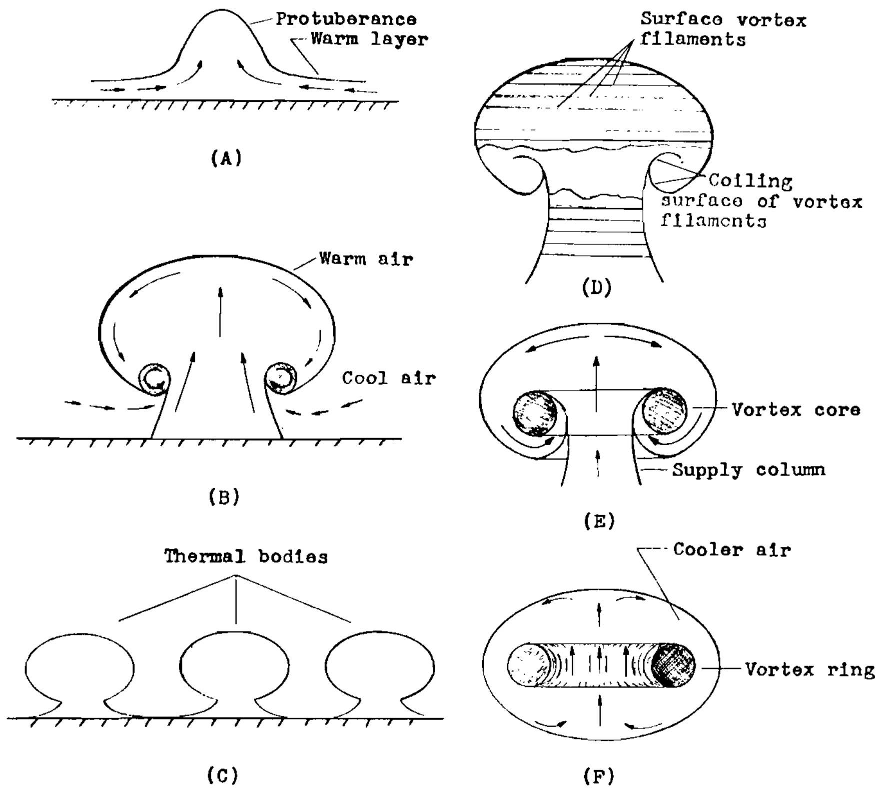

Fig. 1. Stages in the development of a free thermal. (Cross-sectional views.)

the facts indicate that fixed sources are rare compared to the total thermal production, especially over flat land. The great significance of free thermals to soaring has not been generally appreciated primarily because they are difficult to locate and follow, that is, for conventional sailplanes to follow. A knowledge of the structure of free thermals should help considerably in their utilization by soaring pilots. Therefore let us consider the formation and growth of a typical free thermal.

Formation and structure of free thermals.—Consider a free thermal in its initial stage of formation as the protuberance pushes into the cooler air (figure 1A). The protuberance grows as more and more warm air flows into it until finally the warm air supply in its vicinity is exhausted and the cool outer air settles in and pinches off the protuberance. It now becomes an isolated shell or bubble of warm air surrounded by cool outer air (figure 1B). This "bubble" may contain from a few to many millions of cubic feet of warm air, the size depending upon many factors but primarily upon the frequency with which other bubbles are forming in the warm air layer (figure 1C). As the protuberance pushes up into the still air, vorticity is continuously produced at the boundary between the buoyant and outer air. This vortex surface (actually a continuous distribution of elemental vortex rings) begins to coil up under the action of the induced velocity field (figure 1D) in much the same manner as the flat vortex sheet behind a lifting airfoil coils up into concentrated vortices.*

As the shell of buoyant air rises, the production of vorticity continues with the coiling process increasing the size of the interior vortex ring. The exact details of this vorticity production process are not clear but after some relatively brief development period the buoyant air has assumed the form of a vortex ring. (See figure 1E, 1F.) Observations of the formation of free thermals from the hot gas cloud of surface explosions show that the time required for the ring to form from the initial cloud is only a matter of a few seconds so that we may reasonably expect atmospheric thermals to form into vortex rings rather rapidly also, say within a few hundred feet of altitude. We need not be too concerned with this initial development, however, for the really important fact is that after the development is complete, the form of the thermal sufficiently approximates that of a vortex ring that we may with reasonable accuracy consider the subsequent motion of the thermal to be that of a buoyant vortex ring system.

This is a very important result, since the motion of non-buoyant vortex rings is indirectly amenable to mathematical treatment and the effects of the buoyancy of the ring can be appropriately accounted for with a few reasonable assumptions.

A vortex ring has a rather remarkable property. Provided the diameter of the ring is less than 86 times the diameter of the core (and this is nearly always the case, especially with thermals), the vortex ring will not travel alone through the air as a ring, but the velocity pattern it induces is such that a body or shell of external air is entrapped by the ring and carried along with it as it rises (figure 1F). Thus the ring entraps and imparts motion to a relatively large mass of air which was originally motionless in the surroundings. The struc-

* C. D. Cone, Jr.: "The Limit of Circulation Lift on Airfoils of Finite Aspect Ratio," *Thesis*, Department of Aeronautical Engineering, University of Virginia, May, 1960.