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(Use of IBM-[illegible] "Defense [illegible] Contours of examples
are [illegible] 100 [illegible] and [illegible] R/hr at H+1 hr
Dose [illegible] Total Dose to H+48 hr)

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A Method of Estimating Radioactive Fall-Out

T. N. White, LASL

1. The method described herein is designed with an objective that is intermediate between operational requirements, and the requirements of a strictly scientific investigation. It is designed to include what are assumed to be the most important factors that determine a fall-out pattern, with the idea that we might find out enough about what is going on to produce a good simplified method for operational use. One simplified version that was used for local fall-out forecasting is described in Incl. 3, Close-in Forecasting by New Techniques Developed after BRAVO, Tab D "Fall-out Forecasting Techniques" of the Task Force Castle Report. It seemed good enough to justify further investigation of the basic ideas as applicable to any range of distances over which a constant wind field could be assumed.

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2. The basic assumptions of the method are as follows:

a. The whole cloud, up to its height of stabilization, is formed instantaneously at the time of detonation. This is what we call the "initial cloud".

b. In any height layer of the initial cloud, the concentration (radioactivity per unit volume) is distributed according to the Gaussian law

$$c(h, r, a_c) = c_0(h) \ \exp(-r^2 a_c^{-2})$$

where c(h) is the central concentration at height h, r is the radial horizontal distance, and a_c is a "spread parameter" (analogous to standard deviation) that is also considered to be a function of height. From this assumption it follows that the total amount of radioactivity in a slice of unit vertical thickness is $\pi c_0(h)\ a_0^2$.

c. Throughout all of any such layer, the radioactivity is distributed normally with respect to the logarithm of the rate of fall of the particles. Thus at any distance r the fraction of radioactivity that falls with speeds in the range f to f + df is given by

$$\frac{1}{\sigma(h)\sqrt{2\pi}} \ \exp\left\{-\frac{1}{2}\left(\frac{\ln\frac{f}{f(h)}}{\sigma(h)}\right)^2\right\} \frac{df}{f}$$

where f(h) is the fall-rate for particles of greatest radioactivity, and σ (also considered to be a function of height) is the standard deviation of the logarithm of fall-rates, weighted according to radioactivity. f(h) and $\sigma(h)$ are constant thruout the layer.

d. The rate of fall of any particle remains constant until it reaches the ground.

e. Any particle that starts from the central axis will follow a path strictly in accordance with the wind pattern, while all other particles that fall at the same rate from the same level will diffuse laterally from the central particle in such a way that the gaussian distribution is maintained.

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During this process, the increase of the spread parameter is described by

$$\frac{a}{a_o} = \left(1 + \frac{S}{\beta a_o}\right)^{\frac{m}{2}} = p^{\frac{m}{2}}$$

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where S is the distance travelled by the central particle until it reaches the ground. (It is to be noted that S is not the straight-line distance from the origin to the landing point unless all winds at all levels are in the same direction). β and m are parametric quantities that may be used to describe the amount of diffusion. They are not at present regarded as functions of height. (The quantity p is merely an abbreviation for the quantity in brackets).

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3\. a. From these assumptions it follows that the dose rate on the ground is

$$I = \frac{K}{\sqrt{2\pi}} \int_0^H \int_0^\infty \frac{C_c(h)}{\sigma(h)\, p^m} \exp\left[-\left(\frac{\left(\ln \frac{f}{f_0}\right)^2}{2\sigma^2} + \frac{r^2}{a^2 p^m} \right) \right] dh \, \frac{df}{f}$$

where K is dose rate per unit of surface concentration, H is the height of the top of the cloud, and r is the distance from the point at which the dose rate is estimated to each of the landing points of central particles. These landing points will depend on the wind pattern below the level from which the central particle originated, so that r is a function of h. The landing points also depend on the rate of fall, so that r is also a function of f. Changing from rate of fall to time of fall, one obtains

$$r^2 = \left(t\,\bar{u}(h) - X \right)^2 + \left(t\,\bar{v}(h) - Y \right)^2$$

where (X,Y) are the rectangular co-ordinates of the point where dose rate is estimated and $\bar{u}$, $\bar{v}$ are the wind components in the same co-ordinate system, averaged up to the height h.

b. We may also express

$$p = 1 + \frac{t\bar{w}(h)}{\beta\, a_c(h)}$$

noting that $\bar{w}$ is the average speed regardless of direction. ($\bar{u}$ and $\bar{v}$ are not, in general, the components of $\bar{w}$.) This expression is correct if one is satisfied that the diffusion depends on the total horizontal distance travelled by a central particle. If one wishes to assume that the vertical distance should be included, p becomes much more complicated.

c. The significance of β and m can now be visualized. If $m = 2$, then

$$\frac{a}{a_0} = \frac{\beta a_c + t\bar{w}}{\beta a_c}$$

so that the lateral dimensions of any segment of the cloud will increase

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as if the segment had come from a point source located at a distance βa_o upwind. The size increases linearly with distance travelled by the central particle. If m is greater than 1, the borders of the cloud will diverge more rapidly, and if m is less than 1 they will diverge less rapidly. One can prevent any increase in size either by making β infinite or by making m equal to zero. This method of describing the diffusive process is similar to that of Sutton, but not exactly the same.

d. If m = 2, then at sufficiently large values of t, the area covered by a segment of cloud is proportional to the square of the time, as in Felt's method. However, the proportionality factor varies, as $\bar{w}$ varies with height, and further, the overall average proportionality factor changes with the overall strength of the wind field, and in these respects it differs from Felt's method.

e. Returning to the basic equation, the change of variable from f to t changes the argument of the logarithm to

$$\frac{t\ f(h)}{h}$$

and $\frac{df}{f}$ becomes $\frac{dt}{t}$

One notes also that concentrations in the initial cloud must be reduced to those that would have existed at the time for which the dose rate is being estimated.

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4. The information that is needed for a calculation is then:

   a. The winds pattern at heights up to H.

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   b. H, the height of the top of the cloud.

   c. a_o, the initial spread parameter, or radiological radius, as a function of height.

   d. C_o, the central concentration as a function of height in the initial cloud, adjusted to the time of dose-rate estimation.

   e. f, the logarithmic mean rate fall (weighted according to radioactivity), as a function of height in the initial cloud.

   f. σ, the logarithmic standard deviation of this distribution as a function of height in the initial cloud.

   g. β, diffusion parameter, described above.

   h. m, diffusion parameter, described above.

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5\. a. Testing of the method requires the use of high speed computing machinery. With such machinery one can make many changes in the quantities described above, proceeding on a trial and error basis. In order to achieve some degree of objectivity, the following approach is adopted.

b\. The logarithm of the ratio of calculated to observed dose rate is estimated at a number of points for a given shot. This quantity is called γ (gamma). Then the mean gamma, and the statistical variance of the individual gammas about the mean gamma, are calculated. This process is repeated for a number of values of some parametric quantity, beta for example. One then plots the variance against beta, and selects as the best value the one that gives the least variance. One then moves on to other parametric quantities, and treats them in the same way, hoping that there is not too much correlation between the effects of the different types of parameters.

c\. It will be noted that this application of the "least squares" method discounts the overall ratio of calculation to observation. In principle it is possible to get zero variance (an exact fit) when each calculated value is, for example, exactly ten times the observed value. One would then suspect that 90% of the radioactivity had remained in the crater. If, however, one should obtain a good fit but with only 10% of the observed activity accounted for, one would have to consider other possibilities. One would first look to see whether any large fraction of the activity was excluded from the calculation. In numerical integration it is not practical to go all the way from zero to infinite time, and part of the activity might have fallen outside of the time range chosen. If this explanation fails, and if the fit is really good, one has to conclude that the least squares criterion, as applied here, is not useful. We have not yet encountered this particular obstacle.

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d. The method of approach is subject to a hackneyed old criticism running as follows: by subdividing the height of the cloud at will, you can obtain as many discrete parametric values of a_0, c_0, f, etc. as you wish, so that you should be able to fit any number of observations exactly. This is true, in principle. But if one can get a set of values that look reasonable, and can be scaled in a reasonable way with yield over a wide range, the method can serve a useful operational purpose even though the values might be scientifically unsound.

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6\. a. For machine integration, using the IBM Model 701 "Defense Calculator", those parametric quantities (a, ..., and f) and the mean wind components ($\bar{u}$, $\bar{v}$, $\bar{w}$), which are functions of height, may be loaded as tables of data. The total height of the initial cloud, h, is subdivided into M equal layers, each identified by an integer i = 0, 1, 2, ... (M-1). The time variable is laid off on a logarithmic scale, each time being identified by an integer j = 1, 2, 3, ... N. Storage limits the maximum value of M to 32. N may be any value that doesn't take too much machine time, and the minimum and maximum limits of the time integration may be changed at will. The exponential factor in the formula is regarded as zero if the absolute value of the exponent exceeds a value A which may be as large as 10.

b. The coding is so arranged that the time integration is performed first and the height integration second. At each location, the fraction of the dose rate that comes from each initial cloud layer is computed and may be printed along with the calculated and observed dose rates and the co-ordinates of the location. Or one may by-pass this printing and obtain only the statistics (mean gamma and variance) for a preselected series of locations.

c. The codes are not yet frozen, and additional features are being added from time to time. We have two codes (1) a fast "fixed-point" code as outlined above, and (2) a slower "floating-point" code that is more precise and which is more flexible in some respects.

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H-6

2 February 1955

Lt. Col. H. H. Rankin
Department of Defense
Armed Forces Special Weapons Project
Washington 25, D. C.

Dear Col. Rankin:

Enclosed is the completion of the account of our method of fall-out calculation and the "homework" problems connected with the AFSWP Fall-out Symposium.

Very truly yours,

THOMAS N. WHITE, Leader
Radiological Physics Group
Health Division

TNW/eh

Distribution:

CC Lt. Col. H. H. Rankin
(w/encl. H-6-72 Cy. 1A)
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7. Since starting on this problem about seven months ago, a considerable part of the time has been spent on coding and de-bugging, which we undertook ourselves in order to learn how to use the Model 701. Using Bravo fall-out data, we demonstrated that least squares solutions could be obtained for the various parametric quantities involved. However, the "best" values, as selected in this way, gave distant fall-out predictions that were only 20 to 30% of the observed values, and the "fit" was not good. We then turned attention to Nevada data for a while, and became interested in an approximation that seemed to offer a hope of eliminating one of the two steps in the double integration. Before this possibility had been fully explored, Mr. Vay Shelton, Livermore Operations Division, joined forces with us, and we worked together for a week on UK-1 and UK-7. Mr. Shelton then took our codes to Livermore and continued working on the Nevada data, while we turned attention again to the Bravo shot. Mr. Shelton has reported recently that the method gives satisfactory results for UK-1 and UK-7, and he is continuing work on other shots. We have concentrated on the problem of predicting the Bravo fall-out on the assumption that practically all of the activity in the initial cloud was located above the tropopause. To date, our method of calculation has not been able to give satisfactory results, even when the winds were arbitrarily twisted to make the fall-out occur in more nearly the right place. At this point we feel, therefore, that we do not have any cloud model in which we have confidence. We have merely a mechanism of calculation, the value of which has not yet been proven as far as Bravo is concerned.

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8. Lacking any satisfactory cloud model for Bravo, we tackled the "homework" predictions on a guess-work basis, which does not justify a description. The values that we used in the calculations are:

	1 MT	50 MT
Height of cloud (sea miles)	11.5	19.0
Height of stem (" ")	7.0	7.0
a for mushroom (" ")	0.94	4.58
for stem (" ")	0.41	1.49

Beta: 9.1[illegible] m 1.0 Sigma: 1.0

The values of a were taken as constant up to the tropopause, and thereafter decreased with air density. (The machine program requires only the entry of relative values, from which the actual values are adjusted so that the total radioactive content of the cloud is in accordance with the yield). Logarithmic mean rates of fall were assigned to the 16 layers of the cloud as follows, counting from the bottom. (Rates are in knots)

Layers 1 thru 4		20
" 5 " 8		7.4
" 9 " 12		[illegible]
" 13 " 16		[illegible]

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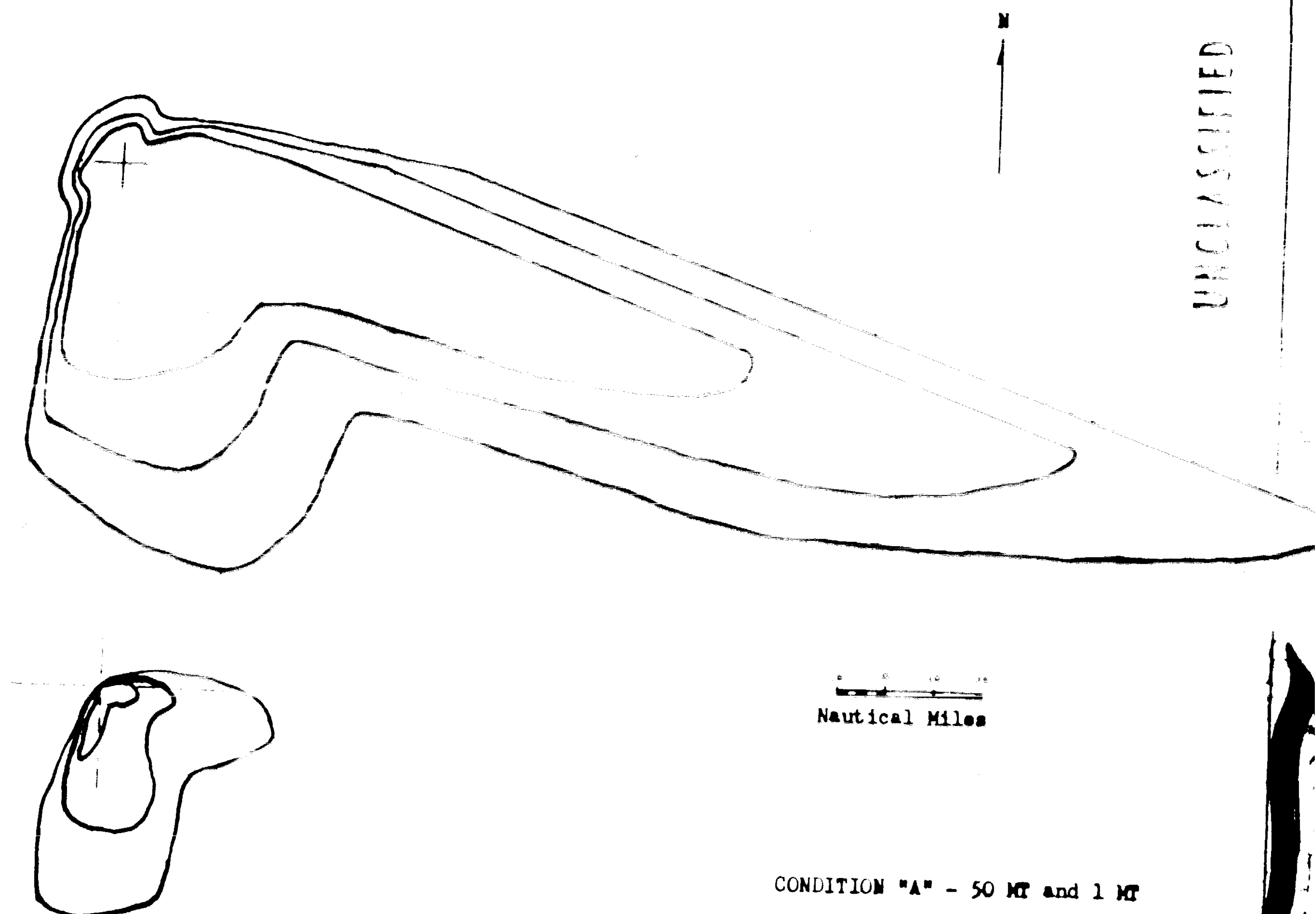

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CONDITION "A" - 50 MT and 1 MT

Intensity - "Reference" Time H + 1 Hours

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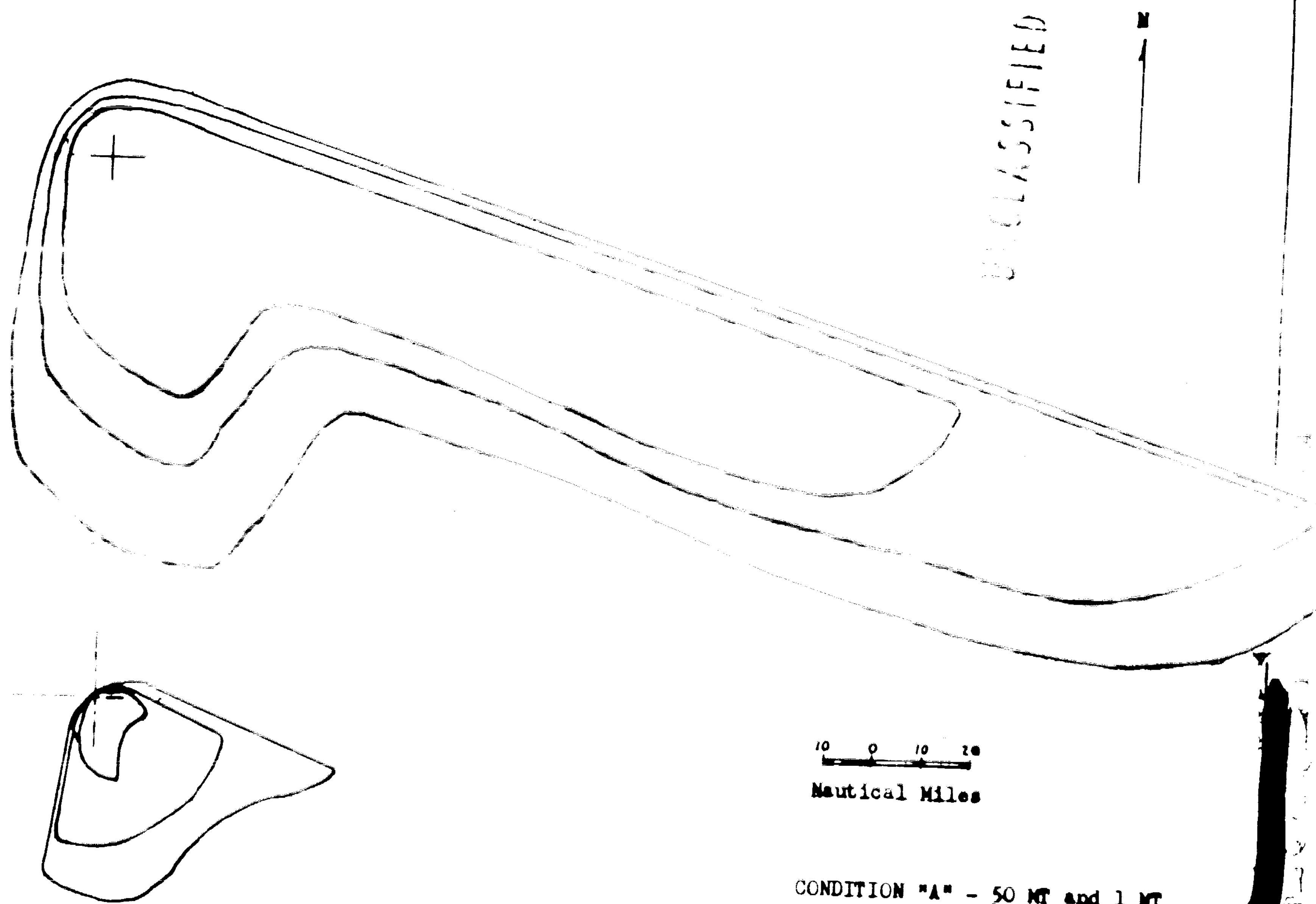
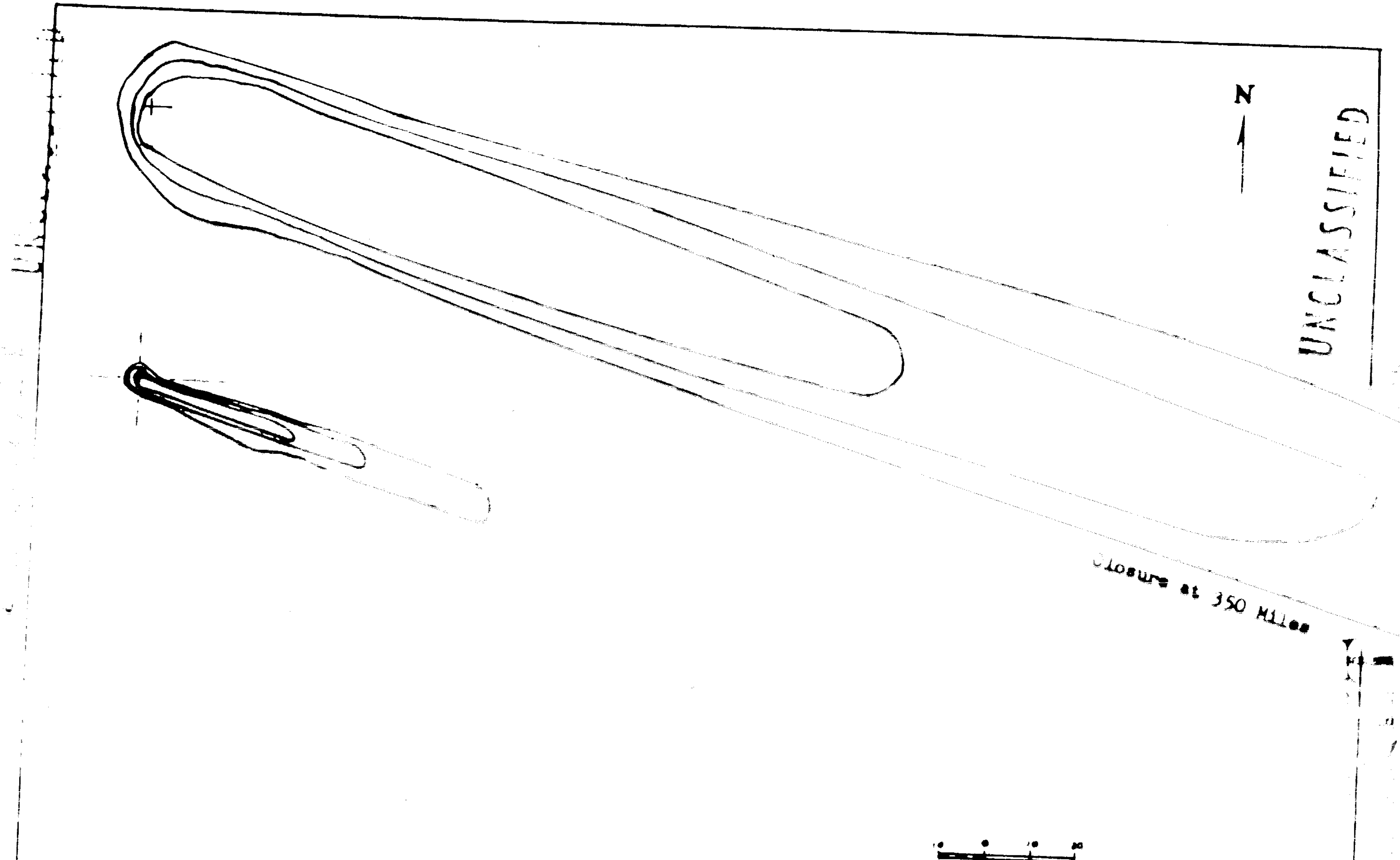


CONDITION "A" - 50 MT and 1 MT

Dose - To 48 Hours

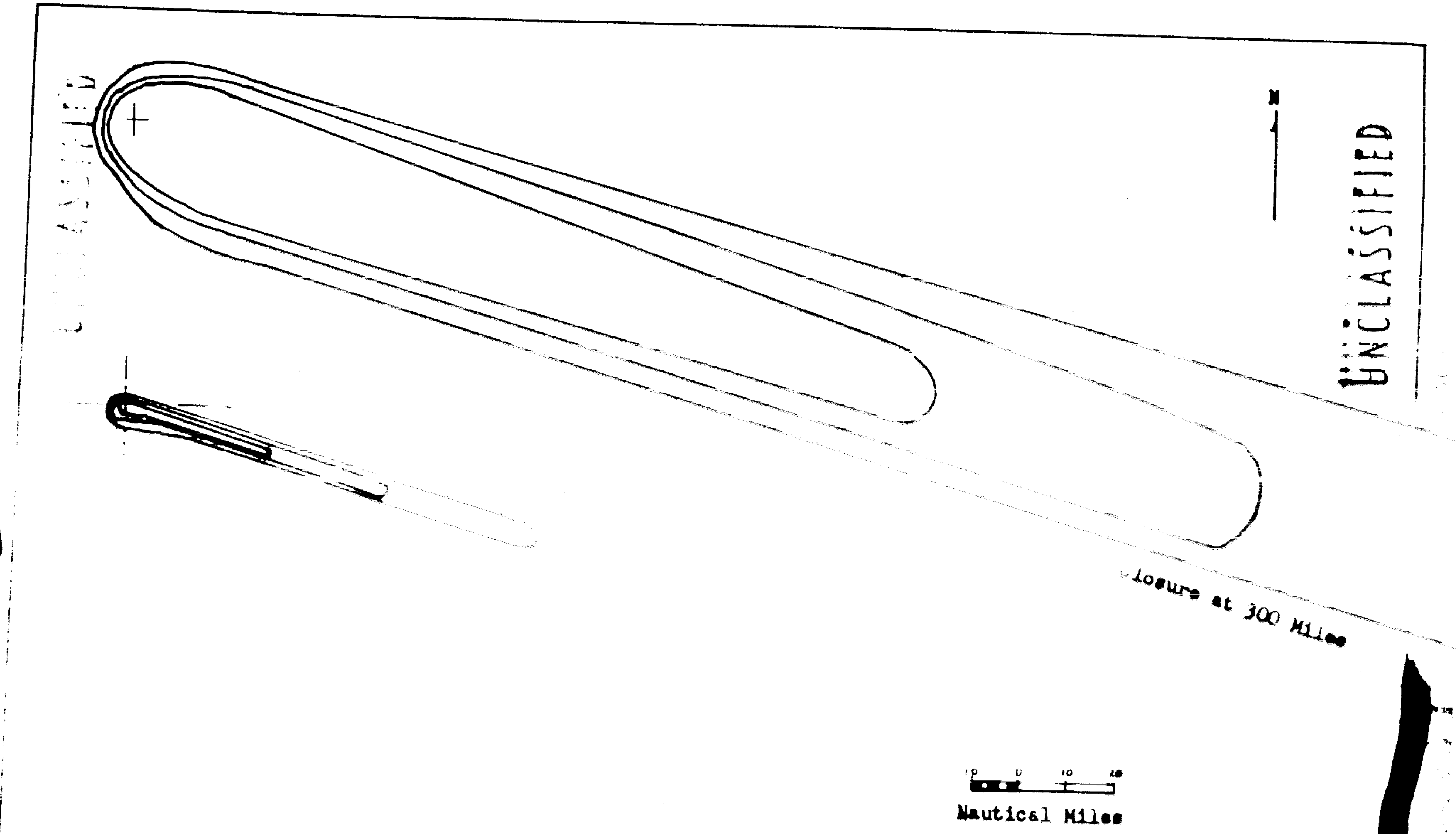
LASL - T. N. White



CONDITION "B" - 50 and 1 MT

Intensity - "Reference" Time H + 1 Hours

LASL - T. N. White



CONDITION "B" - 50 MT and 1 MT

Dose - To 48 Hours

LASL - T. N. White