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Alpha – Particle Profiles

H. A. Hussain , T. A. Selman
Department of Physics, College of S cience, , University of Basrah, Basrah, Iraq.
hkhursan@yahoo.com
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ABSTRACT

To calculate the shape of the etch pits in the solid state nuclear track detector (SSNTD) with a depth dependent V_b, we used the generalized equations for the etch-pit profiles by using the variational principle, since these equations are applicable to the general case where neither the bulk nor the track etch rate is constant, these equations were used for analysis of etch pit shapes, by using cellulose nitrate as a detector, this analysis have been done for the first time.

The calculated shape for the etch pit in cellulose nitrate, using the derived equations with depth dependent V_b, are in good agreement with the observed shapes.

1. INTRODUCTION

Solid State Nuclear Track Detectors (SSNTD's) have been used in many field such as nuclear particle detection[1-3], radiation dosimetry[4-6], cosmic rays[7], solar physics[8] and fusion research[9].

In various applications of SSNTD's the calculation of etch-pit profiles is necessary to determine the particle parameters such as charge, energy and mass.

A knowledge of etch – pit profiles is also important in order to have an understanding of the response of a plastic detector to charged particles.

Fujii et, al[10] shows that the solid state nuclear track detectors are sensitive to the energy and charge of the nuclear particle, this sensitivity can be indicated by using the etch – rate ratio V_T / V_B as a function of Z thus, the accurate measurement of the bulk etch rate, V_B, as well as of the track etch rate, V_T, are required. Selman[11], studied the variation of bulk etch rate as a function of depth for nuclear track detectors.

Somogyi et. al[12] pointed out that the diameter of the each pit is sensitive to the energy and charge of the nuclear particle, and also obtained a general theoretical description for the variation of track diameter of etch pit, this was done for particles entering solids at arbitrary angles, this model can be applied to detectors with both isotropic and anisotropic etching properties, and the determination of the formulas which used in this model, described the variation of etch – pit axes during the etching process for constant and varying track etch – rates.

Etch – pit profiles can be calculated by using generalized equations for etch – pit profiles using generalized equations for etch – pit profiles using the variation principle, which is a directed consequence of Huygens principle.

These equations are applicable not only to the case of varying V_T, but also to varying V_B. Etch – pit profiles and the contours of the openings have been calculated numerically by assuming a depth dependence of bulk etch rate V_B.

2. THEORY

The etching time required for the etchant to move from point O to point B on the etch – pit profile through the path OAB, shown in figure 1, is

$$t = \frac{X_1}{V_T} + \frac{X_2 - X_1}{V_B Sin\delta} \quad (1)$$

Where

δ : is the 1/2 cone angle,

X_1: is the coordinate of point A,

X_2 : is the coordinate of point B,

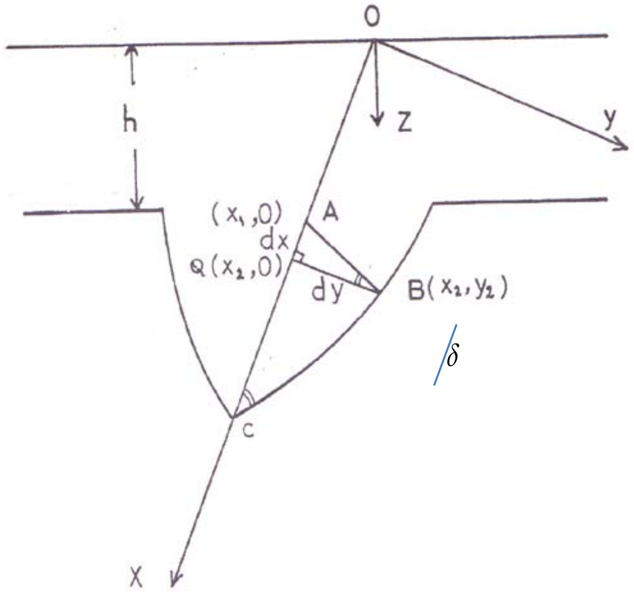

Fig.1. Etch – pit geometry in solid with bulk etch – rate V_T (z).

Equation (1) can be applied for constant track etch rate V_T and bulk etch rate V_B. From figure (1), one can obtain,

$$AB = [(dx)^2 + (dy)^2]^{\frac{1}{2}}$$

$$\sin\delta = \frac{dx}{[(dx)^2 + (dy)^2]^{\frac{1}{2}}}$$

$$\frac{1}{\sin\delta} = [1 + y'^2]^{\frac{1}{2}} \quad (2)$$

Thus, from equation (1) and (2), the etching time, t, to reach point B(x,y) on the etch – pit profile is given by the following equation, which is a generalization of equation (1):

$$t = \int_0^{x_1} \frac{dx}{V_T(x)} + \int_{x_1}^{x_2} \frac{\sqrt{1+y'^2}}{V_B(z)} dx \qquad (3)$$

Where the bulk etch rate V_B (z) is a function of depth of SSNTD (see figure 2).

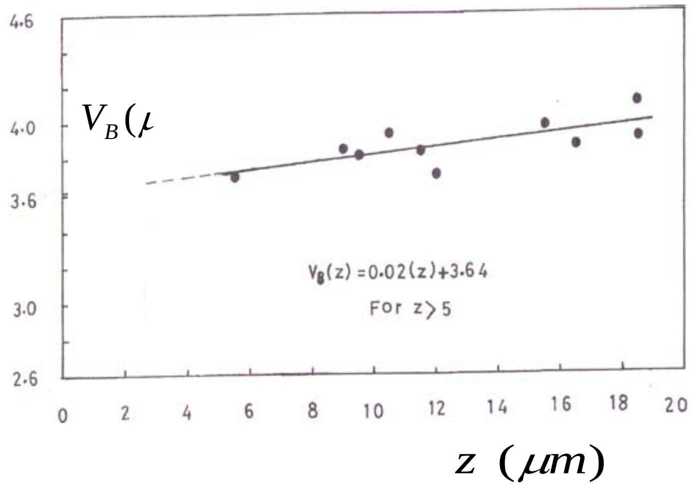

Fig.2. Bulk – etch – rate as a function of detector depth.

The depth z is given by

$$z = x\cos\theta + y\sin\theta \qquad (4)$$

Where θ is the angle of incident particle, as shown in Fig. 1,

Since the etching time t is a function of x, y and y', thus we can express t as,

$$t = \int_0^{x_2} f(x, y, y')dx \qquad (5)$$

During etching time t the etching reagent proceeds along the path OAB (see Figure 1) when the bulk etch rate is depth dependent. The etching path AB, which corresponds to the least time, is no longer a straight line. Then , the curve AB is given by Euler`s equation.

$$\frac{d}{dx}\frac{\partial f(x, y, y')}{\partial y'} - \frac{\partial f(x, y, y')}{\partial y} = 0 \qquad (6)$$

Where the function f is given by,

$$f(x, y, y') = \frac{1}{V_T(x)} + \frac{\sqrt{1+y'^2}}{V_B(z)}$$

Thus we obtain

$$\frac{d}{dx}\left[\frac{\partial}{\partial y'}\frac{\sqrt{1+y'^2}}{V_B(z)}\right] - \frac{\partial}{\partial y}\frac{\sqrt{1+y'^2}}{V_B(z)} = 0 \qquad (6`)$$

Since point A(x,0) cannot be fixed a priori and is free to move along the X axis, the following auxiliary condition of variation is necessary for x_1 to give the least time[13],

$$[f + (f_1^{'} - Y^{'})\frac{\partial f}{\partial y^{'}}]_{x=x_1} = 0 \qquad (7)$$

Where

f_1 is a function of x_1.

since x_1 lies on the x axis then, $f_1(x_1) = y_1 = 0$

and $f'_1(x_1)=0$

$$\frac{\partial f}{\partial y'} = \frac{y'}{V_B(z)\sqrt{1+y'^2}}$$

Thus we obtain a condition at $X = X_1$,

$$[\frac{1}{V_T(x)} + \frac{\sqrt{1+y'^2}}{V_B(z)} - \frac{y'^2}{V_B(z)\sqrt{1+y'^2}}]_{x=x_1} = 0 \qquad (7')$$

Equation (7') can be rewritten as

$$y' = \pm\sqrt{[\frac{V_T(x_1)}{V_B(x_1\cos\theta)}]^2 - 1} \qquad (8)$$

Equation (8) gives the boundary conditions needed to solve the differential equation (6').
If we represent the etch – pit profile by the function,

$$y_2 = f_2(x_2) \qquad (9)$$

The other auxiliary condition of variation can be written as

$$[f + (f'_2 - y')\frac{\partial f}{\partial y'}]_{x=x_2} = 0 \qquad (10)$$

Where

$$f = \frac{\sqrt{1+y'^2}}{V_B(z)}$$

And

$$\frac{\partial f}{\partial y'} = \frac{y'}{V_B(z)\sqrt{1+y'^2}}$$

Thus we obtain a condition at $X = X_2$

$$\frac{\sqrt{1+y'^2}}{V_B(z)} + \frac{f'_2\, y'}{V_B(z)\sqrt{1+y'^2}} - \frac{y'^2}{V_B(z)\sqrt{1+y'^2}} = 0 \qquad (11)$$

Thus we obtain

$$f'_2\, y' = -1$$

Therefore, the etching path y is perpendicular to the etch – pit profile f_2, as in the case of optical theory where the light path is perpendicular to the wave front.

Thus, if we know $V_T(x)$ and $V_B(z)$ functions, the dimension of etch – pit profile can be calculated theoretically, by using equation (3), (6') and (8).

From equation (6') we obtain,

$$y'' = (1 + y'^2)(y'\cos\theta - \sin\theta)\frac{V'_B}{V_B} \quad (12)$$

Equation (12) can be integrated by Runge – Kutta method if V_B is given as a function of depth. The boundary condition needed to solve equation (12) can be obtained from equation (8)

i.e at $X = X_1$

$Y = Y_1 = 0$

And

$$y'_1 = \pm\sqrt{\left[\frac{V_T(x_1)}{V_B(x_1\cos\theta)}\right]^2 - 1} \quad (13)$$

The solution of equation (12) gives the path AB along which the etching proceeds.

The etch – pit profile, can't be derived from equation (12) alone, because this equation dose not contain any information about the etching time.

The time during which the etching reagent proceeds along the path AB is given by

$$t_{AB} = \int_{x_1}^{x_2} \frac{\sqrt{1 + y'^2}}{V_B(z)} dx \quad (14)$$

The time t_{AB} is equal to

$$t - t_{OA} = \int_0^h \frac{dz}{V_B(z)} - \int_0^{x_1} \frac{dx}{V_T(x)} \quad (15)$$

Where h is the layer removed from the foil and the depth z measured in unit of the surface removal h.

If we assume a certain value of X_1, the time $t - t_{OA}$ can be calculated from equation (15), then equation (14) can be integrated step by step until t_{AB} becomes equal to $t - t_{OA}$, by the Simpson method using the values Y and Y' which obtained by integration equation (12). The X and Y coordinates at this time $t_{AB} = t - t_{OA}$, give a point on the etch – pit profile, if we find a point B(x,y) which satisfies the relationship

$$Z = X\cos\theta + Y\sin\theta = h \quad (16)$$

Then this point B(x,y) gives the coordinates of a point on the contour of the etch – pit opening.

3. NUMERICAL CALCULATIONS OF THE ETCH – PIT PROFILE

A special computer program has been developed to solve equation (12), in this program the Runge – Kutta method has been used, where the variation of bulk etch rate as a function of depth used in the equation (12) shows in fig,2.different initial – values have been found for X, and values of y' which obtained by equation (12), these values were given in table (1) and table (2). Then we find out the value of $t - t_{OA}$ from equation (15). The value of t_{AB} has been found from equation (14) by using values of y and y' which we obtained from equation (12) and then choose the value of coordinate x,y at which the value of t_{AB} equal to value of $t - t_{OA}$, value of x which satisfy equation (16) represents the value of etch – pit diameter.

Table.1. Calculated points on the etch pit profile after 9 μm layer removed from the detectors, for normally incident alpha – particles.

X_1	$Y_1 = [(V_T/V_B(X_1))^2 - 1]^{1/2}$	$T - T_{OA} = T_{AB}$		
			X	Y
11.0	0.622	0.000	11.000	0.000
10.0	0.633	0.213	10.693	0.434
09.0	0.645	0.433	10.380	0.897
08.0	0.656	0.653	10.070	1.312
07.0	0.668	0.873	09.740	1.812
06.0	0.679	1.093	09.385	2.331
05.0	0.691	1.313	09.020	2.798
04.0	0.702	1.533	08.641	2.281
03.0	0.714	1.753	08.239	3.782
00.0	0.749	2.413	06.919	5.307

Table.2. Calculated etching path to find out etch – pit profile at 9 μm depth.

X_1	$Y_1 = (V_T/V_B(X_1))^2$ ½	B'X, Y)	
		X	Y
11.0	0.622	11.000	0.000
10.0	0.633	10.693	0.434
09.0	0.645	09.500	0.312
		10.000	0.637
		10.380	0.897
08.0	0.656	08.500	0.318
		09.000	0.648
		09.500	0.980
		10.070	1.312
07.0	0.668	07.500	0.323
		08.000	0.659
		08.500	0.997
		09.000	1.336
		09.500	1.678
		09.740	1.812
06.0	0.679	06.500	0.329
		07.000	0.671
		07.500	1.014
		08.000	1.359
		08.500	1.705
		09.000	2.052
		09.385	2.331
05.0	0.691	05.500	0.334
		06.000	0.682
		06.500	1.031
		07.000	1.381
		07.500	1.733
		08.000	2.087
		08.500	2.442
		09.020	2.798
04.0	0.702	04.500	0.340
		05.000	0.693
		05.500	1.048
		06.000	1.404
		06.500	1.762
		07.000	2.122
		07.500	2.482
		08.000	2.845
		08.641	3.281
03.0	0.714	03.500	0.345
		04.000	0.705
		04.500	1.065
		05.000	1.427
		05.500	1.791
		06.000	2.156
		06.500	2.523
		07.000	2.891
		07.500	3.261
		08.239	3.782

The coordinates of points on the etch-pit profile were given in table 1,3,5 for different layer removed, from the detector. And the data for the etching path were given in table 2,4,6.

Table.3. Calculated points on the etch – pit profile after 11 μm layer removed from the detector, for normally incident alpha – particles.

Table.4. Calculated etching path to find out etch – pit profile at 11 μm depth.

X_1	$Y_1 = (V_2/V_B(X_1))^2$	B(X, Y)	
		X	Y
19.8	1.341	19.800	0.000
18.0	1.359	18.300	0.385
		18.630	0.796
16.0	1.380	16.500	0.670
		17.000	1.368
		17.259	1.790
12.0	1.424	12.500	0.701
		13.000	1.434
		13.500	2.172
		14.000	2.917
		14.360	3.463
10.0	1.446	10.500	0.691
		11.000	1.411
		11.500	2.138
		12.000	2.872
		12.500	3.611
		12.810	4.123
8.00	1.468	08.500	0.712
		09.000	1.456
		09.500	2.207
		10.000	2.964
		10.500	3.727
		11.000	4.498
		11.197	4.809
7.50	1.474	08.000	7.151
		08.500	1.461
		09.000	2.214
		09.500	2.973
		10.000	3.740
		10.500	4.513
		10.790	4.980
6.00	1.491	06.500	7.239
		07.000	1.479
		07.500	2.241
		08.000	3.011
		08.500	3.787
		09.000	4.571
		09.519	5.362
4.0	1.514	04.500	0.735
		05.000	1.502
		05.500	2.277
		06.000	3.059
		06.500	3.848
		07.000	4.645
		07.500	5.449
		07.744	5.773

Table.5. Calculated points on the etch – pit profile after 18.5 μm layer removed from the detector, for normally incident alpha – particles.

X_1	$Y_1 = [(V_T/V_B(X_1))^2 - 1]^{1/2}$	$T - T_{OA} = T_{AB}$	B(X, Y)	
			X	Y
10.0	1.007	3.005	17.461	7.864
11.0	0.996	2.822	18.176	7.347
11.5	0.991	2.730	18.488	7.200
12.0	0.986	2.638	18.811	6.948
13.0	0.976	2.455	19.458	6.543
14.0	0.961	2.271	20.075	5.970
15.0	0.955	2.088	20.677	5.600
16.0	0.945	1.904	21.262	5.138
18.5	0.920	1.446	22.655	3.934
20.0	0.905	1.171	23.443	3.116
21.0	0.895	0.987	23.926	2.620
22.0	0.885	0.804	24.420	2.136
23.0	0.875	0.620	24.897	1.664
24.0	0.866	0.437	25.348	1.118
25.0	0.856	0.253	25.792	0.673

Table.6. Calculated etching path to find out etch – pit profile at 18.5 μm depth.

X_1	$Y_1 = [(V_T/V_B(X_1))^2]^{1/2}$	B(X, Y)	
		X	Y
11.0	0.996	11.5	0.483
		12.0	0.985
		12.5	1.490
		13.0	1.999
		13.5	2.509
		14.0	3.023
		14.5	3.540
		15.0	4.059
		15.5	4.582
		16.0	5.107
		16.5	5.636
		17.0	6.167
		17.5	6.701
		18.0	7.239
		18.1	7.347
11.5	0.991	12.0	0.480
		12.5	0.980
		13.0	1.483
		13.5	1.988
		14.0	2.496
		14.5	3.007
		15.0	3.521
		15.5	4.038
		16.0	4.557
		16.5	5.080
		17.0	5.605
		17.5	6.134
		18.0	6.665
		18.5	7.200
16.0	0.945	16.5	0.458
		17.0	0.934
		17.5	1.413
		18.0	1.895
		18.5	2.379
		19.0	2.866
		19.5	3.355
		20.0	3.847
		20.5	4.341
		21.0	4.838
		21.2	5.038
		21.3	5.138
18.5	0.920	19.0	0.446
		19.5	0.909
		20.0	1.375
		20.5	1.844
		21.0	2.315
		21.5	2.788
		22.0	3.264
		22.5	0.424
		24.0	0.865
		24.5	1.308
		24.9	1.664

4. COMPARISION BETWEEN CALCULATION AND EXPERIMENTS

A foil of cellulose nitrate CN-85 have been used as a solid state nuclear track detectors, these detectors were exposed to a 5.4 MeV alpha particles, after exposure, these detectors were etched for 120 min in 2.0 N NaOH solution at 60^0C. the circular opening were chosen for normal incident.

In the present calculation, V_T is assumed to be constant, and the V_B of CN-85 plastic sheet increases by about (0.02 $\mu m/hr$) during etching, the depth dependence of V

$_B$, thus measured can be approximated by the following function.

$V_B(z) = 0.02(z) + 3.64$

Where the depth z was measured in unit of the surface removal h. the calculated etch – pit profile and the surface openings of alpha particles are shown in figures (3, 4, and 5).

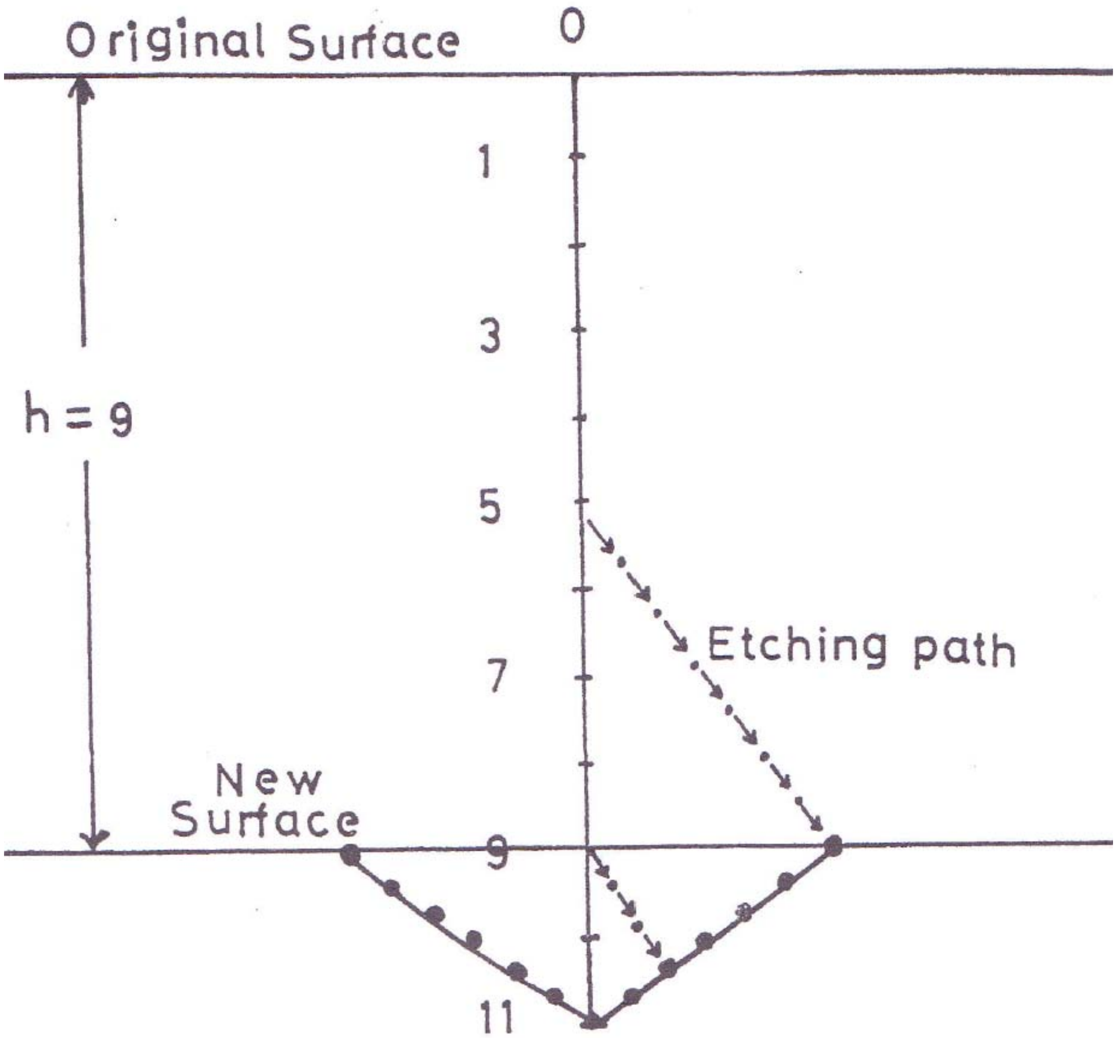

Fig.3. Calculated etch – pit profile for h= 9 μm, V $_T$ = 4.546 μm/hr, V $_B$ = 0.02X + 3.64 and normal incident of 5.4 MeV alpha – particles.

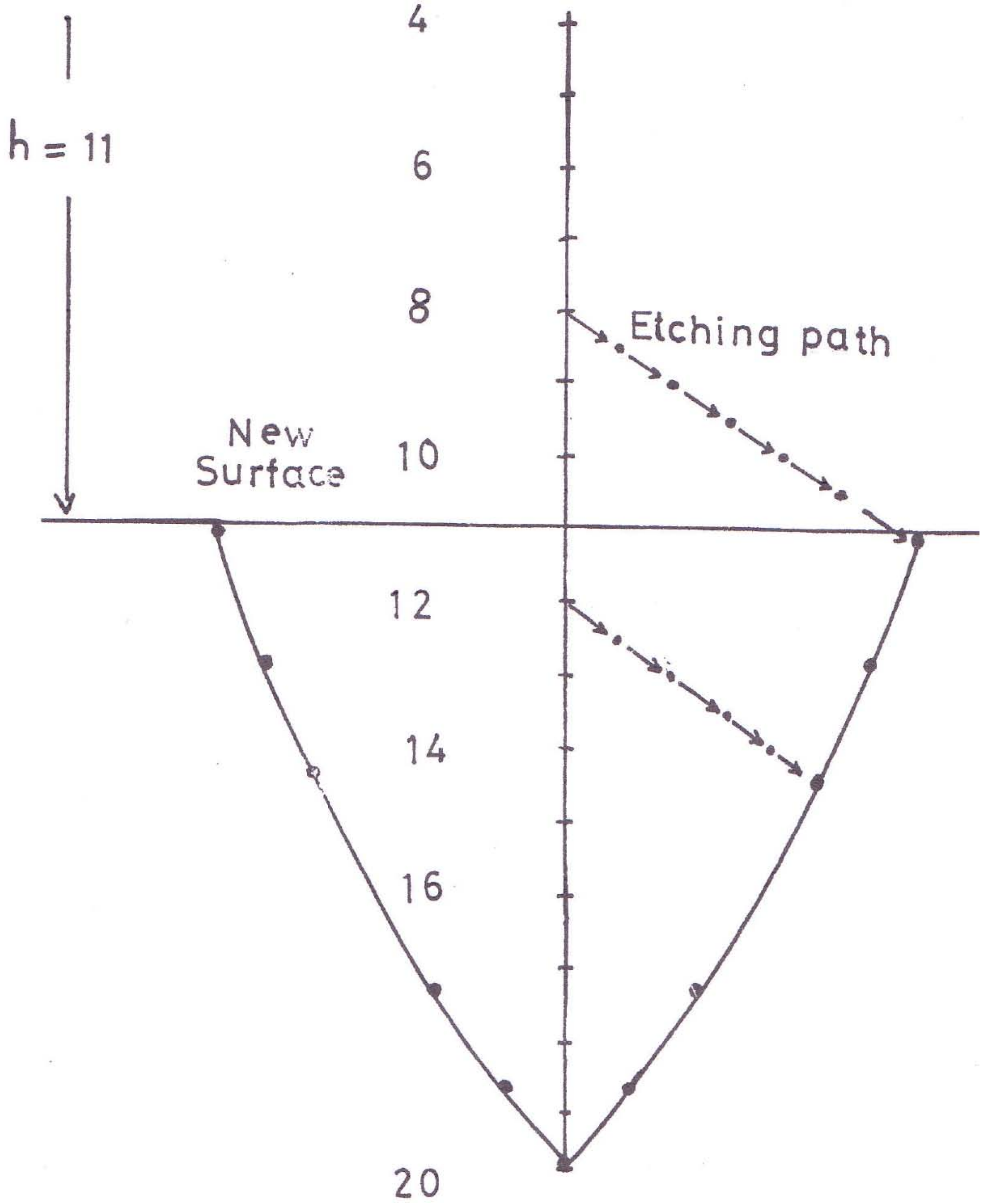

Fig.4. Calculated etch – pit profile for h = 11 μm , V_T = 6.751 μm , V_B =0.02X + 3.64 and normal incident of 5.4 MeV alpha – particles.

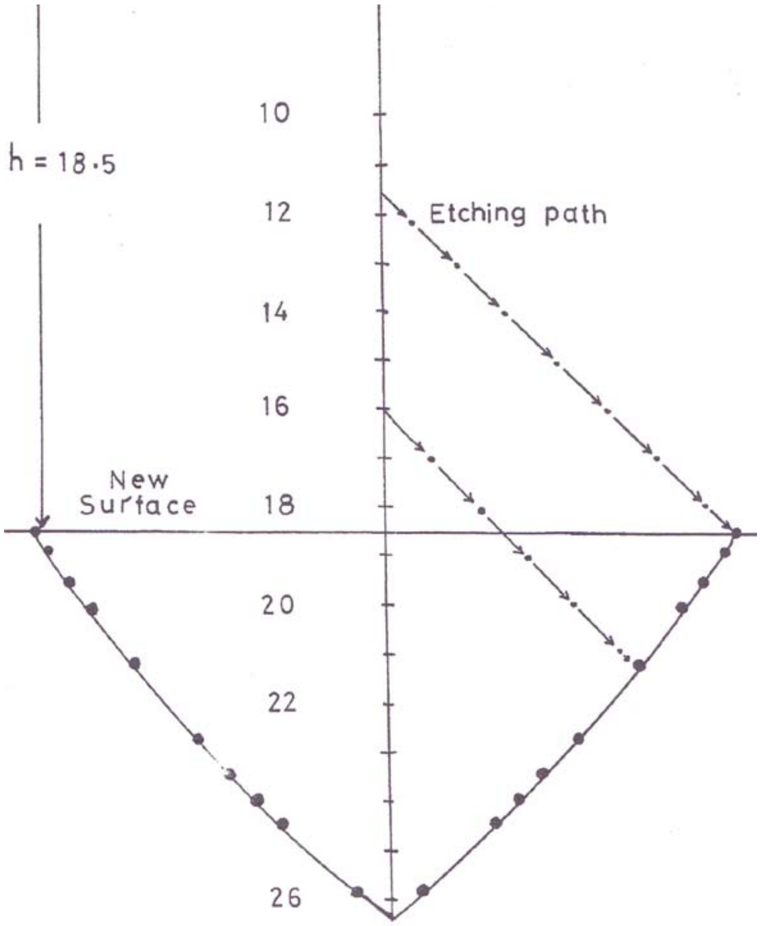

Fig.5. Calculated etch – pit profile for h = 18.5 μm, V_T =5.450 μm/hr , V_B =0.02X +3.64 and normal incident of 5.4 MeV alpha – particles.

The calculated shape observed at 9 μm, 11 μm and 18.5 μm depth in cellulose detector. Calculated diameter were compared with observed shapes of etch pits. Table (7) shows this comparison,

Table.7. Calculated and observed diameter for etch – pit profile.

E (MeV)	h ± 0.5 μM	EXPERI. D/2 μM	NUMERICAL D/2 μM	V_T μM/HR
5.4	9	2.691	2.798	4.546
5.4	11	5.767	4.800	6.751
5.4	18.5	7.305	7.200	5.450

there are good agreement between the calculated shapes and the observed shapes of etch – pits.

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