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THE FUTURE OF RADIOACTIVE

MATERIALS IN A TORNADO

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ABSTRACT

The behaviour of radioactive, particulate material incorporated into a tornado vortex is hypothesized. A general description of the tornado is included with evidence of the probability for a tornado strike. From the literature concerning tornado mechanics, component velocity profiles are obtained. The method of generation for air parcel trajectories is explained and a sample mapping is included. The air parcel trajectories are utilized to estimate interim movement of the particulate material.

The effect of tornadic winds upon isotope containment devices is considered. Failure of containment due to the wind-pressure explosive effect is found to be a significant problem. The result of containment apparatus becoming a tornado borne missile is the release of contaminants into the environs. This release of contaminants is primarily caused by the tremendous energy expended upon impact.

A means of generating deposition areas for heavy contaminated debris is discussed. By utilizing maximum projectile characteristics, limiting distances can be calculated which will determine the boundaries of tornado transport. The single reconcentrating factor of the severe storm

system is precipitation. Rainfall contours are found to be the best estimate of deposition for small particulate materials. A combined mapping of these two deposition patterns is presented for a tornado incident at a hypothetical nuclear facility.

The absence of definitive vortex modeling and the constantly changing geometry of each vortex are shown to prevent exact prediction of the ultimate fate for tornado borne materials. Attempts to model air movement, on the micro-meteorological scale necessary, are proven hazardous due to the individuality of each tornado and the unique structure for each nuclear facility.

With presently available knowledge, the estimates remain qualitative in nature. Thus from the radiological health viewpoint, the nuclear facility should be constructed to withstand the tremendous forces of the tornado.

CONCLUSIONS

1) The best available models of the tornado, for predictive use, are the engineering design formulas. More complex systems of differential equations require theoretical parameters whose values are not presently obtainable.

2) Wind velocity profiles are nearly the same regardless of the mathematical sophistication employed. By use of vector summation, these velocity profiles may be combined to generate air parcel trajectories.

3) Particulate material will move in a distorted spiral upward and inward toward the vortex center. The ultimate behavior for the material is dispersion within the parent storm cell.

4) The major reconcentrating factor of a severe storm is the precipitation. Rainfall concentration profiles should provide the best estimate of deposition for particulate debris.

5) Precipitation occurs predominately north and east of the vortex. Nuclear facilities should, therefore, be constructed northeast of more densely populated areas.

6) A more complete description of material behavior could be obtained if a study were made of the probability for incorporation of materials at a given point in the vortex system.

7) A more complete study of the washout by rainfall should be undertaken. For accuracy, the correlation between rainfall

concentration and deposition of radioactivity needs to be determined. Considerable work has been done in regard to particulate materials already in the atmosphere but little has been done concerning materials swept from the surface into the convective storm cell.

8) Containment of radioactivity will undoubtedly be violated due either to the wind-pressure explosive effect or to impaction of the device as a tornado-borne missile.

9) Limiting distance of transport for heavy debris can be estimated by use of maximum possible projectile characteristics.

10) Heavy debris deposition areas can be generated by utilizing the limiting distance of transport and the width of the storm path. These areas will be forward along the path due to the translational motion of the vortex.

11) Research should be conducted to determine the deposition patterns of heavy debris. This study should determine deposition according to the dimensions and the mass of the objects.

12) A combined mapping of deposition areas for heavy debris and rainfall concentration contours provide the best available estimate for location of radioactive contamination.

13) In event of a tornado incident, the radar history of the storm movement would prove invaluable. Immediate access to weather bureau or private radar data should be required where the probability for a tornado is large.

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CHAPTER I

INTRODUCTION

The installation and operation of any nuclear facility requires that no undue risk be presented to the public. The major consideration is that in event of an accident, there should not be sufficient radioactivity discharged to the environs to result in doses exceeding the limits set by the federal government. These limits are described in Title 10 of the Code of Federal Regulations Part 20.

Many unpredictable events might induce large scale accidents. The possibilities are too numerous to list here except that in recent years much attention has been directed toward severe storms. One of the most violent and destructive storms is the tornado and a consideration of this phenomenon is the subject for this dissertation.

It is generally recognized that a tornado is a tremendous whirlwind. However the occurrence, characteristics and effects of tornados are, at best, scarcely understood. Notable efforts have been undertaken to analyze the mechanics of the tornado and a number of studies have considered the design and integrity of nuclear facilities in relation to a tornado incident. Nevertheless, a thorough understanding of this phenomenon is not readily available. Considering the above, much of the evaluation for radiological safety, in case of a tornado, must be based upon "best" estimates.

A tornado is a vortex of air, of great intensity, extending from a larger storm cloud. It is usually visible due to the condensation about that vortex. The diameter may vary from a few yards to a few miles with the average about two hundred fifty yards. Vortices of larger diameter (perhaps one-half mile or more) are generally called tornado-cyclones. The winds at a particular point in the system can be considered to have three vector velocity components, the tangential, the radial, and the vertical. The tangential component may attain values of five or six hundred miles per hour, though the average is considered approximately two hundred. The other vector components would most likely maximize at about one hundred miles per hour. Another parameter often discussed is the translational velocity, or that speed at which the tornado moves along the surface. The translational velocity is quite variable between perhaps twenty and eighty miles per hour, with the average being about sixty. For purposes here, this component will be considered only as it modifies the three mentioned previously.

The passage of a tornado is accompanied by a sudden drop in atmospheric pressure. This characteristic is often considered to be the major cause for failure of structural integrity. The creation of large pressure differentials from inside to outside of a building results in unusual stress for which buildings are not normally designed. This problem will be of primary concern here in regard to failure of radioactive containment devices. The consideration of buildings and their structure has been the subject of many authors such as Bates and Swanson (1967), Hoecker (1961) and Doan (1969). A graph of the results from a study by Hoecker (1961) are presented as Appendix A. This graph gives the time-distance variation of the pressure drop and the force upon a hypothetical wall. Curves are presented for "on" and "off" the tornado path. An estimate yield point for the wall is indicated by a solid triangle on the force scale.

The majority of tornados in the United States occur in connection with squall lines and cold fronts but are also observed in isolated thunder storms of great intensity. Those associated with fronts tend to move in the direction of the wind in the warm air and usually have long paths. Those occurring in isolated severe storms are generally short-lived and have irregular paths. The majority of tornados approach from a direction somewhere between the south and the northwest. There appears to be a preference for the direction along a southwest to northeast line.

A number of studies have been devoted to determination of the probability for a tornado strike. The details of these calculations will not be discussed since they are readily available in current literature. The results of a study by Thom (1963) are presented in Figure 1.1. It is noted that the highest probability occurs in the state of Oklahoma. A somewhat different presentation is offered in Figure 1.2, a contour map of tornado probabilities in the United States, as determined by Bates and Swanson (1967). Most events are observed east of the Rocky Mountains but it is well to remember that the probability of a tornado incident is finite anywhere.

Quite naturally, no tornado is physically a duplicate of another and efforts to bring sophisticated mathematics into the description have proven quite frustrating. However, there are many pertinent characteristics that are common to most tornados. Thus, one might hope to utilize these "common" characteristics to arrive at best estimates and so predict material trajectories within the storm.

The intent in this dissertation is to demonstrate that analysis of tornado mechanics produces very similar results whether derived from sophisticated mathematical theory or by the empirical approach. There is still confusion concerning air flow within the core of the vortex but generally profiles of air movement exterior to the tornado core will be in quite reasonable agreement. Once this has been

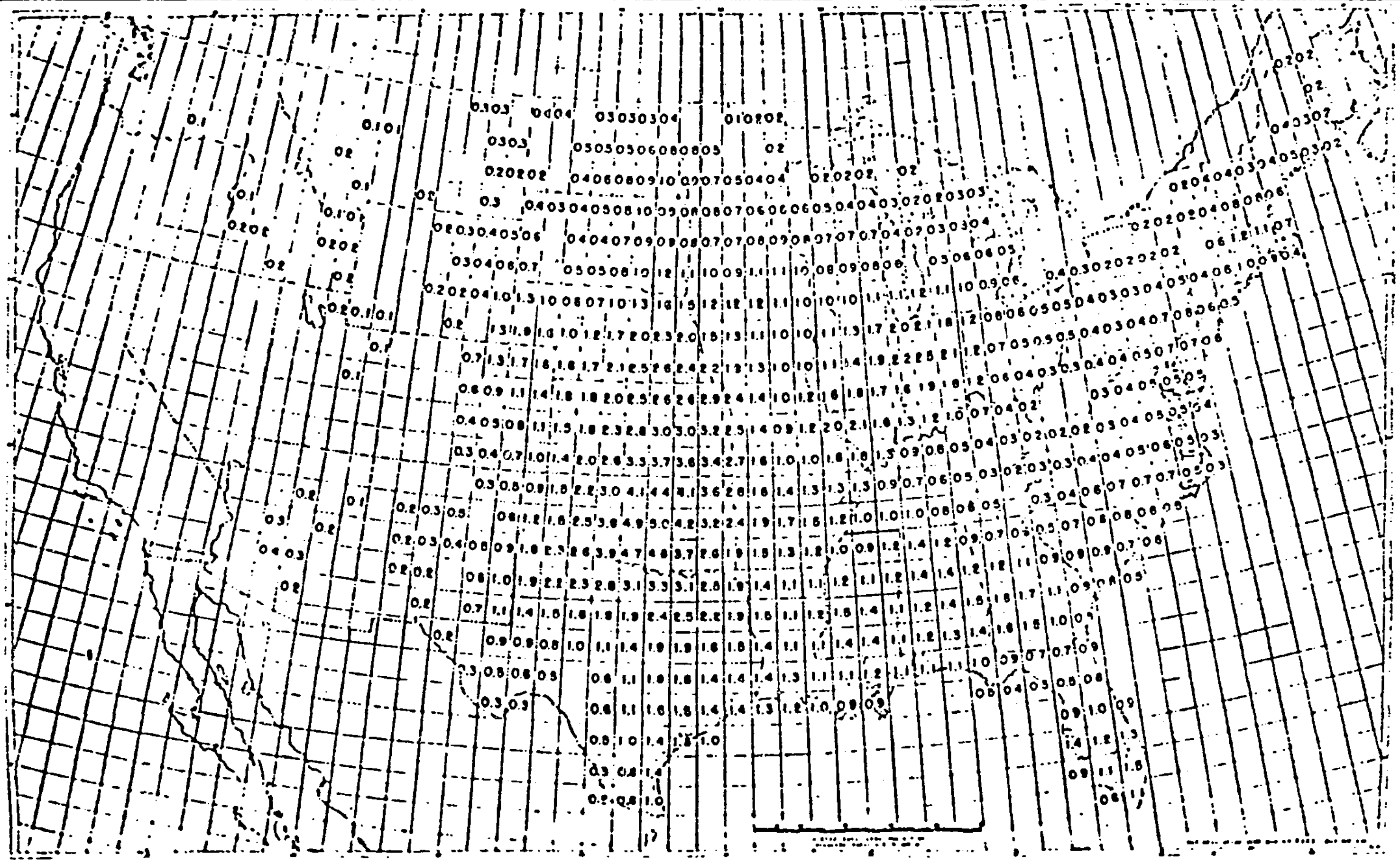


FIGURE 1.1

Mean Annual Frequency Of Tornadoes For One-degree-square Areas of The United States From Thom (1963).

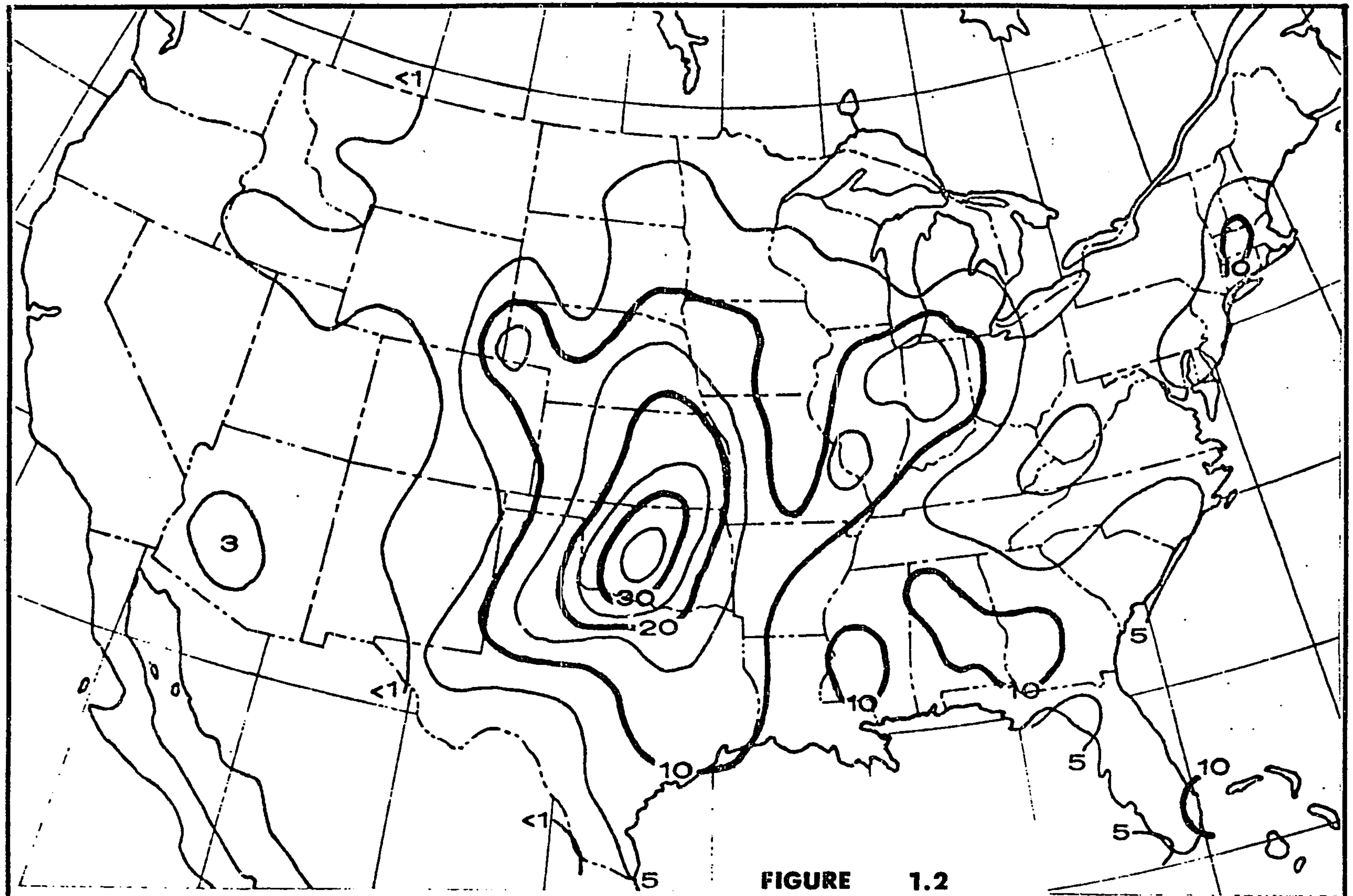


FIGURE 1.2

Contours Of Annual Tornado Probability For The United States From Bates And Swanson (1967). Numbers Are Chances In 10,000.

established, it should be permissible to utilize derived air parcel trajectories for predicting the movement of materials incorporated by the vortex. The objectives of this dissertation may then be stated as follows:

1) To determine, from the literature, what are the best estimates for the mechanical characteristics of a tornado vortex.

2) Utilizing these estimates, to derive air parcel trajectories which predict the movement of material within the vortex.

3) To determine possible reconcentrating factors involved in such a severe storm.

4) To discover whether the integrity of isotope containment devices will be violated.

5) Finally, to estimate the deposition pattern of radioactive debris.

CHAPTER II

TORNADO MECHANICS

As far as fluid dynamics aspects are concerned, a few useful features may be identified as done in a recent paper by Ying and Chang (1970):

1) A tornado is a huge vortex column with a low pressure visual core of tremendous rotational velocity and centrifugal force.

2) Circulation is maintained by the rotating mother cloud not by the earth's coriolis force. The sense of rotation usually coincides with that of the associated mother cloud.

3) The bouyant updraft in the tornado vortex core comes from the warm humid air of low density next to the ground.

4) The visual vortex column is formed by the reverse flow of the moist condensing air.

5) The inward spiral flow of warm humid air occupies a ground boundary layer and is sucked toward the foot of the vortex core where the pressure drops appreciably.

Measurements in an actual tornado are nearly
due to the huge size, dangerous and severe winds
sudden occurrence and uncertainty of location.
tematic measurements are rare except for ground pres
data such as that of Lewis and Perkins (1953) and Hoecke
(1961).

Long (1961) made laboratory studies of the hydrodynamic sink of a tall rotating column of water but his work is not easily related to the study of a tornado close to the ground. Turner (1966) tested a vortex in a rotating tank of water with a stream of gas bubbles injected in the center of the tank. He found that the tangential and radial velocity, in the strong swirling flow, are independent of height. The vertical velocity varied linearly with height. Based on his observations a theory was developed by assumption of a form of stream function describing flow in the vertical direction. The integral momentum method, in the theory for boundary layer flow, was used. Solutions were matched and checked with the experiments.

Kuo (1966) (1967) studied the theoretical nature of the atmospheric vortex above the ground boundary layer and included the heat release of moisture condensation. Recently Kuo (1969) developed an important theory on the mechanism of the tornado vortex and its boundary layer in the laminar range. Rott and Lewellen (1966) studied both the laminar and turbulent boundary layer with approximate momentum integral methods but their theoretical model does not agree with that of Ying and Chang (1970). Chi et al (1969) have improved upon the above theory and attempted extropolation to the full scale of a real tornado. Morton (1966) gave a review of the geophysical vortex and pointed out the complexity of the phenomenon. While most of the above cited studies have been theoretical in nature, the empirical approach is shown by Hoecker's reports (1960) (1961). Fujita's efforts (1958) (1960) further demonstrate the use of empirical data in an attempt to achieve understanding of tornado vortex dynamics.

No mathematical model was selected for generation of airflow patterns in this study. Ying and Chang (1970) describe part of the difficulty by stating four criteria that need be fulfilled in order to make a realistic simulation.

1) A single stationary vortex column touching the ground is needed.
2) A pressure drop with an updraft in the central core is required.
3) One needs to generate a ground boundary layer with flow spiralling inward to the core.
4) The vortex flow should be in the turbulent regime.

The authors continue with the statement that the first three of these can be met experimentally. Next they point out that laboratory conditions generate axial symmetric flow which is a useful simplification but unrealistic due to tilting and translational motion of a natural tornado.

Quoting the authors, "The fourth or last criterion is the most difficult to fulfill mechanically because the law of turbulent flow is neither theoretically nor experimentally known fully and there is doubt as to whether any scaled down version can match the turbulent flow properties of the natural tornado." Even the accuracy of the first three criteria is doubtful. Later it will be documented that many tornadoes do not exhibit the characteristic of the high speed updraft in the vortex core. In addition a number of papers, such as that of Bigler (1960), report that observers in proximity to tornado passage have not witnessed the radial winds hypothesized.

Long (1958) derives three ordinary, non-linear differential equations and provides a qualitative discussion since no numerical results were obtainable.

Goldman (1965) in his study of the Illinois tornadoes of April 1963, discusses the rapid changes in the width of the vortex. A number of still photographs and motion picture frames are provided as direct evidence. He further describes the changes in continuity of the condensation funnel and even mentions such effects as differing soil conditions, on the region near the surface. In consideration of translational motion the author points out how small errors in angle measurement would result in disproportionate errors in final results. Errors in linear measurement with such short distances as tenths of miles also contribute to the inaccuracy of the estimations. He further comments that distributions of vertical motion within the vortex changed sufficiently that a normalization was attempted in order to give more representative results.

Kuo (1966) developed what appears to be a very good theoretical model. He makes note of the qualitative resemblance of his theoretical profiles to those derived from actual data. He comments further: "Close agreement between theoretical and observational results is not to be expected at this stage of our investigation because of the lack of more accurate measurement and lack of refinement of the theory." He concludes that closer agreement between theory and the actual mechanics can only be achieved by introduction of more realistic models.

Fujita et al (1967) attempt estimations of tornado wind speeds from ground marks. It is noted that most estimates have been made indirectly and, among the other problems, it is difficult to separate pressure effect from wind effect. The wide variation of the values estimated by previous workers is cited and in the final discussion it is explained that there are no ways of knowing the micro-scale airflow patterns. Browning (1968) writes that the strong updraft in the central core "extends several kilometres above the tropopause." Waite and Lamoureux (1969) suggest a rhythmic up and down pulsing effect. Fujita and Bradbury (1969), using pictures from ATS III, report significant divergence at the anvil level modifies the jetstream-cloud velocities. The result of their work is the posing of new questions rather than the solution to previously noted problems.

Ward (1956) offers a practical mechanical idea of vortex geometry. In this paper, the difference between tornado producing storms and those not accompanied by a vortex is discussed. It is pointed out that all severe storms have sufficient energy for tornado formation. The idea is advanced that, within the convergence, a layer is formed in the atmosphere by a temperature inversion. Next a subsiding cloud pinches off the exhausting area, reducing vertical motion to a small region as in Figure 2.1. Considering first that there is no circular motion, then as in Figure 2.2, most of the exhausting mass is easily provided by layer one. If any degree of circular motion is introduced, centrifugal force will arrest convergence at some point. At this point, an approximately cylindrical surface is formed in that layer. Formation of this surface would drastically reduce the amount of air exhausting from the first layer. In addition this surface would behave as a duct transmitting the pressure differential to the next layer. The process would repeat itself step by step until friction at the surface reduces circular motion and thereby centrifugal force.

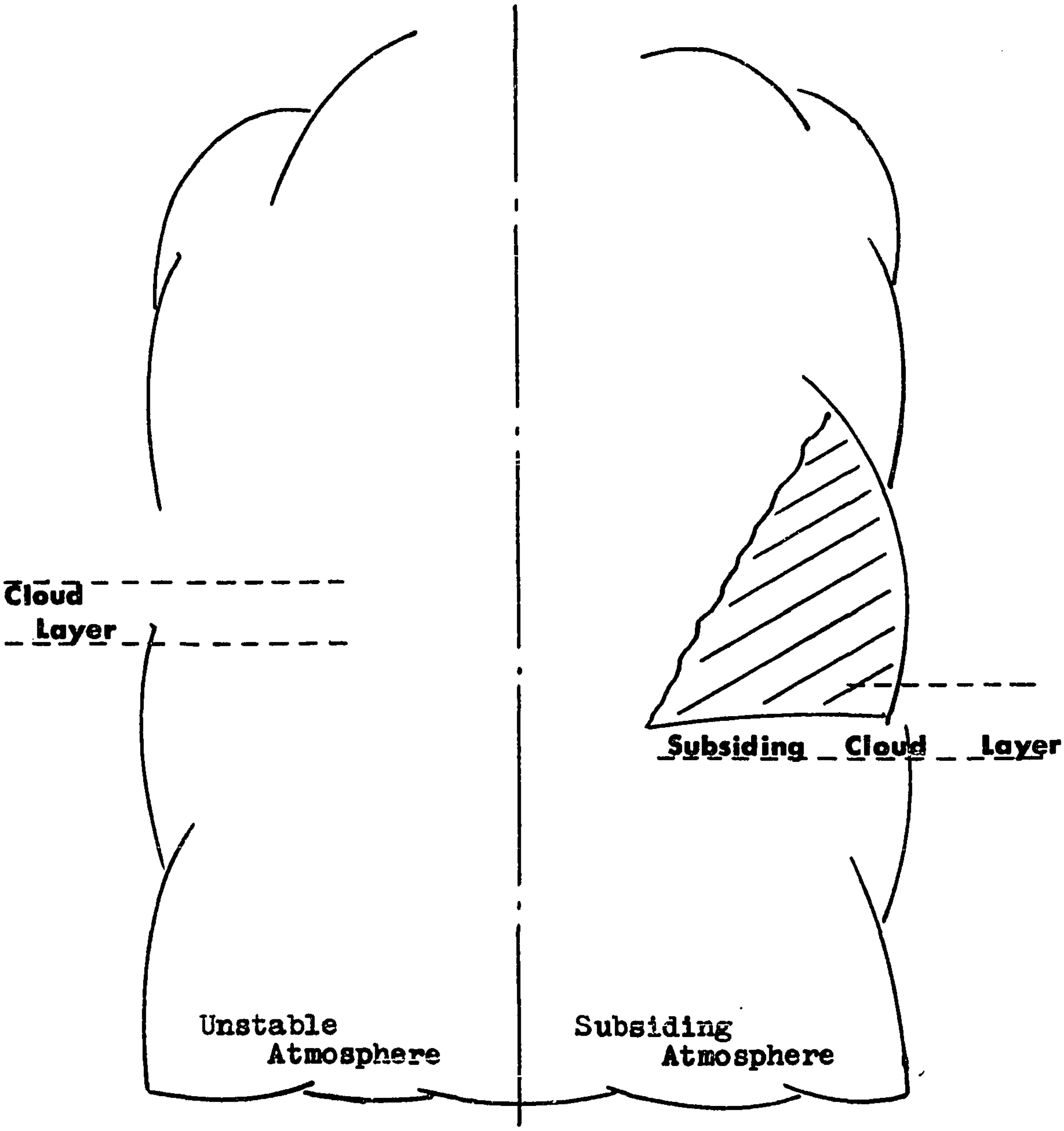


FIGURE 2.1

Diagram Of A Cumulus Cloud, Left Side In Unstable Air, Right Side In Subsiding. From Ward (1956).

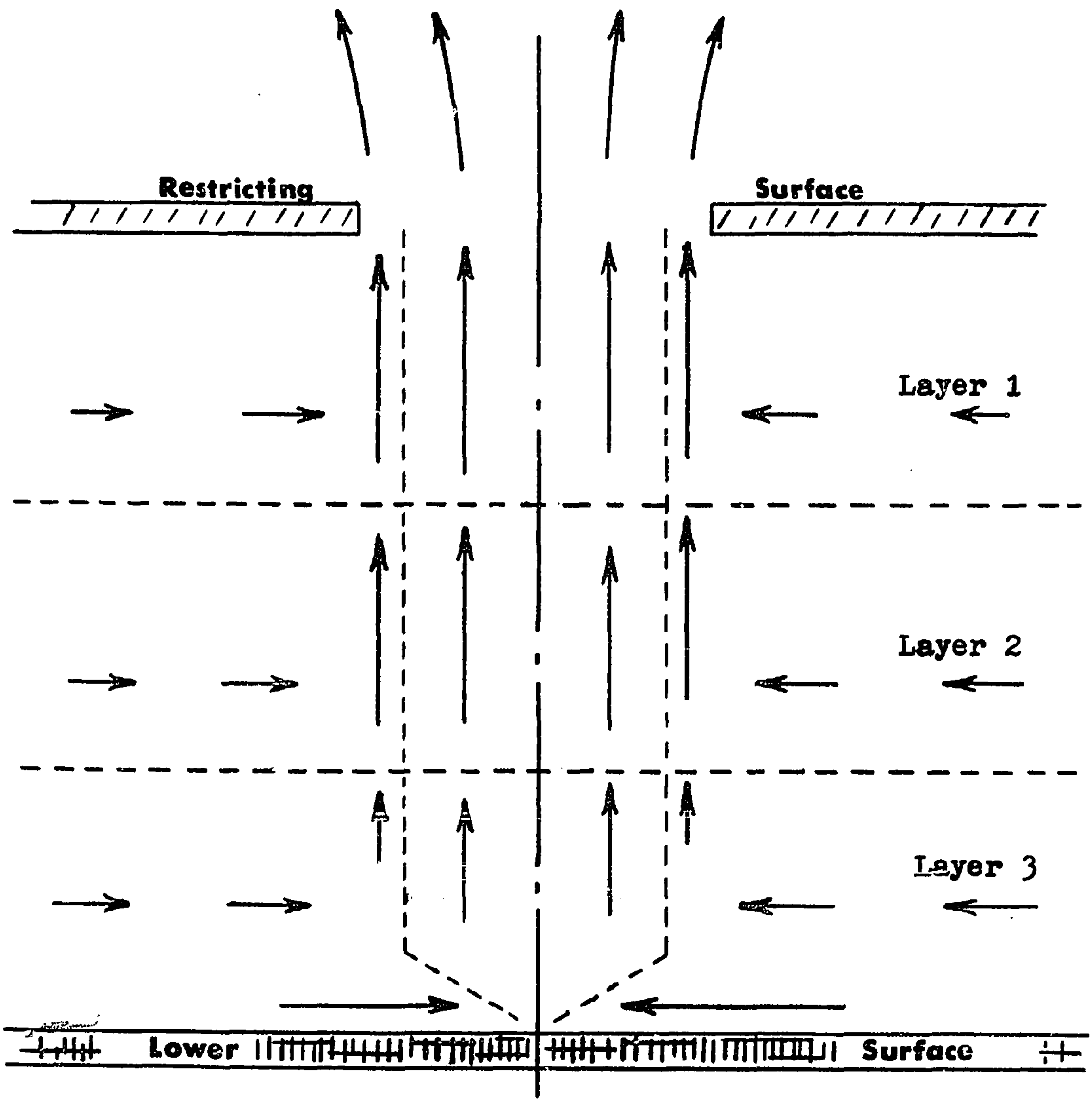


FIGURE 2.2

Converging-Exhausting System With Slight Circular Motion. From Ward (1956).

Under these conditions the surface layer should continue to exhaust through the core, providing the updraft theoretically required. However, the central pressure may be dynamically reduced to less than the pressure above the restriction so that reverse flow could occur instead. Regardless of the accuracy of this theory, it offers an understandable picture of how known inconsistancies may occur within a tornado vortex. Tilting, translational motion, topography and stage in the lifetime could alter the fluid mechanics of the vortex. Any variation at any time could disturb the geometry of the vortex so that airflow within the cell must be expected to possess individual characteristics and also to change constantly. This precludes a useful mathematical formulation since the changes would be unpredictable.

CHAPTER III

VELOCITY PROFILES AND AIR PARCEL TRAJECTORIES

Figures 3.1 through 3.3 are velocity profiles as derived by several authors. There are innumerable other profiles that have been omitted in order to avoid an inordinate catalog of graphs and charts. The profiles shown were chosen as representative of the general body of literature. As an example, Kuo (1966) makes direct comparison of his theoretically derived profiles to the empirically obtained profiles of Hoecker (1960). He finds that they match exceedingly well. Therefore, only the latter are included here as representative of both authors.

The tangential velocity profiles are found to match closely with that of the Rankine combined vortex. This configuration is characterized by a core of forced convection (rotational motion) surrounded by an area of irrotational motion or free convection. There are numerous references in regard to the Rankine combined vortex such as Lamb (1932) or Milne-Thompson (1960). Further discussion of this type of configuration may be found in the theses of H. Nouri (1966) and M. Martinez (1966). The tangential velocity within the

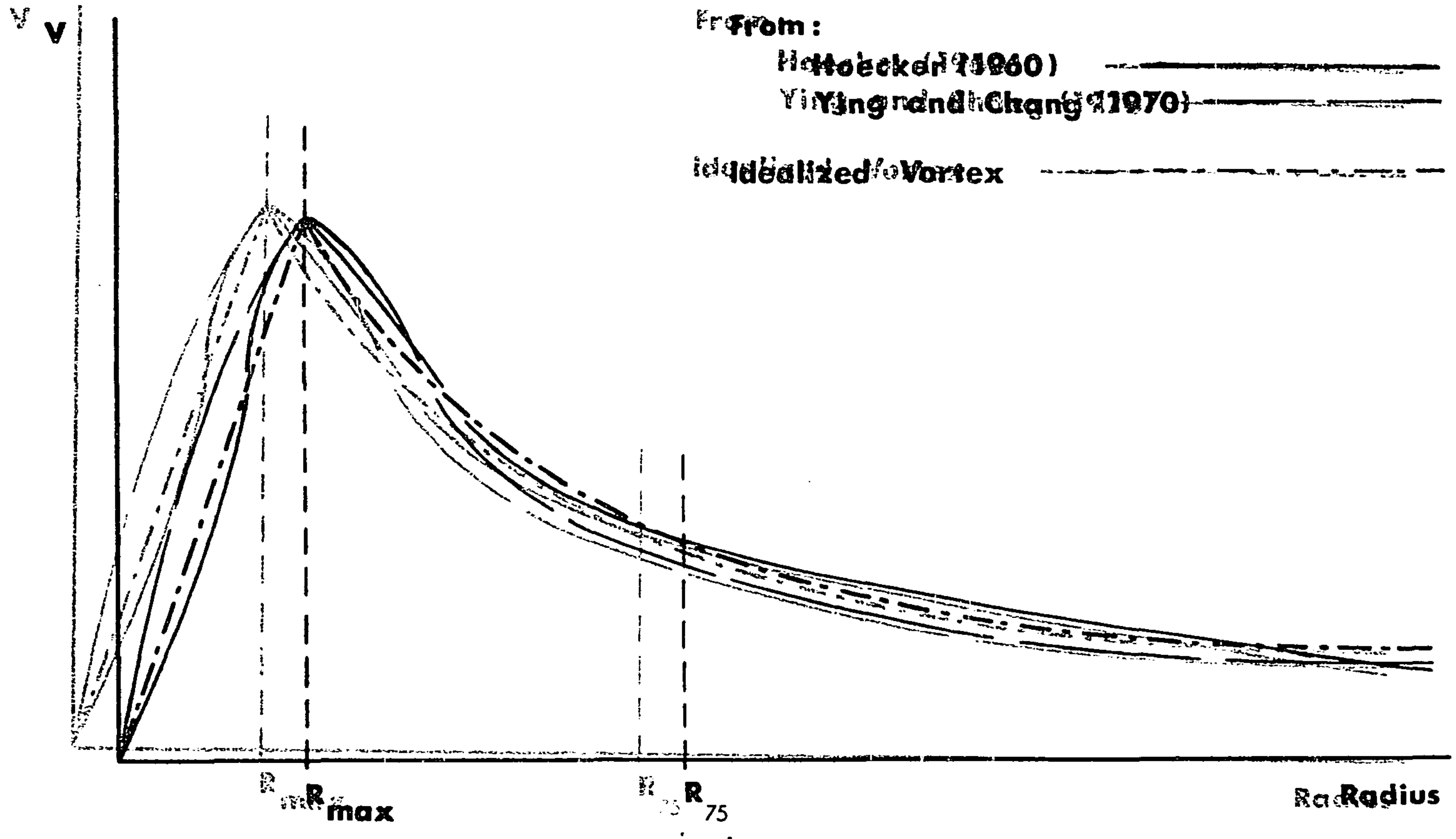


FIGURE 3.1

Derived Tangential Velocity Profiles Compared To That Of The Idealized Vortex. The Radius Of 75 Mile Per Hour And Radius Of Maximum Tangential Velocity Are Marked For Reference.

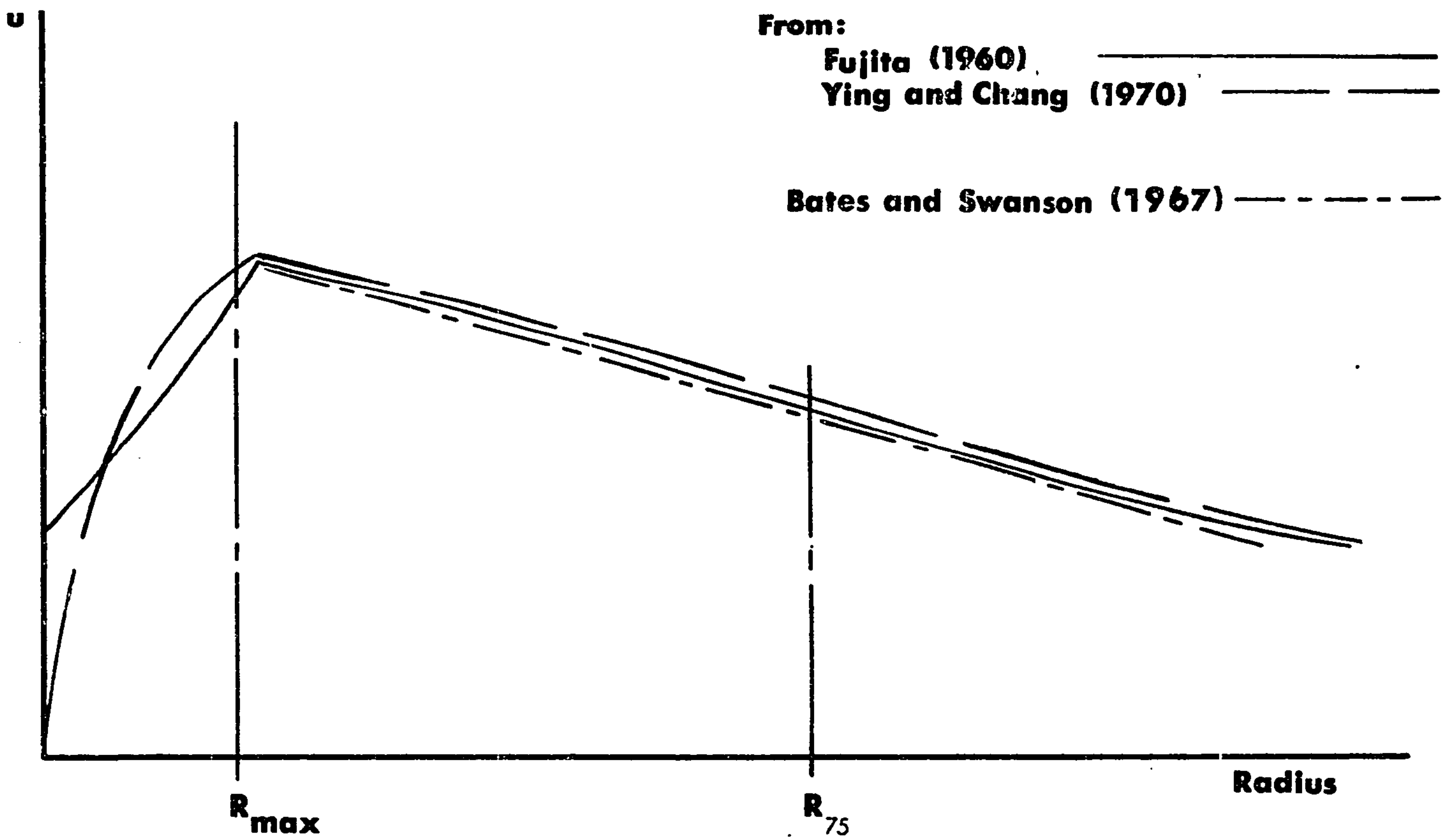


FIGURE 3.2

Derived Radial Velocity Profiles Compared To The Engineering Design Formula Of Bates And Swanson (1967). Radius Of Maximum And Of 75 mph Tangential Winds, Marked For Reference.

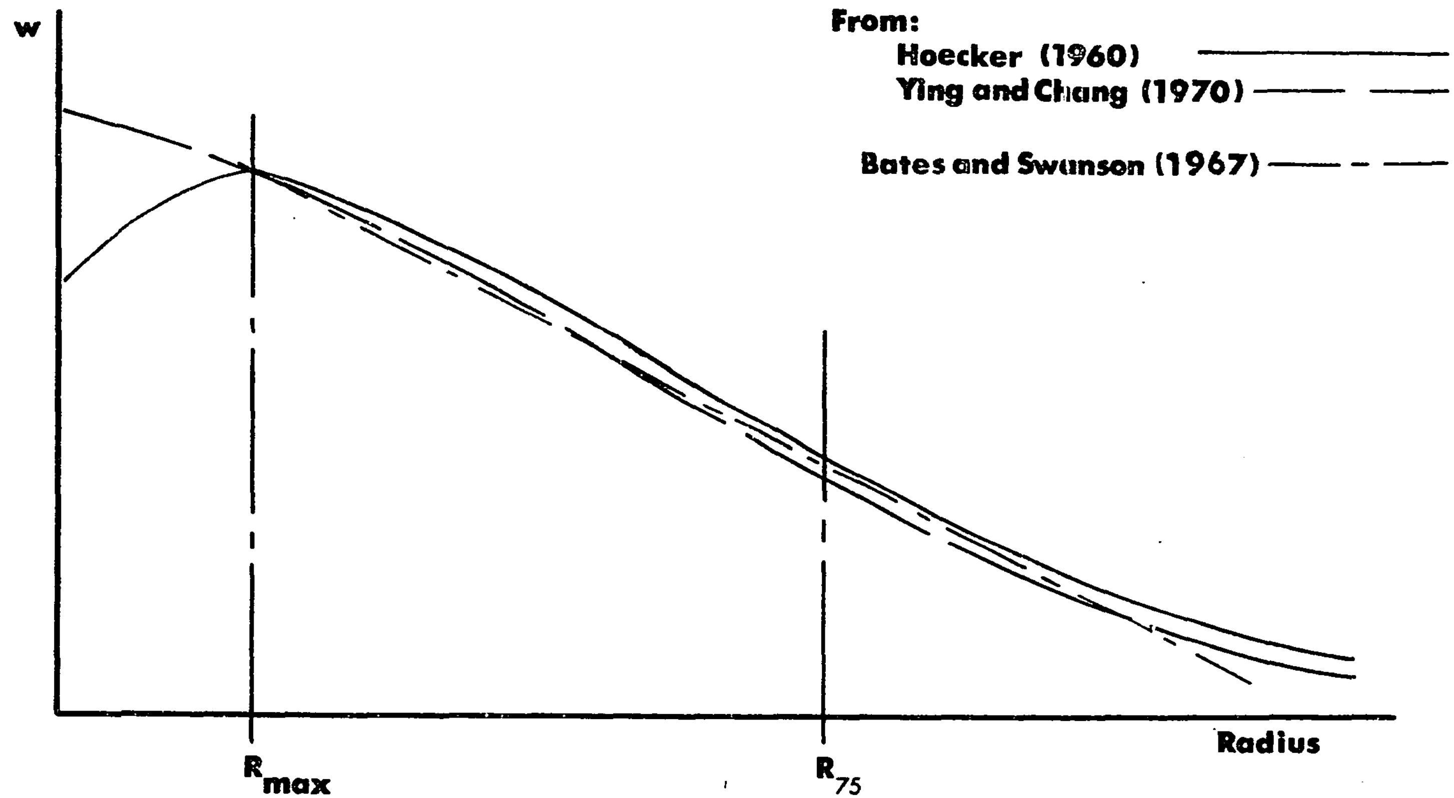


FIGURE 3.3

Derived Vertical Velocity Profiles Compared To The Engineering Design Formula Of Bates And Swanson (1967). Radius Of Maximum And Of 75mph Tangential Winds Marked For Reference.

forced convection may be expressed as $V = rC$ which is characteristic of solid body rotation. In the area of irrotational motion, the tangential velocity is described by $Vr = C$. The radial distance parameter is represented by r in both instances and C is a constant associated with the rotary motion. It is noted that regardless of the radial and vertical velocity profiles imposed, the tangential velocity profile varies insignificantly from that of the Rankine combined vortex where the assumption has been made that the radial and vertical velocities are zero.

In contrast to the independence of the tangential velocity profile, the vertical and radial profiles are extremely interdependent. Investigators commonly assume one profile, then derive the other to satisfy the requirements of continuity and incompressibility. Theoretically obtained radial profiles are not universally accepted even though close matching is noted by several authors, including Hoecker (1960), Fujita (1960), Kuo (1966), plus Ying and Chang (1970). Since the radial momentum of the moving air is converted to vertical motion of growing impetus as it nears the vortex core, one would expect the maximum radial velocity to occur at the boundary of the convective area with a minimum coinciding to the maximum vertical velocity.[1]

[1]Discussion with N. B. Ward, N.S.S.L., Norman, Oklahoma, 5 April 1971

This may explain the previously cited reference to observers noting the absence of radial winds in immediate proximity to vortex passage. In the ground boundary layer, however, a peak in the profile may occur just at the radius of forced convection. Since friction has arrested the rotary motion, the balance of centrifugal force and inward momentum has been prevented so that air may rush beneath the vortex "wall."

Despite the apparent contradictions, the best available estimates are those cited. Expressions for the vertical velocity and radial velocity based upon the work of Hoecker (1960) have been derived by Bates and Swanson (1967) for engineering design purposes. These formulae will be presented rather than the more sophisticated, extremely complex system of differential equations such as those of Kuo (1966). In the first place, all expressions contain parameters that would have to be determined for the individual vortex before realistic numbers could be obtained. Secondly, it has been pointed out that all profiles match exceedingly well so that use of the engineering design formulae should be admissable. Accordingly, the expressions for each of the instantaneous speeds would be

$$\text{radial speed} = \frac{(r_{75} - r)\, z}{r_{75} - r_{max}}$$

$$\text{tangential speed} = \frac{C}{r}$$

$$\text{vertical speed} = \frac{(r_{75} - r)\, z}{r_{75} - r_{max}} + 0.33\frac{C}{r}$$

The subscripts of the radial parameter denote the radius of 75 mile-per-hour tangential velocity and the radius of maximum tangential velocity. The radial distance of the point of interest is r and height above the surface is z.

One immediately recognizes the straight line relationship of the engineering design formulae for radial velocity values. If considering only the area of free convection, this relationship closely approximates that section of the profile curves.

The aim is to consider the irrotational portion of the vortex, combine the velocities vectorally, and derive a map of air parcel trajectories. Behaviour of material in the forced convection core is extremely problemmatical and will be discussed in a later section.

The first step is to establish a frame of reference. A useful simplification is to assume that the axis of the vortex coincides with the z axis of a set of cylindrical coordinates. In this case, the radial velocity vector direction is along the r coordinate and the tangential velocity vector along the ϑ direction. Unit vectors in the r, ϑ and z directions may be denoted in the usual manner as $\hat{h}$, $\hat{m}$ and $\hat{k}$ respectively. As a result, vector addition can be accomplished quite simply according to the standard rules.

First let the scalar values be described such that

$$\text{radial speed} = f(r,z)$$
$$\text{tangential speed} = f(r)$$
$$\text{vertical speed} = g(r,z)$$

where r represents the radial distance from the vortex axis to the point of interest and z represents the height above the surface. Then the velocities may be defined in vector notation as

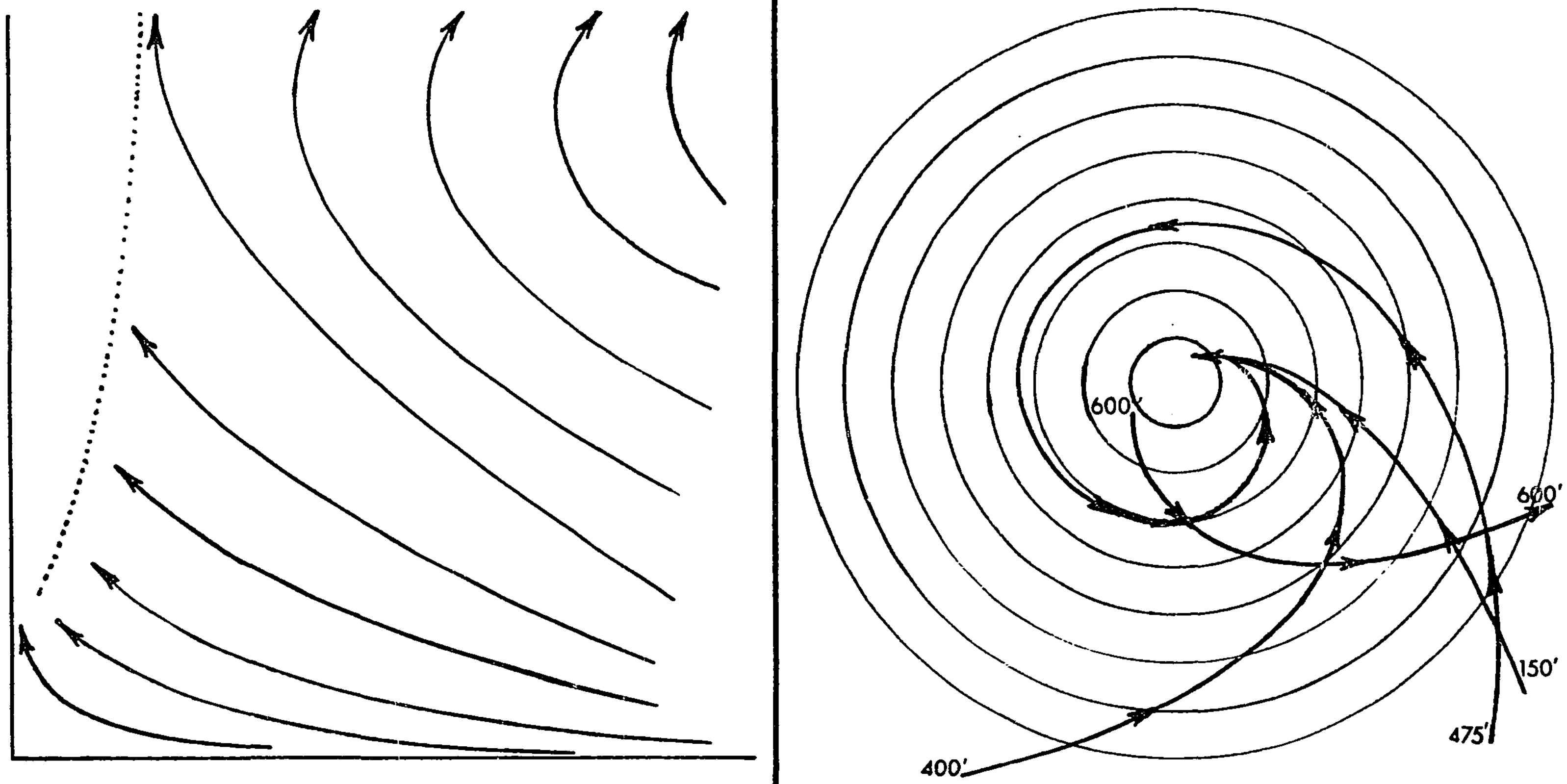
$$u = f(r,z)\vec{n} + (0)\vec{m} + (0)\vec{k}$$
$$v = (0)\vec{n} + f(r)\vec{m} + (0)\vec{k}$$
$$w = (0)\vec{n} + (0)\vec{m} + g(r,z)\vec{k}$$

The vector summation or resultant velocity vector is finally given by

$$V = f(r,z)\vec{n} + f(r)\vec{m} + g(r,z)\vec{k}$$

the instantaneous velocity at a point in the irrotational portion of the vortex. By a continuous mapping of the instantaneous velocities, air parcel trajectories may be generated. Figure 3.4 is an example of such a mapping from the work of Hoecker (1960).

By this means, prediction of air movement within the vortex is accomplished. Small particulate material, in an unconfined state, will follow the trajectory of the air parcel in which it is located. Except in the highly turbulent core, the material will not be subjected to extreme mixing and should remain essentially as a slug. Analysis of tornado mechanics supports the theory of very little



Trajectories in a Vertical Plane **Horizontal Streamlines at Several Levels**

FIGURE 3.4

Typical Air Parcel Trajectories In The Vertical And Horizontal Planes. Patterned After The Work Of Hoecker (1960).

transfer across the boundary of the vortex core.[2] This is because of the balance between inward momentum and the centrifugal force due to the rotation. Exterior to the core, then, a large portion of the problem has been solved once mapping of air parcel trajectories has been accomplished.

By study of the air parcel trajectories it becomes apparent that the movement is a somewhat distorted spiral, vertically upward and at the same time toward the vortex center.

The spiral is distorted by the aforementioned translational velocity of the funnel. The translational velocity will add to the radial and tangential velocities in some portions of the vortex while subtracting from them at other points. The final result, however, is independent of the interim path. The ultimate behaviour of the material is to rise to the height of the mother cloud. Within this cloud, the material is likely to become widely dispersed according to the eddies and currents within a severe thunderstorm. The situation from this point becomes very similar to the conditions in considering "fallout." In some of the more severe storms the material may even be injected into the tropopause where similarity to fallout conditions is enhanced. For discussion of radioactive fallout, the reader may turn to any one of a large number of references on the subject such as that by Teller et al (1968).

[2]Discussion with N. B. Ward, N.S.S.L., Norman, Oklahoma, 24 July 1970

Turning our attention to the vortex core we find an almost insurmountable complexity. In the first place, the flow within the core is highly changeable. At certain stages of the tornado, core flow is actually a high speed jet, vertically upward into the parent storm cell. Debris including radioactivity could be swept beneath the condensation wall and lifted to great altitudes. Again dispersal occurs and the problem approaches that of fallout. At other stages the core flow is partially laminar then highly turbulent. It has been postulated that there is an upward jet meeting with a downflow so that at some altitude a volume of extreme turbulence exists. A study by McNaughton and Sinclair (1966) showed that this type of action occurred in submerged jets not subject to rotation. Introducing a stream of gas at the bottom of a liquid, full laminar flow was first obtained. As the rate of inflow was increased, the height of the laminar portion receded with turbulence and counterflow appearing above. As the flow rate was further increased, the turbulence and counterflow progressed toward the inlet until no laminar flow existed. Dinwiddie (1952) observed this apparent behaviour in a tornado-waterspout at Nagshead, North Carolina and many others have reported similar characteristics. Ward (1970) discusses this phenomenon in regard to the tornado core. He references numerous observations and offers a theory of tornado mechanics which would produce such an effect.

From the above, it becomes apparent that prediction of the future for materials becomes mostly chance when they are incorporated within the core flow of the vortex. The results could range from dispersal about the base of the vortex, to injection of the entire amount into the tropopause. Between these extremes would be the scattering of material about the vortex base with a portion incorporated and elevated into the mother cloud. One must assume mediant behaviour as the most likely to occur. From the standpoint of material accountability this behaviour is the most difficult with which to work. Small particulate material in an unconfined state may well be discovered widely dispersed about the immediate area of a stricken facility as well as along the future storm path. In addition, should the intensity of the storm be great enough, material may be dispersed into the tropopause so that fallout is a significant factor. The quantity of the material in the incident and its specific activity would be the final determinant insofar as the seriousness of the threat to public health is concerned.

To summarize the conclusions to this point, we may make several observations. Small particulate material that becomes elevated will eventually be dispersed within the parent storm cell regardless of the interim path. Exterior to the vortex core there is little dispersion until it reaches the mother cloud. Incorporated within the core, the most likely future is considerable mixing with part of the material scattered about the funnel base and part of it elevated and dispersed into the mother cloud. In more intense storms, the material is likely to be injected into the tropopause where the considerations become those of a fallout problem. Figure 3.5 is a schematic of the tornado storm system showing the pattern of air flow as determined by Fujita (1960).

One must make the observation that the greatest concentration of radioactivity would occur at the point where material is injected into the storm. From this point the prime phenomenon would be dispersion. For smaller amounts of material and lower specific activity, the concern would then be greatest in the immediate environs of the facility. Should large amounts of material and high specific activity be present, the hazard would be extended to one of public safety.

The one characteristic of severe storms that may act to reconcentrate radioactivity is the accompanying rainfall. A number of studies such as those of Saucier, Hall and Nelson (1965), and Gatz and Dingle (1965) have shown that rainfall will scavenge particulate debris from the atmosphere.

An overwhelmingly predominant feature of tornado producing storms is the location of the precipitation in relation to the vortex. According to N. B. Ward of the National Severe Storms Laboratory, 80% of the well formed tornado

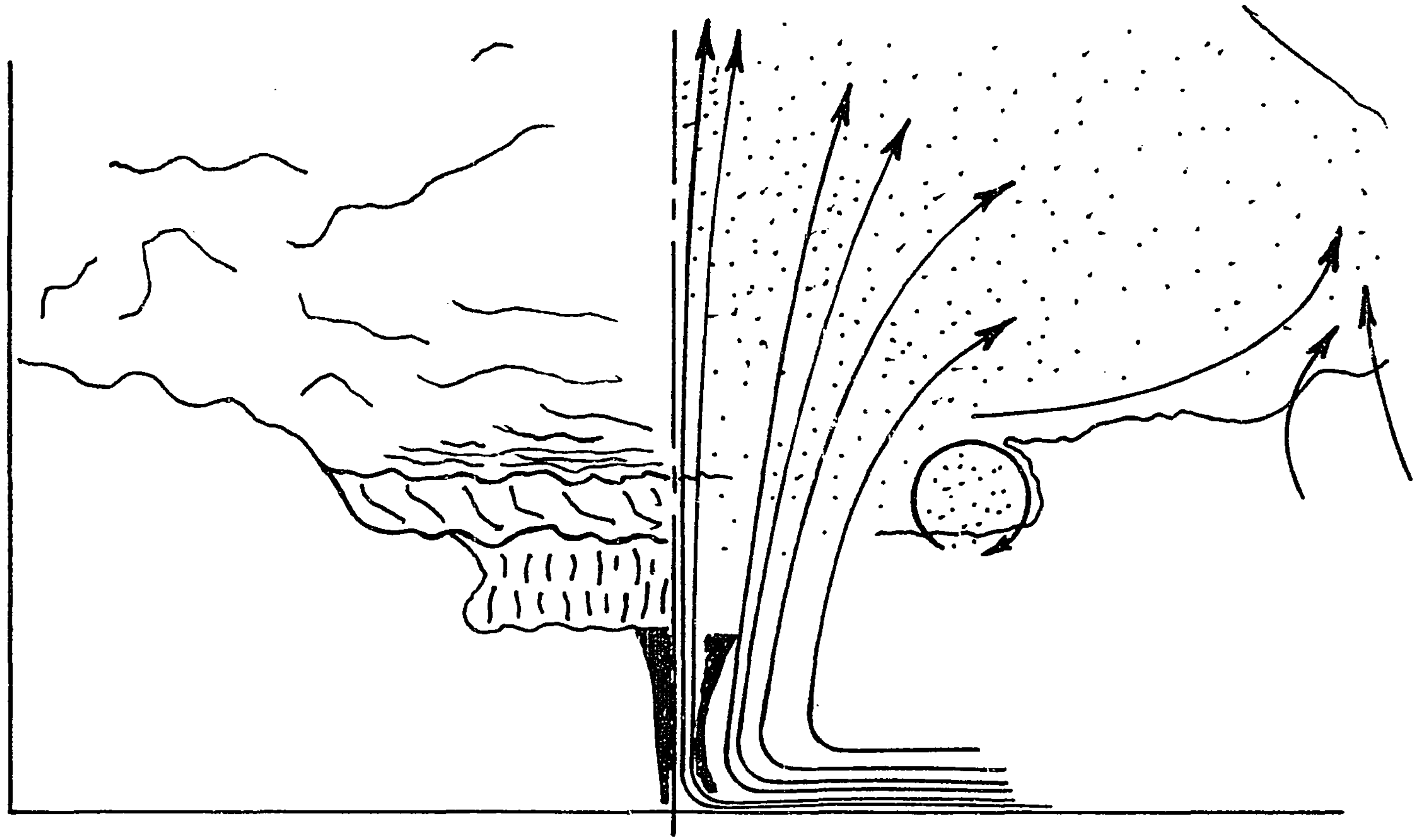


FIGURE 3.5

A Schematic Of General Airflow Within A Tornado. From Fujita (1960).

cyclones have the vortex located in the southwest quadrant. Certainly there are exceptions and "transient" type tornados do occur in isolated storm cells which do not exhibit this relationship. This characteristic feature is verified by such studies as that of Goldman (1965). In this report on the Illinois tornados of April, 1963, a time sequence of radar echoes is provided showing the "hook" or "vault" to be located in the southwest quadrant of the cell. The term "hook echo" refers to the shape of the image observed on the radar scope. This image is the reflection from precipitation accompanying the storm. This shape is peculiar to tornado producing systems.

An interesting situation is noted by Bigler (1960) where the vortex location is again recorded as the southwest quadrant of the storm. The unusual feature of this case was that the tornado moved from south to north, then northwesterly, rather than in the typical southwest to northeast direction. Quoting directly from this paper: "These pictures show that the tornado was located on the southwest side of an echo, the same as is usually observed. The northward movement of the echo placed the tornado in the left rear quadrant of the echo with respect to motion. Tornados have been most frequently observed in the right rear section of the echo." This tornadic system, passing through Dallas, Texas in 1957, still exhibited the usual characteristic of having precipitation occur predominately north and east of the vortex track.

A series of radar-scope photographs from Battan (1959) are reproduced in Figure 3.6. These show the hook location in the southwest quadrant with clearly depicted movement of the echo to the east and north. Figure 3.7 shows the typical right rear quadrant location of the hook, in the pictures and diagram of the radar echo, from the work of Browning and Fujita (1965). The first picture is of the echo from the Kansas tornado of May 19, 1960. The other picture is from the Illinois tornado occurring April 9, 1963. The lower drawing diagrams the typical radar observance of a tornado producing cell. Staats and Turrentine (1956) note a tornado at Udall, Kansas, in May 1955, that is located in the left rear quadrant of the parent storm. It is also noteworthy that a second vortex, located in the familiar right rear or southwest quadrant of the same cell, struck Blackwell, Oklahoma. The precipitation was north-northeast of the Blackwell tornado and slightly north of east in relation to the vortex at Udall, Kansas.

Figure 3.8 is a mapping of rainfall concentration from a severe storm system accompanied by several tornados. This diagram was included in a study by Browning and Fujita (1963). Once more it is evident that the precipitation occurred predominately north and east of the tornado tracks.

It becomes quite apparent that radioactive materials, incorporated by the vortex, will normally be deposited north

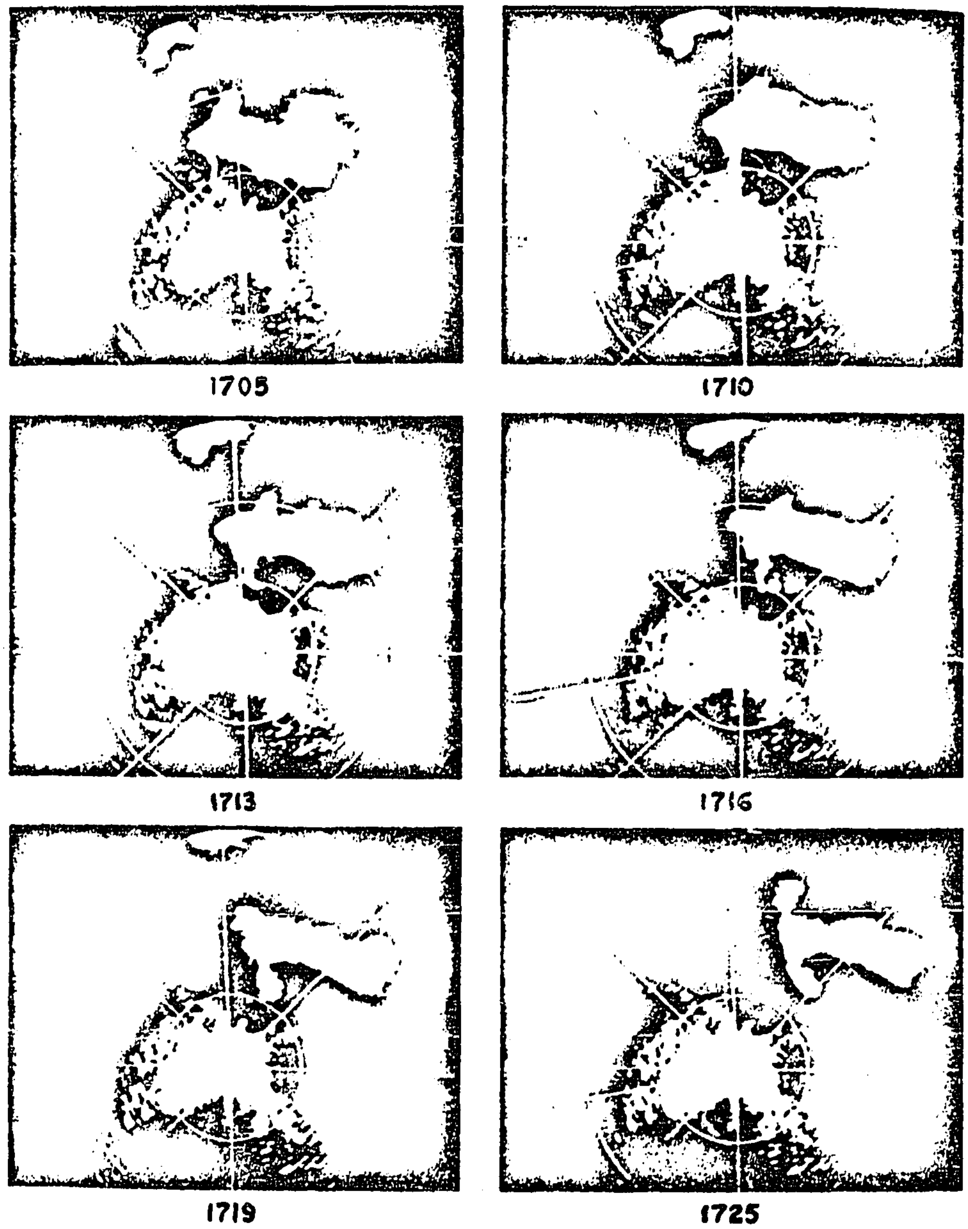


FIGURE 3.6

Series Of Radar Scope Photographs Showing Formation Of A Tornado Hook Echo. From L. J. Battan (1965).

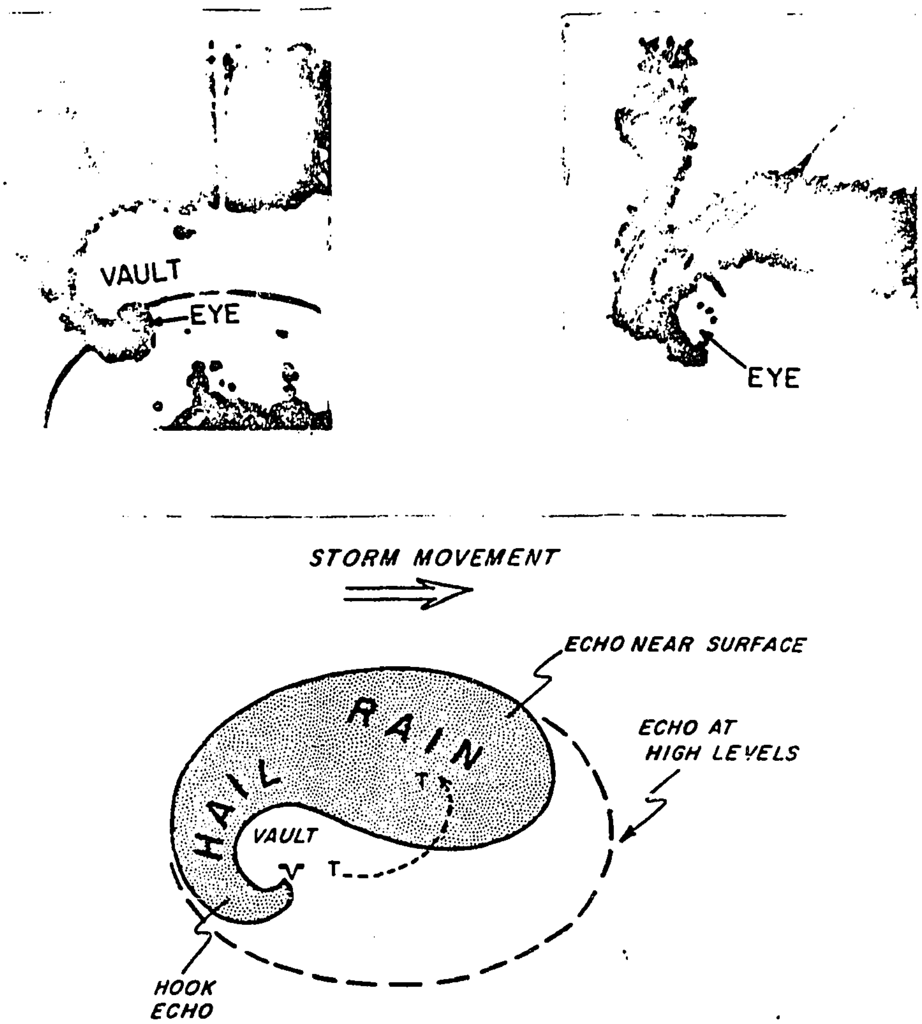


FIGURE 3.7

Pictures And A Diagram Of Typical Radar Hook Echoes From A Tornado Cyclone. From Browning And Fujita (1965.

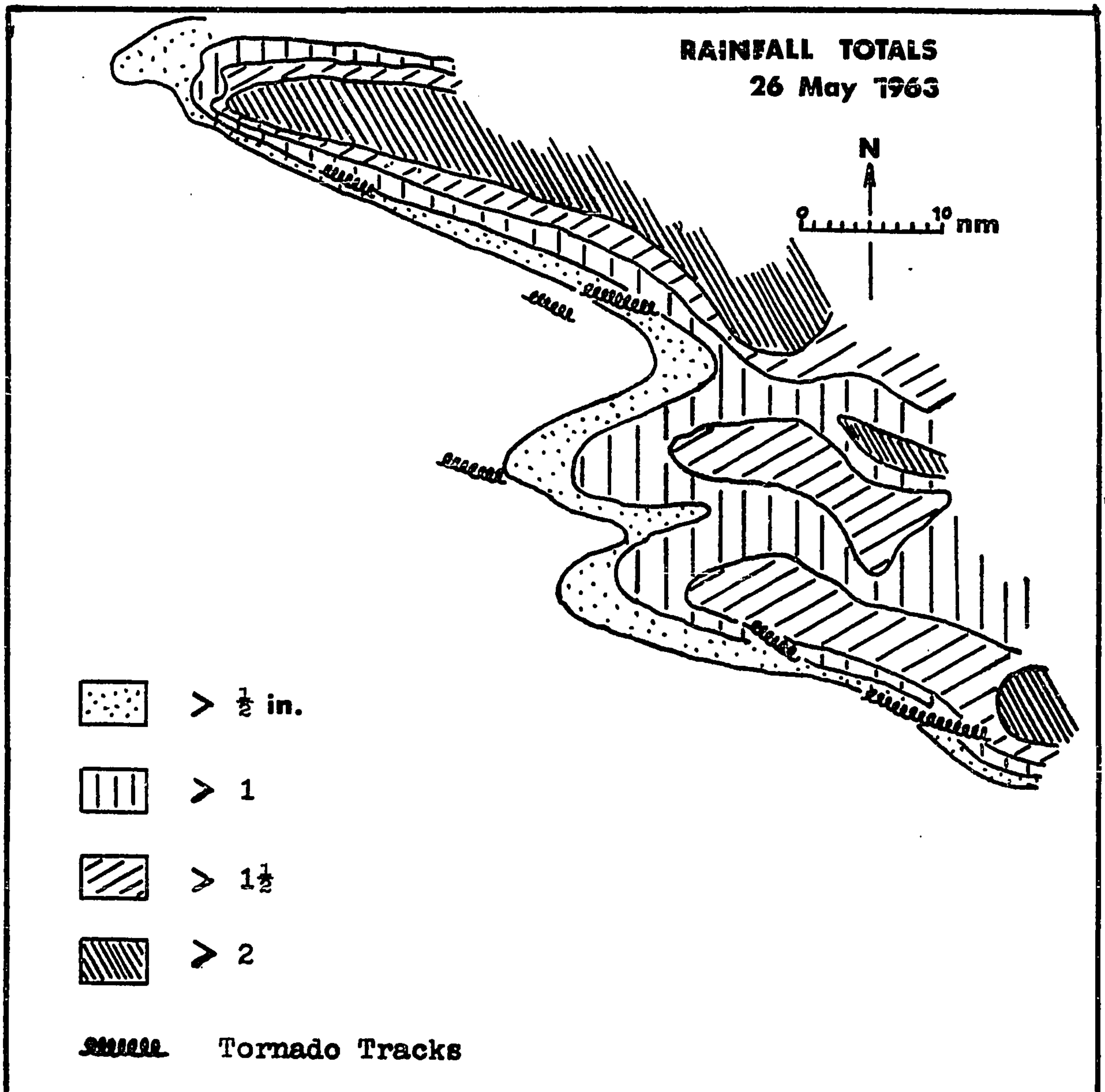


FIGURE 3.8

Rainfall Density Contours For A System Of Severe Storms As Reported By Browning And Fujita (1963).

and east of the original location. This is due to two factors characteristic of these storms. First, the movement of the cell is usually to the northeast and, secondly, the precipitation is located to the north and east of the vortex.

In event of a tornado incident, the radar history of the storm movement would prove invaluable. It is suggested that a definite arrangement be made, with the nearest weather radar station, to provide this information to the safety office of a nuclear facility. Should a facility be damaged by a tornado, a mapping similar to that of Figure 3.8 could be made from weather bureau data.[4] The radar history of cell movement and the rainfall mapping should provide an estimation of the deposition pattern for radioactive debris.

[4] Discussion with Stanley Barnes, Ph.D., N.S.S.L., Norman, Oklahoma, 3 April 1971

CHAPTER IV

CONSIDERATION OF ISOTOPE CONTAINMENT

Since most radioactive materials are not unconfined, one must turn attention to the future of materials within containers and/or shielding. Bates and Swanson (1967) have an excellent discussion of the aerodynamic lifting and propulsion of objects. The text of their calculations will not be presented here, only some of their conclusions. First, the average force acting on a relatively small object is given by

$$F = \tfrac{1}{4}C_d q(A_= + A_+)$$

where A_+ is the surface area perpendicular to the wind, $A_=$ is the surface area parallel to the wind, q is the dynamic wind force and C_d is the drag coefficient. The value of q is obtained from the equation

$$q = \tfrac{1}{2}\rho V^2$$

when ρ is the ambient air density and V is the wind velocity. The value of the drag coefficient is usually determined empirically or taken from a list of approximations. The authors of this work chose a value of 1.3. The final speed of the object and its kinetic energy are calculated by

$$V = \frac{Ft}{M}$$

$$E = \frac{F^2t^2}{2M}$$

with t representing the average time that force is applied (which has been determined as 0.2 seconds) and M being the mass of the object. If all the acquired energy is used to lift vertically, the maximum height attainable would then be

$$H = \frac{F^2t^2}{2M^2g}$$

in which g is the familiar acceleration due to gravity.

Table 4.1 is included to provide insight to the behaviour of typical pieces of equipment associated with a nuclear facility. Items directly associated with a reactor are not included since they have been considered in a number of other studies such as the one just cited. Obviously these numbers are estimations since exact aerodynamic behaviour cannot be determined, the coefficients are approximations and the assumptions of the mathematical formulae may not all be followed.

The first striking characteristic is that using these calculations, a typical glove box might be elevated to a height of three or four hundred feet while a standard lead brick may only rise as high as one or two feet. Most likely the majority of the items would be rolled and tumbled rather than elevated and thus the integrity of containment becomes the primary concern. Glove boxes would be likely to fail

Item	Size (ft)	Wt. (lbs)	V (fps)	E (ft lbs)	H (ft)
Glove Box	2 x 2 x 5	96	150	2×10^5	350
Lead Brick	1/6 x 1/3 x 2/3	25	9	40	1.2
Storage Box	2/3 x 5/6 x 2/3	150	6.8	114	0.7
Counting Shield	5/4 x 5/6 O.D.	250	4.3	73	0.3
Lead Vault	1 x 1 x 1	1000	2.1	67	0.1
Lead Pig	1/4 x 1/6 O.D.	1	93	134	134
Lead Pig	5/6 x 5/6 O.D.	150	10	272	1.7
Carrying Case	1/4 x 1/6 O.D.	25	2.9	4.1	1.3
Carrying Case	1/2 x 1/2 O.D.	225	1.7	25	0.1

TABLE 4.1

Typical Items In A Nuclear Facility With Maximum Possible Projectile Characteristics In A Hypothetical Tornado. Calculations Based Upon Bates And Swanson (1967).

due to the glove ports. The remaining equipment is likely to fail due to lids or doors opening during erratic movement and bouncing. Should containment fail and radioactive material be spilled into the atmosphere, it would behave in the same manner as unconfined material incorporated at the point of atmospheric injection.

During a tornado, there are two aspects of behaviour for isotope containment devices that are of importance. First, passage of high winds over outer surfaces of an enclosure creates pressure differentials which could cause explosive failure. The other concern, missile generation, could be the result of several phenomena. Projectiles may result from the explosive failure of structures, direct wind forces that lift and/or impel, and by impingement of a missile which imparts its energy to the object. Projectiles resulting from the first two processes are called primary missiles while those generated by impingement are called secondary.

Since containment of radioactive materials is the primary concern, we first turn attention to the problem of explosive failure. One accepted parameter of a design tornado is the value of 300 mph for the horizontal wind. Winds of this velocity would induce a pressure differential of 1.6 psi across the walls of an enclosure that internally has ambient atmospheric pressure. Since the problem for buildings has been adequately referenced in chapter one, and since the interest here is isotope containment, the result upon typical items within the facility is the next subject.

First, the effect upon a drybox containing materials is of importance. It is unlikely that this particular effect would cause failure of the walls, commonly made of 304 stainless steel. Likewise the viewing windows of safety glass should remain intact. The weakest point of the enclosure would be the connection of the neoprene gloves at the ports. Considering a typical set of gloves eight inches in diameter, and making certain fairly reasonable assumptions, the force applied to the juncture can be calculated. To obtain the surface area, assume the gloves are twenty-four inches from port to wrist and ignore the surface of the hands and fingers. This results in a surface of about 100 square inches and the total force at the connection would be near 160 pounds. Since the gloves have an eight inch diameter and the standard thickness is on the order of 0.30 inches, the cross-sectional area would be 7.54 square inches. Thus the force would correspond to approximately 21 psi. Standard neoprene is rated at approximately 380 psi tearing resistance.[4] Therefore, the gloves are very unlikely to fail due merely to the wind-created pressure differential. It would be unusual, then, should a drybox fail for this reason only.

[4] H. Barron, 1943: Modern Synthetic Rubber, D. Van Nostrand Co., Inc., New York

The next problem is whether other types of containment would be violated by the effect of this pressure drop. Consider the storage box as included in Table 4.1 of this chapter. The lid dimensions of this particular item are eight inches by ten inches with a thickness of one inch. The construction is of lead and the weight of the lid would be 34 pounds. If one calculates the force across this surface, caused by the 1.6 psi pressure difference, the value of 128 pounds is obtained. With this pressure difference, the lid will be lifted and containment is violated. Table 4.2 displays the results of similar calculations in regard to other items typical of an isotope facility. It is noted that two of the others are likely to fail due to the wind-pressure effect. The small lead carrying case could be opened.

Certainly the wind-created pressure drop is not the only effect of importance. Each of the items is shown to have the probability of becoming a tornado-borne projectile. Thus the containment is endangered by the impacting of these objects as missiles.

According to P. L. Doan (1969), there is no way to specify the exact nature, speed and impact effects of missiles generated by tornadoes. It is possible, however, to identify some of the more important objects likely to become projectiles and roughly compute the maximum characteristics possible. The upper speeds depend upon the relative position

Item	Cover Dimensions (in)	Surface Area (sq in)	Cover Weight (lbs)	Force of Pressure (lbs)
Storage Box	1 x 10 x 12	80	34	128
Lead Vault	2 x 12 x 12	100	230	160
Lead Pig	½ x 2 O.D.	0.8	0.6	1.3
Lead Pig	2 x 6 O.D.	50	64	1.3
Carrying Case	1 x 2 O.D.	0.8	1.3	1.3
Carrying Case	2 x 6 O.D.	13	23	20

TABLE 4.2

Comparison Of Lid Cover Weight To Force Exerted Upon That Cover By The 1.6 psi Pressure Differential Of A 300 mph Wind. Typical Dimensions Taken From Atomic Development And Machine Corporation Radiation Shielding Catalog, August, 1970.

of the object with respect to the wind as well as its size, mass, and shape.

As a means of estimating the force of impact, calculations were made assuming that the missile attained the maximum possible terminal velocity. One can either assume all the force went into lifting and calculate the impact of a free falling body from the maximum attainable height or use the impulse-momentum method and the maximum possible terminal velocity. Due to the assumptions of the previous derivations, the results will be nearly equal. The total force for the impacting of several of these items is shown in Table 4.3. It was also assumed for ease of estimation that the force was dissipated constantly over a time lapse of one millisecond. These calculations are intended in no sense as exact values. Most of the numbers are approximations and it is very unlikely that maximum height possible, nor maximum velocity theorized would ever be attained in an actual tornado. The purpose here is to demonstrate the tremendous energy of tornado induced projectiles. Such tremendous energy expended in an instant will undoubtedly disrupt the integrity of most containment equipment utilized in a nuclear facility. Such items as the storage vault or the large lead carrying case have bolted or locked covers so that impact could deform them considerably and still not release materials into the atmosphere. It is most likely, however, that contained radioactive materials will be released from the impaction process.

Item	Mass (slugs)	Max. Height (ft)	Max. Velocity (fps)	Impact Force (lbs)
Glove Box	3	350	150	4.5×10^5
Lead Brick	1	1.2	9.0	9.0×10^3
Storage Box	5	0.7	6.8	3.4×10^4
Counting Shield	8	0.3	4.3	3.5×10^4
Lead Vault	31	0.1	2.1	6.5×10^4
Lead Pig	0.03	134	93	2.9×10^2
Lead Pig	5	1.7	10	5.0×10^4
Carrying Case	1	1.3	2.9	2.9×10^3
Carrying Case	7	0.1	1.7	1.2×10^4

TABLE 4.3

Maximum Impact Force For Typical Items Of Equipment In A Nuclear Facility When Behaving As Tornado-generated Projectiles.

Consider, as an example, the much discussed drybox. If this enclosure should be lifted, as previously calculated, the energy at impact would be on the order of $3X10^4$ ft.lbs. The U. S. A. standards for safety glass are established by a maximum impact test of 400 ft.lbs. energy.[5] The glass of the box will obviously shatter upon impact releasing the contents to the environs.

If the box has become airborne in the assumed situation, the containment will surely have been violated previously by the tearing away of the connecting service lines. Thus by one means or another, the containment of radioactive materials is most probably violated by the complex forces of the tornado. Successful containment during direct, or near direct, passage of the vortex would be the exception. It has been previously explained that once contained material will behave as would the same material, uncontained, incorporated into the airflow pattern at the point of release to the environs.

The last problem concerning the containment apparatus is an estimate of deposition for such heavy debris. Since these and other large items may be highly contaminated, it is important to determine the distance they are likely to move. It is extremely difficult to arrive at a quantitative

[5]U.S.A. Standard, Performance Specification and Methods of Test for Transparent Safety Glazing Material Used in Buildings, National Safety Council

estimate since there is insufficient data and no accurate tornado model is available. The decision here is to apply the health physics philosophy of determining the maximum possibility and use this as a limiting condition.

Earlier in this chapter the pertinent formulas were given for determining the maximum projectile velocities and the maximum height to which an object could be elevated. Utilizing these maximum parameters, it is possible to generate limiting contours for an object of particular dimensions and mass. The same idealizations stated previously are used in these calculations. From the maximum height one may determine the maximum time an object could be airborne. The formula for a falling body can be stated as $H = V_o t + 1/2\ gt^2$ wherein H is that maximum height attainable, V_o is the velocity at that height (in this case zero), and t represents the elapsed time.

Once the maximum time airborne is determined, a simple multiplication of this value by the maximum velocity possible will generate a limiting distance within which the projectile should fall. To diagram these contours, a radius can be marked off from the point of original location. This radius is of a length equal to the calculated maximum distance of transport. The radius may then be cut into an arc by the limiting width of the storm track. The debris pattern can be limited to a forward direction due to the translational movement of the vortex. Even if debris is thrown from the vortex on the back side, it would be forward along the storm track since the average translational velocity is 60 mph. or 88 feet per second. The successive drawings of Figure 4.1 show the steps in plotting such a limiting contour.

Several hypothetical objects were considered next. The dimensions and masses of these objects were chosen arbitrarily but an attempt was made to approximate such things as metal or wood of various shapes and lengths. The maximum values determined for these hypothetical projectiles are given in the tables of Appendix B.

The typical items of containment, already discussed, are listed again in Table 4.4. The maximum values of height, velocity and time airborne are shown and the last column gives the limiting distance of transport that is possible. Using the method described, and the values from this table, limiting contours for deposition were plotted. These are displayed in Figure 4.2. The contours define an area within which the object could be located. It is noted that only two items could travel far enough for display on this scale. The glove box and the small lead pig could be transported far enough to escape the immediate environs and may be found somewhere within the designated areas. The contours are distorted in the forward direction due to the translational motion of the vortex.

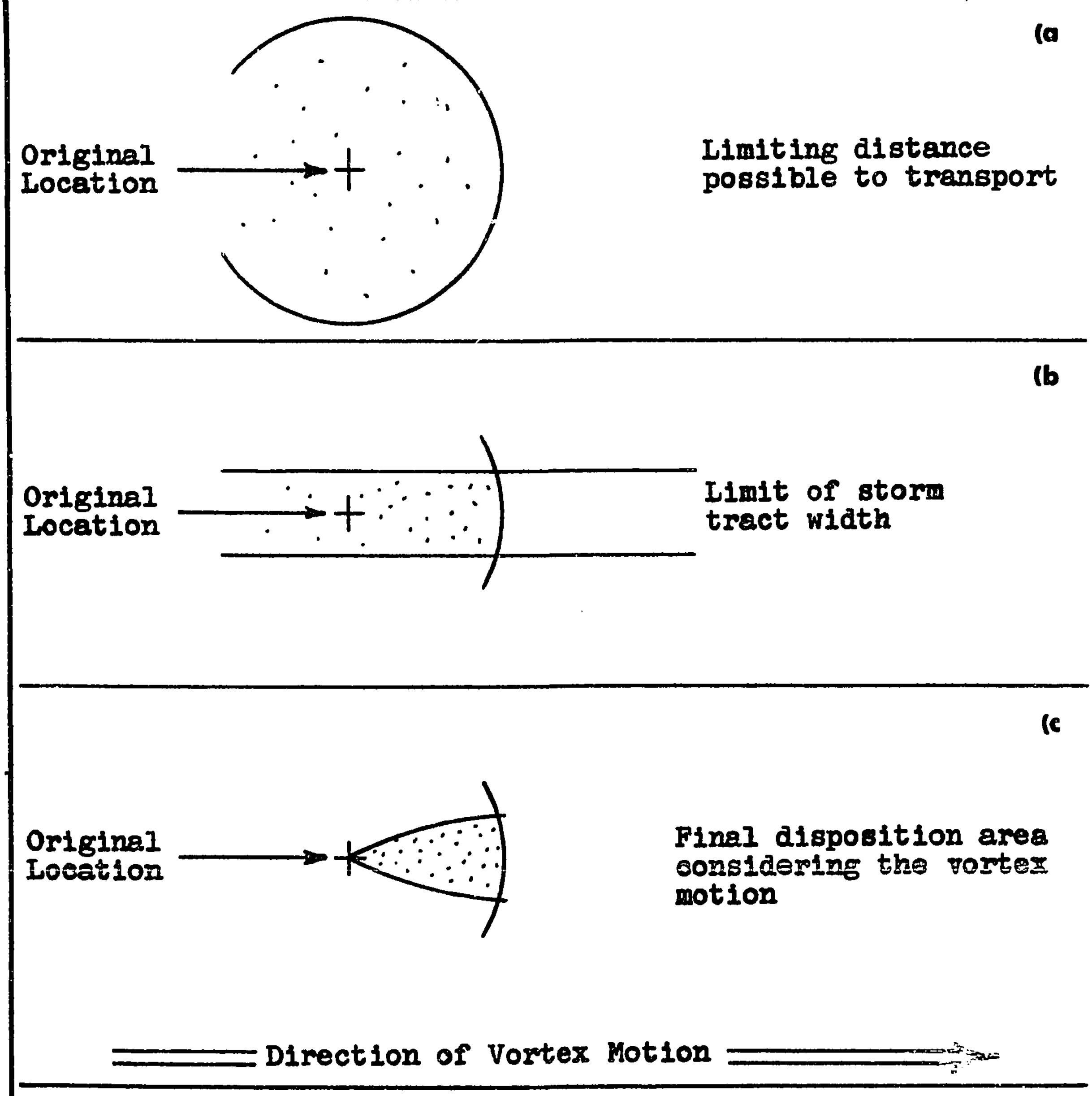


FIGURE 4.1

The Steps Taken In Plotting An Area Of Deposition For Debris Of Particular Mass And Dimensions

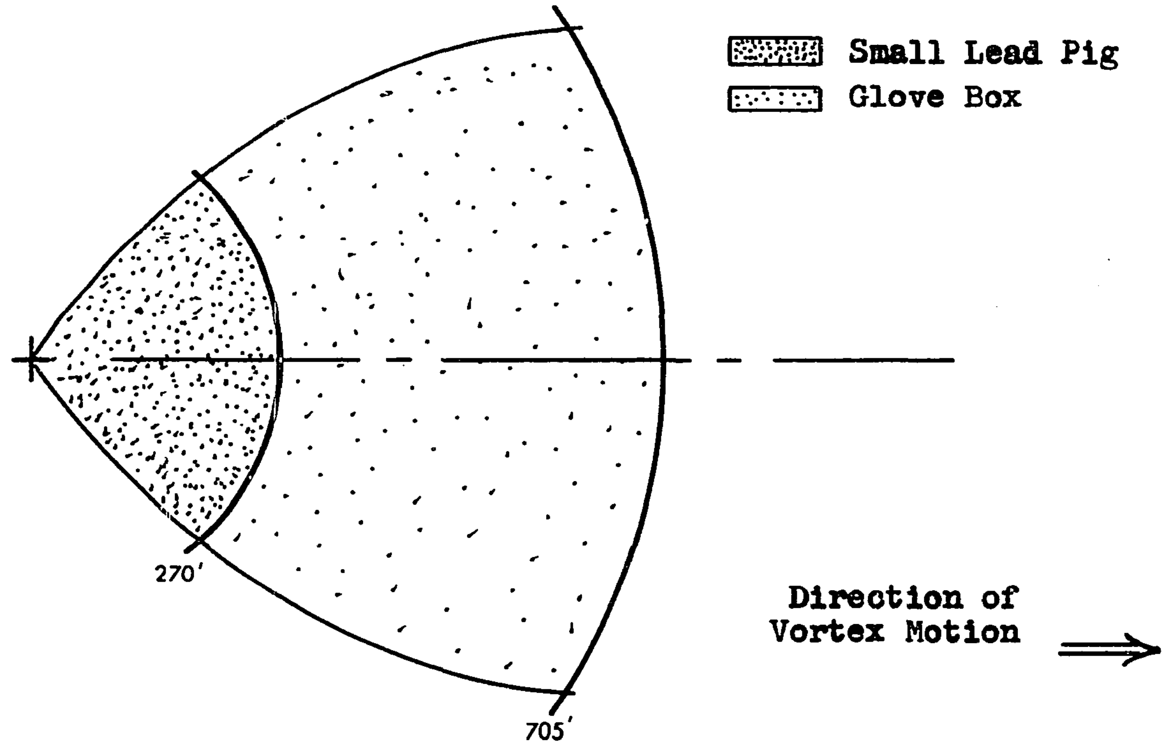


FIGURE 4.2

Deposition Areas For Two Of The Containment Devices Typically Found In A Nuclear Facility

Item	Max. Height	Max. Velocity	Max. Time Airborne	Max. Distance
Glove Box	350	150	4.7	705
Lead Brick	1.2	9.0	0.3	2.7
Storage Box	0.7	6.8	0.2	1.4
Counting Shield	0.3	4.3	0.14	0.6
Lead Vault	0.1	2.1	0.07	0.2
Lead Pig	134	93	2.9	2.7
Lead Pig	1.7	10	0.3	3.0
Carrying Case	1.3	2.9	0.1	0.3
Carrying Case	0.1	1.7	0.05	0.1

TABLE 4.4

Parameters For Determination Of Deposition Areas. Time Is Given In Seconds, Velocity In Feet Per Second And The Other Values Are Measured In Feet.

CHAPTER V

RESULTS AND DISCUSSION

It is immediately apparent that the fluid mechanics of the tornado are fantastically complex. The best estimates ar , those models based upon an idealized vortex, ignoring translational motion and assuming axial symmetry. Utilizing these estimates, one can generate trajectories within the vortex and exterior to the core. Interim movement is seen to be a distorted spiral upward and inward toward the vortex center. It is unlikely that particulate material incorporated into the irrotational portion will be subjected to mixing across the boundary of forced convection. Within the core behavior is much more difficult to predict. A portion of the material may be elevated to great heights while the remaining is likely to be scattered in the immediate environs.

For the particulate material elevated into the parent storm cell, dispersion becomes the major phenomenon. The single reconcentrating factor of the severe storm is the precipitation. In well formed tornado cyclones the precipitation occurs north and east of the vortex at least 80% of the time. This indicates that nuclear facilities should be located to the north and east of more densely populated areas.

Calculations indicate that the integrity of isotope containment devices will be violated. The device is likely to fail either due to the wind-pressure explosive effect or upon impaction from behavior as a tornado-borne missile. Once contained material would then behave in the same manner as would any material injected at the point of release. The containment devices will undoubtedly be contaminated and the after-storm location would be of extreme importance. Contours of limiting distance can be constructed to define an area within which a particular object would be deposited.

With the presently available information, the rainfall concentration profiles provide the best available estimate of deposition for particulate radioactivity. The maximum deposition areas provide the best available estimates for contaminated heavy debris. Figure 5.1 is the combined mapping of these two estimates for a tornado incident at a hypothetical nuclear facility. A similar mapping could be done in event of an actual incident. The heavy debris patterns were generated from objects in the tables of Appendix B, which are considered representative of typical items found in a nuclear facility. Note that the radial distance has been measured on a log scale so that both patterns may be displayed simultaneously. Years of diligent effort have not yet produced a mathematical model which adequately

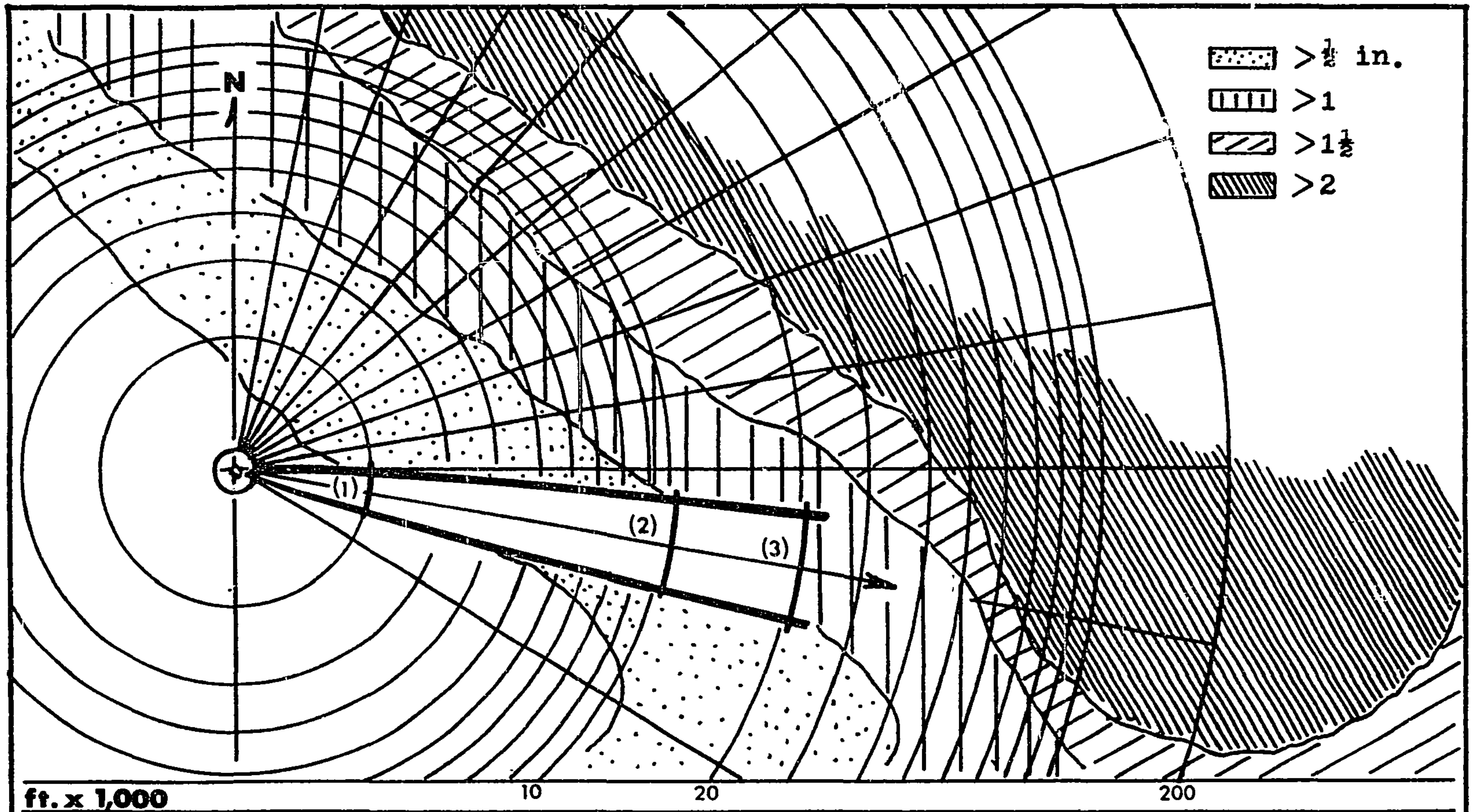


FIGURE 5.1

Combined Mapping Of Rainfall Concentration And Areas Of Deposition For Heavy Debris. Deposition Limits Are Shown For Objects (1) 0.2 x 0.2 x 4.0 ft.; 5lbs. (2) 0.2 x 0.5 x 2.0 ft.; 1 lb. And (3) 2.0 x 2.0 x 2.0 ft.; 10 lbs.

describes the fluid mechanics involved. Study of available literature offers no applicable means of deriving realistic numerical values. The individuality of each storm and the unique structure of each facility preclude modeling of air movement on the micro-meteorological scale necessary. The deposition patterns in this dissertation are presented as the best estimates possible with the current knowledge of tornado producing storms.

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APPENDIX A

TORNADO TIME-PRESSURE PROFILE

The cyclostrophic wind equation for a tornado vortex is:

$$\frac{\partial P}{\partial R} = \rho \frac{V^2}{R}$$

where P represents the pressure, R the radial distance from the center of the vortex, V the horizontal wind velocity, and ρ the ambient air density.

By integrating this equation over R, a theoretical pressure pattern can be generated for the tornado region. This method was used by Hoecker (1961) to derive the pressure pattern for the Dallas tornado of 1957. The average translational velocity of that vortex was 27 mph. By translating the pressure field over a point at 27 mph., the rate of pressure change, at that point, was obtained.

Figure A.1 shows the time-distance variation of the pressure drop for points at different distances from the tornado path. The drop is expressed in terms of per cent of the total pressure drop and force on a hypothetical wall. An estimated yield point for the wall is indicated by the triangle on the right-hand scale. The estimated yield point was obtained by assumption that the wall was nailed about the perimeter using two 20-penny nails per foot. Since the pull strength of this nail was given as 70 lb., a force of 140 lb. per foot of perimeter would cause it to yield.

This information might be extrapolated to provide structural design requirements for the walls of a nuclear facility.

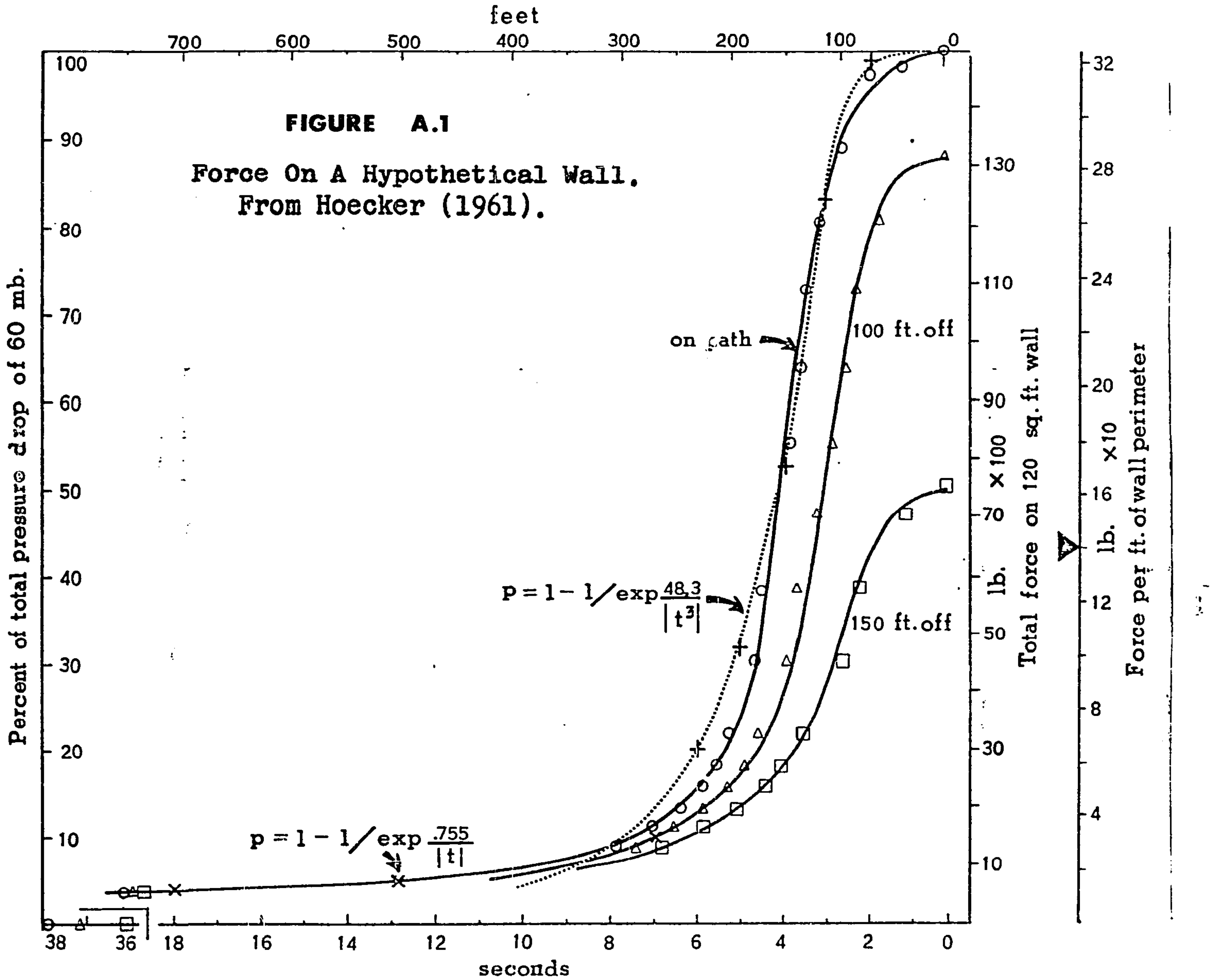

FIGURE A.1

Force On A Hypothetical Wall. From Hoecker (1961).

Dimensions (ft.)	Weight (lbs.)	Velocity (ft./sec.)	Time (sec.)	Distance (ft.)
0.2 x 0.2 x 0.2	5	116	3.5	406
0.2 x 0.2 x 4.0	5	256	8.0	2048
0.2 x 0.5 x 2.0	1	1180	37	43660
0.2 x 0.5 x 2.0	2	590	18	10620
0.5 x 0.5 x 2.0	5	256	8.0	2048
0.5 x 0.5 x 4.0	20	121	3.8	460
1.0 x 1.0 x 1.0	10	205	6.4	1313
2.0 x 2.0 x 2.0	10	825	26	21270
0.2 x 0.2 x 2.0	10	35	1.1	39
0.2 x 0.5 x 2.0	10	118	3.6	425

TABLE B.1

Maximum Deposition Parameters For Several Hypothetical Objects In A Design Tornado Having 300 mph Horizontal Winds.