capillary action, as in a wick. Textiles, paper, fiber board, clay products, and the sapwood of most species of lumber represent material of this type, as well as finely-divided materials which come in granular or powder form. In such substances the free water is removed usually without difficulty in the successive stages of saturated surface drying and unsaturated surface drying, followed by the removal of the hygroscopic moisture in the form of sub-surface drying.

In certain other materials of thick and more or less rigid form, notably the heartwood of some kinds of lumber, the free water contained in the capillary spaces appears to be, in a sense, *bottled up* and cannot be made to flow from the interior to the surface in appreciable amounts. To remove the free water from such substances necessitates sub-surface vaporization within the material at the boundary of the free water zone, followed by diffusion of the vapor through the surrounding zones either as vapor or as adsorbed hygroscopic moisture. In either case, the zone surrounding the free water must be dried below its fiber saturation point in order to lower the vapor pressure to a point below saturation and thus permit this diffusion to take place. This means that shrinkage and other physical changes such as stiffening or hardening must occur in this outer zone before the interior portions have lost their free water and are ready for such changes. Consequently severe and harmful tensile and compressive stresses are apt to be set up in the drying of this type of material, due to unequal and non-synchronous shrinkage in the different zones, resulting in such injuries as surface cracking, honey-combing, warping, and *case-hardening*, or the setting of the surface portion in a stiffened expanded condition.

In obtaining maximum speed of drying of materials in which there is no capillary flow of free water to the surface, an increased moisture movement may be produced by passing an electric current through the material or by applying heat by contact directly to the interior or to one or both sides. Such means are usually impracticable, however, and dependence must be placed in most cases upon the effect produced by heated air or other gas surrounding the material. In such cases the speed of drying can be increased in only two ways, first by lowering the moisture content at the surface through the use of a lower humidity, or second, by increasing the temperature. The risk of harmful shrinkage limits the first, and the risk of exceeding the critical temperature of the material limits the second.

The use of too high a temperature in removing the free water from fibrous or cellular materials of this kind, increases the plasticity of the structure and at the same time is apt to create a liquid tension within the cells themselves. This force, which may amount to many atmospheres under certain conditions, tends to draw the walls of the cells together, thus producing a *collapse* of these cells. This phenomenon is the cause of much injury in the drying of certain kinds of lumber and is probably present to a greater or less extent in the drying of all refractory material of a cellular nature through which the free water cannot flow by capillarity.

Another result of trying to force the drying of these refractory materials at too fast a rate is the increasing resistance to the passage of heat from the surface to the interior and the passage of vapor outward, as the

dryness of the surface increases. With many materials of this type, if the surface is allowed to dry below a certain point, it becomes increasingly difficult, not only for additional heat to penetrate to the interior, but also for vapor to work its way outward through the dry outer zones to the surface. Under these conditions the drying becomes very slow or ceases entirely and is replaced by a baking operation.

Internal Moisture Gradient

In drying by surface evaporation, an internal concentration gradient is set up between the moisture content at the center of the material and the moisture content close to the surface. The steepness of this gradient is dependent upon the rate of evaporation at the surface and the rate of transfusion of moisture from the center outward. In general, the steeper the gradient, the faster the drying. Since raising the temperature increases the rate of transfusion, the rate of drying is thereby increased without increasing the steepness of the gradient. For this reason the maximum temperatures which can be used without injury to the material will usually be found to produce the maximum rate of speed consistent with safety.

In keeping the moisture gradient within safe limits, during those stages of drying when surface shrinkage is taking place, the drying should be retarded by preventing the surface from drying below a certain critical moisture content which must be determined experimentally for different materials. This control of surface drying is accomplished by regulation of the relative humidity of the air in the dryer in conjunction with the regulation of the temperature. In continuous dryers of the counter-current type, the fresh material is subjected to the lowest temperature and highest humidity while the dried product at the discharge end meets the hottest and dryest conditions, thus furnishing a degree of automatic regulation to suit the needs of the stock. A higher humidity can also be provided by recirculating a portion of the air in the dryer and by means of steam jets.

Equilibrium Moisture Content

With every material having hygroscopic properties, a point of equilibrium is reached between the vapor pressure of the moisture in the air and the vapor pressure of the moisture in the surface of the material. Every combination of temperature and humidity produces a corresponding equilibrium moisture content in the material. It is, therefore, possible to so regulate the conditions in the dryer at any stage of the operation that moisture in the material cannot drop below a certain equilibrium point, as may be desired for best results.

In the drying of most hygroscopic materials, the drying is continued until a somewhat lower moisture content is reached than equilibrium under conditions in use, to allow for enough regain to balance the moisture remaining in the interior and surface to a uniform condition. It is usually undesirable to carry the drying much beyond the equilibrium point of the material in use, as over-drying is liable to produce undesirable physical changes in the material, and such over-drying also unnecessarily prolongs the time and increases the cost of the operation.