(*23*). It appears that the binary Fe-Ni diagram is a poor approximation to the real situation, and it is of interest that Vogel (*24*) has proposed an altogether different mechanism of formation of the Widmanstätten pattern, based on the fact that the stability field of the α-phase is extended up to the liquidus in the presence of only a few tenths of one per cent of phosphorus, as is commonly found in iron meteorites. However, even in Vogel's model it is assumed that the iron meteorites cooled very slowly through the temperature range 600–400°C.

This condition presents a formidable difficulty for the planetary hypothesis. The core of the "planet" must have been molten at one time, to permit the segregation of metal and silicate, but Urey (*25*) has shown that a body of only lunar size, if melted by any process whatever, could not cool to the required low temperatures in the entire age of the solar system, even if heating by uranium, thorium, and potassium-40 is ignored. If the heating effects of these radionuclides are considered (*26*), it is found that the radius of the parent body cannot have exceeded 1000 km. It does not seem possible, therefore, to account for the detailed features of the iron meteorites by postulating their origin in planetary-sized parent bodies.[3]

Primary and Secondary Objects

The second of the principal theories of meteorite origin was conceived by H. C. Urey. He proposed that the meteorites developed in two successive generations of bodies (*6, 7, 22, 25*). The first of these (the primary objects) accumulated at low temperatures, incorporating a substantial content of thermodynamically unstable compounds and possibly free radicals. Chance events, occurring from time to time, triggered exothermic chemical reactions in this material. Provided the primary object had grown to sufficient size to prevent the explosive dispersal of the reaction products (Urey has estimated that a lunar-sized object would be required), localized reduction, melting, and segregation of metal and silicate phases would result in the formation of pools of perhaps meter or tens-of-meter dimensions. The silicate pools would differentiate upon cooling into more or less pure minerals, the precursors of the achondrites, whereas the metal pools provide material for the iron meteorites. These reactions must occur near the surface, due to the difficulties in storing the reactive compounds at depth. Continued growth of the object would cause some of these segregated regions to be buried at great enough depths to permit formation of diamonds from graphite. If the temperatures in the interior of the object happened to remain near 450°C, the Widmanstätten pattern could form.

The secondary objects are thought to have been bodies of asteroidal size, or, alternatively, the surface regions of primary objects. In the secondary objects, the chondrites were agglomerated from debris resulting from collisions between primary objects, and were compacted under varying but generally low-temperature conditions. Still later in cosmic history, further collisions occurred which, in turn, broke apart these secondary objects and produced the meteoroids.

This theory has the advantage of being able to explain, or at least accommodate, most properties of the meteorites, although it often relies upon events which would seem to have low probabilities of occurrence. Some of the difficulties of the planetary hypothesis also apply to Urey's theory. If the primary objects were of lunar size or larger, the problem of mass loss from the asteroidal belt discussed above, and perhaps also the problem of breaking up such a body, must be considered. Probably the most severe disadvantage of this theory is that the range of permissible conditions in the interior of the primary object seems to be quite small. Pressures must be high enough, at some point, to synthesize diamonds, yet high pressures would lower the γ-α

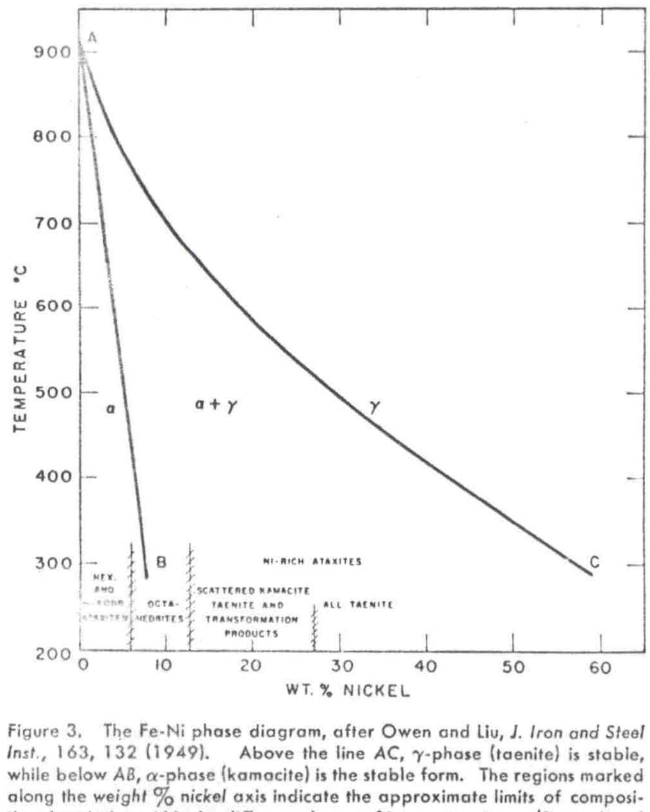

Figure 3. The Fe-Ni phase diagram, after Owen and Liu, *J. Iron and Steel Inst.*, 163, 132 (1949). Above the line AC, γ-phase (taenite) is stable, while below *AB*, α-phase (kamacite) is the stable form. The regions marked along the *weight % nickel* axis indicate the approximate limits of compositional variation within the different classes of iron meteorites. (Reproduced from (*27*) with permission of the editor.)

[3] In fairness to the proponents of the planetary hypothesis, it should be pointed out that two otherwise puzzling features of the iron meteorites may be explained by the effects of high pressures. The nickel-rich ataxites ($\geqslant$16% Ni) do not display a Widmanstätten pattern, but only a rather irregular mixture of α and γ phases. The same is true of plessite ($\geqslant$12% Ni) in octahedrites, which would also be expected to display a miniature Widmanstätten pattern according to Figure 3. As pointed out by Uhlig (*27*), pressure lowers the γ-α transformation temperature, so that both plessite and the nickel-rich ataxites might have been kept in the γ-form by high external pressures. Upon release of pressure during the break-up of the parent bodies, it is suggested that these alloys suddenly found themselves in the α-region, and transformed promptly to an irregular mixture of α- and γ-phase. However, this explanation of the absence of a Widmanstätten pattern in alloys of high nickel content is not unique. The phase diagrams presented by Vogel (*24*) indicate that, at phosphorus contents commonly found in iron meteorites, these alloys differ from those of lower nickel content in that there is no high-temperature α or $\alpha + \gamma$ field adjoining the liquidus in their phase diagrams. In Vogel's model, the formation of a Widmanstätten pattern would thereby be precluded. Regardless of which theory is finally agreed upon, it would seem that changes in the binary Fe-Ni phase diagram induced by the inclusion of minor constituents of iron meteorites should be carefully considered.