Design and Growth of Novel Materials

Paul C. Canfield
Distinguished Professor,
Department of Physics
Senior Physicist, Ames Laboratory
Iowa State University
By the end of this lecture I want you to know where single crystalline samples come from and the effort that goes into discovering and optimizing new materials and properties.

The reason for this is simple. Many physicists have a poor idea of what is involved. This means that they can be lazy or sloppy when it comes to understanding the importance (as well as the limitations) of single crystalline samples.

*LET'S START WITH A STORY...*
Once upon a time, there was a nice single crystal

THAT GOT DROPPED AND BROKEN BY A HURRIED STUDENT
THERE WAS A GREAT ANGER IN THE LAND.
Do you have ANY idea where single crystal samples come from?????!!!
Yes…

Said the little student….
Yes…

Single crystal come from FedEx Express
NO....I want you to know the proper reply.
This class will draw heavily from these three papers:


CHAPTER 2

GROWTH PAPER ONE

SOLUTION GROWTH OF INTERMETALLIC SINGLE CRYSTALS: A BEGINNER’S GUIDE.
Paul C. Canfield

GROWTH PAPER TWO

PHILOSOPHICAL MAGAZINE B, 1992, VOL. 65, NO. 6, 1117–1123

Growth of single crystals from metallic fluxes
By P. C. Canfield and Z. Fisk
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

GROWTH PAPER THREE


High-temperature solution growth of intermetallic single crystals and quasicrystals
Paul C. Canfield*, Ian R. Fisher
New Materials development / single crystal growth is often done with very modest equipment
The spaces are small, and there can be a delivery room-like atmosphere. Crystal growth, like birth, can be messy. It is a fantastic, exciting, and addictive experience, *(spontaneous symmetry breaking at its best)*.

Let’s see how this works
First you need an idea….

This is often the tricky part of research….

Next, you should check some phase diagrams to see what might work….

Most of the diagrams I will show come from these books.
Binary phase diagrams are fundamentally like maps: they show the extent of liquid and solid.

Let’s develop a little vocabulary.
Solution growth requires readily accessible liquid regions. Often these are found in eutectic valleys.
Eutectic points: minima in liquid regions

Here is a familiar one associated with melting ice with salt, or lower freezing point of sea water.
Eutectic points: minima in liquid regions

Here is a familiar one associated with melting ice with salt, or lower freezing point of sea water.

At 23.3 weight percent NaCl, H$_2$O melts / solidifies just below -21 °C.
Deep Eutectics offer tempting liquid regions for growth.
Congruently melting compounds transform from a homogeneous solid to a homogeneous liquid at melting point.

Congruently melting compounds can be made by a wide variety of growth techniques that simply melt and solidify samples of fixed composition.
As we cool through the liquid, we ultimately cool enough to hit the liquidus-line for AgBa. At this temperature AgBa starts crystallizing and the remaining liquid becomes more Ba rich. The sample is no longer homogeneous and instead contains a solid of one stoichiometry and a liquid of another, changing stoichiometry.
Once we cool low enough to hit the liquidus line, the system enters a TWO PHASE REGION. The liquidus line tells us the composition of the remaining liquid, which changes as we form solid phases.

More on this in few slides.
Incongruently melting compounds undergo a peritectic decomposition into a mixed solid and liquid phase, only to form a homogeneous liquid at higher temperatures.

If you cool a liquid with composition AgBa, it will first form Ag$_2$Ba as the remaining liquid becomes more Ba rich and only forms AgBa below the peritectic temperature of 560°C.

AgBa and Ag$_2$Ba$_3$ decompose peritectically (melt incongruently).
Ag$_5$Ba can form with a variety of compositions and even have a single crystal with a spread of stoichiometries.

Ag$_2$Ba, AgBa and Ag$_2$Ba$_3$ are show to have no width of formation and are called “line” compounds.
Crystal growth of CeSb$_2$?

This is all nice in theory....But how do we REALLY DO THIS???

WITH OUR HAND AND BODIES NOT SOME MENTAL EXERCISE

CeSb$_2$ is incongruently melting at a relatively high temperature. An attempt to cool a melt of CeSb$_2$ would end up with a mixed phase and lots of mess (high vapor pressures).

On the other hand there is a very open line of primary solidification. Grow CeSb$_2$ out of a “self flux” of excess Sb.
As a rule of thumb, if we are below ~12 % R we can use Al$_2$O$_3$ crucibles. We need to seal the crucible in a silica tube to contain and protect the growth.

Shown below are two 2 ml crucibles and a snugly fitting silica tube.
Place the Ce and Sb into the growth crucibles

Put quartz wool into the catch crucible

Place the growth crucibles and catch crucibles into the silica tubing
Place quartz wool on top of the crucibles

Use the H$_2$-O$_2$ torch to neck down the silica
Evacuate the silica and seal off the ampoules
Clean off any finger prints, grease, etc.
Place ampoules into furnace
Program the temperature – time profile and let the thermodynamics take place

When growth is done, pour off the excess liquid.
(a = 10-1000 g is better than a = 1 g = 9.8 m/s²)
Flux growth (slow cooling of a melt)

Basic idea: slow cool into 2-phase region

eg: CeSb$_2$ / Sb

- self flux
- \( \text{Ce}_{0.05}\text{Sb}_{0.95} \)
- 1190 °C → 700 °C
Instead of using silica wool as a filtering agent, we recently developed a frit-disc filtering mechanism and were able to integrate it with the alumina crucibles. This allows for clean separation of the solids and liquid phases during the decanting process.
Clean recovery of both growth side as well as spin side materials allow for weighing and reuse. This allows for fractionation of the growth as well as phase diagram determination (at least in some cases).
These three piece sets are now available in a variety of sizes.
Use of frit-disc crucibles for routine and exploratory solution growth of single crystalline samples

Paul C. Canfield, Tai Kong, Udara S. Kaluarachchi and Na Hyun Jo

https://lspceramics.com/canfield-crucible-sets-2/
2\textsuperscript{nd} example, let’s see how to grow CoSn.

It is deeply peritectic, but it has a large exposed liquidus line.

We can cool a binary melt with more than 78% Sn and grow CoSn.

eg: CoSn / Sn

- self flux
- Co_{0.20}Sn_{0.80}
- 1050 °C \rightarrow 650 °C
Before we continue....When I taught this nine years ago, I was accused of engaging in
Before we continue....When I taught this nine years ago, I was accused of engaging in **ALCHEMY!!!**
This is associated with the apparent change in the stoichiometry of the liquid as we cool into a two phase region.

Even though we start with a $\text{Co}_{20}\text{Sn}_{80}$ solution at high temperature, we end up with a nearly pure Sn solution at low temperature.

How does this work? We cannot change Co into Sn!!!
As we grow CoSn phase the remaining liquid becomes more Sn rich.

- **A**
  - Liquid: 80% Sn
  - Solid: None

- **B**
  - Liquid: 87% Sn
  - Solid: CoSn

- **C**
  - Liquid: 95% Sn
  - Solid: CoSn
The composition of liquid changes BECAUSE we are crystallizing a phase different from initial melt stoichiometry.
We can also think about this in terms of atoms....

Let’s have Sn blue and Co red in the mix to right. There are 80 Sn and 20 red blocks.

In single phase, liquid state
We can also think about this in terms of atoms....

Let’s have Sn blue and Co red in the mix to right. There are 80 Sn and 20 red blocks.

Just starting to grow CoSn
We can also think about this in terms of atoms....
Let’s have Sn blue and Co red in the mix to right. There are 80 Sn and 20 red blocks.

Note: as CoSn grows less Co in liquid
We can also think about this in terms of atoms....
Let’s have Sn blue and Co red in the mix to right. There are 80 Sn and 20 red blocks.

\[ \text{x on liquidus line gives composition of remaining liquid} \]
We can also think about this in terms of atoms....

Let’s have Sn blue and Co red in the mix to right. There are 80 Sn and 20 red blocks.

CoSn crystal has consumed most of initial Co. Liquid is almost pure Sn.
Not *ALCHEMY*, just old fashion chemistry.

By the way, it is interesting to study history of chemistry as it emerged from alchemy into systematic science; very active debate and evolution of science. Look at names of elements to get some of this flavor.
OK, now higher melts: what about growth of the congruently melting compound, CeSb?

This is tricky if done just out of the binary: very high temperatures and lots of defects (due to vapor pressure and entropy).

But why would you want to grow this compound anyway?
Multiple transitions in temperature and field

**CeSb**

$M(H)$, $M(T)$, $\rho(H)$ and $\rho(T)$ data can be used to assemble an H-T phase diagram of fantastic detail. This system was studied extensively in the 70’s and 80’s by several neutron scattering groups as well as serving as the inspiration for the ANNNI model.
OK, now higher melts: what about growth of the congruently melting compound, CeSb?

This is tricky if done just out of the binary: very high temperatures and lots of defects (due to vapor pressure and entropy).

Can this be grown out of extra elements in manner similar to growing a salt out of water?

This question is the essence of flux growth.
When I was first faced with this goal I simply tried several of the “usual suspects”, i.e. low melting elements that offered good solubility for both Ce and Sb. Sn worked best
We are now talking about a ternary growth. 

*We have added another dimension.*

In many cases we are guessing how to ski blind, on a slope we can only speculate about.

Note, when the ternary diagram is known (rarely) it looks a lot like a topo-map.
We can use binary phase diagrams to give sense of edges of the ternary.
There are only low melting compounds of Sn and Sb.
If the Ce is dilute in Sn, then we only worry about CeSn$_3$ at low temperatures.
3\textsuperscript{rd} element flux

In this case we can think of this as a pseudo-binary cut through the Ce-Sb-Sn ternary phase diagram.

\[(\text{CeSb})_{0.05}\text{Sn}_{0.95}\]

1150 °C → 800 °C

(Spin at 800 to avoid the CeSn\textsubscript{3} 2\textsuperscript{nd} phase)
M(H), M(T), ρ(H) and ρ(T) data can be used to assemble an H-T phase diagram of fantastic detail.

Complex field and temperature dependent magnetism can be found in CeSb, especially very high purity single crystals grown out of Sn in this method.
For the rest of this lecture we will review other examples of growth design and implementation. I will try to point out issues associated with:

Silica Softening---When using silica tubing you must respect $T \sim 1200$ C

Vapor pressure (attack)

Crucible stability

But before that do be aware of:

Toxicity of compounds before reaction

Toxicity of compounds after reaction

Expense of it all...Quartz, crucibles, elements....
Let’s start with an example of a growth that appears to be easy, but requires attention to

**Silica Softening---**When using silica tubing you must respect $T \sim 1200 \, \text{C}$

**Crucible stability**
Let’s try to grow $\text{GdFe}_2$.

Heat to 1200 C and cool

$\text{SiO}_2$ softening
Let’s try to grow GdFe$_2$. This presents several problems. The first is the fact that both elements are relatively high melters. If we just put Gd and Fe in a crucible and heated to 1200°C they would not react (surface area of contact matters).
To solve this problem, an arc-melter can be used to pre-alloy (essentially finely mix through quench cooling) the elements to allow growth below 1200 C.
Second problem:
Lots of Gd will attack Al₂O₃ via a thermite-type reaction

Classic thermite reaction: \( \text{Fe}_2\text{O}_3 + 2\text{Al} \rightarrow \text{Al}_2\text{O}_3 + 2\text{Fe} + \Delta \text{ (heat)} \)

Or in this case, Gd reacts with Al₂O₃.....
\( \text{Al}_2\text{O}_3 + 2\text{Gd} \rightarrow \text{Gd}_2\text{O}_3 + 2\text{Al} + \Delta \text{ (heat)} \)

(Results in damaged/leaking crucible as well as contaminated and depleted melt.)
Lots of Gd which attacks $\text{Al}_2\text{O}_3$ via the thermite reaction

We solved this by developing a 3-cap Ta crucible.
We extended the use of Ta-3-cap crucibles from R-rich melt to Mg-based melts all the way to Li- and Ca-base melts. This allowed us to handle a wide variety of reactive elements for solution growth.
For example, we grew Li$_3$N out of excess Li and then were also able to study (Li$_{1-x}$T$_x$)Li$_2$N compounds for T = Mn, Fe, Co, Ni.
Now, let’s look at ternary phase diagrams in a little more detail.

Corners are pure element
Line parallel to one edge gives percentage of element on opposite corner.
Given point in phase diagram defines unique composition.
If we draw a line from a point on edge to tip, then ratio of edge elements stays same as we simply add tip element. E.g., \( \text{A:C} \) ratio stays same as we add \( \text{B} \).
RAgSb$_2$ compounds can be grown out of excess Sb. This is similar in spirit to growing CeSb$_2$ out of excess Sb: we are growing out of an excess of one of the constituent elements.

Now for some ternary compounds.

RAgSb$_2$ to start

RAgSb$_2$ compounds can be grown out of excess Sb.

This is similar in spirit to growing CeSb$_2$ out of excess Sb: we are growing out of an excess of one of the constituent elements.
CeAgSb$_2$ (Ce$_{25}$Ag$_{25}$Sb$_{50}$) can be grown from a melt with initial stoichiometry of Ce$_4$Ag$_9$Sb$_{87}$. Same works for R = La, Ce, Pr, Nd...

This growth can be place in Al$_2$O$_3$ and sealed in silica. Temperature profile is:

1200 C $\rightarrow$ 670 C

120 hours
Now ternary growths out of eutectics: \( \text{RNi}_2\text{Ge}_2 \) and \( \text{RCu}_2\text{Ge}_2 \) series.

Both the Ge-Cu and the Ge-Ni binaries have low, broad eutectic valleys.
Ce_{0.05}Cu_{0.475}Ge_{0.475} is placed in an Al_{2}O_{3} crucible, sealed in a quartz ampule and heated to 1190°C. The ampule is cooled to 825°C over 200 h and then the excess liquid is decanted. The resulting crystal
CeCu$_2$Ge$_2$ (m = 2 g)

Grown in a 5 ml Al$_2$O$_3$ crucible, sealed in silica

1190°C → 200 hours → 825°C
Here is a 1992 summary of binary and ternary samples that I had grown out of binary, ternary and quaternary melts.

This is a very powerful technique for exploratory growth. Over about two (plus) decades my group has made close to 10,000 growths similar to the ones I have been describing.

<table>
<thead>
<tr>
<th>Crystals</th>
<th>Flux</th>
<th>Dilution*(% at.)</th>
<th>Temperature (°C)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB₄</td>
<td>Al</td>
<td>R, 0-2</td>
<td>1450–700</td>
<td>R ≡ Sm, Gd–Lu, also U, Th</td>
</tr>
<tr>
<td>YbAlB₄</td>
<td>Al</td>
<td>Yb, 1-0</td>
<td>1450–700</td>
<td>R ≡ La–Eu, Yb, Ca, Ba, Sr, Np, Am</td>
</tr>
<tr>
<td>RB₆</td>
<td>Al</td>
<td>R, 0-2</td>
<td>1450–700</td>
<td>R ≡ La–Lu, Y, U, Th BeO crucible</td>
</tr>
<tr>
<td>RBe₁₁₃</td>
<td>Al</td>
<td>R, 5-0</td>
<td>1250–700</td>
<td>R ≡ Yb, Lu, Y, Sc</td>
</tr>
<tr>
<td>RAl₃</td>
<td>Al</td>
<td>Yb, 0</td>
<td>1200–660</td>
<td>No spin, NaOH etch</td>
</tr>
<tr>
<td>TiB₂</td>
<td>Al</td>
<td>Ti, 2-0</td>
<td>1440–800</td>
<td>No spin, NaOH etch</td>
</tr>
<tr>
<td>CeSi₂₋ₓ</td>
<td>Al</td>
<td>Ce, 5-0</td>
<td>1150–800</td>
<td>BeO crucible</td>
</tr>
<tr>
<td>UAl₃</td>
<td>Bi</td>
<td>U, 2-0</td>
<td>1150–700</td>
<td></td>
</tr>
<tr>
<td>UPt₃</td>
<td>Bi</td>
<td>U, 7-0</td>
<td>1250–800</td>
<td></td>
</tr>
<tr>
<td>YPd</td>
<td>Bi</td>
<td>Y, 10</td>
<td>1175–600</td>
<td></td>
</tr>
<tr>
<td>RBiPt</td>
<td>Bi</td>
<td>Ho, 6-0; Yb, 10; Lu, 3-0</td>
<td>1150–500</td>
<td>R ≡ Nd–Lu</td>
</tr>
<tr>
<td>R₃Bi₄Pt₃</td>
<td>Bi</td>
<td>Ce, 13</td>
<td>1150–500</td>
<td>R ≡ La–Pr</td>
</tr>
<tr>
<td>RB₈</td>
<td>Bi</td>
<td>Ce, 10</td>
<td>800–400</td>
<td>R ≡ La, Ce, Pr, Yb</td>
</tr>
<tr>
<td>R₂Bi</td>
<td>Ce</td>
<td>Bi, 15</td>
<td>1150–900</td>
<td>R ≡ La, Ce, Ta crucible</td>
</tr>
<tr>
<td>Ce₂Sb</td>
<td>Ce</td>
<td>Sb, 12</td>
<td>1150–900</td>
<td>Ta crucible</td>
</tr>
<tr>
<td>CeFe₂</td>
<td>Ce</td>
<td>Fe, 45</td>
<td>1100–700</td>
<td>Ta crucible</td>
</tr>
<tr>
<td>RSb</td>
<td>Ga</td>
<td>Ce, 5-0</td>
<td>1150–650</td>
<td>R ≡ La–Nd</td>
</tr>
<tr>
<td>R₂Pt₄Ga₈</td>
<td>Ga</td>
<td>Ce, 1-0</td>
<td>1100–500</td>
<td>R ≡ La–Nd, Sm, Gd, etc.</td>
</tr>
<tr>
<td>CeCu₂Ge₂</td>
<td>In</td>
<td>Ce, 3-0</td>
<td>1175–750</td>
<td>Plates 2 mm × 2 mm × 0.2 mm</td>
</tr>
<tr>
<td>CeNi₃Ge₂</td>
<td>In</td>
<td>Ce, 3-0</td>
<td>1175–700</td>
<td>Plates 2 mm × 2 mm × 0.2 mm</td>
</tr>
<tr>
<td>YbCu₂Si₂</td>
<td>In</td>
<td>Yb, 40</td>
<td>1150–600</td>
<td>Plates 2 mm × 2 mm × 0.2 mm</td>
</tr>
<tr>
<td>RPb</td>
<td>Pb</td>
<td>Ce, 10</td>
<td>1100–800</td>
<td>R ≡ La, Ce</td>
</tr>
<tr>
<td>RPbPt</td>
<td>Pb</td>
<td>Ce, 7-0</td>
<td>1150–500</td>
<td>R ≡ La, Ce</td>
</tr>
<tr>
<td>RBiPt</td>
<td>Pb</td>
<td>Ce, 7-0</td>
<td>1150–500</td>
<td>R ≡ La, Ce, Pr</td>
</tr>
<tr>
<td>YbCu₂Si₂</td>
<td>Sn</td>
<td>Yb, 3-0</td>
<td>1150–700</td>
<td>R ≡ La, Ce, Pr</td>
</tr>
<tr>
<td>TiNi₃Sn</td>
<td>Sn</td>
<td>Ti, 9-0</td>
<td>1150–600</td>
<td>Pyramidal</td>
</tr>
<tr>
<td>MnSnNi</td>
<td>Sn</td>
<td>Mn, 10</td>
<td>1150–450</td>
<td>Pyramidal</td>
</tr>
<tr>
<td>RSb</td>
<td>Sn</td>
<td>Ce, 5-0</td>
<td>1150–750</td>
<td>R ≡ La–Nd</td>
</tr>
<tr>
<td>RSb₂</td>
<td>Sb</td>
<td>Ce, 10</td>
<td>1175–750</td>
<td>R ≡ La, Ce</td>
</tr>
<tr>
<td>U₂Sb₄Pt₃</td>
<td>Sb</td>
<td>U, 8-0</td>
<td>1150–750</td>
<td></td>
</tr>
<tr>
<td>PtSb₂</td>
<td>Sb</td>
<td>Pt, 10</td>
<td>1150–750</td>
<td></td>
</tr>
</tbody>
</table>

* All materials in this table are dissolved in the flux stoichiometrically. The values shown for dilution are the amounts of one of the crystal components with respect to the flux.
Since 1992 we have made on the order of 10,000 more growths and published several “growth papers” in Philosophical Magazine B, 1992, Vol. 65, No. 6, 1117–1123.

**Growth of single crystals from metallic fluxes**

Philosophical Magazine
Vol. 92, Nos. 19–21, 1–21 July 2012, 2436–2447

Development of viable solutions for the synthesis of sulfur bearing single crystals

Philosophical Magazine
Vol. 92, Nos. 19–21, 1–21 July 2012, 2448–2457

**Growing intermetallic single crystals using in situ decanting**

Philosophical Magazine, 2014
Vol. 94, No. 21, 2372–2402, http://dx.doi.org/10.1080/14786435.2014.913114

Single crystal growth from light, volatile and reactive materials using lithium and calcium flux

Philosophical Magazine, 2016
Vol. 96, No. 1, 84–92
http://dx.doi.org/10.1080/14786435.2015.1122248

Use of frit-disc crucibles for routine and exploratory solution growth of single crystalline samples
Summary:
I hope that some of you now simply want to get into the lab a play around with growth.

--------

You are NOT limited to the four samples that your Professor found in a drawer.

All Physics does not *have* to be found in Si.

You can try to discover, design, and make crystals that will allow you to pursue the specific science that interest YOU.
Questions?
Optimization of the crystal growth of the superconductor CaKFe$_4$As$_4$ from solution in the FeAs-CaFe$_2$As$_2$-KFe$_2$As$_2$ system

W. R. Meier, T. Kong, S. L. Bud’ko, and P. C. Canfield
Ames Laboratory US DOE and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA
(Received 28 April 2017; published 19 June 2017)

This is a true quaternary growth!!
PHYSICS 590B FALL 2018 SCHEDULE     MWF 1:10 – 2:00 p.m.     Room 38 Physics Hall

Week 1 / Aug 20 Intro (Canfield), Aug 22, 24 Measuring of Temperature (Prozorov)

Week 2 / Aug 27, 29 Cryogens: generation and handling (Bud'ko) Aug 31 Low pressure generation and gauging (Kaminski)

Week 3 / Sept. 5, 7 Low pressure generation and gauging (Kaminski)

Week 4 / Sept 10, 12, 14 X-ray and Neutron Generation (in-house as well as facilities) (Goldman/McQueeny/Kreyssig)

Week 5 / Sept 17, 19, 21 Elastic X-ray and neutron scattering (Goldman/McQueeny/Kreyssig)

Week 6 / Sept 24, 26, 28 E and B field generation (Kaminski and Bud'ko)

Week 7 / Oct 1, 3, 5 First sets of 10 plus 6 minute talks from students.

Week 8 / Oct 8, 10, 12 Magnetization measurements (d.c.) (Prozorov)

Week 9 / Oct 15, 17, 19 Magnetization measurements (a.c., magneto optics, NV) (Prozorov)

Week 10 / Oct 22, 24, 26 Specific heat and scanning calorimetry measurements (Bud'ko/ Dennis)

Week 11 / Oct 29, 31, Nov 2 Compositional phase diagrams, how to read them and how to make them (W. Meter)

Week 12 / Nov 5, 7, 9 Elemental Analysis and e-beam (Straszheim / Kramer)

Week 13 / Nov 12, 14 High pressure generation, gauging and measurements (Bud'ko) Nov 16 Specific heat under pressure (Gati)

Week 14 / Nov 26, 28, 30 Electrical resistivity measurements (Tanatar)
We can start with the formal tetrahedron.

And then make a “simplifying” pseudo-ternary cut.
We could identify the red region in the pseudo-ternary cut as primary solidification for the CaKFe$_4$As$_4$ crystals. This can be seen in the pseudo-binary cut below.
By hitting this very limited region of primary solidification we can grow sizable CaKFe$_4$As$_4$ crystals.
PHYSICS 590B FALL 2018 SCHEDULE  MWF 1:10 – 2:00 p.m.  Room 38 Physics Hall

Week 1 / Aug 20 Intro (Canfield), Aug 22, 24 Measuring of Temperature (Prozorov)

Week 2 / Aug 27, 29 Cryogens: generation and handling (Bud'ko) Aug 31 Low pressure generation and gauging (Kaminski)

Week 3 / Sept. 5, 7 Low pressure generation and gauging (Kaminski)

Week 4 / Sept 10, 12, 14 X-ray and Neutron Generation (in-house as well as facilities) (Goldman/McQueeney/Kreyssig)

Week 5 / Sept 17, 19, 21 Elastic X-ray and neutron scattering (Goldman/McQueeney/Kreyssig)

Week 6 / Sept 24, 26, 28 E and B field generation (Kaminski and Bud'ko)

Week 7 / Oct 1, 3, 5 First sets of 10 plus 6 minute talks from students.

Week 8 / Oct 8, 10, 12 Magnetization measurements (d.c.) (Prozorov)

Week 9 / Oct 15, 17, 19 Magnetization measurements (a.c., magneto optics, NV) (Prozorov)

Week 10 / Oct 22, 24, 26 Specific heat and scanning calorimetry measurements (Bud'ko/ Dennis)

Week 11 / Oct 29, 31, Nov 2 Compositional phase diagrams, how to read them and how to make them (W. Meier)

Week 12 / Nov 5, 7, 9 Elemental Analysis and e-beam (Straszheim / Kramer)

Week 13 / Nov 12, 14 High pressure generation, gauging and measurements (Bud'ko) Nov 16 Specific heat under pressure (Gati)

Week 14 / Nov 26, 28, 30 Electrical resistivity measurements (Tanatar)
We were able to work with, and contain, this melt with a combination of \( \text{Al}_2\text{O}_3 \), fritted crucibles that we seal in Ta tubing.

Use of frit-disc crucibles for routine and exploratory solution growth of single crystalline samples

Paul C. Canfield, Tai Kong, Udharma S. Kaluarachchi and Na Hyun Jo

PHILOSOPHICAL MAGAZINE, 2016
VOL. 96, NO. 1, 84–92
http://dx.doi.org/10.1080/14786435.2015.1122248

https://lspceramics.com/canfield-crucible-sets-2/
Next Semester 590B Spring 2019

Topics to cover in no particular order

Crystal growth and sample synthesis