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1. *Introduction.*

Although tornado occurrence is concentrated notably in such regions as the midwestern section of the United States, various parts of the world have experienced them. During the historic period and no doubt previously, people have been terrified and also mystified by these most violent of meteorological apparitions. In spite of increasing general knowledge about tornadoes in recent years, the intrinsic processes involved in their genesis remain largely undetermined, mainly because sufficiently detailed observational descriptions of various specific actions are still too difficult to obtain. This condition has invited the promulgation of many hypotheses concerning the true nature of tornadic disturbances, which differ basically in regard to the mechanisms proposed [see, e.g., KESSLER ([3]) for an enumeration of some of these schemes]. Since direct verification is not possible, each scientist must form his own judgement as to which of these are most plausible. The prospect is that this state of affairs will continue, at least for some time to come.

It must be recognized, however, that what may appear plausible or implausible depends not only upon our knowledge of facts concerning the tornado phenomenon itself, but also upon extrinsic factors such as our general scientific knowledge, and even more directly, our knowledge concerning other instances of rotating fluid systems in the atmosphere and elsewhere. Thus, as it happens, although our information regarding requisite details of tornado structure has grown but slowly, much progress has been made for example in specifying the principal actions maintaining the differential rotation of the atmosphere as a whole. Furthermore, not only have quite successful mathematical models been made of the atmospheric general circulation, but also laboratory fluid models have been constructed which duplicate the main actions involved. We therefore find ourselves in a new conceptual environment from which we may view afresh the physical problem possed by the mechanics of the tornado circulation.

This is not to say that many of the models which already exist in the literature do not present valid points which are known or may prove to be correct. However, as far as essentials for completeness go, probably no existing tornado model, whether of the mathematical or laboratory kind, is really adequate. The present purpose is then to suggest some physical features which may turn out to be precisely the needed additional ingredients. These features described below are of such a nature as to suggest that circulations comparable to the natural ones found in a tornado, except restricted in vertical extent, may possibly be capable of being initiated artificially, through the utilization of a properly designed and engineered, man-made structure. The actual use for such a device would be as a prime mover to produce power for commercial needs. The energy source would derive from the latent heat of condensing water vapor.

2: *Negative viscous action in convective systems.*

During the past two decades or so it has come to be known in meteorological (and to some degree astrophysical) circles that concentrations of angular momentum in a rotating fluid system can be brought about and maintained by a radial eddy transport of such momentum into the zone of concentration of high mean angular velocity. From the standpoint of kinetic energy, generally speaking this implies a transformation of the energy associated with the eddy motions into kinetic energy associated with the mean rotation. A physical source must therefore be in operation to provide the eddy kinetic energy. A common circumstance is that the eddy motions comprise a form of thermal convection, and are driven by some appropriate mode of differential heating. The process of obtaining concentrations of angular momentum in systems which operate in this manner I have called negative eddy viscosity [see STARR ([5]), STARR & GAUT ([9])].

Aside from these references, the literature concerning eddy processes has become most extensive, and the variety of natural phenomena investigated from the present viewpoint is increasing. Most of the initial descriptions were derived observationally for the case of the terrestrial atmospheric general circulation. No effort can be made here to provide bibliographic information, although the reader may derive some guidance to more recent results, mainly for the atmosphere, from articles by STARR, PEIXOTO & GAUT

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([10]); STARR, PEIXOTO & SIMS ([11]); PEIXOTO, GAUT & ROSEN ([1]); STARR ([6, 7, 8]).

In our atmosphere the large scale convection expresses itself in warm poleward and cold equatorward currents separated by fairly large sectors of longitude, which produce a net transport of heat away from the more tropical regions. Due to the coriolis effects and other factors, the poleward branches also carry more angular momentum than do the equatorward return currents. As a result angular momentum accumulates in a belt of circumpolar mean westerly winds in each hemisphere and corresponding belts of mean easterlies near the equator. The warm poleward currents have also a small upward velocity, while the cold equatorward flows descend as they proceed. In this way the warm air rises to higher geopotential levels while the cold air sinks to lower ones — a necessary condition for a convective process with respect to the field of terrestrial gravity.

Although one might use other systems to exemplify this kind of convective action, such as that in a rotating laboratory model [see HIDE & MASON ([2]), for instance], the atmosphere is perhaps one which has been studied the most. Without going farther afield in this general area, we shall therefore attempt to look upon the tornado circulation as having a basic mechanical similarity to what has been described. It is immediately clear that new concepts must be introduced beyond what is pictured as taking place in a tornado according to the more common views of the subject.

3: *The tornado vortex.*

The most obvious immediate fact in regard to the tornado vortex is that it represents an intense concentration of angular momentum around its axis. The latter need not be vertical, but instead may be even practically horizontal for a portion of its length. For simplicity in the first instance, we may however consider a vertical tornado for our model, except as otherwise necessary. It is convenient to develop the discussion by enumerating a number of individual arguments concerning various aspects of the problem.

a) The primary question is how the observed high concentration of angular momentum about the axis is achieved and maintained. It seems improbable that coriolis forces acting on a symmetric convergence of mass can generate it. Also, such convergence acting in combination with a pre-existing region of strong relative cyclonic vorticity, although a more plausible explanation, still has many difficulties as regards vertical motion in the vortex tube and otherwise. We therefore propose to examine the hypothesis that there exists an inward eddy flux of angular momentum from the environment into the vortex. The necessary eddy-type velocity distribution would then be present on cross sections normal to the axis, with the familiar tilted trough and ridge formations. The effects of the drain of angular momentum from the environment, i.e. a decrease in cyclonic rotation or an appearance of actual anticyclonic rotation, would not be marked because of the large radii involved. At a given instant not all cross sections of the vortex tube would necessarily be active, of course.

b) The quasi-horizontal inward and outward eddy components of motion would again comprise a mode of convection with certain distinctions, however, as compared with the general circulation process in the atmosphere. First, these actions would take place not with respect to the earth's gravity field, but with respect to a substitute. This substitute is the outward centrifugal force of the mean rotation, perhaps two orders of magnitude larger than true gravity. Secondly, the basic thermal asymmetries between the inward and outward flows would be provided by the release of latent heat of water vapor, preferentially in the inward moving air. Further essential aspects of the thermodynamic processes become difficult to specify *a priori*, and must await further study later.

c) Under the present views the source of energy for the tornado circulation is the latent heat of condensing water vapor. This energy can be liberated at all cross sections of the vortex tube, so that the driving process can take place along its entire length, if moisture conditions etc., are proper. It may be noted that the process described can take place equally well along stretches of the tube that are more or less horizontal — or even at an angle slightly inverted, as might sometimes happen. This follows, since the energy release does not involve true gravity, nor does it involve the coriolis force (directly at least). These forces no doubt are of importance in setting the stage in the atmosphere for the initial genesis of the tornado, however.

d) The hypotheses here presupposed lead us to a view of the sufficiently moist atmosphere as being in a sense a potentially explosive mixture, mechanically speaking, because of its large latent energy content. It requires but little computing to show that if 10 grams of moisture associated with 1 kilogram of air were to be condensed, and the entire resulting latent heat liberated were converted into kinetic energy of translation of the kilogram of air, the velocity would be inordinately large, i.e., about 200 m sec^{-1}. Wind speeds in tornadoes are normally much less, though concentrated gusts can be as large or larger. The important question concerns the manner in which the energy release mechanism can be triggered, so as to initiate a spontaneous cataclysmal reaction. That this does happen in nature with devastating results we know to be true. Can we perhaps penetrate somewhat beyond what is commonly said about this subject and put together a more detailed picture?

e) The initiation process, as we know, takes place in a mammato structure on the under surface of a storm cloud. This formation is likely due to extremely unstable conditions. We suppose, as in many traditional discussions, that due to the presence of cyclonic vorticity in the vicinity of shear zones, where other conditions also are proper, a mild local rotation develops somewhat by chance in the vicinity of the dependent bullate cloud. This we now say would cause a mild local depression of isobaric surfaces, and bring about the introduction of a small component of gravity substitute, in our terminology. The rather turbulent convective action on a smaller scale can now have a component radially inward and outward normal to the vertical axis at the center. The negative eddy viscous action can now take hold and concentrate angular momentum near to the axis. This inward momentum flow takes place at the expense of the visible outer portions of the bulla where little evidence of rotation is to be seen at this stage.

Once this initial « ignition » stage has been reached and other conditions are proper, a small intense vortex develops within the cloud and achieves perforation through the lower surface by a further downward self-ignition process into the otherwise often cloud-free air below. The shape of the tornado cloud now assumes the form of the familiar funnel. If moisture conditions are proper this pointing stage is surpassed, and the self-propagation continues to extend itself downward, perhaps to the surface. The important feature of the present view is that the downward extension process must be nourished by an adequate latent heat supply at each level that the vortex penetrates, through the (local) agency of radial convective action and the negative (moist) eddy viscous process.

The downward lowering of the vortex by the actions described above need not be strictly vertical, as the boring effect might be deflected by inhomogeneities in the air, or the vortex tube might be bent aside as a result of larger scale wind conditions. By « boring » we do not mean that there is a feeding downward of the main energy needed, as has been said, except for a small such transport of what we may call « ignition energy ». It is probably significant for the scheme being presented in this paper, that near the earth's (level) surface the axes of tornado vortices tend to be vertical. This follows because near the surface the eddy motions (which presumably extend some radial distance outside of the vortex proper) must be quasi-horizontal and are therefore incapable of supporting any but an essentially vertical vortex tube.

Apparently the birth of tornadoes takes place near or at the condensation level, as has been described. It is conceivable that upon occasion this level is rather low, so that even the somewhat vague early stage is experienced at the ground. In such cases a well organized vortex may never be formed. The initiation attempt is abortive, but even so damaging tornadic winds may befall a small region for a brief period of time during a strong thunderstorm. In such a case the energy for the disturbance probably originates directly in the low layers, from moisture available in the vicinity.

h) Some tornado vortices, when visible, present a ragged, turbulent appearance. In these instances probably the condensation level is low and the air even close to the surface is almost saturated. The inward turbulent eddy motions soon reach condensation, even with a small penetration of the vortex, since only a slight adiabatic pressure decrease suffices to cause saturation. Under such circumstances the tornadic engine develops a high horsepower output, especially near the surface where it performs a large amount of shaft work against ground friction. On the other hand, some vortices have a smooth appearance especially in their middle and upper reaches. The very fact that these segments are visible probably signifies that the ambient air is not close to saturation. The funnel cloud then is found only near to the axis of the vortex, and the vigour of the radial turbulent eddy motions is minimal. The segments of the vortex tube involved are operating under a throttled down condition, generating only a small horsepower output so to speak, commensurate with a low shaft work demand during an idling situation. Of course the inner radii of the vortex, which rotate with a high angular speed can appear much smoother than in fact they really are.

i) Once a tornado vortex is in existence the rotation of the earth does not enter significantly in the energy aspects of its circulation, although there might be other effects. Thus, so far as the preceding discussion goes, an anticylonic tornado is not excluded. However, its initiation would require a much less likely set of circumstances than for a cyclonic one, although by a suitable accident they may on rare occasions arise [see, e.g., CROWLEY (1)].

4: *Artificial generation of a tornado-like vortex.*

This proposition is rendered feasible in terms of the foregoing theory which pictures the tornado as a mechanism sui generis, which exemplifies the rather direct conversion of latent heat of water vapor into vigorous and concentrated kinetic energy. The fact which is important presently is that according to the views described the kinetic energy for each segment of the vortex tube is generated in situ, even though there may be certain equalizing processes among the segments to produce an articulate whole structure for the entire vortex tube. Thus the low pressure at the axis of a segment must connect with that of adjacent segments until at the upper reaches the ambient atmospheric pressure is low enough for the vortex tube to open out. At the lower end the chain effect of self-ignition lowers the small end of the tube to the ground or with, say insufficient moisture, the end retreats upward.

Clearly then, in an engineering attempt to generate the tornado type process under controlled conditions one must deal with only a segment of the vortex tube, and the problem of the end conditions must be dealt with in some satisfactory manner. All that we can do in this discussion is to offer one suggestion in this regard, being mindful that it might serve merely as a point of departure for much further comment later.

We may start with a rudimentary design for a latent energy power plant. For reasons of convenience in construction the smallest practical size of the structure should be envisioned. So far as is known the smallest diameter of bona fide tornadoes in the atmosphere is about 50 meters [see picture in Encyclopedia Britannica, 1960 ed. under TORNADO]. We may assume this size for our purposes, although still smaller functioning ones may perhaps be possible. The length of the (vertical) segment to be used should probably be much larger, say about 500 meters. The main working part of the installation would be a vertical rotor in the form of a large spool having these dimensions and a stem diameter of perhaps ten meters, mounted on bearings so that it may rotate about its long axis. Small radial impellers might be needed, affixed to the stem to increase frictional interaction with the surrounding moist atmosphere.

The mode of operation is as follows. Assuming the air to be of proper high humidity, the rotor is given a suitable rate of spin by a conventional starting motor of some convenient type, to create a vortex in the environment. The vortex would presently become unstable with respect to moist adiabatic inward moving eddy components of motion, thus creating a turbulent regime in the vortex. The eddy motions would then tend to cause an inward eddy momentum flux, i.e., exhibit the negative eddy viscous phenomenon. Henceforth the vortex would be self-supporting with, let us say, a pressure at the rotor stem of perhaps 50-100 millibars below the ambient atmospheric pressure. The (plane) rotor flanges would prevent a filling of this partial vacuum from the top or bottom. Power take-off would now be made from the rotor, since the latter would be driven by the self-sustained vortex.

The moist eddy turbulence would continuously exchange air from which water vapor has been squeezed out by the convective aspect of this turbulence, for more moist air from the environment. We assume that the environment has a continued new supply of moist air (a natural breeze might feed it to the plant site from the up-wind direction). The condensed fresh water would be flung outward from the vortex in the form of drops and could be collected by some appropriate catchment structure.

Numerous items of interest and of critical detail are naturally brought into focus by the material which has been outlined. Some of these may be listed as follows.

1) How sure are we that a power plant of the kind described could, at least eventually, be made to work as indicated? In a subject so complicated as the natural turbulence in a tornado — of which our device can be only an approximate artificial analogue — nothing can be really certain. However, our view of tornado mechanics has many features which commend it as realistic. If in picturing the experimental analogue the essential ones are not sacrificed or compromised excessively, the model should work, although its perfecting and construction would be a rather imposing project to contemplate. However if we are to find new sources of power, installations of large physical size no doubt will have to receive consideration in many of the novel processes which doubtless will be envisioned, not alone the one projected herein.

2) Why cannot small scaled-down laboratory versions be made to test out the prospects of success for a full scale model? All manner of preliminary experimentation, even perhaps some at first unlikely looking investigations, should be made in order to examine the subject as thoroughly as possible, since if final success can be attained, the importance of the results would justify these efforts. One problem in scaled-down models would be whether liquid water (or drops of other water-substitute) could be removed from the vortex to prevent re-evaporation which would annul the energy releasing action.

3) Could mathematical models be made of the turbulent energy release process in the moist air? No doubt once the physical actions are known in greater detail through physical thinking, more observation of prototypes and from various kinds of experimentation, many forms of mathematical treatment will contribute to an increased knowledge of such turbulence processes. Unfortunately numerical models involving condensation phenomena are difficult to make, requiring extremely fine grid meshes.

4) Most sources of commercial power utilize fossil fuels which represent stored energy in some form. Nuclear power is an exception. Water power on the other hand utilizes more recently received solar energy stored in the liquid hydrosphere. Latent energy represents solar energy acquired most recently and stored in the gaseous hydrosphere. Its supply is continuously replenished and is conveniently available, although some geographic areas have relatively richer supplies of it than others. Its utilization would make but little impression on the supply available, because of its rapid regeneration. Also, no particular pollution problem should accompany its use as outlined above, since the by-product is fresh water at close to normal temperatures — an increasingly valuable commodity.

5) Power output estimates are difficult at best for our plant. Some conditional notions may however be made to indicate at least some potentialities. Let us assume that under load conditions the vortex condenses out one kilogram of water per second for each one meter of vertical distance along the central axis — seemingly a possible expectation. The total for the entire height is therefore 5×10^5 gm sec^{-1}. The corresponding latent energy release is roughly 3×10^8 cal sec^{-1} or about 1.25×10^{16} erg sec^{-1}. At an efficiency of 4

percent this is equivalent to an output of 50 megawatts, which is certainly an acceptable amount.

6) No doubt there is a minimum water vapor content of air below which a given design of a latent energy power plant could not function properly. Thus climatological factors would be of prime importance in locating plant sites. It of course does not follow that the most favored locations would be those having highest frequencies of tornadoes. Tornado occurrence depends not only upon high moisture but also upon the triggering operation which is provided naturally by rather infrequent proper combinations of other meteorological factors. The second of these would not be needed in the case of the power plant as been stated already.

7) The equipment described for the generation of power was suggested to me partially through efforts to design a machine to produce fresh water from atmospheric sources [see STARR, ANATI & SALSTEIN ([13]) and STARR, ANATI & GAUT ([12])]. In order to bring air to its adiabatic condensation pressure, a large vertical lift was needed, i.e., about 1-2 km, so that the vertical tube used would have to be of at least somewhat greater height. The only way to eliminate this trouble seems to be to use a gravity substitute as we have done here. Parcels of air migrating inward may then experience the requisite drop in pressure by moving a much shorter distance, if the gravity substitute is sufficiently large. Since a practical means for doing this is to use the centrifugal force in a strong vortex, the linkage with tornado mechanics is an obvious one. On the other hand, the possibility of producing an organized pool of kinetic energy from turbulent eddy form through the agency of the negative eddy viscous phenomenon has long been a preoccupation of mine. My long quest for a means of using it to generate power in substantial amounts has at length now prospered somewhat, although what has been said here is of course but the merest of beginnings. Moreover, we must in any event recognize that there may be other methods by which latent energy can be utilized fot the generation of power.

8) My colleague, Dr. NORMAN E. GAUT, has suggested to me that the type of plant described above might be advantageously combined with a conventional thermal or, perhaps more especially, with a nuclear plant. The point being that the rejected heat from these latter could be used to enrich the input for the latent energy plant, so that the total over-all effect of the system would be to secure an enhanced efficiency of power production and a decrease of heat pollution for the entire environment. Study of this question might show also that an enriched input for the latent energy component can reduce its minimum necessary size for a given output, and make initial trial construction less expensive.

9) All methods of high output power generation carry a risk of accidents with possible loss of life and destruction or damage of property. In the case of our projected latent energy plant, besides other risks, there could be a danger that under structural collapse the tornado-like vortex would escape into the atmosphere, forming an actual tornado to ravage the surrounding countryside. Not much can now be said about such eventualities — presumably the risk could be reduced by proper safety measures.

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Summary — A dynamic mechanism for the genesis and maintenance of the tornado is described and compared with various known facts of observation. The view is taken that the circulation derives its energy from the latent heat of condensation of water vapor. The kinetic energy appears first in eddy form as a product of moist convection, not with respect to the earth's gravity but with respect to a gravity substitute which is much larger, namely the centrifugal force of the mean tornadic circulation itself. The eddy kinetic energy is then transformed into the kinetic energy of the mean circulation through the well known negative eddy viscous process. Each segment of the tornado vortex tube can thus generate its own energy supply in situ. A proposal is made that the tornado mechanism outlined could be initiated and controlled in a properly engineered latent energy power plant, for the commercial generation of electricity. Using the smallest diameter vortex observed in natural tornadoes (i.e., 50 meters) and a vertical segment height of 500 meters, a very crude estimate of the output is of the order of 50 megawatts.