They hypothesized that the breakdown between the models and reality occurred for two reasons: one relating to the shape and size of the particles and the other to the process of packing.

The first part of the Basic Energy Sciences research aimed at making unfired ceramic powder that consisted of tiny, uniformly sized spheres, made as perfectly round as possible. Methods for producing such spheres from titanium dioxide (TiO_2) were developed using carefully controlled *chemical* processes instead of milling. Both wet chemistry precipitation and, later, laser-heated gas-phase chemistry provided the tiny monosized powder particles with the desired characteristics. Each particle was so small, in fact, that tens of thousands of them could be lined up within a span of a single inch.

The second part of the research focused on solving the packing problem. The tiny spheres were suspended in a liquid and allowed to settle out slowly as a sediment. But even when the spheres were uniformly sized and perfectly round, they tended to clump together in a process called agglomeration. This clumping resulted in uneven densities and relatively large structural flaws.

The researchers knew that agglomeration was problematic because the tiny particles were so small. Under such conditions, the normally weak interparticle forces become comparatively strong and influenced the nature of particle dispersion in the settling process. These forces, most notably Coulomb and van der Waals forces, arise from variations in the physical distributions of atoms and their electrons on the surfaces of the tiny particles.

Building on methods borrowed from other fields, such as surface and colloidal chemistry, Basic Energy Sciences researchers recognized the importance of acidity in controlling these interparticle forces. By adjusting the acidity (pH level) of the suspension liquid, the researchers were able to prevent agglomeration during the sedimentation step. The powder was then collected as sediment from the stable dispersion.

With these two advances, the packed particles achieved nearly homogeneous density, closely approaching that of theoretical limits. This arrangement of closely packed spheres also resulted in a uniform distribution of voids. This, in turn, promoted uniform shrinkage and densification during the sintering process. Such uniformity had never before been achieved with conventionally milled powders and less controlled sedimentation processes.

Importantly, two other advantages appeared. The sintering time required to achieve 96 percent of the theoretical density was dramatically reduced, from 120 minutes to 10. Further, the firing temperature was reduced from 1500°C (degrees Celsius) to 1060°C.

Besides providing obvious efficiency gains to the manufacturing process, the lower temperature and shorter sintering time greatly impeded the growth of fused grains in the ceramic microstructure. This is important because the physical properties of ceramics are strongly dependent on both the size and uniformity of the grains. Smaller and more uniform microstructures markedly improve the mechanical characteristics of the bulk material. The new process routinely demonstrated reduced grain growth by factors of 20 to 1, and in some cases, 50 to 1.

Finally, the lower firing temperatures led to one immediate benefit for the electronics industry. It allowed certain ceramics to be used as parts in large integrated circuits. Before, the higher temperatures of the sintering process would have melted the attached electrical solder.

The focus of the Basic Energy Sciences research was soon broadened to include other ceramic powders, such as silicon dioxide (SiO_2) and silicon carbide (SiC). As the research continued to yield new insights, worldwide enthusiasm for commercializing ceramic materials was renewed.

The simplified concepts developed through this research, expressed as paradigms for reliable manufacturing, proved to be as important as the detailed results. They enabled other research groups, especially corporate ones, to better focus their intellectual resources on further developments.

A number of major corporations formed a consortium, which provided industrial funding of more than $1,000,000 per year to the Ceramics Processing Research Laboratory in Massachusetts. New experimental facilities were developed, and scientists with expertise in surface, colloid, and inorganic chemistry were added to the group.