measurements of the diameter variations along the etched track, the reading out being done conveniently by means of a silicone rubber replica of the etched track. This work is described in Appendix II.

2. CONCLUSIONS AND RECOMMENDATIONS

Since our understanding of the damage produced by heavily ionizing particles is highly imperfect, it follows that conclusions as to the biological importance of the observed particle flux cannot be firm. In Table II of Appendix I we have made estimates of the numbers of various non-regenerative cells that were damaged, numbers that for these Apollo missions were small fractions of the total number available, typically 1 cell in 10^7 for small cells and 1 in 10^4 for giant cells. For extended space missions we note that these numbers can readily become worrisome -- upper limits exceeding a 1% loss for large cells on two year missions. At times of solar minimum and diminished solar modulation the loss would in fact be somewhat greater.

Our recommendations are two in number:

1. Direct studies of the biological effects of heavy ions on non-regenerative cells should be carried out at least to the extent that the deactivation cross sections for the major types of cells are known for the most abundant of the heavy track forming cosmic ray particles (the iron group nuclei).

2. As at least an interim measure, Lexan dosimetry should be continued so that the exposure of each astronaut is either known or can be determined if circumstances after a space mission suggest that it would be useful. To carry out this second recommendation we do not believe that helmet dosimetry is best, since the helmets are cumbersome and unnecessarily time consuming and expensive to use, as well as being a source of great mental anguish to the Smithsonian Institution. Rather, direct examination of the helmets shows that a simple attachment of 2" x 7" x .040" Lexan sheets on the back, outside of each helmet would provide dosimeters that would be more satisfactory in several ways:

1. They could be read out much more easily, rapidly, and cheaply following each mission.
2. They would free each helmet for display purposes and preserve it in a closer approximation to its appropriate historical condition.
3. The detectors could be simply and securely fastened on the outside of the helmet behind the head

rest at any time prior to launch merely using gummed tape to hold them in place. At the same time they would impede no astronaut functions.

4. They could be located in a biologically significant site -- separated by less than one gm/cm^2 of material from the astronaut's head and therefore less than 2½ gm/cm^2 from his brain.

The above suggestion was made in a letter to Mr. Charles Lutz (Code EC-9 at NASA MSC) for evaluation.

COSMIC RAY TRACKS IN PLASTICS:
THE APOLLO HELMET DOSIMETRY EXPERIMENT

Abstract: Counts of tracks from heavy cosmic ray nuclei in Apollo helmets from missions 8 and 12 show variations caused by solar modulation of the galactic cosmic ray flux. We have made specific estimates of the biological damage to certain non-replaceable cells by track forming particles during these space missions. The fraction of deactivated cells could range from a lower limit of 3×10^{-7} to an upper limit of 1.4×10^{-4}.

In passing through condensed matter a heavily ionizing particle can produce unique effects by creating a narrow, roughly cylindrical region that is crowded with ionization and excitation, atomic displacements and broken bonds (1). Unfortunately our minute knowledge of the biological effects of heavy ion irradiations stands in striking contrast to the extensive documentation that exists of the effects produced by more usual, randomly dispersed defects such as are caused by β or γ radiation. Although it has been demonstrated that heavy ions can have lethal effects upon colony forming cells (2,3), for non-regenerative human cells such information is totally lacking, difficult to obtain, and hence unlikely to be available soon. Because of this gap in our knowledge and of the probable loss by space travelers of irreplaceable cells by heavy ions in the cosmic rays, such particles have been monitored on the Apollo 8 and 12 missions by using Apollo helmets as heavy particle dosimeters.

The Apollo helmets consist of Lexan polycarbonate, a material that records the tracks of particles whose ionization level lies above that produced by neon at ∿7 MeV/nucleon (4), essentially the same level as corresponds to inactivation with unit efficiency of human kidney T1 cells by a particle that traverses the cell nucleus (2). Because of the approximate identity of these two thresholds -- for track formation and for cell destruction (at least for T1 cells), Lexan is an appropriate detector material for assessing the dose of biologically destructive particles to which the astronauts were exposed.

The helmets used for this experiment include the one worn by Lovell on Apollo 8, all three of the Apollo 12 helmets, and a control helmet that was exposed to cosmic rays at a balloon altitude of 138,000 feet at Fort Churchill. The helmets were stored in the dark to avoid ultraviolet enhancement effects (5) and were later chemically etched to reveal tracks (6) using a stirred 1:1 solution of ethanol and 6.25N NaOH at 23°C for 196 hr., sufficient to remove a veneer of ~80μ of plastic and to develop tracks similar to those shown in Figure 1. The helmets themselves were used as etching tanks, only the forward facing ~600 cm^2 portions of the helmets being etched to avoid damage to the headrest and other fittings. The etched portions were replicated with silicone rubber (7) and the gold coated replicas such as are shown in reference 7 were scanned in a stereomicroscope at 14 times magnification. Features having vertical relief down to approx. 15μ were readily visible under our viewing conditions, a height that for a track at 45° corresponds to a ~135μ total etched length. Although our cutoff for track observation is not perfectly sharp, we can use our estimate for effective value of 135μ minimum total etched length to show (8) that the tracks we observe correspond entirely to nuclei of atomic number (Z) $\geq$ 10 and that from the known abundances in this charge region (9) most of these will be iron or iron group ($24 \leq Z \leq 28$) nuclei.

The results summarized in Table 1 show that the Apollo 12 helmets experienced nearly three times the integrated flux of heavily ionizing cosmic rays as did the Apollo 8 helmet.

Table 1

HEAVY COSMIC RAY TRACK DENSITIES AND FLUXES IN APOLLO HELMETS

Helmet and Mission	Location (Date) [Climax Neutron Monitor]	Track Density cm^{-2} ($\pm 1\sigma$)	Fluxes* tracks/cm^2-sec-str		Relative to Apollo 12	
			Observed ($\pm$10%)	Calculated ($\pm$30%)	Observed ($\pm$15%)	Calculated ($\pm$15%)
Apollo 8 057 (Lovell)	CM (Dec. 21-27, 1968) [3709]	0.56 ($\pm$0.053)	0.765×10^{-7}	1.39×10^{-7}	0.49	0.66
Apollo 12 007 (Gordon)	CM (Nov. 14-24, 1969) [3843]	1.41 ($\pm$ .146)	1.56×10^{-7}	2.11×10^{-7}	1.00	1.00
Apollo 12 504 (Bean)	CM, LM, LUNAR SURFACE	1.55 ($\pm$ .154)	1.71×10^{-7}	$\approx 2.24 \times 10^{-7}$	1.09	$\approx$1.06
Apollo 12 506 (Conrad)	CM, LM, LUNAR SURFACE	1.47 ($\pm$ .152)	1.62×10^{-7}		1.04	
Fort Churchill	2.5 gm/cm^2 atmospheric depth July 11-12, 1970 [3715]	0.076 ($\pm$.012)	2.35×10^{-7}	2.36×10^{-7}	1.51	1.12

*Assumes 2π solid angle at and near moon or earth, 4π trans moon and earth; this flux is the flux of particles capable of producing etched tracks of >150 microns length under the etching conditions that were used.

When the different lengths of the two missions are allowed for, the track formation rate on Apollo 12 is still significantly higher (by a factor of 2.0). The track formation rate in the balloon flown helmet was 3.1 times higher than that on the Apollo 8 mission. On the Apollo 12 mission, helmets 504 and 506 were in the lunar module for 25 hours and were outside the lunar module while the astronauts were doing extra vehicular activity for nearly 8 hours. During this 33 hour period the average thickness of shielding material surrounding the helmet is considerably reduced relative to the environment in the command module, where the remainder of the trip was spent. This different environment produced no statistically meaningful difference between the track densities in Gordon's helmet 1.41 (±.15) and Bean's and Conrad's 1.51 (±.11), although the possibility of as much as a 30% increase is allowed by these one standard deviation limits. Two relevant considerations are that the LM and EVA portions of the trip make up a small fraction of the total time of 244.5 hours in space and that during the stay on or near the moon, half of the incident cosmic rays are shielded out by the moon itself.

We now assess whether the track accumulation rate from Apollo 8 (Dec. 1968) to Apollo 12 (Nov. 1969) is explainable by the effects of decreasing solar activity during this period of the present solar cycle -- the so called solar modulation of the galactic cosmic rays. During times of decreasing solar activity the radially expanding irregularities in the solar magnetic field become progressively less effective in scattering back out of the solar system the low energy cosmic ray particles that are continually diffusing inward. The solar activity level was essentially the same for Apollo 8 and the balloon flight (July, 1970). The difference in these fluxes is due to the overlying material, command module wall and atmosphere respectively.

We have calculated both the absolute number of tracks we should have expected and the variations over time as affected by solar modulation. We used known energy (10) and abundance (9,11) spectra for heavy cosmic rays together with a modulation model (12) which correlates the variations in Climax, Colorado neutron monitor rates with the energy spectra for particles of given velocity and magnetic rigidity, and allowed for slowing down (13) and loss by fragmentation (14) in inelastic collisions (15) while passing through the spacecraft walls. The thickness distribution of stopping material in the command module, supplied by W.N. Hess (personal communication), was approximated as consisting of pure aluminum for purposes of calculating energy loss and deciding appropriate cross sections for inelastic collisions. Etching efficiencies were derived from unpublished calibration curves.

The results of these calculations are included in Table 1 along with the observations. Track density ratios from one mission to another should be more reliably calculable (expected to be good to ±15%) as compared with the absolute fluxes (good to roughly ±30%). Examination of Table 1 shows the agreement to be compatible with the estimated errors. The absolute number observed here of 0.56 (±10%) per cm^2 for Apollo 8 should be compared to the observations of Benton and co-workers (16) on Lexan sheets that were attached to the space suit of astronaut Borman in the same flight. Using a different etch, ultraviolet sensitization, and scanning at 100 times magnification they found 0.62 (±.11)/cm^2, based on 34 tracks. Allowing for the differences in scanning and etching would reduce this value by approximately 10% which is in complete agreement with 0.56 (±.06), if we neglect the effect of the possible difference in shielding of the two locations.

Since this experiment was primarily for personnel dosimetry purposes, the following comments are appropriate. When worn, the helmets give to a very high approximation the heavy particle dose incident on the head and face of the wearer. Of the 244.5 hours of the Apollo 12 mission, helmets 504 and 506 were worn approximately 8 hours, and the other helmets were worn still shorter times. It follows that a 1 to 1 correspondence of track in helmet to biologically damaging particle in astronaut does not exist. We have found, however, as noted earlier, that the doses at the helmets were not very sensitive to position within the spacecraft or in fact which spacecraft they were in, but depend primarily on the solar activity at the time of the mission. For this reason, the dose of heavy particles experienced by the astronauts will in a statistical sense be well measured by the track density in the helmets.

We can attempt to calculate limits on the number of cells deactivated from the track density ρ and assumptions based on limited and inexact biological evidence. A lower limit on the number of cells killed comes from Todd's observations (2) for human kidney cells that a heavy particle will cause a cell to cease to reproduce if it passes through a cell nucleus. With increasing ionization the size of the region of damage is widened (as noted in (2) for Ar^{40} irradiation), and a reasonable upper limit on the number of affected cells comes from the model that each cell that is penetrated will be killed, giving rise to a continuous column of dead cells for each such heavy particle. This behavior is made plausible by recent work by Haymaker et al (17), who found track-like lesions consisting of columns of dead cells in brains of monkeys that had been exposed to primary cosmic rays. Although these lesions could, at least in part, have been of cosmic ray origin, definite conclusions must await detailed experiments where tracks in suitable detectors can be lined up with the biological damage.

Limits on the fraction of cells killed can be arrived at if we know the cell size (in terms of the diameter D) and the track density ρ of heavily ionizing particles from Table 1. For the upper limiting case the fraction of killed cells is $\pi\rho D^2/2$, the product of the projected cross sectional area $\pi D^2/4$ and the line length per unit volume 2ρ. In converting from length in Lexan polycarbonate (specific gravity 1.20) to biological matter we multiply the line length by 1.2). An additional factor of 10/7 included to allow for the fact that only 70% of the tracks crossing the etched surface are revealed. If d is the diameter of the nucleus, then $\pi\rho d^2/2$ gives a lower limit using the criterion that a particle must pass through the cell nucleus. Since the spectrum of cell sizes, nuclear sizes, and volume fractions of cellular material are immense, we restrict our estimates to non-regenerative cells such as those in the retina and in the central nervous system. We take estimates of cell dimensions from several sources (2,17,18, and W. Haymaker, Ames Conference, June 1970, unpublished). For the cerebral cortex we assume 10^{10} cells in a 300cc total volume composed of 25% neurons and 75% glial and endothelial cells. The average diameter is then 19μ and we assume a nuclear diameter of 7μ. In Table II the limits on cell loss from heavy cosmic ray particles passing through any part of the cell (upper limit) or through the cell nucleus (lower limit) are given for the Apollo 12 flight and extrapolated to a flight of 2 years duration under the same conditions. Depending on cell size, the limits for fractional loss range from $\sim 4 \times 10^{-7}$ to 10^{-4} for Apollo 12.

Although these numbers are moderately small, assessing whether such damage is of importance is by no means simple, particularly since the damage is strongly concentrated at contiguous or nearby cells. On an extended space mission of, for example, 2 years duration (such as is being considered for Mars) the table shows that the fraction killed could rise to 0.12% in the cerebral cortex, 0.05% in the retina, and more than 1.5% for some of the giant cells -- numbers that may be highly worrisome since additional safe shielding would impose important weight considerations on spacecraft design.

Table II

ESTIMATES OF CELL LOSS FRACTIONS FOR APOLLO 12 FLIGHT AND HYPOTHETICAL 2 YEAR FLIGHT

Cells	Cell Diameter (microns)	Nuclear Diameter (microns)	FRACTION LOST (PARTS PER MILLION) Apollo 12 Flight	2 Yr. Flight*
GRANULAR LAYER CEREBELLUM	4	3.6	.50 - .65	40 - 50
LIGHT RECEPTORS	6 x 20	4	.64 - 5.7	50 - 500
HUMAN CEREBRUM	19	7	2 - 14	16 - 120
GIANT BETZ	45	18	13 - 83	1050 - 6600
ANTERIOR HORN	70	25	26 - 200	2000 - 16,000

*Same flux as during Apollo 12 flight assumed

The results here lead to the interesting apparent paradox that for extended space missions times of near maximum solar activity provide the greatest safety from heavy particles. This is because the increased flux of solar particles (in all but the most intense flares) is stopped by the rather modest shielding of the spacecraft while the more penetrating galactic particles are decreased in number by the effects of solar magnetic field irregularities. From the standpoint of astronaut safety then the early 1980's would be superior to the latter half of the decade for a Mars voyage.

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8. As is clear from reference (4), for each heavy particle there is a maximum length over which the damage rate is above threshold so that a track is formed and can be etched. The frequency of such tracks is proportional to this length (minus the 135 microns) and to the abundance of the particular heavy particle. Consequently many of the iron tracks are revealed (lengths up to 8 mm and few neon tracks (lengths < 200 microns) even though their abundances in the cosmic radiation are approximately equal.

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19. We are pleased to give thanks to C.P. Bean and J.A. Bergeron of General Electric, V. Bond of Brookhaven National Laboratory and W. Haymaker of Ames Research Center for helpful discussions, to M. Fulkerson and T. Pappus of Raven Industries for balloon flights of Apollo control helmets, to K.C. Hsieh of the University of Chicago for communicating the recent Climax neutron monitor results, and to R.L. Golden of the NASA Manned Spacecraft Center for cheerfully dealing with an astonishing variety of official obfuscation. This work was supported in part by NASA under contract NAS 9-9828.

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Fig. 1. Examples of tracks of heavy cosmic rays on the inside of an Apollo space helmet. Left: A track from a particle entering the helmet. Right: An ending track, from a particle that has crossed from the opposite side of the helmet and come to rest. The tracks are 500 and 700 microns in length respectively.

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CLASS 1

PARTICLE TRACK IDENTIFICATION:
APPLICATION OF A NEW TECHNIQUE TO APOLLO HELMETS

by

R. L. Fleischer, H. R. Hart, Jr., and W. R. Giard,
General Physics Laboratory

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SUMMARY

The Apollo helmets are being used to record the dose of heavy particles to which astronauts are exposed on space missions. An improved method for examining and identifying the etched tracks of heavy charged particles consists of replicating tracks and measuring the etching rate as a function of position along the track. Tracks of trans-iron nuclei have been observed in Apollo helmets.

KEY WORDS

cosmic rays, particle identification, biological radiation damage, space

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RD-54 (3/69)

PARTICLE TRACK IDENTIFICATION: APPLICATION OF A NEW TECHNIQUE TO APOLLO HELMETS*

R. L. Fleischer, H. R. Hart, Jr., and W. R. Giard

Recent reports by Apollo astronauts of lines of light apparently seen with the eyes closed(1) have rekindled interest in possible biological effects of heavily ionizing particles that penetrate the shielding of the spacecraft or space suit during missions outside the earth's magnetosphere. A dosimetry experiment in progress(2) consists of using the plastic Apollo helmets as recorders of heavy cosmic ray particles directly incident on the face and heads of the astronauts. In this work the particle tracks are revealed by chemically etching(3) the interior of the Lexan® polycarbonate helmet to produce cone-shaped holes, which are later counted.

We have replicated these tracks using a silicone rubber that faithfully reproduces the shapes and dimensions of the etched tracks and at the same time allows the tracks to be viewed while placed on a flat surface for ease of observation.(4) Alternatively we can cut out a single track and rotate it on a goniometer so that it can be viewed in profile as illustrated in Fig. 1.

The procedure for particle identification makes use of the fact that the etching rate along a track is a monotonically increasing function of the primary ionization of the particles,(5) so that if we can measure the ionization point-by-point along a track we have redundant information that will allow the particle to be identified. This new method is a simplification of our previous procedure of measuring track lengths to provide measures of the average ionization along the portions of a track.(6)

The ratio of V_G (the general dissolution rate of the etchant on undamaged plastic) to V_T (the local rate of attack along the particle track) is the sine of the cone angle θ at the corresponding point along the track(3) as illustrated in Fig. 2. The diameter D at a range x from where the particle came to rest gives the cone angle at a range R. Straightforward geometry gives us the quantity we wish to measure, V_T:

$$V_T(R) = V_G[(\tan\theta)^{-2} + 1]^{1/2}$$

also

$$R = x + 1/2\, D(x)\tan\theta,$$

an equation that is needed since θ is measured as a function of x rather than R. $\tan\theta$ is $1/2\, dD/dx$ and therefore a measure of either D and θ, or D and dD/dx allows V_T to be found point-by-point along a track.

To use this procedure to identify particles we would normally compare the observed variations of V_T with residual range with those observed for known ions with appropriate allowances for charge and mass differences being made. For the purposes of this work we have integrated the observed V_T values to compare with track length measurements made previously(5, 7, 8) on cosmic ray tracks using the same etchant (50% 6.25 N NaOH solution: 50% ethanol, at room temperature). Such intercomparison allows us to infer that the track on the right hand side of Fig. 1 is from a zinc ion, that in Fig. 3 from nickel, with a resolution† of one atomic number on each.

Note should be made of the probable direct relevance of particle track numbers to measuring heavy particle damage of biological cells. Experiments(9) have indicated that cell nuclei are their most vulnerable portions. The likely (but unproved) explanation of this is the interference with the replicating properties of long chain molecules caused by the intense electronic ionization and excitation produced by energetic massive charged particles. It has been noted(10) that the same processes determine track formation(11) in polymeric material, since it consists of long chain organic molecules.

Therefore, the presence or absence of tracks in plastic adjacent to biological matter (for example, the Apollo helmets) should correlate directly with the presence or absence of heavy particle damage to biological cells.(10)

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†The calibration curves of Ref. 5 indicate that the charge assignment depends on the dip angle of the track relative to the surface. The silicone rubber replica preserves the dip angle and allows the proper calibration curve to be selected. The precision or resolution of the charge assignment is to the nearest atomic number. The absolute charge assignment is less well known since the calibration(5) was made on Lexan having a markedly different processing history, the etching time was different, and the number of cosmic ray particles in Ref. 5 yields a calibration having a statistical charge assignment uncertainty of at least one atomic number, with two atomic numbers being conceivable but highly unlikely. For tracks with rounded tips the place where the particle came to rest is known and hence the energy can be determined at each point along the track, making identification more precise than in a case such as Fig. 3 where the range is uncertain and only the cone angle variation along the track can be used to decide the range.

Comparison of the curvatures of the track sides reveals that the particle whose track is illustrated in Fig. 3 comes from outside the helmet (since looking along the track reveals that the cone angle decreases toward the base), while by contrast the ion corresponding to the track on the right hand side of Fig. 1 came from within the helmet (cone angle increasing toward the base). Thus, in Fig. 1 three of the tracks (right, lower center, and upper left) represent particles that came through the helmet and came to rest in the opposite side on their way out.

For the replica technique to be useful it must faithfully reproduce the shape and dimensions of the etched track. By intercomparing etched tracks with their replicas it is clear that the replica does reproduce the dimensions down to submicron sizes, but that (perhaps due to surface charges) the shapes for slender tracks of <2μ in diameter are often bent. Figure 4 shows a tapering track due to a particle that nearly crossed a sheet of Lexan polycarbonate as sketched on the left. A replica was made (as diagrammed in the figure), gold coated by evaporation, and photographed. On the right the photographs of the replica are compared to those taken directly of the Lexan. Fine detail is reproduced on a micron scale. In cellulose nitrate we have successfully replicated conical tracks with lengths up to 18μ and 0.4μ to 0.5μ diameter bases.

The replicating procedure makes possible the use of optically anisotropic plastic sheets as particle track identifiers. Meaningful direct optical measurements of track dimensions are difficult in such materials, e. g., Cronar, Melinex, and Mylar; the use of a replica allows accurate measurements to be made.(12)

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12. Even in Lexan, which is an optically more uniform material than the plastics named above, discrepancies exist between measurements on individual tracks when viewed through the material with the track pointing down vs when it is pointing up--and viewed through the whole sheet thickness (Ref. 7). Our measurements suggest that the down pointing position gives numbers that are closer to the true values.

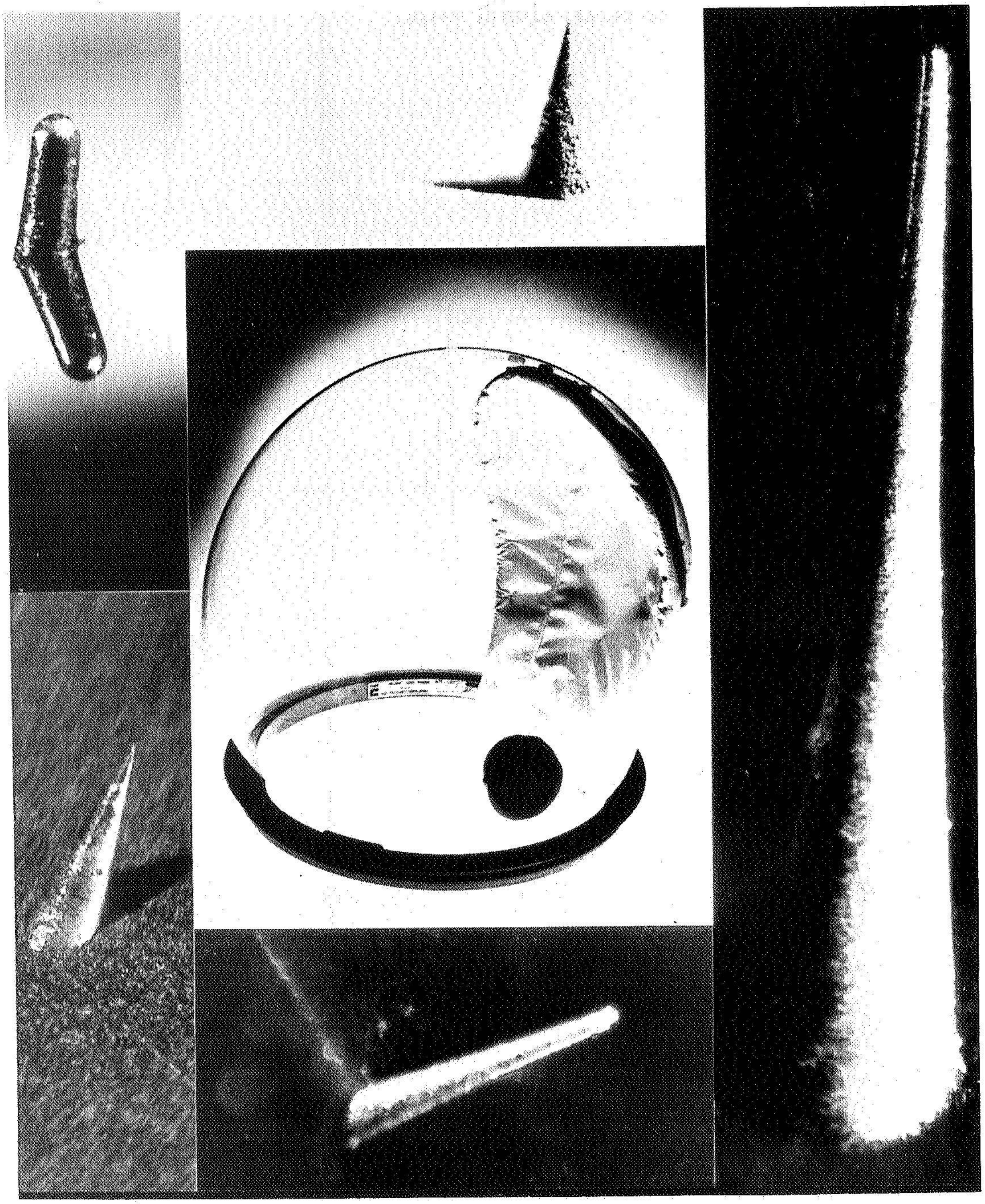

Fig. 1 Cosmic ray tracks in Apollo helmets. The Apollo 8 helmet of James Lovell, one of several used in a personnel dosimetry experiment, is surrounded by replicas of etched cosmic ray tracks. The tracks on the left and bottom are from the helmets of Apollo 12 astronauts Conrad and Gordon, the others from a control helmet exposed to primary cosmic rays. The particle on the right was a zinc ion. The lengths (in microns) of the track replicas are, starting at the top and moving clockwise: 300, 700, 600, 480, and 350.

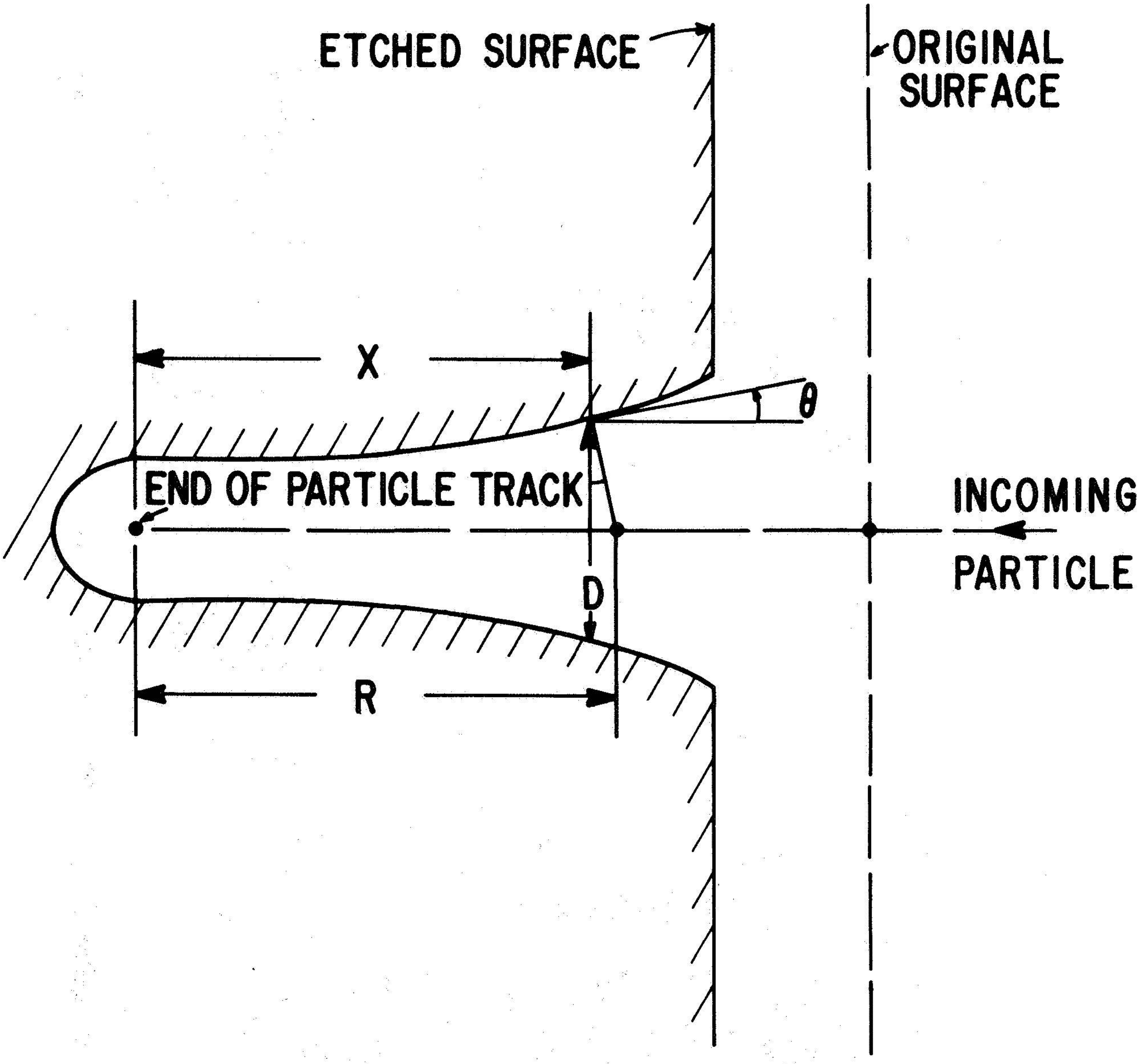

Fig. 2 Sketch illustrating how a measure of diameter vs distance determines the cone angle at positions along an etched track.

Fig. 3 Replica of an etched cosmic ray track caused by a nickel ion passing into an Apollo helmet. The track is 500μ long.

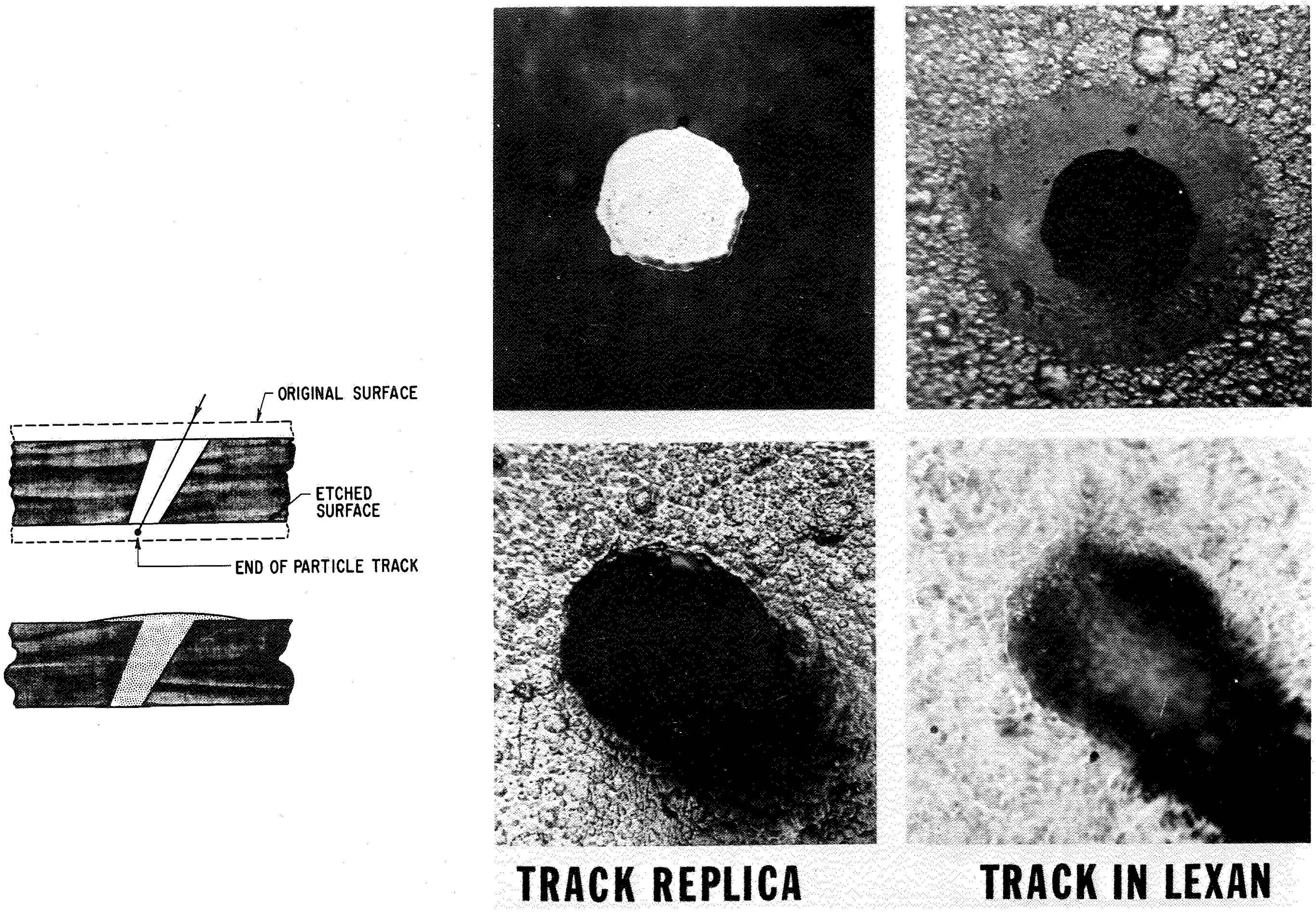

Fig. 4 Track replica compared to the etched track viewed directly in the Lexan polycarbonate. Left: track geometry; right: photo of replica at tip (top left) and base (bottom left photo) and photo of track viewed on narrow end (top right) and through the Lexan to the wide end (bottom right). Details are faithfully reproduced on the replica and are revealed more clearly than where the plastic is looked through. The semi-minor axis of the tip is 22μ.