**METALLOGRAPHIC COOLING RATE OF IVA IRONS REVISITED.** J. Yang[1], J. I. Goldstein[1] and E. R. D. Scott[2], [1]Dept. of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, MA 01003, USA, Email: jiyang@ecs.umass.edu and jig0@ecs.umass.edu, [2]Hawai'i Institute of Geophysics and Planetary, University of Hawai'i at Monoa, Honolulu, Hawai'i, 96822, USA, Email: escott@higp.hawaii.edu.

**Introduction:** There is long standing problem reconciling the chemical evidence that the IVA iron meteorites formed in a core [1, 17] with the diverse cooling rates reported by several researchers (e.g. Moren and Goldstein [2], Rasmussen et al., [3]). This large inferred range of cooling rates suggests that the IVA irons were distributed at different depths in a parent body with a complex structure when the Widmanstatten pattern formed. On the other hand, some researchers (e.g. Willis and Wasson [4], Wasson and Richardson [5]) argued that the diverse cooling rates in group IVA result from inaccurate model parameters such as phase diagram, interdiffusion coefficients, and kamacite nucleation and growth mechanisms. In addition, the measured cooling rates may not apply for the same cooling temperature ranges, and the variation in the crystallographic orientations of the Widmanstatten plates on the analysis surface may result in inaccurate measurements of widths needed for the computer simulation models.

We have revaluated the major parameters in computer model developed by Hopfe and Goldstein [6] and measured cooling rates for the IVA irons. Such data are useful in evaluating whether these meteorites were part of a single core of a parent body during the formation of the Widmanstatten pattern.

**Revised Computer Model:** The metallographic cooling rate model depends on four parameters: phase diagram, interdiffusion coefficients, phase transformation mechanism from taenite to kamacite, and kamacite nucleation temperature.

*Phase Diagrams.* The binary Fe-Ni phase diagram [7] is used to obtain the polynomial equations for the solvus lines. The effect of P on the Fe-Ni phase diagram is a critical parameter especially at lower temperature (<673 K). The available experimental data for ternary Fe-Ni-P in both laboratory alloys and meteoritic metals have been reevaluated and an updated Fe-Ni (P saturated) phase diagram is used

*Interdiffusion Coefficients.* The diffusion coefficient in the binary bcc Fe-Ni phase has been investigated experimentally by several researchers. There are no consistent experimental results available especially below the Curie temperature. Yang and Goldstein [8] explored a new method which utilizes the effect of magnetic ordering on physical, magnetic and mechanical properties of Fe-Ni alloys to directly calculate the diffusion coefficients. The calculated results are consistent with the most recent experimental results by Cermak et al. [9]. Yang and Goldstein [8] also refit the diffusion coefficient in binary fcc Fe-Ni over a large Ni composition range (10~75%Ni).

The significant effect of P on the diffusion coefficients in kamacite and taenite has been shown experimentally by Dean and Goldstein [10]. After re-evaluating the experimental data of Dean and Goldstein [10], we found that the equations given by Saikumar and Goldstein [11] and Hopfe and Goldstein [6] are no longer valid. We have proposed new equations to reflect the modifications of both experimental and theoretical data on the effect of P.

*The Widmanstatten Pattern Formation Mechanism.* The importance of the formation mechanism for the Widmanstatten pattern has not been fully recognized in cooling rate calculations. Yang and Goldstein [12] have shown that three mechanisms may be responsible for the formation of the Widmanstatten structure in meteorites depending on the bulk Ni and P. Because of the low P content of IVA irons, the Widmanstatten structure formed by the transformation: $\gamma \rightarrow \alpha_2+\gamma \rightarrow \alpha+\gamma$. The $\alpha_2$ (martensite) phase forms before the IVA irons enter the $\alpha+\gamma+$Ph three phase field. On cooling, the $\alpha_2$ phase subsequently decomposes into $\alpha$ (kamacite) and $\gamma$ (taenite). The resultant $\alpha$ grows into residual $\gamma$ phase.

*Kamacite Nucleation Temperature*. The kamacite nucleation temperature is controlled by the kamacite nucleation mechanism. For the IVA irons, the kamacite nucleation temperature occurs at the Ms line, martensite start temperature, which also varies with Ni content.

**Cooling Rates of IVA Irons:** We use the central taenite Ni vs. taenite half-width method [13] to obtain the cooling rates for 16 IVA iron meteorites using analytical data from refs [2-4]. The cooling rates vary strongly from ~5000 C/My at the low Ni (~7.7%) low P (~0.02%) end of the group to about 50 C/My at a composition of ~8.6%Ni and ~0.1%P. The cooling rates are constant at ~50 C/My as Ni and P increase from ~8.6%Ni and ~0.1%P to ~10.3%Ni and ~0.18%P

**Discussion:** *Kamacite Nucleation Temperature.* For Widmanstatten pattern formation, the nucleation temperature is known (Ms) and no undercooling in the IVA irons occurs. The calculated cooling rate is relevant over a temperature range from Ms to ~400 C.

*Cooling Rate Comparison*. Our cooling rate results are consistent with previous cooling rate results (e.g. [2-3]). The absolute values of cooling rates are the highest values reported for the IVA irons. For example, Moren and Goldstein [2] reported that the range of cooling rates in the IVA irons is from 3 C/My to 200 C/My and Rasmussen et al. [3] reported the range of cooling rates from 19 C/My to 580 C/My.

*Variable Cooling Rates?* Wasson and Richardson [5] argue that the correlation between the varying cooling rates and the bulk Ni composition could result from a systematic error in the cooling rate model rather than a true variation in the cooling rates experienced by the IVA irons. Since we have used an entirely new mechanism for Widmanstatten pattern formation together with updated diffusivity and phase diagram, it is very difficult to believe that the variable cooling rates in the low-Ni part of IVA result from a systematic error.

*Cooling Rates and Structure of Parent Body*. The wide range of cooling rates in IVA irons that we and most previous authors derive is not compatible with cooling at depth in a core. Haack et al. [14] inferred from the pyroxene microstructures in Steinbach that it cooled at ~~100 C/hr through 1200 C as a result of a catastrophic impact that fragmented the IVA core. Such an impact was also invoked to account for the abundant silicates in Steinbach and Sao Joao [15, 16]. Haack et al. inferred that the diverse cooling rates of the IVA irons reflected burial at diverse depths in a reassembled asteroid consisting of jumbled core and mantle fragments. The inverse correlation between cooling rate and Ni concentration among the low-Ni IVA irons with 7.7-8.4% Ni was inferred to be a spurious result of poor sampling.

Since the thermal conductivity of metal is ~30 × higher than that of unbrecciated mantle, the thermal gradient in deeply buried metal is trivial compared to that in the silicate. But if a catastrophic impact left part of the core exposed with negligible silicate insulation (<100 m), appreciable thermal gradients could have been established in the periphery of the core or core fragment. The low-Ni IVA irons with Ni-correlated cooling rates may be derived from such a core fragment, given that cores crystallize inwards with the lowest-Ni irons on the outside [17]. Interestingly, the cloudy taenite microstructures of IVA irons suggest that cooling rates below 350°C were much more uniform and uncorrelated with Ni [18]. This uniform cooling rate at low temperature can be explained if impacts gradually covered the low-Ni IVA irons with regolith so that cooling rates below 350 C, ~$10^7$ yr after the catastrophic impact, were once again controlled by the thickness of silicate mantle material.

**Acknowledgements:** The financial support from NASA through grant NAG5-11778 is acknowledged.

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