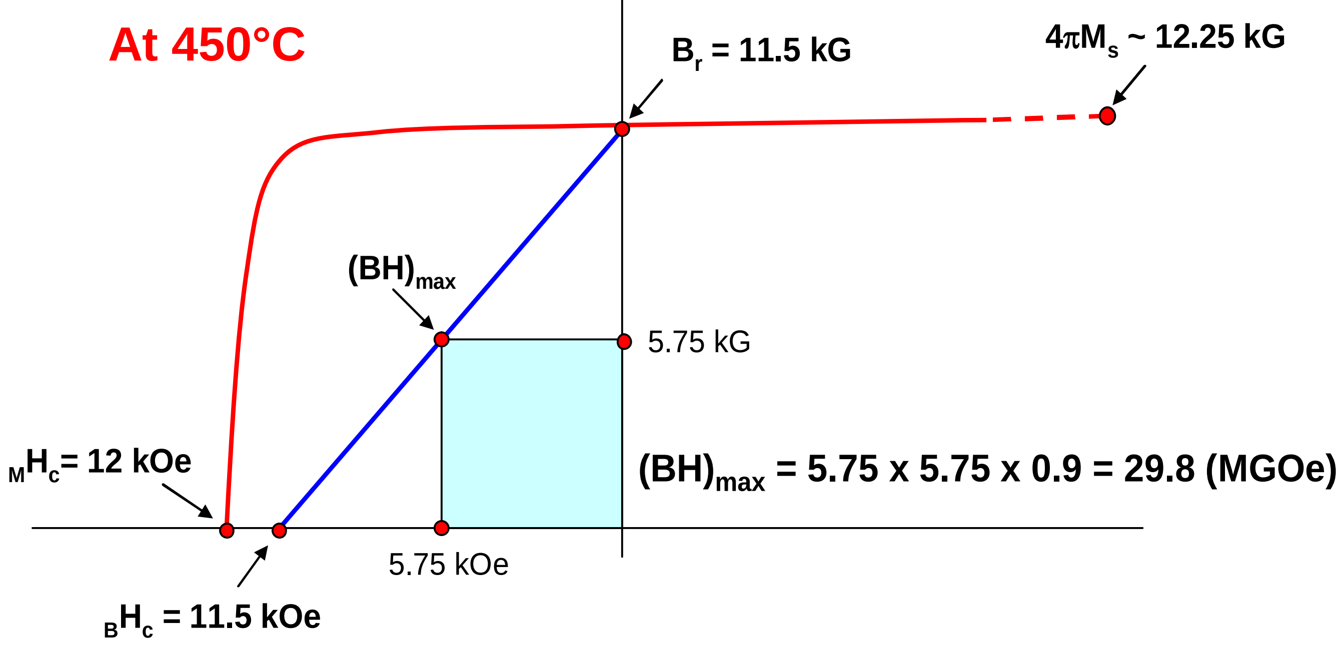
A New Approach to Developing High-Temperature Rare Earth Magnets

Development Trend of Powder Systems

- ***More Electric powder systems***
  - *Gas/Electric hybrid vehicles*
  - *More electric aircraft*
  - *More electric ships*
- ***All Electric power systems***
- ***Advantages***
  - *High efficiency*
  - *Improved reliability and maintainability*
- ***Requirements***
  - *Eliminating hydraulics: Liquid cooling → air cooling*
  - *High-temperature stability of electric and magnetic components*
  - *$(BH)_{max} \approx 30$ MGOe at 450 ° C for powder system of new aircraft*

Assuming a Perfect Magnet with $(BH)_{max} \approx 30$ MGOe at 450°C



	$4\pi M_s$ (kG)	B_r (kG)	$_MH_c$ (kOe)	$(BH)_{max}$ (MGOe)
At 20°C	15.8	15.0	≥ 25	~53
At 450°C	12.25	11.5	≥ 12	~30

***Assuming the new magnets have the same temperature coefficients as Sm-Co**

Current Best High-Temperature Magnets

Magnet	At 20°C		At 450°C	
	B_r (kG)	$(BH)_{max}$ (MGOe)	B_r (kG)	$(BH)_{max}$ (MGOe)
The best current Sm-Co high temperature magnets	9.3	**20.8**	7.2	**11.8**
Goal*	14.8	**52.8**	11.5	**30**

***Assuming the new magnets have the same temperature coefficients as Sm-Co**

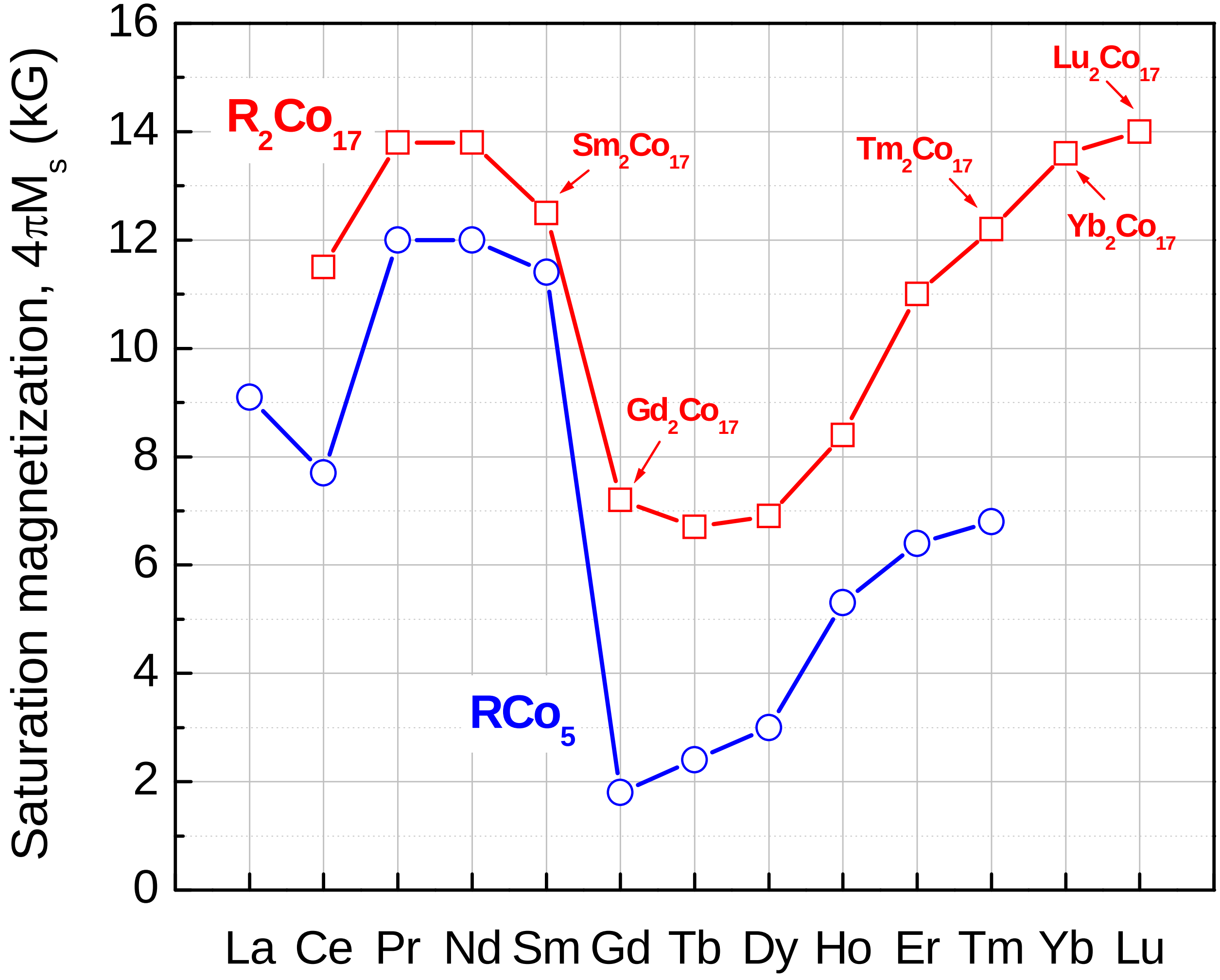
Approaches ???

- ***Improving conventional sintered Sm_2TM_{17} magnets***
  - $\uparrow$ Fe → $4\pi M$ → $\downarrow$ $_MH_c$ at high T
  - Small amount Pr sub. For Sm → $\uparrow 4\pi M$ → $\downarrow$ $_MH_c$
  - It will be very difficult to make Sm_2TM_{17} reach 40 MGOe at 20 ° C or 20 MGOe at over 300 ° C
- ***Nanocomposite $Sm_2(Co,Fe)_{17}/\alpha$-Fe or $Sm_2(Co,Fe)_{17}$/Fe-Co***
  - $Sm_2(Co_{0.9}Fe_{0.1})_{17}/\alpha$-Fe **(70%/30%)**: $4\pi M_s = 15.8$ kG
  - $Sm_2(Co_{0.9}Fe_{0.1})_{17}$/Fe-Co **(70%/22%):** $4\pi M_s = 15.8$ kG
  - Difficulties
    - When soft phase > 20%, it is difficult to have $_MH_c \approx 12$ kOe at 20 ° C , let alone at 450 ° C
    - How to obtain the required grain alignment?

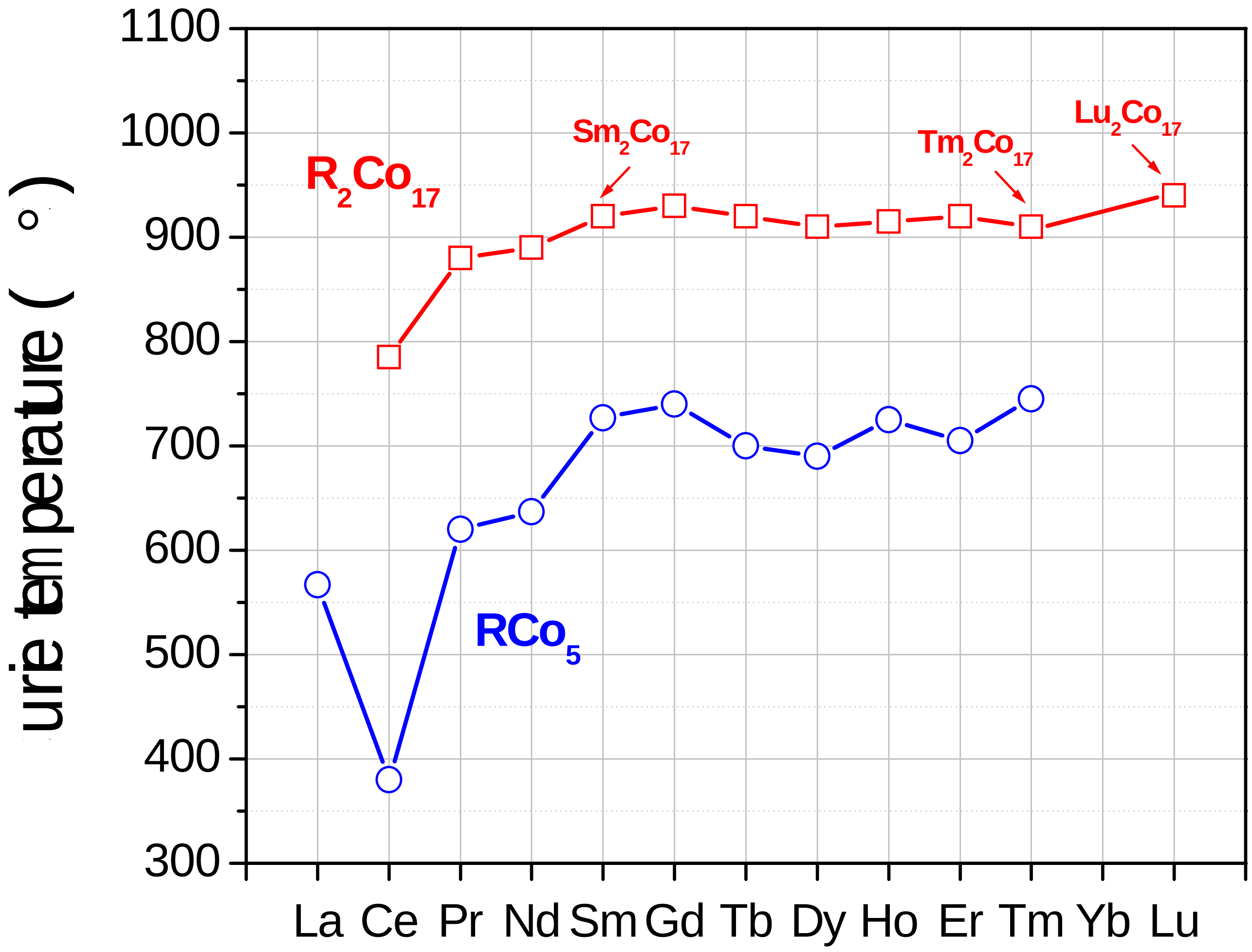
Possible Candidates

- *New compounds*
- *Old materials*
- *A combination of old and new materials*
- *Requirements*
  - *High Curie temperature higher than 850°C*
  - *High $4\pi M_s$*
  - ***Especially high $4\pi M_s$ over 12kG at 400-450°C***
  - *High H_A, at least uniaxial anisotropy*

Saturation Magnetization of R-Co Compounds



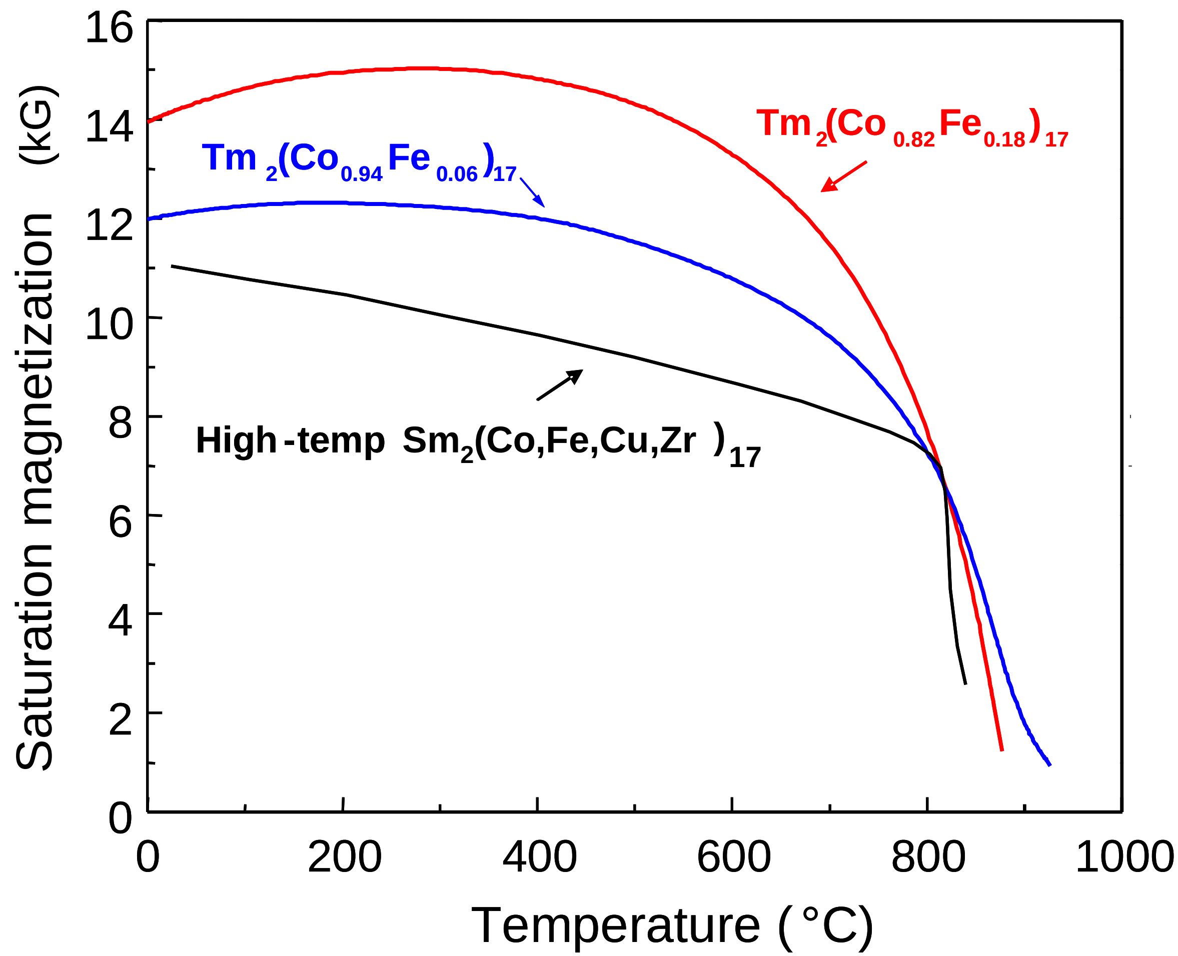
Curie Temperatures of R-Co Compounds



Characteristics of R_2Co_{17} (R = Tm, Yb, or Lu)

- R_2Co_{17} (R = Tm, Yb, or Lu) have **high $4\pi M_s$ & T_C**
  - Tm_2Co_{17}: $4\pi M_s$ = 12.1 kG; T_C = 910°C
  - Yb_2Co_{17}: $4\pi M_s$ = 13.6 kG T_C = ?
  - Lu_2Co_{17}: $4\pi M_s$ = 14.0 kG T_C = 930°C
  - Sm_2Co_{17}: $4\pi M_s$ = 12.5 kG T_C = 920°C
- **With increasing temperature, their $4\pi M_s$ will be higher**, as HE-TM compounds
- $4\pi M_s$ at 400-450°C can be higher than those at 20°C
- R_2Co_{17} (R = Tm, Yb, or Lu) have potential to be developed into new high-performance and high-temperature magnets

$4\pi M_s$ vs. Temperature for $Tm_2(Co,Fe)_{17}$



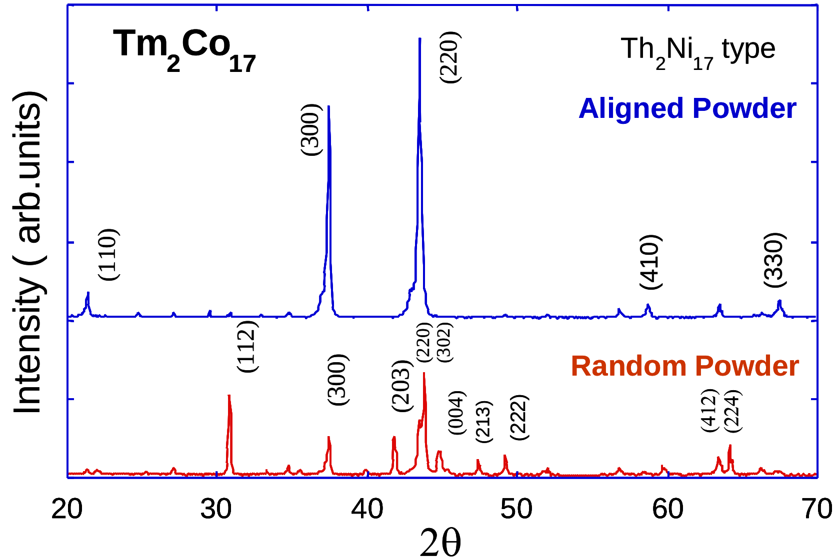
K.S.V.L. Narasimhan & W.E. Wallace, 1974-1977

Potential of $Tm_2(Co_{0.82}Fe_{0.18})_{17}$ Compound

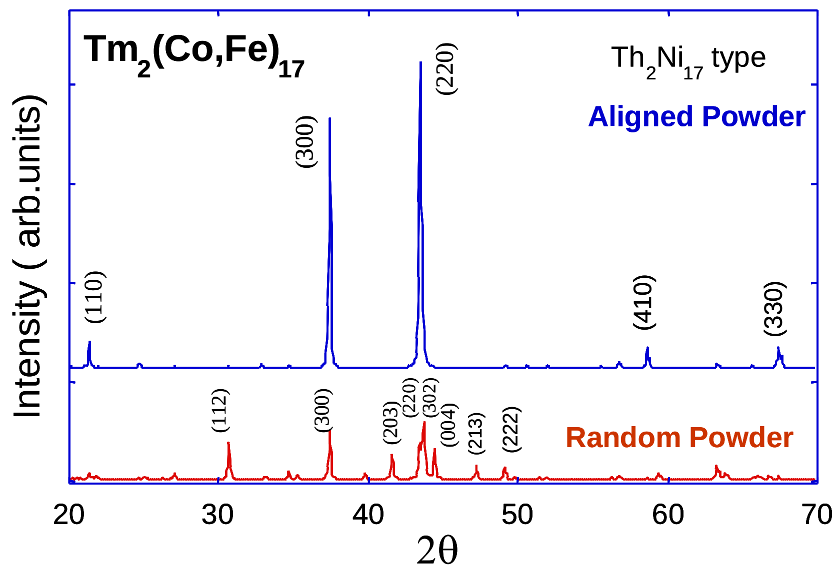
Temperature (°C)	$4\pi M_s$ (kG)	T_C (°C)	H_A (kOe)	Theoretical $(BH)_{max}$ (MGOe)	Achievable $(BH)_{max}$ (MGOe)*
20	14.2	880	~38	50.4	45.4
300	15.0		?	56.3	50.6
400	14.8		?	54.8	49.3
450	14.6		?	53.3	48.0
500	14.3		?	51.1	46.0

**Assuming sufficiently high coercivity and good grain alignment can be developed and the achievable* $(BH)_{max}$ *= 90% of theoretical* $(BH)_{max}$.

XRD Patterns of Tm_2Co_{17} and $Tm_2(Co_{0.85}Fe_{0.15})_{17}$

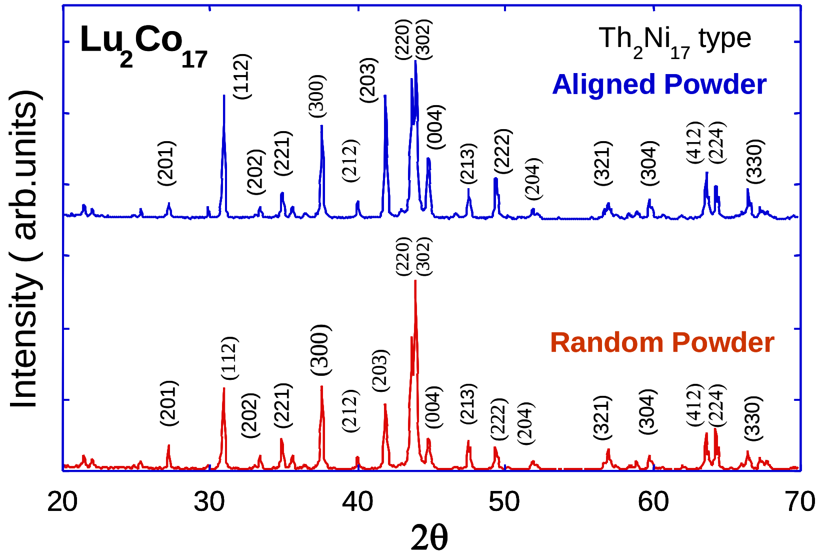


Random and aligned powders of Tm_2Co_{17}

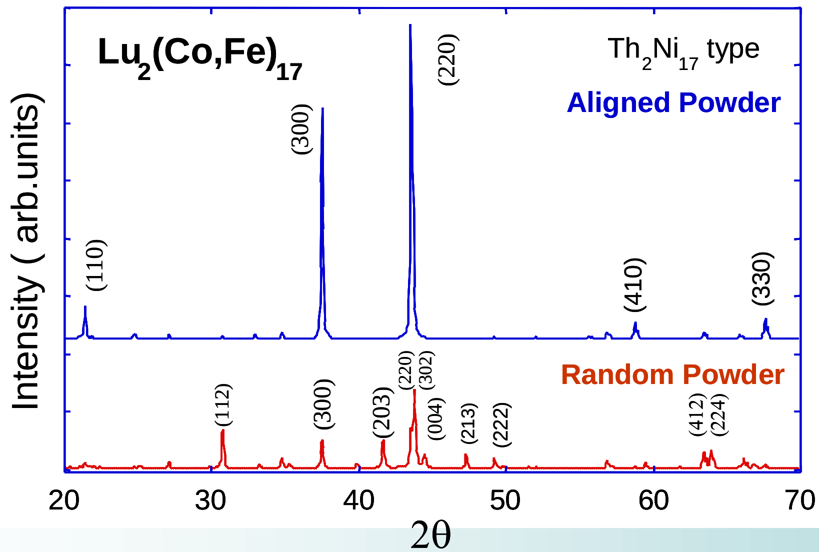


Random and aligned powders of $Tm_2(Co_{0.85}Fe_{0.15})_{17}$

XRD Patterns of Lu_2Co_{17} and $Lu_2(Co_{0.85}Fe_{0.15})_{17}$



Random and aligned powders for Lu_2Co_{17}



Random and aligned powders for $Lu_2(Co_{0.85}Fe_{0.15})_{17}$

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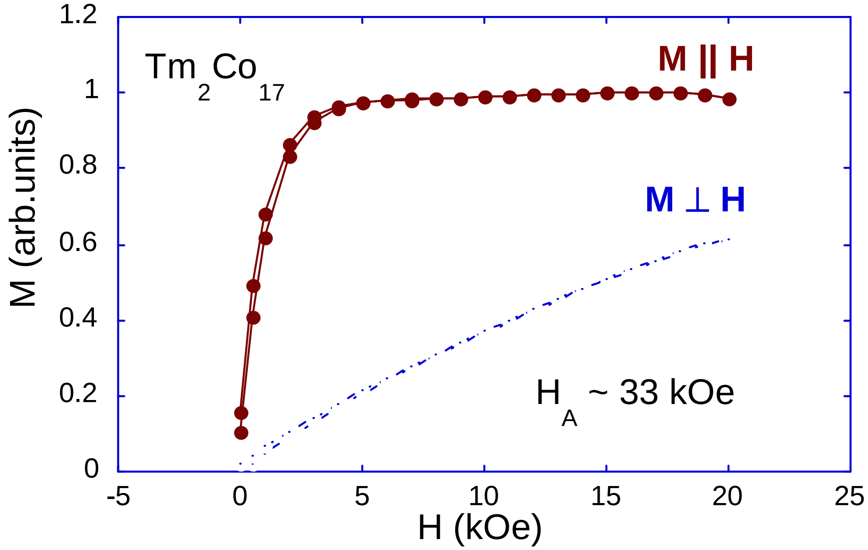
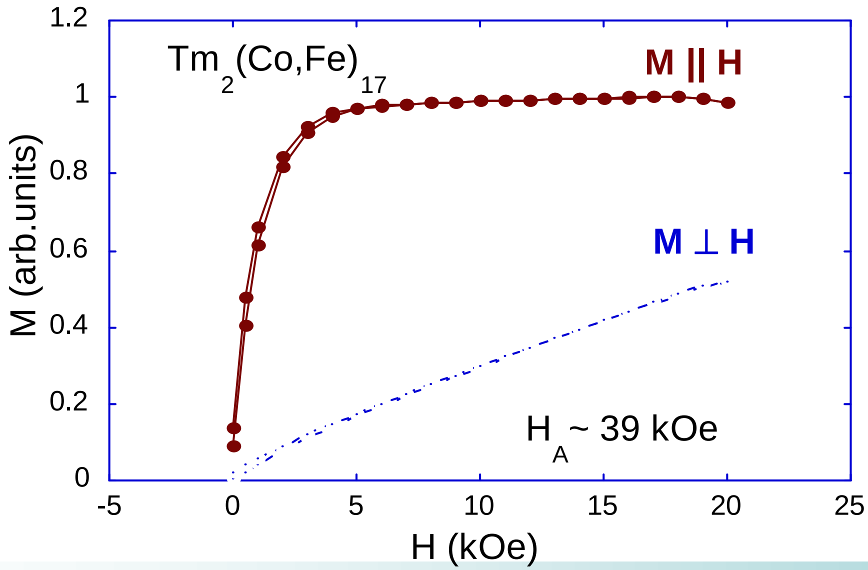
Anisotropy Filed of Tm_2Co_{17} and $Tm_2(Co_{0.85}Fe_{0.15})_{17}$

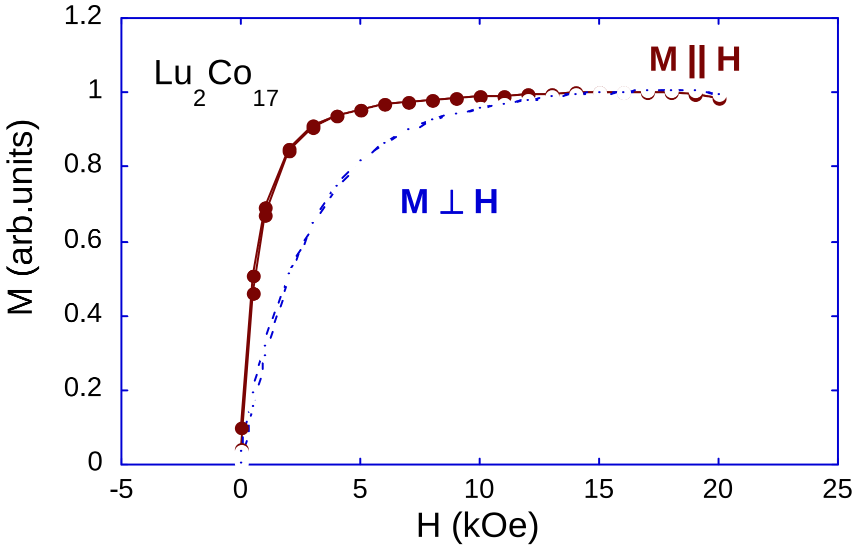


Tm_2Co_{17}

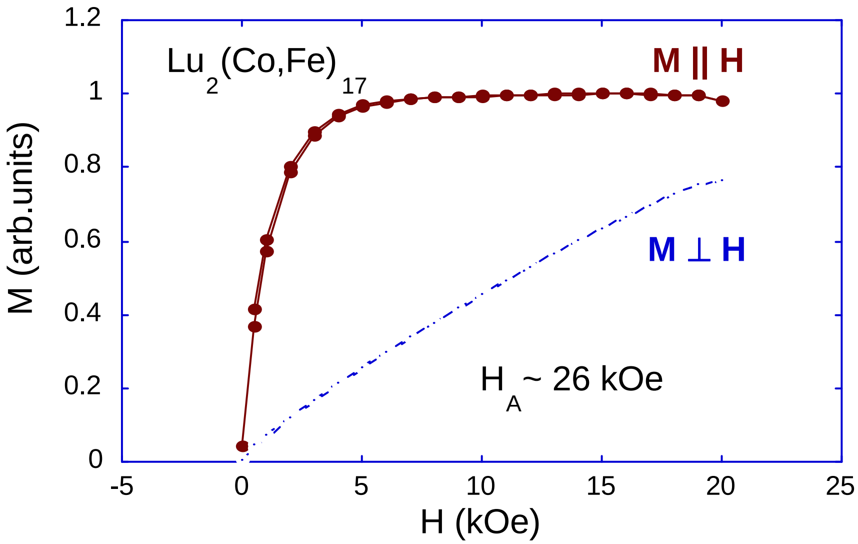


$Tm_2(Co_{0.85}Fe_{0.15})_{17}$

Anisotropy Filed of Lu_2Co_{17} and $Lu_2(Co_{0.85}Fe_{0.15})_{17}$



Lu_2Co_{17}



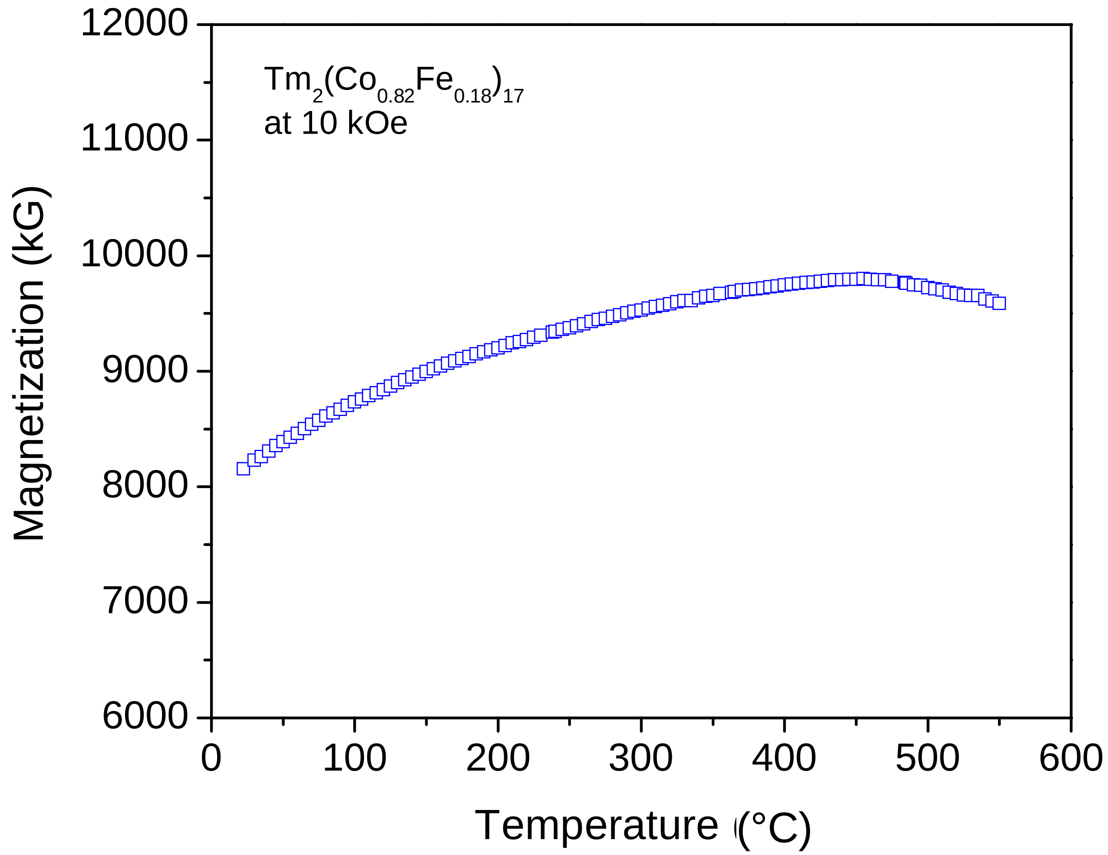
$Lu_2(Co_{0.85}Fe_{0.15})_{17}$

A Summery of Properties for $Tm_2(Co,Fe)_{17}$ and $Lu_2(Co,Fe)_{17}$

Compound	Crystal structure	Lattice constant (Å)		c/a	v (Å^3)	Magnetocrystalli anisotropy
		a	c			
Tm_2Co_{17}	Hexagonal	8.336	8.090	0.970	486.85	uniaxial
$Tm_2(Co_{0.85}Fe_{0.05})_{17}$	Hexagonal	8.328	8.160	0.980	490.12	uniaxial
Lu_2Co_{17}	Hexagonal	8.297	8.098	0.976	482.78	easy basal plane
$Lu_2(Co_{0.85}Fe_{0.05})_{17}$	Hexagonal	8.312	8.152	0.981	487.76	uniaxial

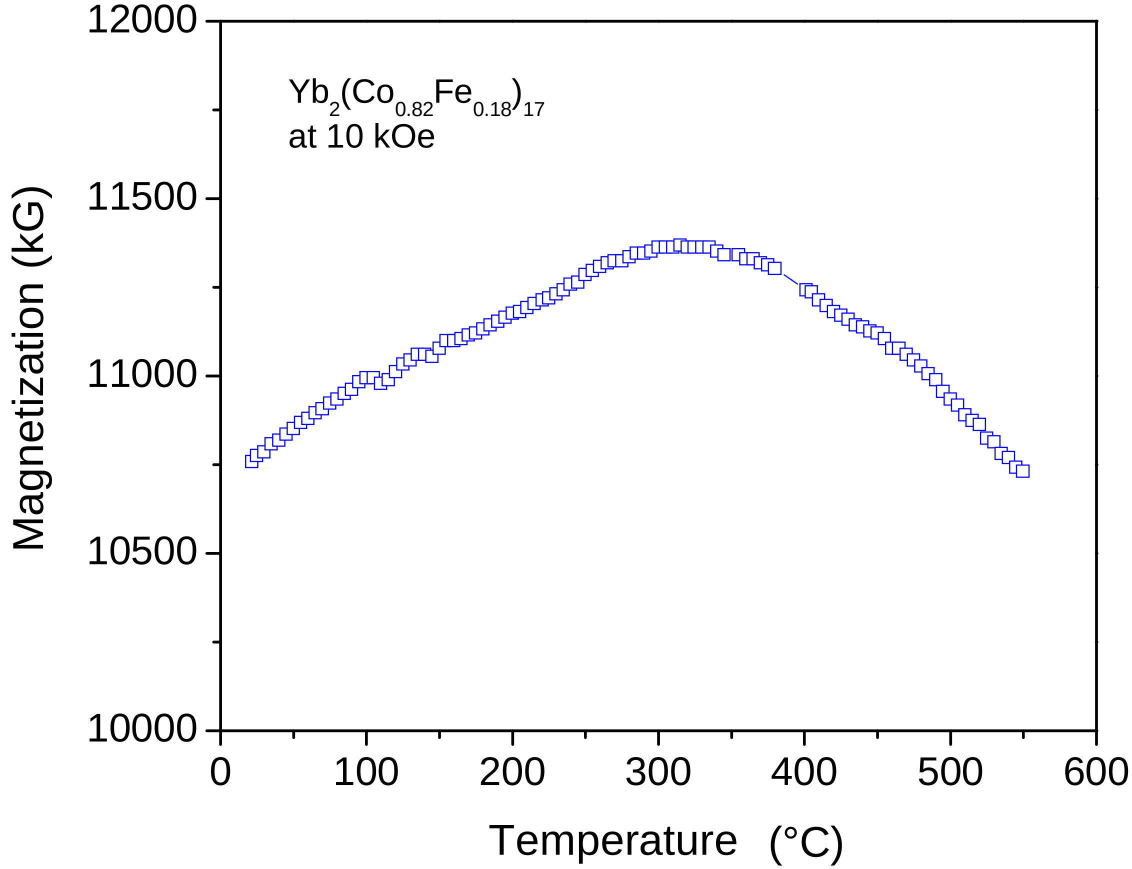
Partial Fe substitution for Co increases c/a values and unit cell volumes

Temperature Dependence of Magnetization for $Tm_2(Co_{0.82}Fe_{0.18})_{17}$



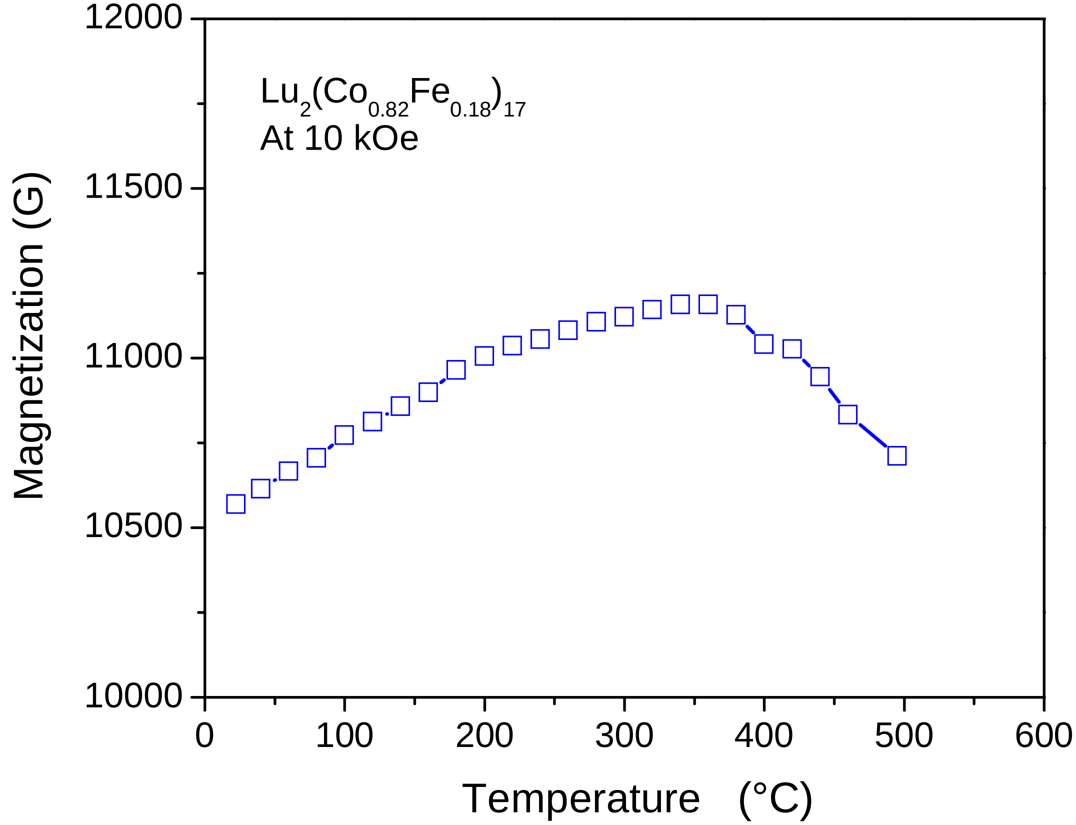
- *Positive temperature coefficient of magnetization from 20 to 450°C*
- *Magnetization at 450°C is higher than that at 20°C*

Temperature Dependence of Magnetization for $Yb_2(Co_{0.82}Fe_{0.18})_{17}$



- *Positive temperature coefficient of magnetization from 20 to 325°C*
- *Magnetization at 450°C is higher than that at 20°C*

Temperature Dependence of Magnetization for $Lu_2(Co_{0.82}Fe_{0.18})_{17}$



- *Positive temperature coefficient of magnetization from 20 to 350°C*
- *Magnetization at 450°C is higher than that at 20°C*

Nanograin $R_2(Co_{0.85}Fe_{0.15})_{17}$ (R = Sm, Tm, Yb, or Lu)

- *Mechanical alloying, hot compaction, and hot deformation were used to synthesize nanograin $R_2(Co_{0.85}Fe_{0.15})_{17}$ magnets (R = Sm, Tm, Yb, or Lu)*
- *Low coercivity*
- *Difficult to obtain anisotropic magnets*
- *Magnetic properties of isotropic materials*

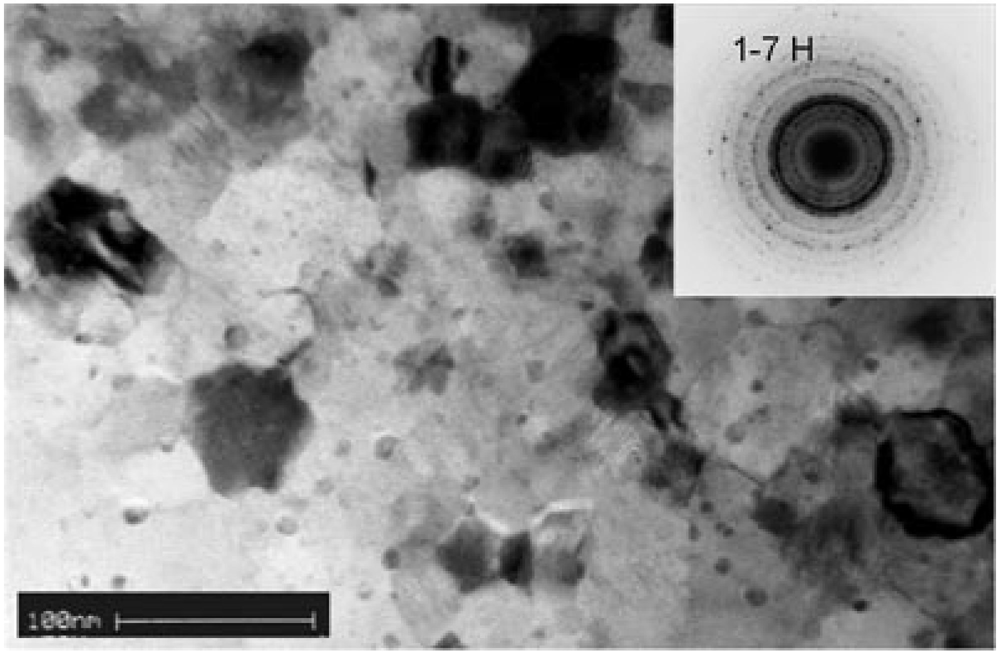
Materials	$4\pi M$ (kG)	B_r (kG)	${}_MH_c$ (kOe)
$Sm_2(Co_{0.85}Fe_{0.15})_{17}$	8.3	7.3	12
$Tm_2(Co_{0.85}Fe_{0.15})_{17}$	8.3	6.5	4.6
$Yb_2(Co_{0.85}Fe_{0.15})_{17}$	12.0	9.2	0.9
$Lu_2(Co_{0.85}Fe_{0.15})_{17}$	11.3	7.5	1.8

Nanograin $(R,Sm)_2(Co_{0.85}Fe_{0.15})_{17}$ (R = Sm, Tm, Yb, or Lu)

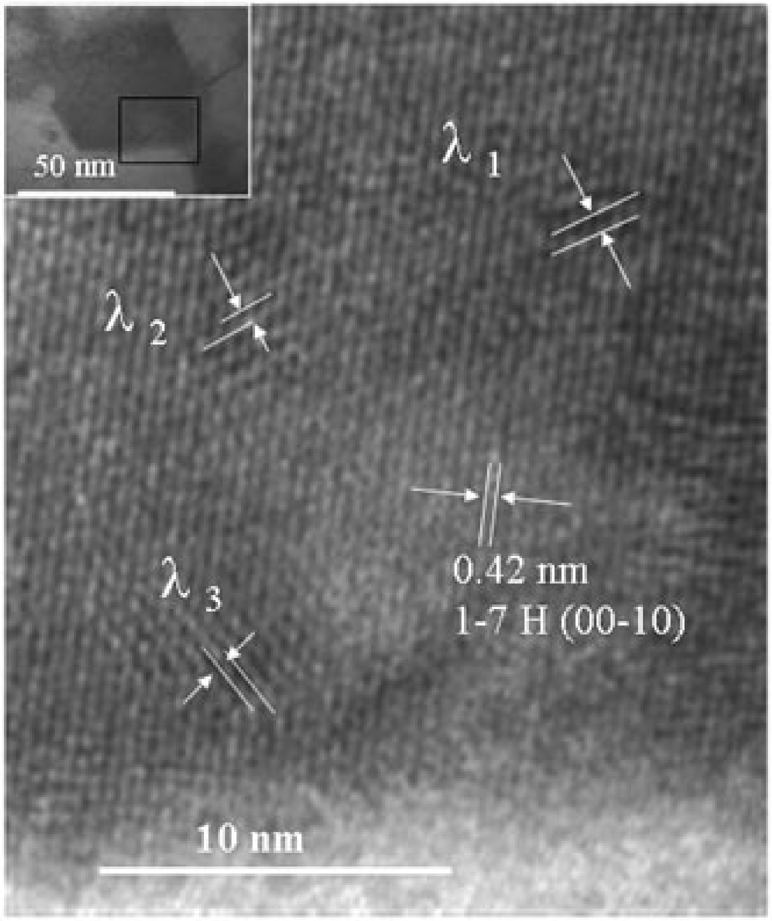
- *Nanograin $(R_{0.4}Sm_{0.6})_2(Co_{0.85}Fe_{0.15})_{17}$ (R = Tm, Yb, or Lu) were made trying to increase coercivity of these materials*

Material	$4\pi M$ (kG)	B_r (kG)	${}_MH_c$ (kOe)
$(Tm_{0.4}Sm_{0.6})_2(Co_{0.85}Fe_{0.15})_{17}$	8.5	7.0	8.0
$(Yb_{0.4}Sm_{0.6})_2(Co_{0.85}Fe_{0.15})_{17}$	9.7	7.7	5.5
$(Lu_{0.4}Sm_{0.6})_2(Co_{0.85}Fe_{0.15})_{17}$	9.2	7.4	6.1

TEM Micrograph of a Hot Compacted $(Yb_{0.4}Sm_{0.6})_2(Co_{0.85}Fe_{0.15})_{17}$ Magnet

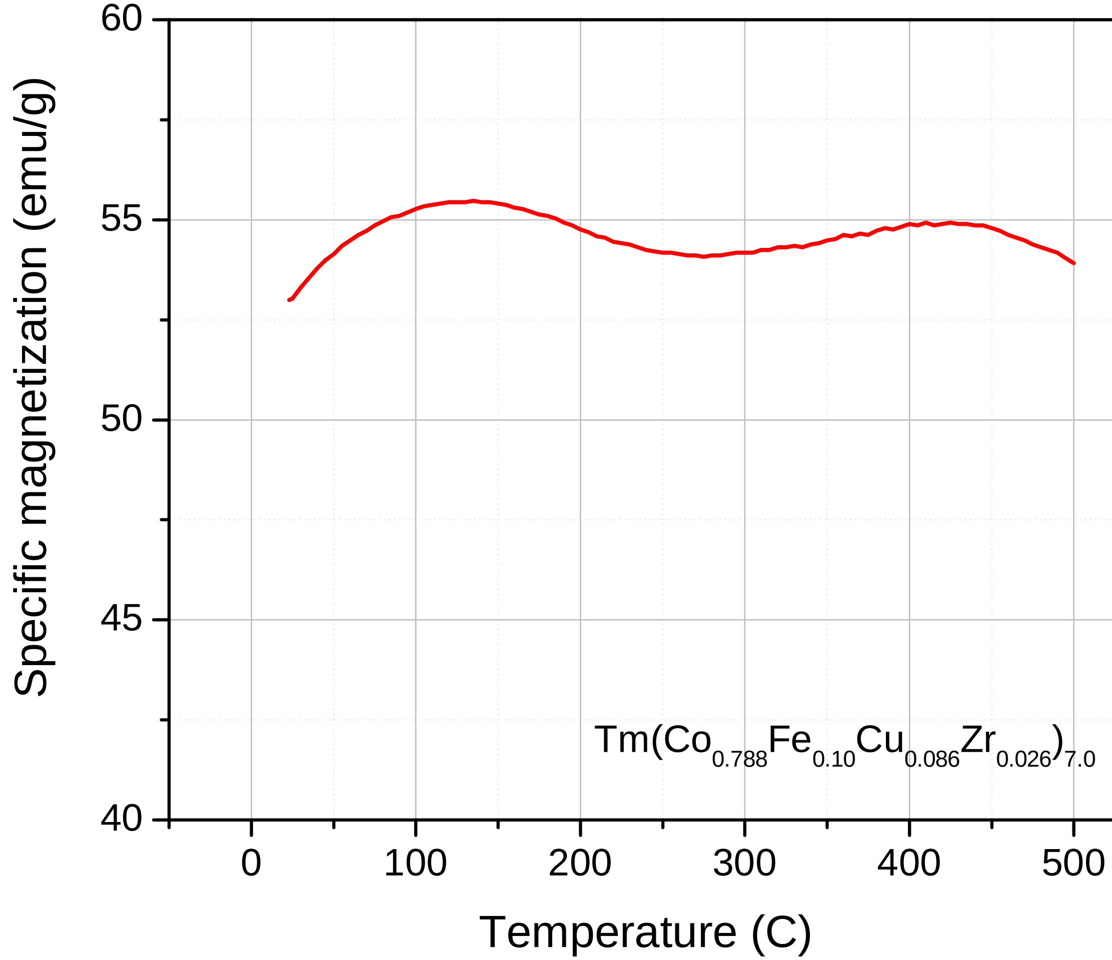


High-Resolution TEM Micrograph of Hot Compacted $(Yb_{0.4}Sm_{0.6})_2(Co_{0.85}Fe_{0.15})_{17}$

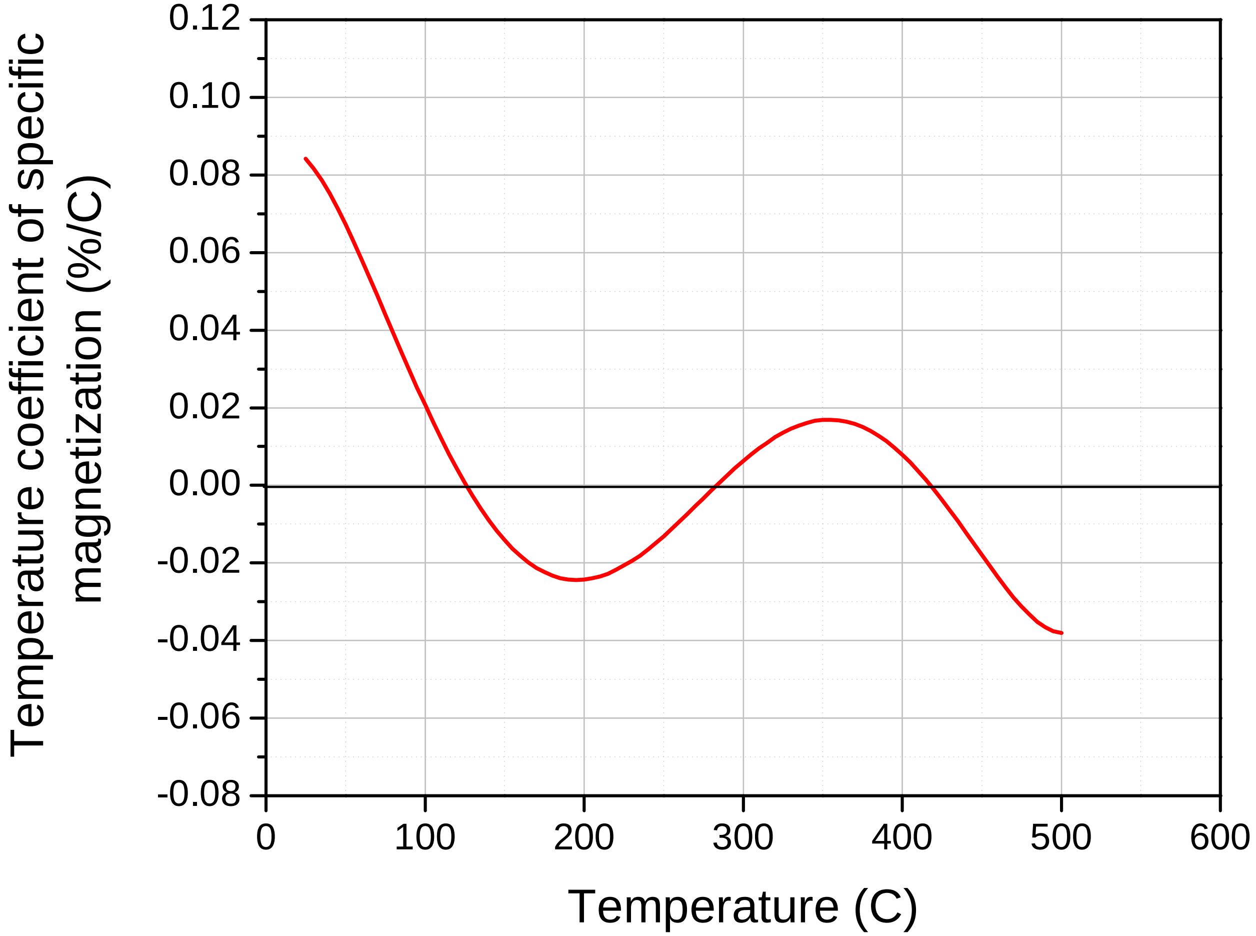


Fine structure within a nanograin was observed

Magnetization vs. Temperature of Micro-Grain $Tm(Co_{0.788}Fe_{0.1}Cu_{0.086}Z_{0.026})_7$



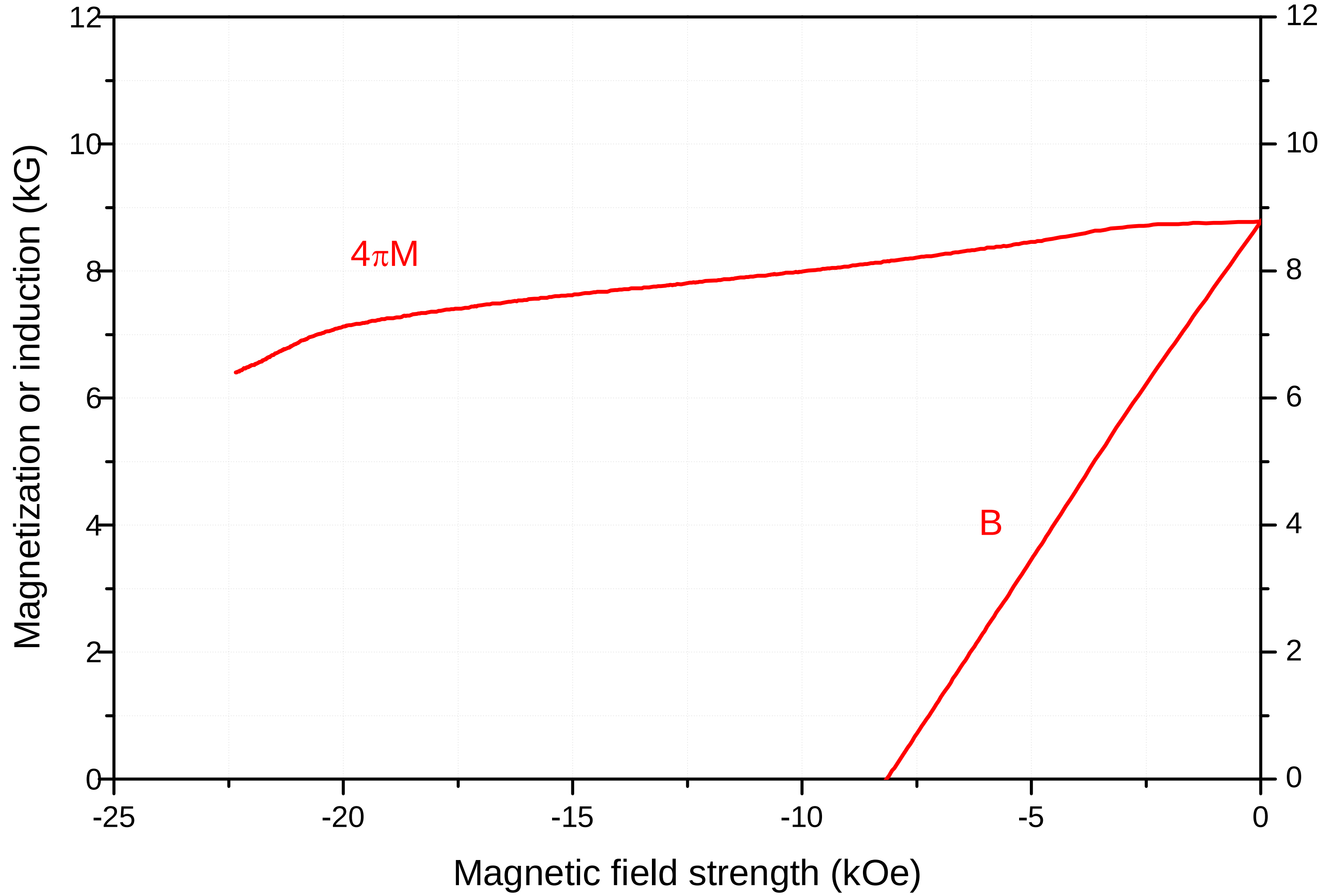
Temperature Coefficient of Magnetization for $Tm(Co_{0.788}Fe_{0.10}Cu_{0.086}Zr_{0.026})_{7.0}$



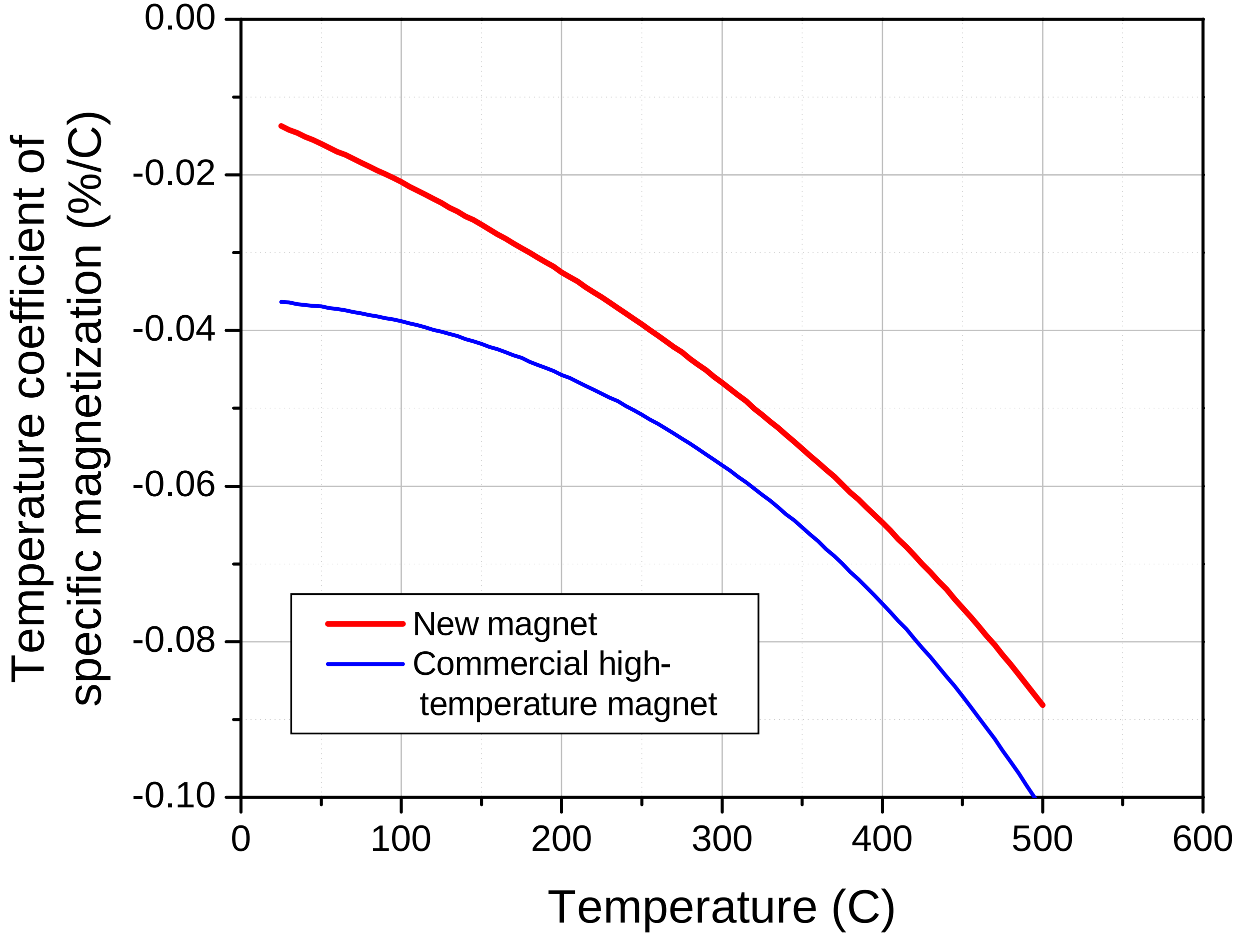
Sintered 2:17 Magnets with Tm, Yb, or Lu Substitution for Sm

- **Sintered 2:17 magnets with Tm, Yb, or Lu substitution for Sm**
  - *To develop sufficiently high coercivity*
  - *To make anisotropic magnets*
- **Non-ferromagnetic Cu, Zr must be added**
- **Processing**
  - *Sintering: ~1200°C – 1 hr*
  - *Solid solution heat treatment: ~1190°C – 3 hrs*
  - *Isothermal aging: ~800°C for 20 - 40 hours*
  - *Slow cooling: ~2°C/min. from 800 – 400°C*

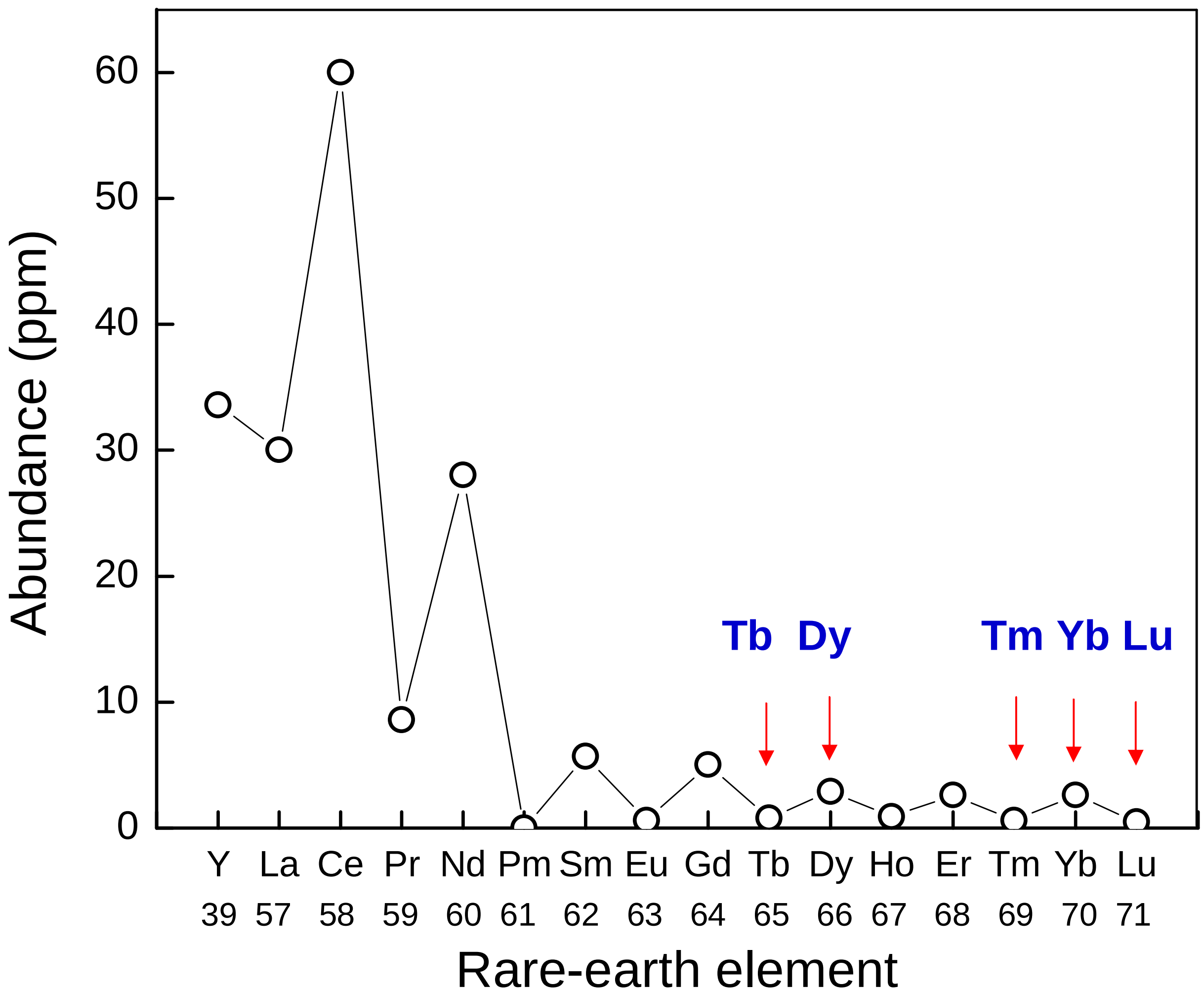
$(Tm_{0.4}Sm_{0.6})(Co_{0.789}Fe_{0.1}Cu_{0.085}Zr_{0.026})_{6.8}$



Temperature coefficient of specific magnetization for $(Tm_{0.4}Sm_{0.6})(Co_{0.729}Fe_{0.16}Cu_{0.085}Zr_{0.026})_{7.02}$



Abundance of RE in Nature



Conclusions & Future Research

- $R_2(Co,Fe)_{17}$ (R = Tm, Yb, or Lu) demonstrates high saturation magnetization and their magnetization values at 450°C are higher than those at room temperature
- High coercivity over 25 kOe was obtained in sintered anisotropic $(Tm_{0.4}Sm_{0.6})(Co_{0.789}Fe_{0.1}Cu_{0.085}Zr_{0.026})_{6.8}$ magnets, which will be new temperature-compensated $(Sm,R)_2(Co,Fe,Cu,Zr)_{17}$ magnets superior to conventional $(Sm,Gd)_2(Co,Fe,Cu,Zr)_{17}$ magnets
- Anisotropic fields of $R_2(Co,Fe)_{17}$ (R = Tm, Yb, or Lu) are to be enhanced by, for example, partial substitution for Co
- Compositions of $R_2(Co,Fe)_{17}$ (R = Tm, Yb, or Lu) are to be modified so that anisotropic magnets can be obtained by hot deformation