An Insight into the Future: A Research on the Development of Superconductors

Abstract:

The purpose of the research paper deals with the preparation of ceramic superconductors and the presence of oxygen within the materials. The most common method for making ceramic superconductors is sintering—the cooking of a material below its melting point—in a furnace. In essence, the theory at hand is that the longer the furnace takes to reach the cooking temperature (the ramping of the furnace) the more oxygen will be able to incorporate itself into the material, thus resulting in a better quality material.

Background:

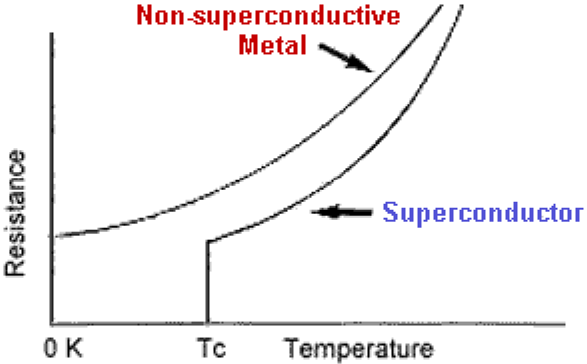

Figure 1: Graph of Resistance versus Temperature of a non-superconductive metal and a general superconductive material.

The phenomenon that has become superconductivity began in 1911 with the research of the Dutch physicist Heike Kamerlingh Onnes who saw that mercury, when super-cooled with liquid-helium (4° Kelvin or -452° Fahrenheit) suddenly lost all electrical resistance (Superconductor.org). As depicted in Figure 1, non-superconductive metals decrease resistance as the temperature decreases. However, with a superconductive material, once a critical temperature (T_c) is reached, the material now has no electric resistance—that is, when a current is passed through the material, it neither exhibits heat, nor inhibits electricity.

In 1933 German researchers Walter Meissner and Robert Ochsenfeld discovered a trend that has come to be an identifier of superconductors. When cooled to a superconducting state, the object exhibited diamagnetism—a property in which the material actually repels a magnet; they also found that not only did diamagnetism exist in the material, but also the material actually levitated the magnet. This property came to be known as the Meissner affect after one of its discoverers (Superconductors.org).

During the 1980's a flurry of research was done in order to find a superconductor that could super-conduct at temperatures higher than 4 Kelvin. This led to the discovery of ceramic superconductors—a bit of an oddity at the time since ceramics are typically insulators—and the subsequent find that deformities in the crystal-structure of the materials produced a property called flux pinning. At the atomic level the magnetic fields from a magnet become trapped in the deformities of the superconductor while, at the same time, it is being repelled; so, in effect, it exhibited the Meissner effect due to the deformities in the cell structure. It was found that the deformities were caused by the abundant presence of oxygen in the superconductive ceramics.

The Experiment:

In the experiment itself, I prepared one of the more common ceramic superconductors—YBCO. YBCO is the common acronym for the compound because it is comprised of yttrium, barium, copper, and oxygen in a balanced chemical equation that produces a stoichiometry for yttrium, barium, and copper of 1:2:3. Therefore, the actual chemical formula for YBCO is $YBa_2Cu_3O_x$ where “x” is the total amount of oxygen present in the compound. To obtain this, I mixed together Yttrium Oxide (Y_2O_3), Barium Carbonate ($BaCO_3$), and Cupric Oxide (CuO) in an anti-contaminate marble mortar-and-pestle and stored them in clean vials in an operating desiccator (to protect from moisture due to humidity) during the intermittent time.

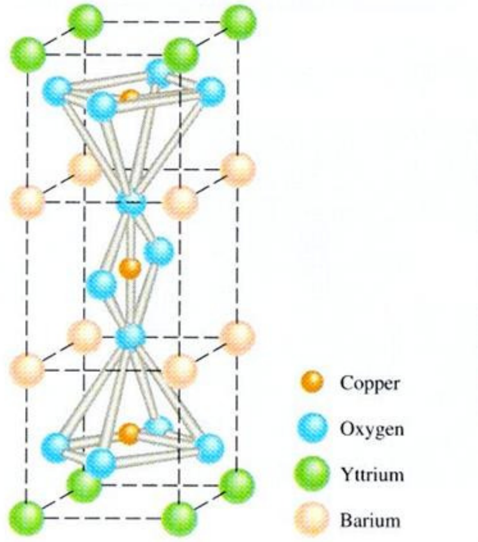

Figure 2: Unit Cell Structure of YBCO (Bowles).

Using YBCO as the experimental chemical was ideal to this research because of the inherent deformities in its unit cell structure. In its crystal structure “it has a perovskite structure with three perovskite cubic unit cells stacked on top of each other” (Smith 704). Therefore, it should have an oxygen content that would equal 9; however, it was found that the oxygen content must range between 6.56 and 7 in order for the compound to super-conduct. From here, I would be able to securely test and identify the oxygen content in the final product to note whether or not a superconductor was formed.

For the purpose of the experiment, I prepared enough of the Yttrium-Barium-Copper-Oxygen powder to separate them into five samples of equal mass that were later ramped at different temperature rates to 900° C (1652° F) during the primary and intermediate firings and held at the cooking temperature for eight hours (see Table 1). Each sample experienced an initial grinding as well as intermittent grindings during the heating process. Each sample was heated in a programmable ceramics kiln which was found to be able to incorporate enough oxygen into the cooking area that the samples were able to absorb the oxygen unimpeded. After each sample had undergone two firings they were ground a third time, crushed into pellets, and kept in a desiccator until all samples were complete. At the end, all samples underwent a final firing together and were ramped at 500° per hour to 950° C (1742° F).

Table 1. Samples and Firing Rates

Sample	***Rate***	***Cooking Temperature*** **(in Celsius)**	**Cooking Time (hr)**
Sample 1	**100 °/hr**	**900°** C	**8 hr**
Sample 2	**200 °/hr**	**900°** C	**8 hr**
Sample 3	**300 °/hr**	**900°** C	**8 hr**
Sample 4	**400 °/hr**	**900°** C	**8 hr**
Sample 5	**500 °/hr**	**900°** C	**8 hr**

To identify the oxygen content in each sample it was necessary to use an X-ray diffraction machine. The X-ray diffraction machine (or XRD) sends a high-powered x-ray towards a sample. The X-rays are then reflected off the planes of the sample at an angle, and a detector sweeps out a circular area measuring the intensity of the reflected rays. The incident rays—the X-rays that are sent from the XRD—have a unique wavelength so that the incident rays hit the plane of the sample at an angle and are reflected back at the same angle. In this way, they sweep an angle of 2θ where θ is the degree of the angle. The equation $2d\sin\theta = m\lambda$ (where m is a constant equal to 1, λ is the wavelength of

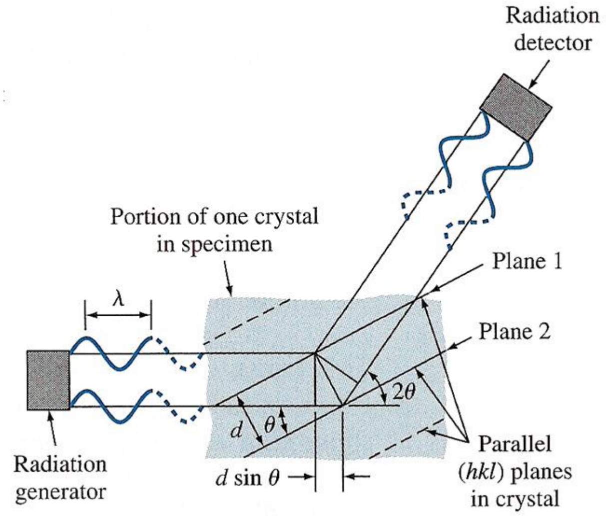

Figure 3: Diagram of X-ray Diffraction method (Bowles).

the ray, and d is the distance the incident angle was diffracted) allows us to solve for the lattice constants of the sample and identify the material (Bowles 20).

The actual results of the experiment were in line with our thesis. Each sample that took progressively longer to heat—that is, from sample 5 to sample 1—the content of oxygen increased. It is worthwhile, however, to note that each sample was within the range of oxygen content to be a superconductor once cooled by liquid-nitrogen (about -183° C) (see Figure 4). In each of the graphs in Figure 4, the black line is the intensity of the material measured in the XRD, and the purple are the “identifying” line that tells what compound it is. Each compound (seen in the top right-hand corner) is the chemical compound that was previously stored in an electronic database system known as Jade. After an XRD scan each compound was measured and compared to best fit those compounds in the database (any major deviations were more than likely produced by impurities or interference in the actual machine).

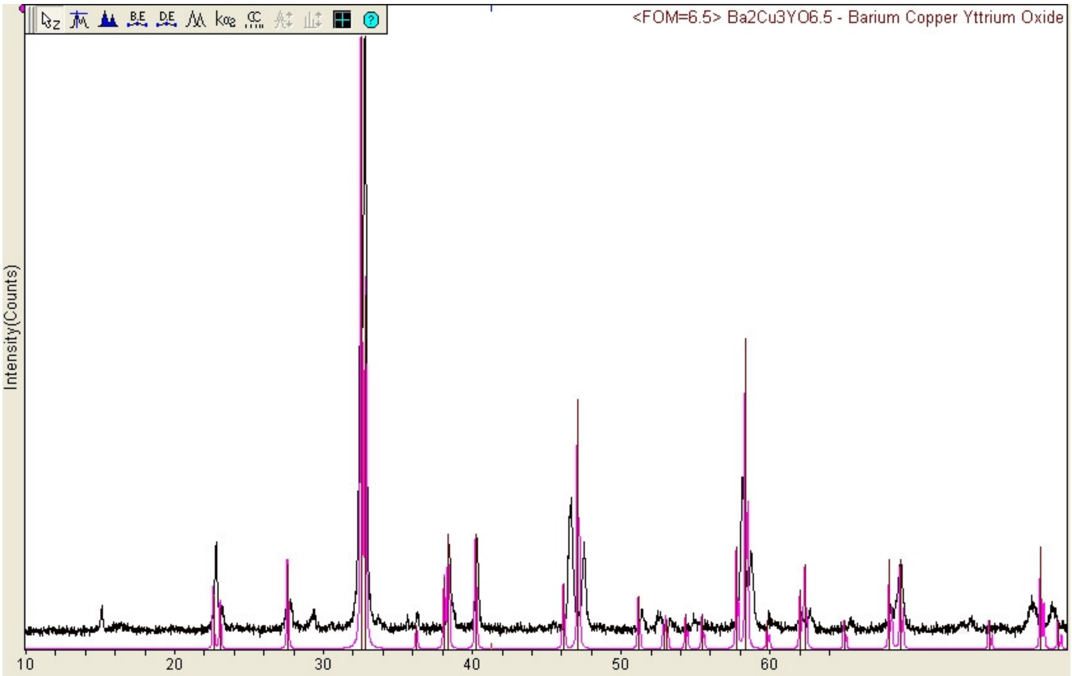

Figure 4a: Sample 5 oxygen content of 6.5.

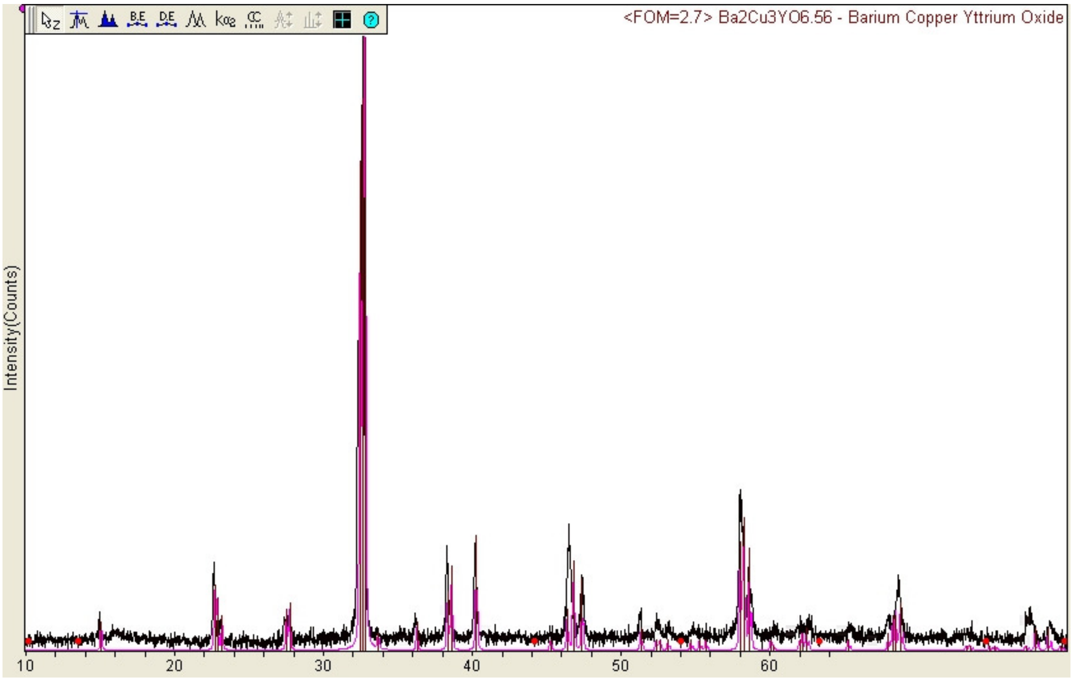

Figure 4b: Sample 4 oxygen content of 6.56.

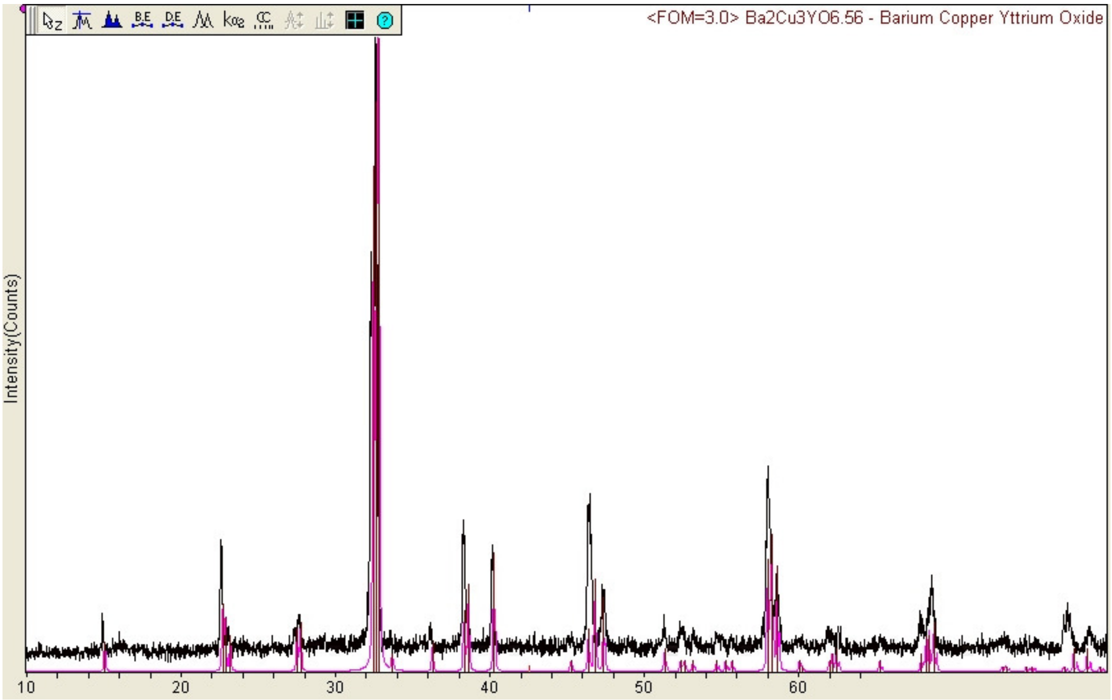

Figure 4c: Sample 3 oxygen content of 6.56.

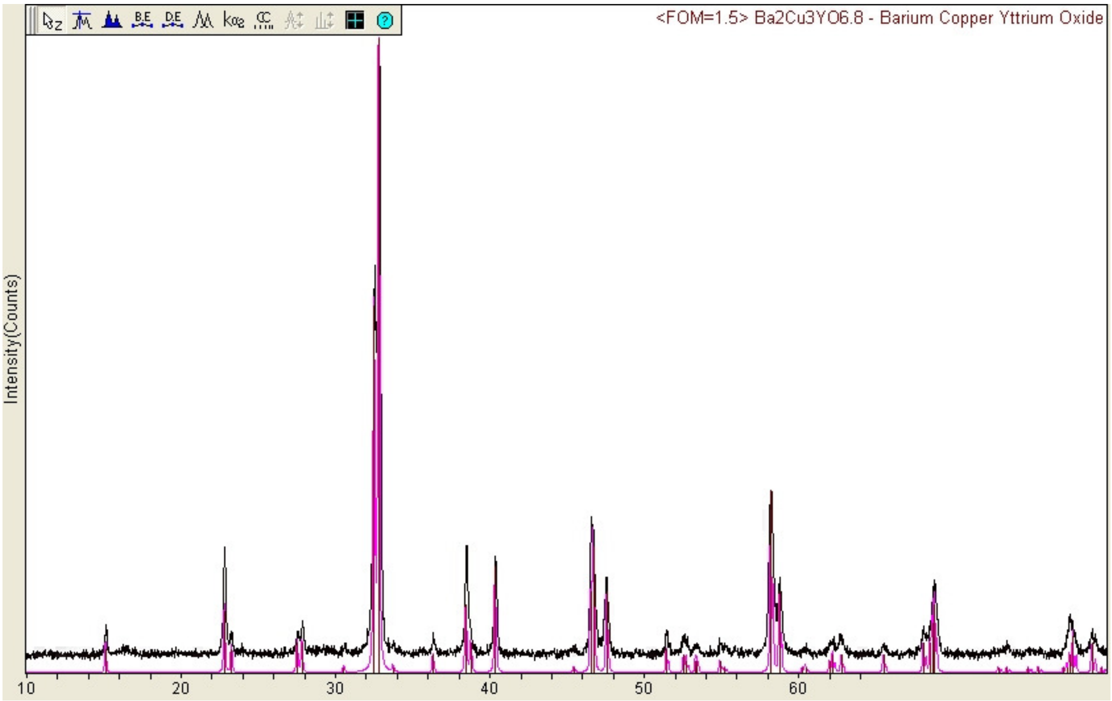

Figure 4d: Sample 2 oxygen content of 6.8

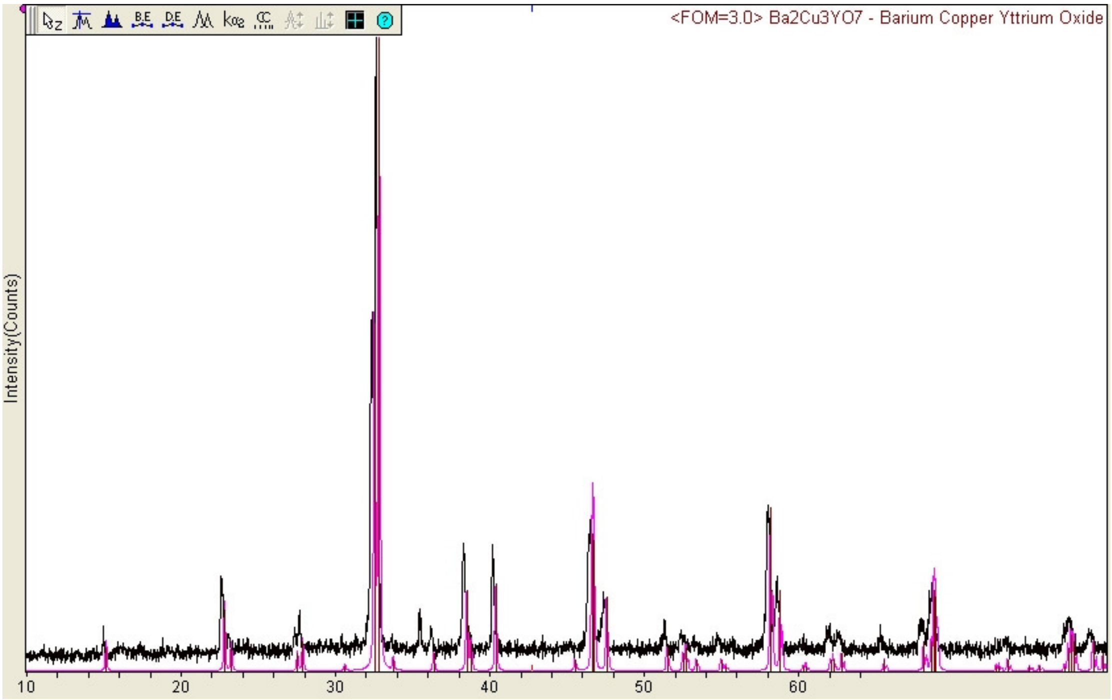

Figure 4e: Sample 1 oxygen content of 7.0.

Reflection:

The success of the experiments shown in Figure 4 coincides completely with the stated hypothesis: that by ramping samples at a low temperature heating rate the content of oxygen will increase in the samples. Because of this fact it can be induced that each sample will, when cooled to its critical Temperature, exhibit the Meissner effect (Figure 5) and zero-electrical resistance.

Figure 5: A superconductor exhibiting the Meissner effect. (Hoadley).

In retrospect, many things about the research could have been done during this experiment. First, as stated, the initial and secondary firings of each individual sample differed from the others'; however, the final heating remained the same. A question arises that ask, "What if the initial and secondary firings were kept the same and the final differed"? It is possible that the samples themselves would not have incorporated as much more oxygen, but at the same time, the oxygen content would still have differed in each sample—even if only a little less noticeable.

Another question, one that questions the quality of the sample themselves, asks just how effective each sample will be. While each sample did obtain enough oxygen in their chemical equation such that each will be able to exhibit superconductive properties, this oxygen content tells nothing of their ability to actually conduct electricity when cooled. Regarding high temperature—referring to the critical Temperature—Type

I superconductors, due to the Meissner effect a magnetic field can only exist on the surface of the material (Rose-Innes, 35). This causes them to have a smaller current density capability than Type II superconductors (Smith 822). The main difference between a Type I and Type II superconductor is that Type II typically superconductors that exhibit anomalous properties in the study of the Meissner effect. This in itself does not mean that Type I superconductors like YBCO are inefficient in any way. It simply means that, comparatively, they cannot withstand or maintain high currents in their structure, which presents another challenge in the development of superconductors.

Now, such superconductors as NbTi and Nb_3Sn are applicable to such things as nuclear magnetic imaging—a potential for a completely non-invasive surgery in the medical field—and levitating vehicles like trains (such as the one in Japan). These are high-current and high field superconductors (also Type II) and therefore can maintain high currents—as the titles imply.

Looking into the future, it is feasible to hope that at some point more advancement will be made in the research of superconductors. With the success of this experiment it has become more plausible for ceramic superconductors to become the bulk-produced superconductors that will redefine the world of tomorrow. Two things about superconductors present Material Scientists and Researchers with absolute goals—the use of superconductors in space and the discovery of a room-temperature superconductor—a superconductor that does not need to be cooled in order to super-conduct. The first is the most probable to occur within the near future. With the record of high temperature superconductors standing at 138° K (-135° C) and the continued advancements of the method of manufacture and effects in the field of superconductors—as well as the theory that outer-space temperature can range from 3 K to absolute zero—it is possible that a compound will be found that can maintain its temperature in the environment of outer-space; thus facilitating not only the launching of spacecrafts, but also the fuel necessary to maintain the spacecraft. The latter, however, is more of a dream. While statements claiming to have found a room temperature superconductor have been reported, but unable to be reproduced, scientists continue to search for the "holy grail" of Material Science.

Sources:

Hoadley, Rick, "Magnet Man—Cool Experiments With Magnets", October 16, 2006, accessed November 1, 2006. http://www.coolmagnetman.com.

Bowles, Kenneth, "Atomic/Crystal Structure and Crystal Geometry", Physics II Curriculum, 19-22.

Rose-Innes, A. C., E.H. Rhoderick, Introduction to Superconductivity, Glasgow, Bell and Bain Ltd., © 1969.

Smith, William F, Foundations of Materials Science and Engineering, New York: McGraw-Hill, © 2004.

"Superconductors.org", October 26, 2006, November 1, 2006, © 2006, http://www.superconductors.org .