Low-noise Magnetic Field Measurements using Copper Permalloy Fluxgate Cores

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What is permalloy, and why do we care?

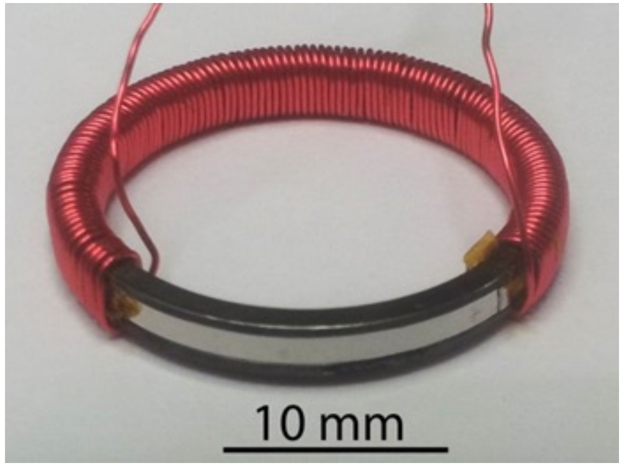
- Permalloy originated in 1923 and is a ferromagnetic alloy of Nickel and Iron. Additional alloying elements have been added to improve magnetic performance, molybdenum, chromium or copper.

- Our particular interest lie in Permalloy’s use in low-noise fluxgate magnetometer sensors, for use in earth sciences, such as magnetotelluric surveys, magnetic observatories or in space physics.

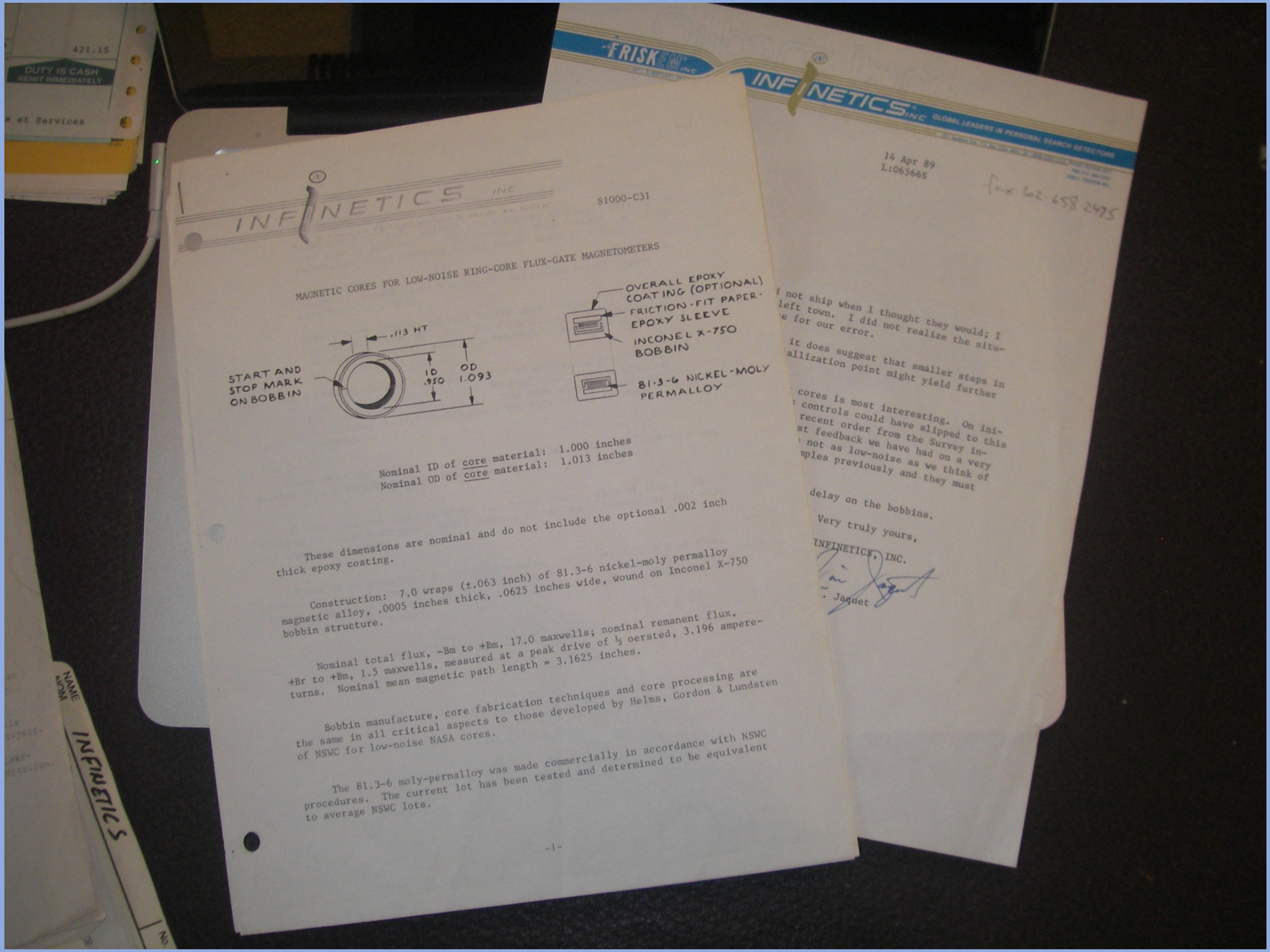
- **At this time there is no long-term viable source of the lowest noise permalloy materials.**

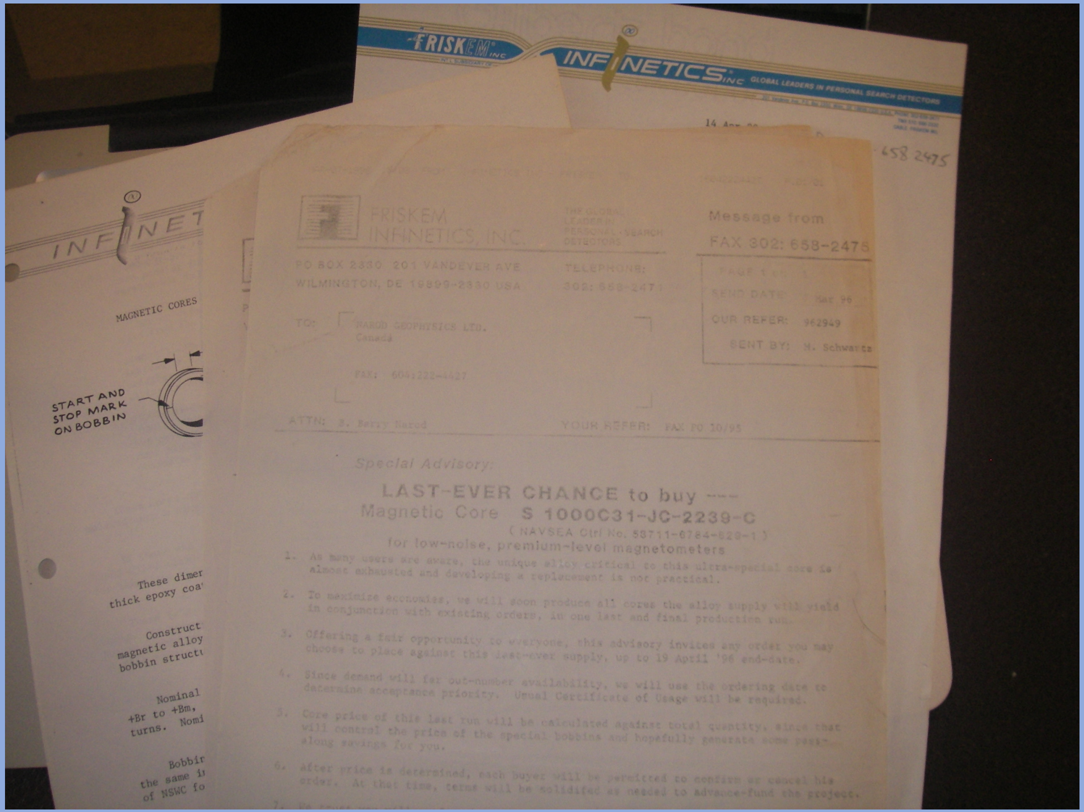
- Our present examination of Copper Permalloys may be thought of as a continuation of a copper Permalloy study undertaken by Siemens & Halske, which terminated in 1937. These results include the first ever tests of copper alloys in fluxgate sensors.

- **Our new permalloys, new in both configurations and materials, should offer much improved performance compared with the now unavailable legacy devices.**



A bit of history about our favored Infinetics S1000 series ring cores





Special Advisory

LAST–EVER CHANCE to buy ---

Magnetic Core S 1000C31-JC-2239-C …

(NAVSEA Ctrl No. 53771-6784-629-1)

For low-noise, premium-level magnetometers…

“…one last and final production run…”

“…last-ever supply, up to 19 April, ’96 end-date…” - M. Schwartz, 7 Mar 1996.

Two events now have moved us forward: 1) Figuring out the physics of magnetometer noise (2010)

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doi:10.5194/gi-3-201-2014

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The origin of noise and magnetic hysteresis in crystalline permalloy ring-core fluxgate sensors

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$$E_\mathrm{d} \propto t^{-1/2} \times \alpha \times B_\mathrm{s}^{3/2} \times K^{1/4}. \qquad (8)$$

ma-
mic
rgy

magnetocrystalline and magnetoelastic anisotropies and saturation induction, are all optimum in the Fe–Ni–Mo system.

In such polycrystalline permalloy fluxgate sensors, a sin-

A simplified domain energy model can then provide a predictive relation between ring-core magnetic properties and fluxgate sensor noise power. Four properties are predicted to

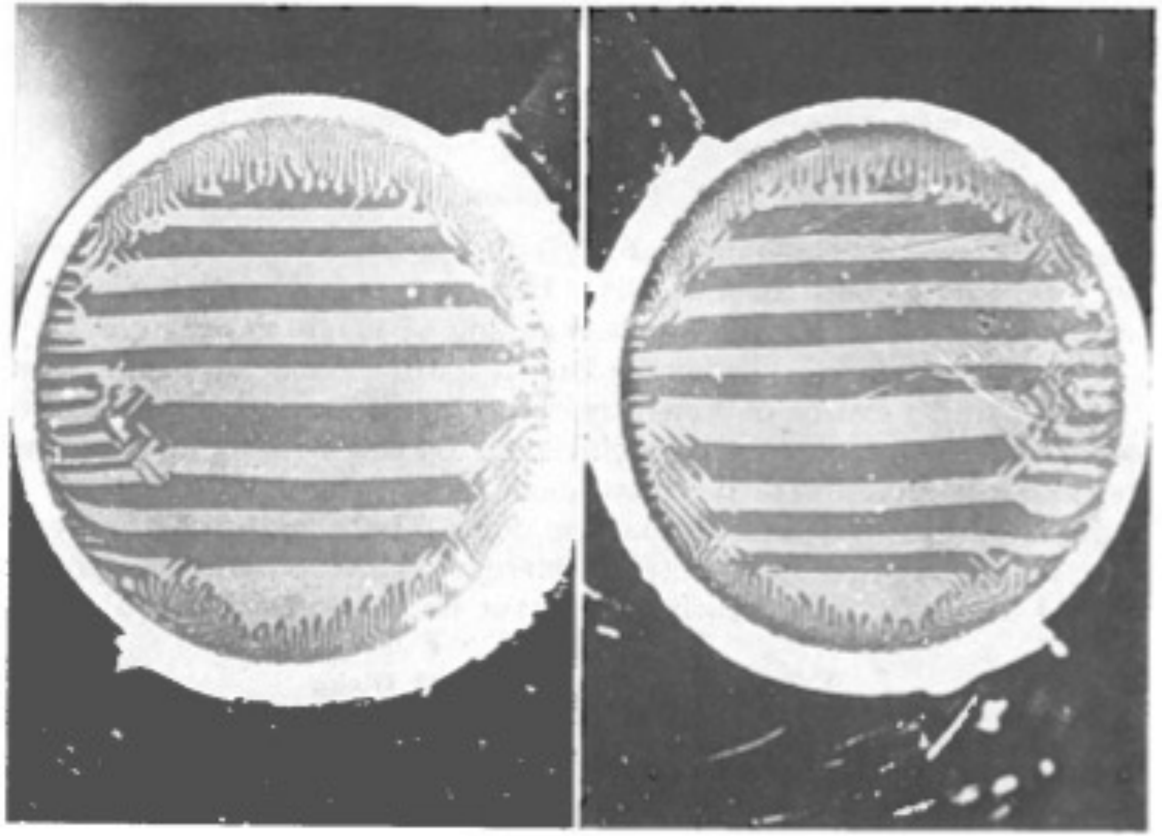
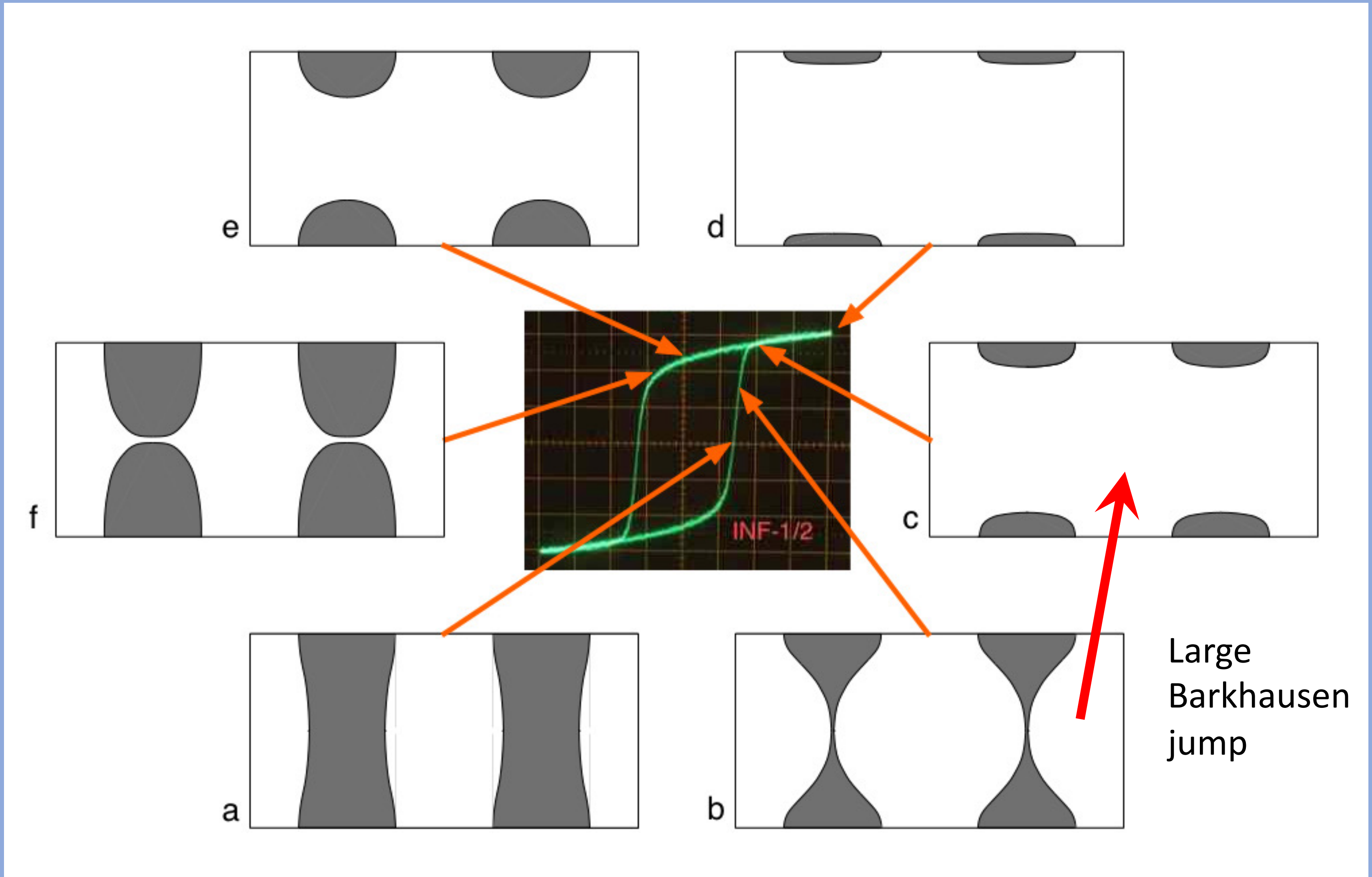
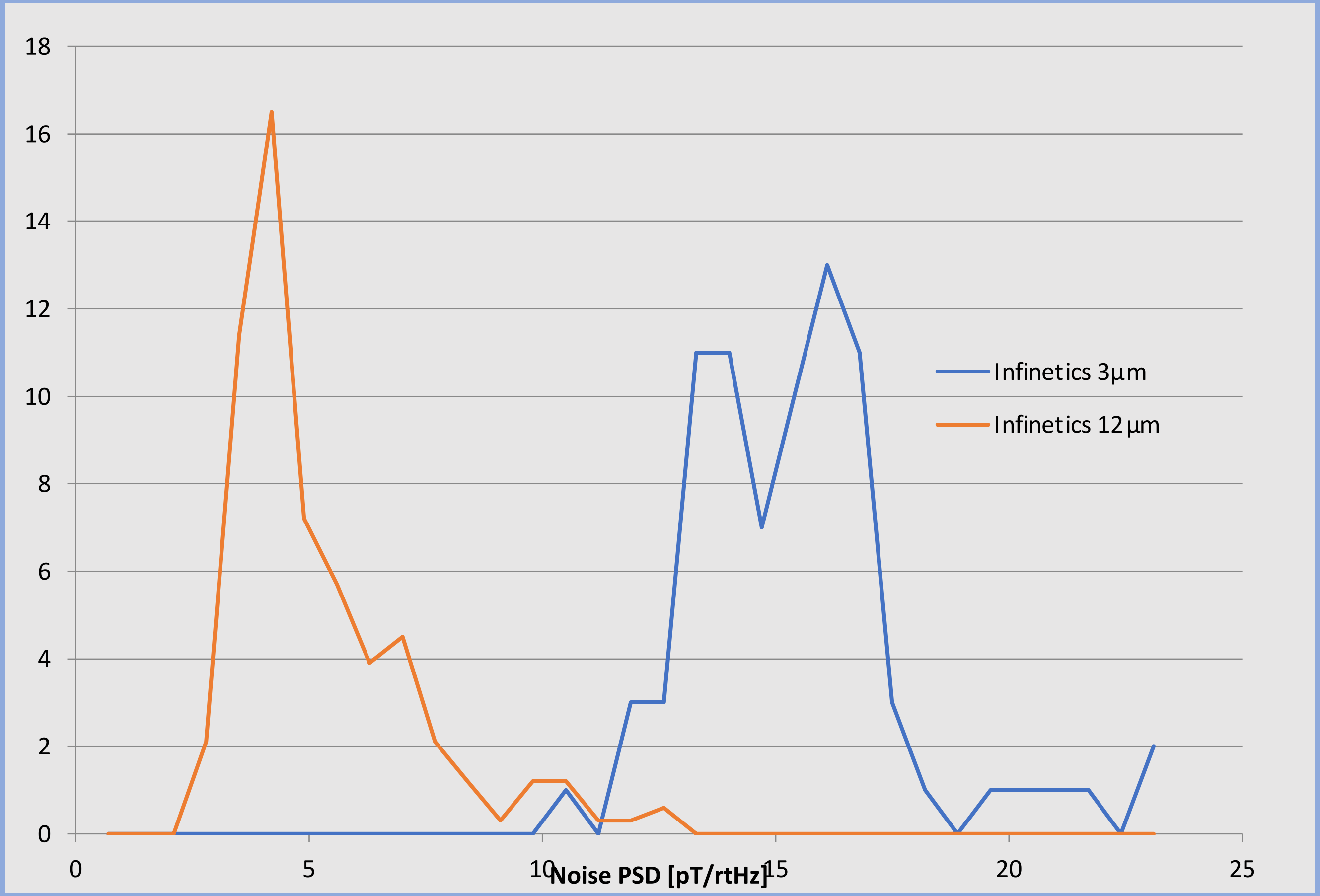


Fig. 1. Magnetic domain structures of the front and the back of a (110) single crystal disk with 38.7 at% Ni in Fe. The diameter of the sample is 7.5 mm; demagnetization in [001] direction

Stremme, 1974

The simplest grain:
Actual stripe domains in a 7.5mm single crystal, viewed on a polished, carefully oriented cut face. Note the complex collection of closure domains at the grain perimeter.


e
d
f
INF-1/2
c
a
b
Large
Barkhausen
jump



Geometry matters! Noise increases with free surface area

$$E_{\mathrm{d}} \propto t^{-1/2} \times \alpha \times B_{\mathrm{s}}^{3/2} \times K^{1/4}.$$

Total magnetic anisotropy

Saturation moment

Crystalline alignment

Foil thickness*

Domain wall volumetric energy density

*or crystal size, whichever is smaller

Two events now have moved us forward: 2) Discovering the potential of Cu-permalloys (2007)

Über Eisen-Nickel-Kupfer-Legierungen hoher Anfangspermeabilität

Von

Otto v. Auwers und Hans Neumann

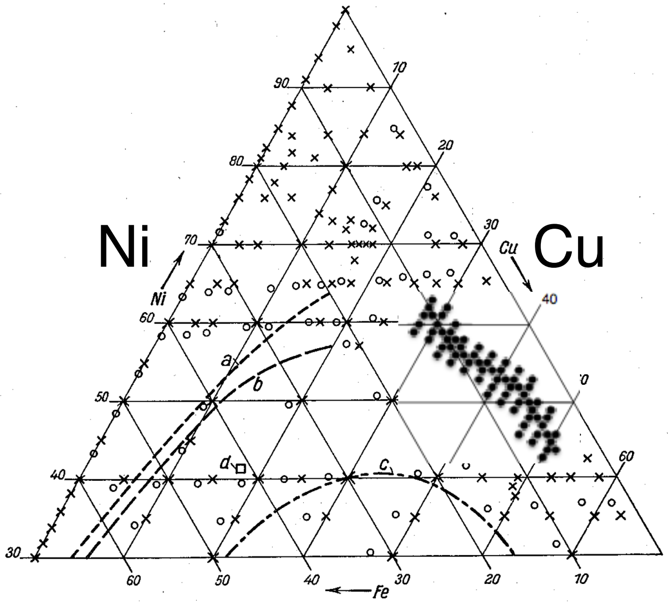
Mit 20 Bildern

Mitteilung aus dem Zentrallaboratorium
und der Abteilung für Elektrochemie des Wernerwerkes der Siemens & Halske A.-G.
und dem Forschungslaboratorium Siemensstadt

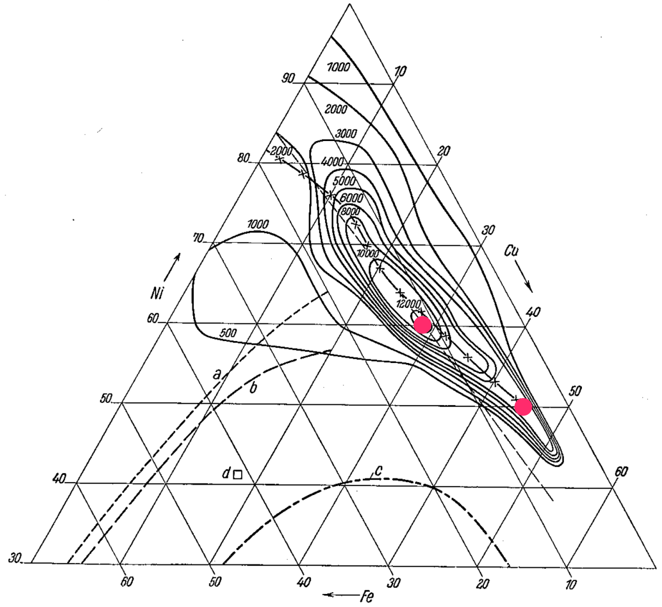
Eingegangen am 25. März 1935

History of copper permalloys

- These composition Figures show the 130 Copper alloys made for the 1935 Siemens and Halske study (circles and crosses), and the 50 Copper alloys made for our present study (left, larger dots).
- The right Figure shows the initial permeability contoured data from the original study.
- The red dots mark the end points of the range we have tested up to today, concentrated on the high permeability ridge.



Locations of alloys investigated in the FeNiCu-diagram



Lines of constant initial permeability - slow cooling

Original Figures from
Otto v Auwers and Hans Neumann, 1935
"Über Eisen-Nickel-Kupfer-Legierungen hoher Angfangspermeabilitat"
(On Iron-Nickel-Copper Alloys of high initial permeability), Springer

Materials results - compositions

- Nickel content is plotted vertically, increasing down in 1% increments.
- Copper content is plotted horizontally, increasing to the right in 1% increments.
- Red circles/text mark compositions for more extensive testing.
- Small numbers are Iron contents, as are color codes.

These data are to be published in an upcoming submission to the EGU Geophysical Instrumentation Journal.

Ni	Cu -->	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
42																						10	9	8	7
43																					10	9	8	7	6
44																				10	9	8	7	6	5
45																			10	9	8	7	6	5	4
46																		10	9	8	7	6	5	4	3
47																	10	9	8	7	6	5	4	3	2
48									17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
49								17	16	15	14	13	12	11	10	9	8	4449	6	5	4	3	2	1	0
50							17	16	15	14	13	12	11	10	9	4250	7	4450	4550	4	3	2	1	0	
51						17	16	15	14	13	12	11	10	4051	8	4251	6	4451	4	3	2	1	0		
52					17	16	15	14	13	12	11	10	9	4052	7	4252	4352	4452	3	2	1	0			
53				17	16	15	14	13	12	11	10	3853	8	4053	4153	4253	4	4453	2	1	0				
54			17	16	15	14	13	12	11	3654	9	3854	3954	4054	5	4254	3	2	1	0					
55		17	16	15	14	13	12	3455	10	3655	3755	3855	8	4055	4	3	2	1	0						
56		16	15	14	13	3256	11	3456	3556	3656	7	3856	5	4	3	2	1	0							
57		15	14	13	12	3257	3357	3457	8	3657	6	5	4	3	2	1	0								
58		14	13	3058	11	3258	3358	3458	7	6	5	4	3	2	1	0									
59		2859	12	3059	3159	3259	8	7	6	5	4	3	2	1	0										
60		2860	11	3060	9	3260	7	6	5	4	3	2	1	0											
61		2861	2961	3061	8	7	6	5	4	3	2	1	0												
62		2862	9	3062	7	6	5	4	3	2	1	0													
63		2863	8	7	6	5	4	3	2	1	0														
64		8	7	6	5	4	3	2	1	0															
65		7	6	5	4	3		3% Fe	4% Fe	5% Fe	6% Fe	7% Fe	8% Fe	9% Fe	10%Fe	11% Fe	12% Fe	13% Fe							
66																									

11 compositions in the original 1935 Siemens study

Typical 30g ingot

Materials results - resistivity

- We present here resistivities as a function of Copper and Nickel contents.
- Red filled specimens are lower resistivity, and blue specimens are high resistivity.
- Resistivities for our Copper alloys are similar to those for more traditional Permalloys, with values increasing with both Cu and Ni contents. Higher resistivity reduces eddy current losses.

Resistivities at 20C, ohm-meters x 10^-7

These data are to be published in an upcoming submission to the EGU Geophysical Instrumentation Journal.

Ni	Cu -->	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
42																						10	9	8	7
43																					10	9	8	7	6
44																				10	9	8	7	6	5
45																			10	9	8	7	6	5	4
46																		10	9	8	7	6	5	4	3
47																	10	9	8	7	6	5	4	3	2
48									17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
49								17	16	15	14	13	12	11	10	9	8	3.62	6	5	4	3	2	1	0
50							17	16	15	14	13	12	11	10	9	**	7	3.93	4.30	4	3	2	1	5.0	
51						17	16	15	14	13	12	11	10	3.15	8	3.78	6	4.24	4	3	2	1	0		
52					17	16	15	14	13	12	11	10	9	**	7	4.04	4.54	4.55	3	2	1	0			
53				17	16	15	14	13	12	11	10	3.44	8	3.85	4.10	4.21	4	4.89	2	1	0				
54			17	16	15	14	13	12	11	3.30	9	3.56	3.79	4.27	5	4.50	3	2	1	0					
55		17	16	15	14	13	12	2.99	10	3.60	3.67	3.72	6	4.22	4	3	2	1	0						
56		16	15	14	13	2.99	11	3.40	3.34	**	7	4.06	5	4	3	2	1	0							
57		15	14	13	12	3.11	3.13	3.56	8	3.88	6	5	4	3	2	1	0								
58		14	13	3.08	11	3.31	3.22	3.57	7	6	5	4	3	2	1	0									
59		2.86	12	2.93	3.27	3.22	8	7	6	5	4	3	2	1	0										
60		3.08	11	3.21	9	3.66	7	6	5	4	3	2	1	0											
61		3.16	3.19	3.45	8	7	6	5	4	3	2	1	4.8												
62		3.24	9	3.55	7	6	5	4	3	2	1	0													
63		3.48	8	7	6	5	4	3	2	1	0														
64		8	7	6	5	4	3	2	1	0															
65		7	6	5	4	3		>2.80	>3.00	>3.20	>3.40	>3.60	>3.80	>4.00	>4.20	>4.40	>4.60	>4.80							
66																									

** data not available

11 compositions in the original 1935 Siemens study

5.0 resistivity data from Delatorre et al, 2003

Materials results – saturation induction

- Maximum saturation moment is at 28%Cu.
- Minumum saturation moment is at 44-45%Cu.
- Test conditions: +/- 1200 A/m 24Hz. Values are consistent with Auwers & Neumann (1935)
- Lower saturation moment reduces both power consumption and sensor noise.

Resistivities at 20C, ohm-meters x 10^-7

These data are to be published in an upcoming submission to the EGU Geophysical Instrumentation Journal.

Ni	Cu -->	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
42																						10	9	8	7
43																					10	9	8	7	6
44																				10	9	8	7	6	5
45																			10	9	8	7	6	5	4
46																		10	9	8	7	6	5	4	3
47																	10	9	8	7	6	5	4	3	2
48									17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
49								17	16	15	14	13	12	11	10	9	8	3.62	6	5	4	3	2	1	0
50							17	16	15	14	13	12	11	10	9	**	7	3.93	4.30	4	3	2	1	5.0	
51						17	16	15	14	13	12	11	10	3.15	8	3.78	6	4.24	4	3	2	1	0		
52					17	16	15	14	13	12	11	10	9	**	7	4.04	4.54	4.55	3	2	1	0			
53				17	16	15	14	13	12	11	10	3.44	8	3.85	4.10	4.21	4	4.89	2	1	0				
54			17	16	15	14	13	12	11	3.30	9	3.56	3.79	4.27	5	4.50	3	2	1	0					
55		17	16	15	14	13	12	2.99	10	3.60	3.67	3.72	6	4.22	4	3	2	1	0						
56		16	15	14	13	2.99	11	3.40	3.34	**	7	4.06	5	4	3	2	1	0							
57		15	14	13	12	3.11	3.13	3.56	8	3.88	6	5	4	3	2	1	0								
58		14	13	3.08	11	3.31	3.22	3.57	7	6	5	4	3	2	1	0									
59		2.86	12	2.93	3.27	3.22	8	7	6	5	4	3	2	1	0										
60		3.08	11	3.21	9	3.66	7	6	5	4	3	2	1	0											
61		3.16	3.19	3.45	8	7	6	5	4	3	2	1	4.8												
62		3.24	9	3.55	7	6	5	4	3	2	1	0													
63		3.48	8	7	6	5	4	3	2	1	0														
64		8	7	6	5	4	3	2	1	0															
65		7	6	5	4	3		>2.80	>3.00	>3.20	>3.40	>3.60	>3.80	>4.00	>4.20	>4.40	>4.60	>4.80							
66																									

** data not available

11 compositions in the original 1935 Siemens study

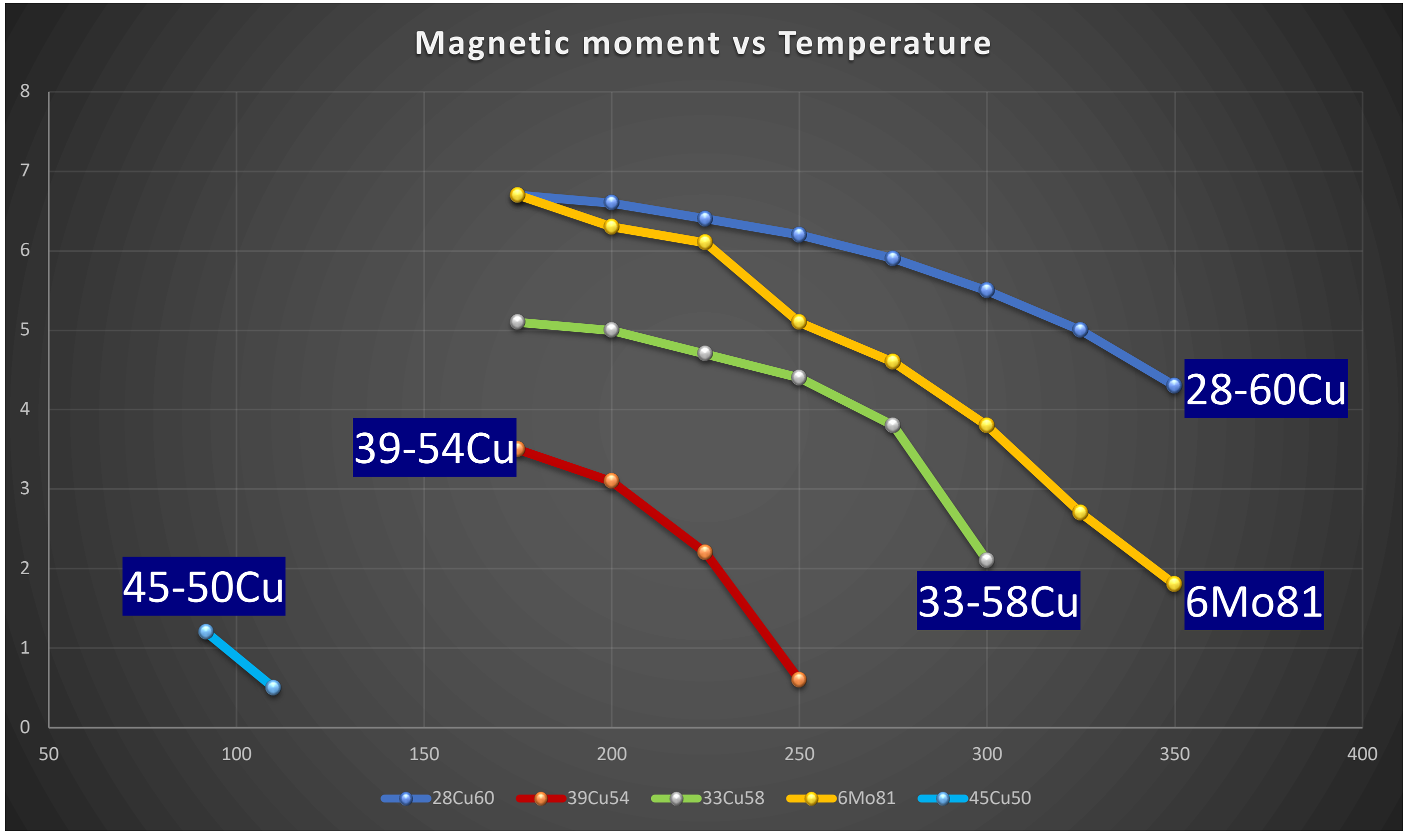
5.0 resistivity data from Delatorre et al, 2003

Materials results – Curie temperature (preliminary)

- We present here Curie temperature data for our four studied Copper alloys, and for 6%Moly' Permalloy.

- Interpreted Tc's are:

- 6Mo81 360C
- 28-60Cu >360C
- 33-58Cu 310C
- 39-54Cu 250C
- 45-50Cu 100C



Materials results – Curie temperature

- Five specimens:
  - 28Cu60Ni
  - 33Cu58Ni
  - 39Cu54Ni
  - 44Cu51Ni
  - 45Cu50Ni
- 44Cu53Ni was paramagnetic.

These data are to be published in an upcoming submission to the EGU Geophysical Instrumentation Journal.

Ni	Cu -->	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
42																						10	9	8	7
43				Curie temperature, C																	10	9	8	7	6
44																				10	9	8	7	6	5
45																			10	9	8	7	6	5	4
46																		10	9	8	7	6	5	4	3
47																	10	9	8	7	6	5	4	3	2
48									17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
49								17	16	15	14	13	12	11	10	9	8	4449	6	5	4	3	2	1	0
50							17	16	15	14	13	12	11	10	9	4250	7	4450	100	4	3	2	1	0	
51						17	16	15	14	13	12	11	10	4051	8	4251	6	100	4	3	2	1	0		
52					17	16	15	14	13	12	11	10	9	4052	7	4252	4352	4452	3	2	1	0			
53				17	16	15	14	13	12	11	10	3853	8	4053	4153	4253	4	<20	2	1	0				
54			17	16	15	14	13	12	11	3654	9	3854	250	4054	5	4254	3	2	1	0					
55		17	16	15	14	13	12	3455	10	3655	3755	3855	6	4055	4	3	2	1	0						
56		16	15	14	13	3256	11	3456	3556	3656	7	3856	5	4	3	2	1	0							
57		15	14	13	12	3257	3357	3457	8	3657	6	5	4	3	2	1	0								
58		14	13	3058	11	3258	310	3458	7	6	5	4	3	2	1	0									
59		2859	12	3059	3159	3259	8	7	6	5	4	3	2	1	0										
60		>350	11	3060	9	3260	7	6	5	4	3	2	1	0											
61		2861	2961	3061	8	7	6	5	4	3	2	1	0												
62		2862	9	3062	7	6	5	4	3	2	1	0													
63		2863	8	7	6	5	4	3	2	1	0														
64		8	7	6	5	4	3	2	1	0															
65		7	6	5	4	3																			
66																									

<20 Curie temperature, C

11 compostions in the original 1935 Siemens study

Materials results – initial permeability

- Test conditions:
- +/- 0.4 A/m,
- 250Hz

- Cells outlined in red are a selection of local high values for permeability, and local low values for coercivity (next slide). Both are indicators for better noise performance (Musmann, 2010).

These data are to be published in an upcoming submission to the EGU Geophysical Instrumentation Journal.

Ni	Cu -->	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
42																						10	9	8	7
43				Iniitial relative permeability, G/Oe																	10	9	8	7	6
44																				10	9	8	7	6	5
45																			10	9	8	7	6	5	4
46																		10	9	8	7	6	5	4	3
47																	10	9	8	7	6	5	4	3	2
48									17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
49								17	16	15	14	13	12	11	10	9	8	360	6	5	4	3	2	1	0
50							17	16	15	14	13	12	11	10	9	10	7	860	660	4	3	2	1	0	
51						17	16	15	14	13	12	11	10	600	8	480	6	3580	4	3	2	1	0		
52					17	16	15	14	13	12	11	10	9	**	7	2180	3920	3620	3	2	1	0			
53				17	16	15	14	13	12	11	10	840	8	3300	3500	3100	4	1	2	1	0				
54			17	16	15	14	13	12	11	1120	9	2400	1880	3620	5	2580	3	2	1	0					
55		17	16	15	14	13	12	1040	10	700	3840	2440	6	3240	4	3	2	1	0						
56		16	15	14	13	840	11	2700	3300	**	7	3120	5	4	3	2	1	0							
57		15	14	13	12	2580	2640	5400	8	3220	6	5	4	3	2	1	0								
58		14	13	1680	11	2440	2560	3920	7	6	5	4	3	2	1	0									
59		2140	12	5140	3900	5620	8	7	6	5	4	3	2	1	0										
60		4460	11	3900	9	4820	7	6	5	4	3	2	1	0											
61		3220	6300	4500	8	7	6	5	4	3	2	1	0				**	data not available							
62		5280	9	5360	7	6	5	4	3	2	1	0					1400	initial relative permealbiity							
63		5040	8	7	6	5	4	3	2	1	0						6200	red boundary indicates local high values							
64		8	7	6	5	4	3	2	1	0							11	compositions in the original 1935 Siemens study							
65		7	6	5	4	3		<2400	<2800	<3200	<3600	<4000	<4400	<4800	<5200	<5600	<6000	>6000							
66																									

Material results – 0Hz coercivity

- Test conditions:
- +/- 50 A/m,
- 10Hz

- Cells outlined in red are a selection of local high values for permeability (previous slide), and local low values for coercivity.

These data are to be published in an upcoming submission to the EGU Geophysical Instrumentation Journal.

Ni	Cu -->	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
42																						10	9	8	7
43				coercivity, measured at 10Hz, A/m																	10	9	8	7	6
44																				10	9	8	7	6	5
45																			10	9	8	7	6	5	4
46																		10	9	8	7	6	5	4	3
47																	10	9	8	7	6	5	4	3	2
48									17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
49								17	16	15	14	13	12	11	10	9	8	13	6	5	4	3	2	1	0
50							17	16	15	14	13	12	11	10	9	35	7	9	4.5	4	3	2	1	0	
51						17	16	15	14	13	12	11	10	36	8	11	6	3.5	4	3	2	1	0		
52					17	16	15	14	13	12	11	10	9	**	7	6	3.5	2.5	3	2	1	0			
53				17	16	15	14	13	12	11	10	10.5	8	7	5.5	4.5	4	**	2	1	0				
54			17	16	15	14	13	12	11	13	9	8	6.5	5.5	5	4	3	2	1	0					
55		17	16	15	14	13	12	24.5	10	12.5	6.5	6.5	6	5	4	3	2	1	0						
56		16	15	14	13	19	11	9.5	8.5	**	7	6	5	4	3	2	1	0							
57		15	14	13	12	11.5	10	7	8	7	6	5	4	3	2	1	0								
58		14	13	13	11	10.5	7.5	7	7	6	5	4	3	2	1	0									
59		12	12	8	9.5	7	8	7	6	5	4	3	2	1	0										
60		10	11	8.5	9	8	7	6	5	4	3	2	1	0											
61		9	7.5	7.5	8	7	6	5	4	3	2	1	0				**	data not available							
62		7.5	9	7.5	7	6	5	4	3	2	1	0					6200	red boundary indicates local high values							
63		7.5	8	7	6	5	4	3	2	1	0						11	compostions in the original 1935 Siemens study							
64		8	7	6	5	4	3	2	1	0															
65		7	6	5	4	3	2	<4	<5	<6	<7	<8	<9	<10	<11	<13	<15	>15							
66																									

Material results – initial permeability

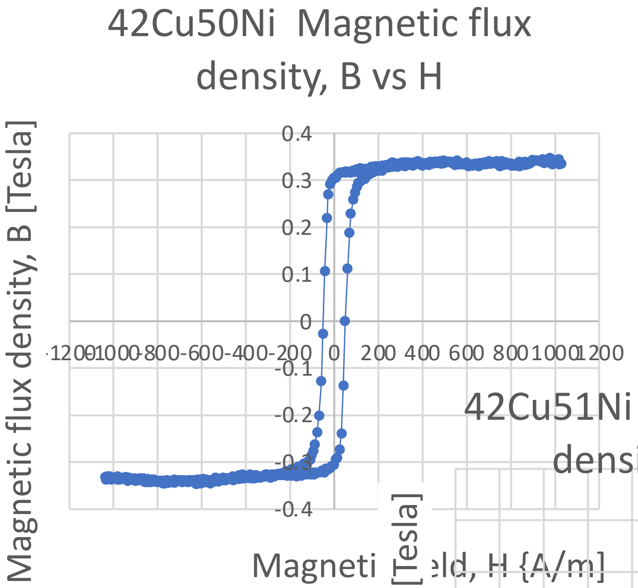
These data are to be published in an upcoming submission to the EGU Geophysical Instrumentation Journal.

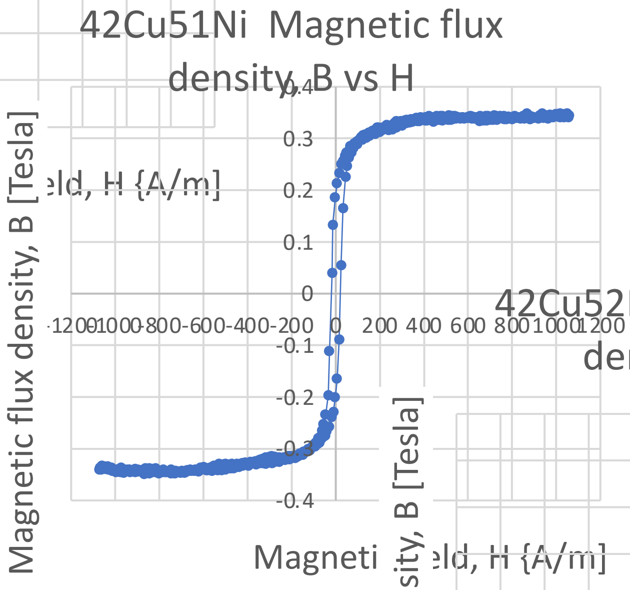
Iniitial relative permeability, G/Oe

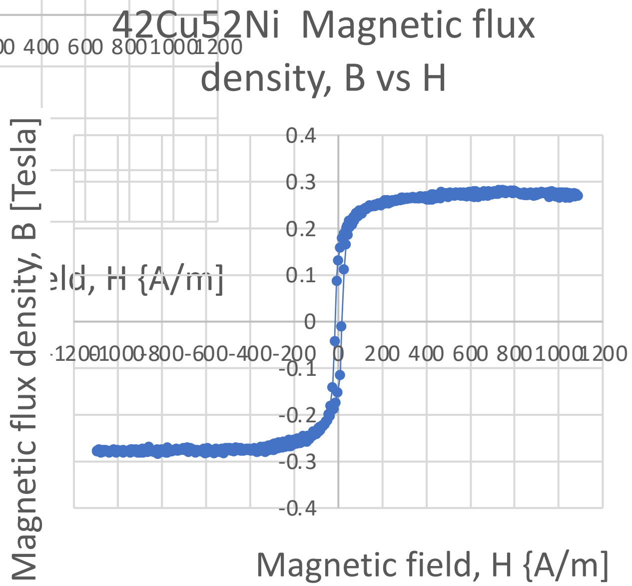
Ni	Cu -->	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
42																						10	9	8	7
43																					10	9	8	7	6
44																				10	9	8	7	6	5
45																			10	9	8	7	6	5	4
46																		10	9	8	7	6	5	4	3
47																	10	9	8	7	6	5	4	3	2
48									17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
49								17	16	15	14	13	12	11	10	9	8	360	6	5	4	3	2	1	0
50							17	16	15	14	13	12	11	10	9	10	7	860	660	4	3	2	1	0	
51						17	16	15	14	13	12	11	10	600	8	480	6	3580	4	3	2	1	0		
52					17	16	15	14	13	12	11	10	9	**	7	2180	3920	3620	3	2	1	0			
53				17	16	15	14	13	12	11	10	840	8	3300	3500	3100	4	1	2	1	0				
54			17	16	15	14	13	12	11	1120	9	2400	1880	3620	5	2580	3	2	1	0					
55		17	16	15	14	13	12	1040	10	700	3840	2440	6	3240	4	3	2	1	0						
56		16	15	14	13	840	11	2700	3300	**	7	3120	5	4	3	2	1	0							
57		15	14	13	12	2580	2640	5400	8	3220	6	5	4	3	2	1	0								
58		14	13	1680	11	2440	2560	3920	7	6	5	4	3	2	1	0									
59		2140	12	5140	3900	5620	8	7	6	5	4	3	2	1	0										
60		4460	11	3900	9	4820	7	6	5	4	3	2	1	0											
61		3220	6300	4500	8	7	6	5	4	3	2	1	0												
62		5280	9	5360	7	6	5	4	3	2	1	0													
63		5040	8	7	6	5	4	3	2	1	0														
64		8	7	6	5	4	3	2	1	0															
65		7	6	5	4	3		<2400	<2800	<3200	<3600	<4000	<4400	<4800	<5200	<5600	<6000	>6000							
66																									

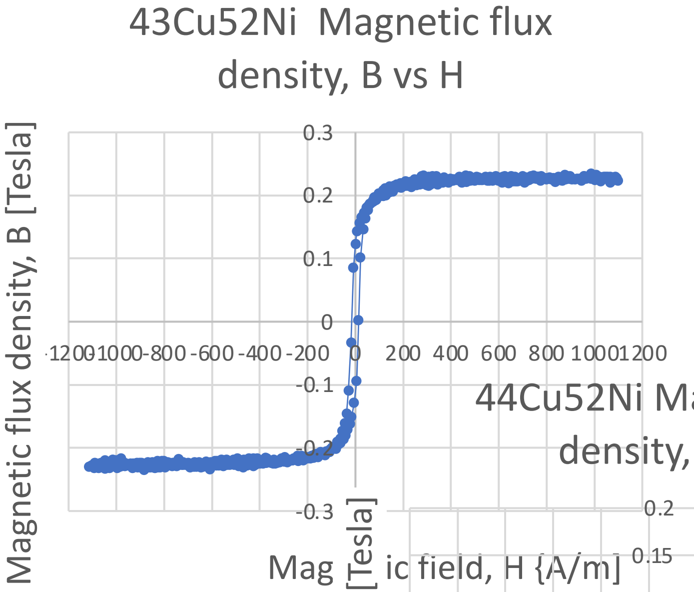
- ** data not available
- 1400 initial relative permealbiity
- 6200 red boundary indicates local high values
- 11 compositions in the original 1935 Siemens study

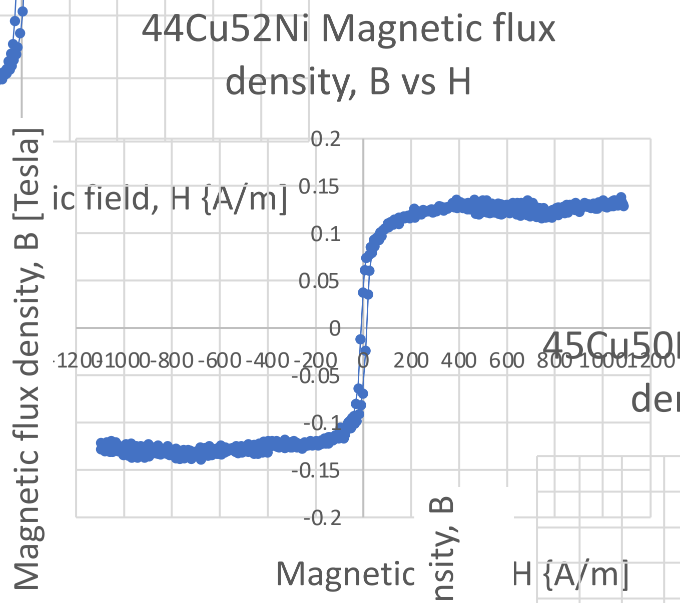
Material results – 0Hz coercivity detail

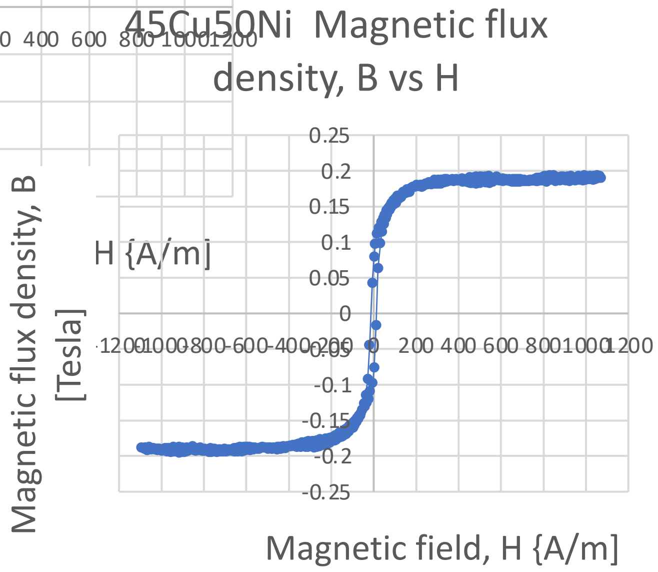






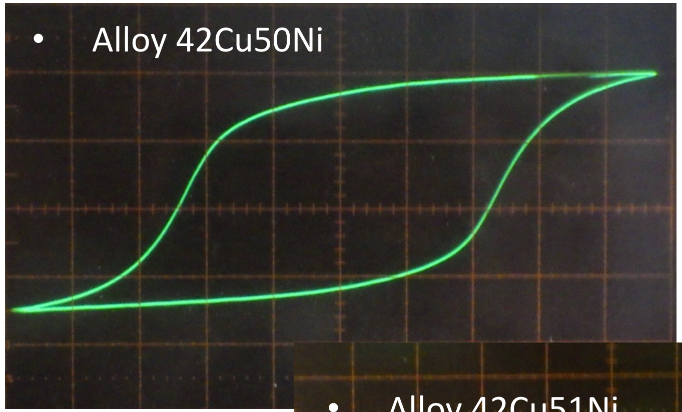


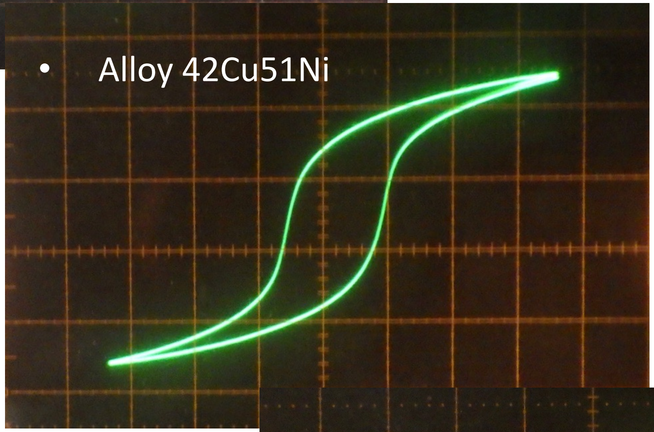




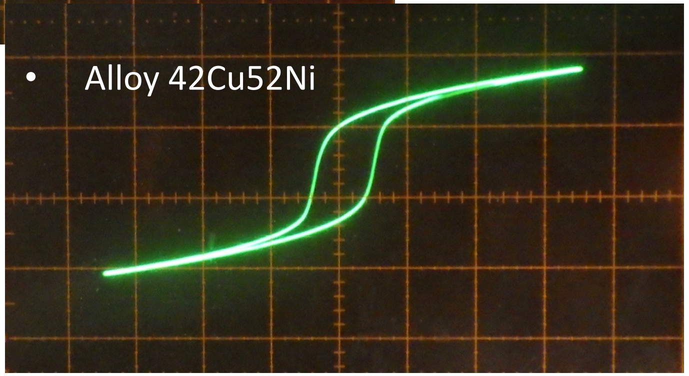
Note:
Common horizontal scale, but differing vertical scales

0Hz coercivity detail

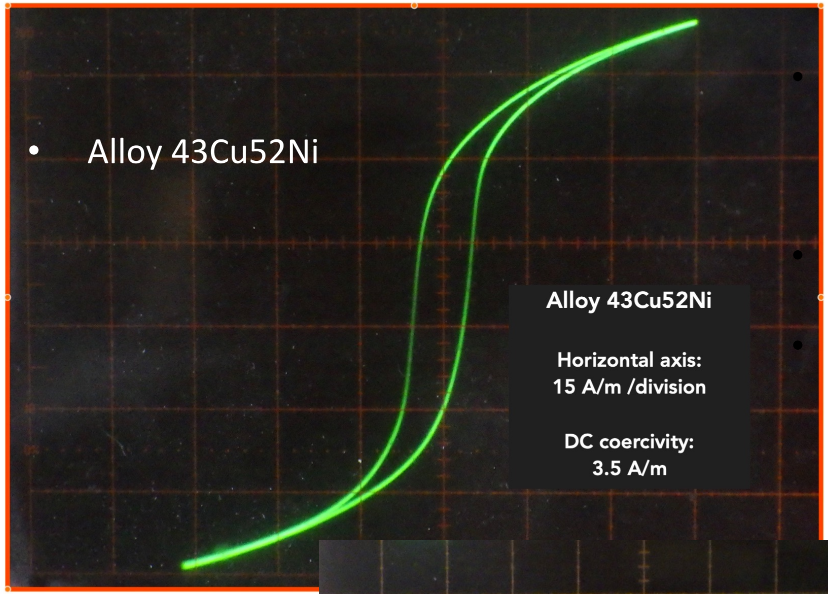




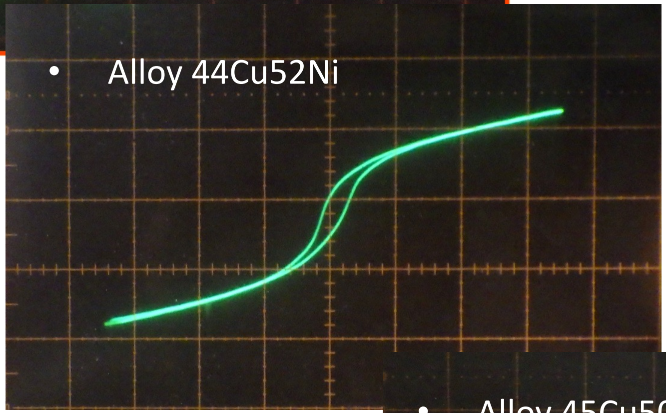
All 200mT/div



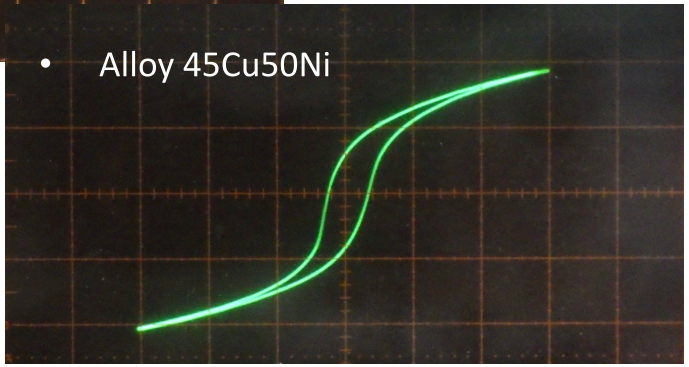
15 A/m/div



- Magnetic parameters of 43Cu52Ni are competitive with the best amorphous materials, e.g.
- VAC 6025
- Advantage: thicker foils

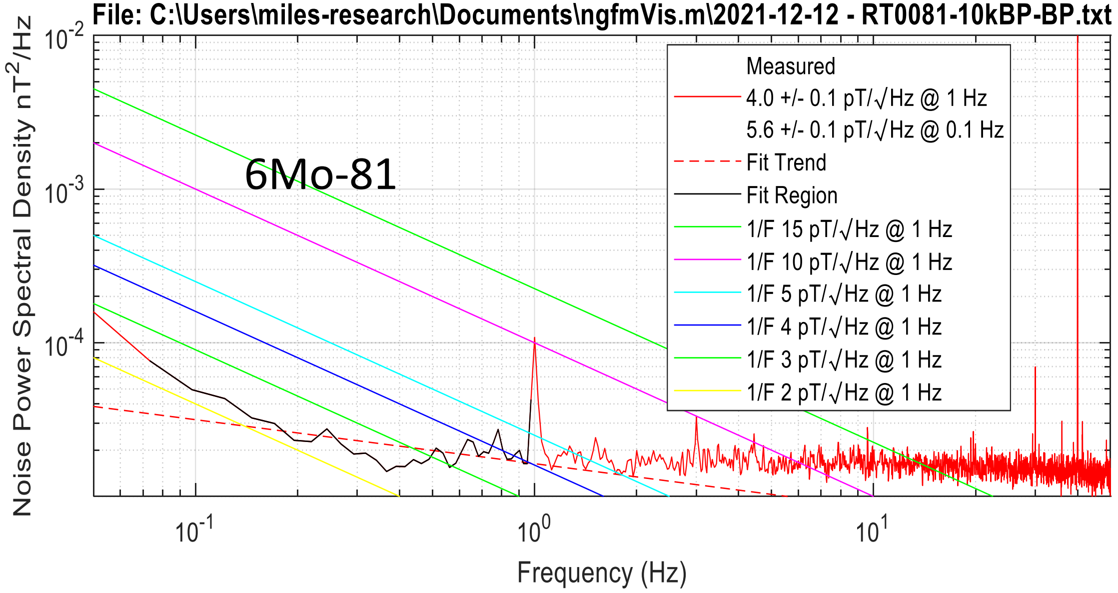


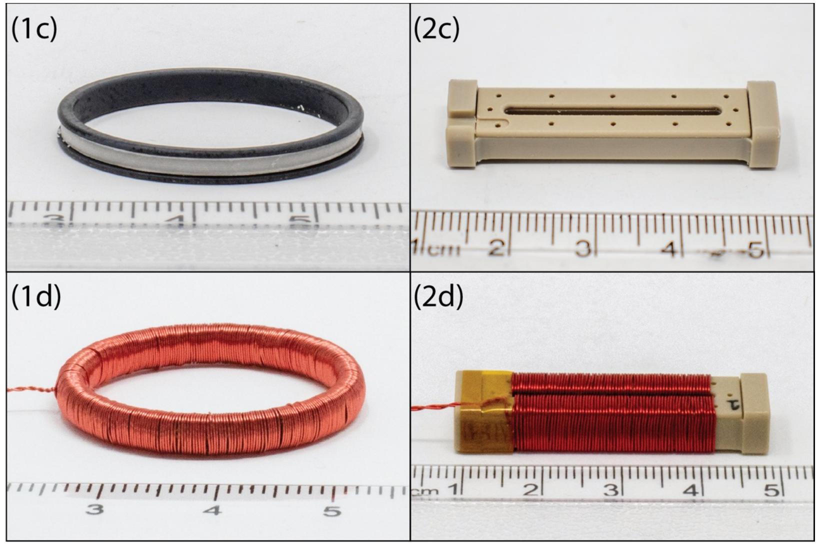
All 100mT/div



Fluxgate performance: Racetrack Test Cores

- Test cores manufactured in racetrack geometry
- Permalloy washers are heat-treated and then stacked with interleaved Kapton
- High repeatability and yield compared to standard 1” ring-core





David M. Miles and others,
Geosci. Instrum. Method. Data Syst., 11, 111–126, 2022
https://doi.org/10.5194/gi-11-111-2022

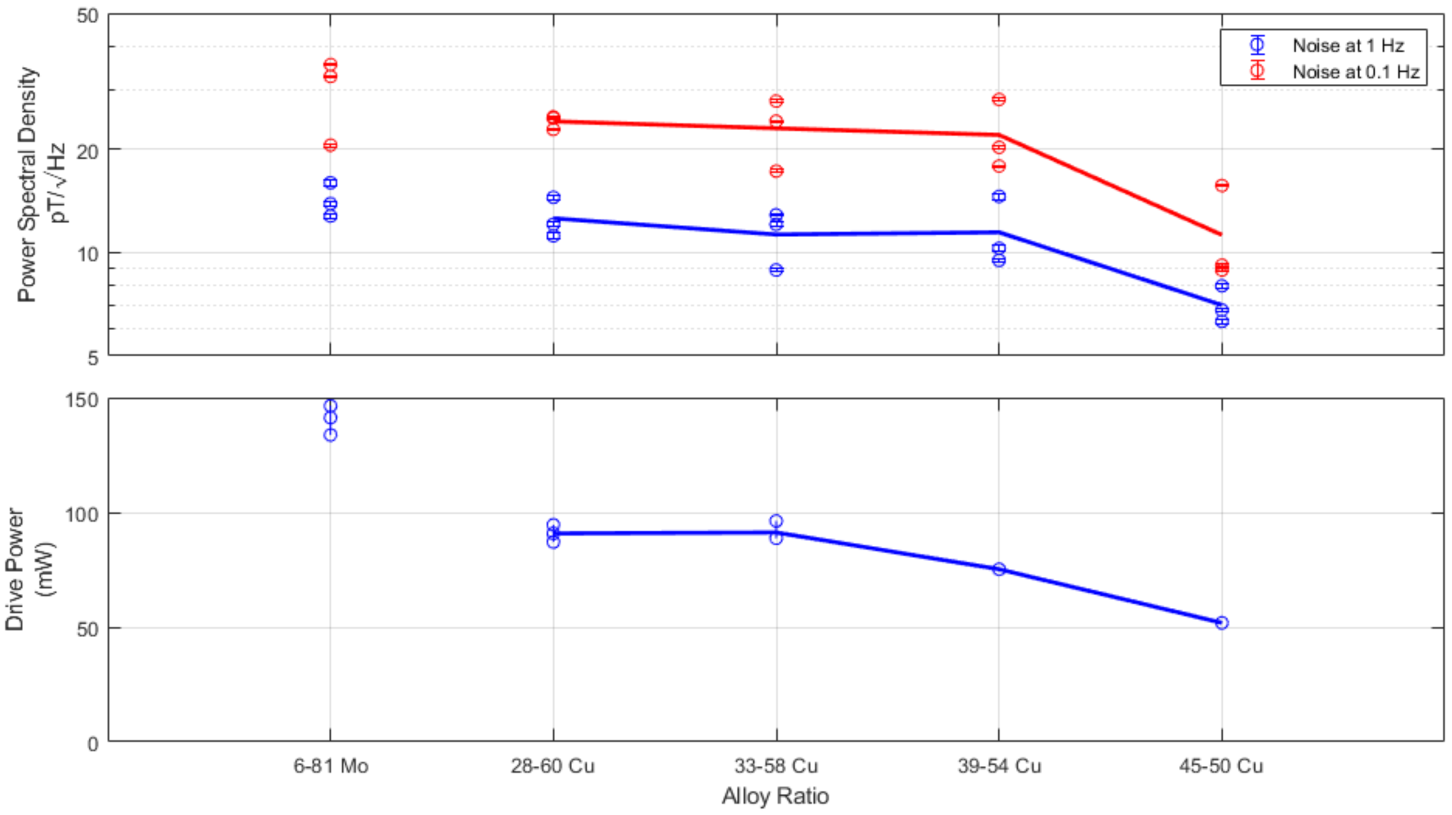
Fluxgate performance - Fluxgate Power/Noise

Experiment:

- Alloy sweep from 28 to 45% Cu
- 6-81 Mo used as a control
- All cores used 3 layers of permalloy
- QTY 3 cores for each alloy

Results:

- Noise in Power Spectral Density improves at all frequencies as %Cu increases
- Power consumption generally decreases as %Cu increases
- Cu permalloy outperforms 6-81 Mo in all metrics.



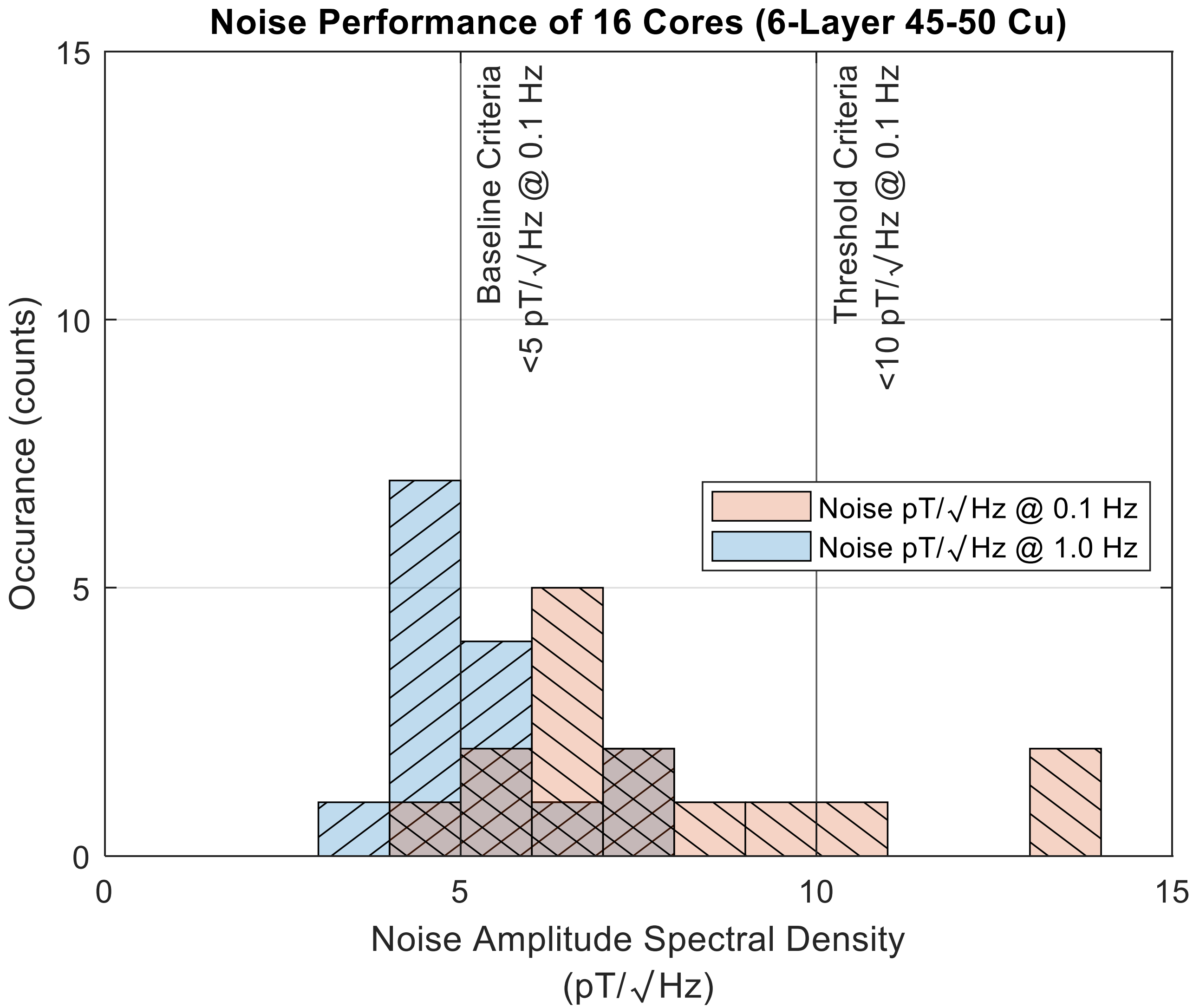
Fluxgate performance - Fluxgate Power/Noise

Experiment:

- Detail study of 45%Cu50%Ni
- 6-81 Mo used as a control
- All cores used 6 layers of permalloy

Results:

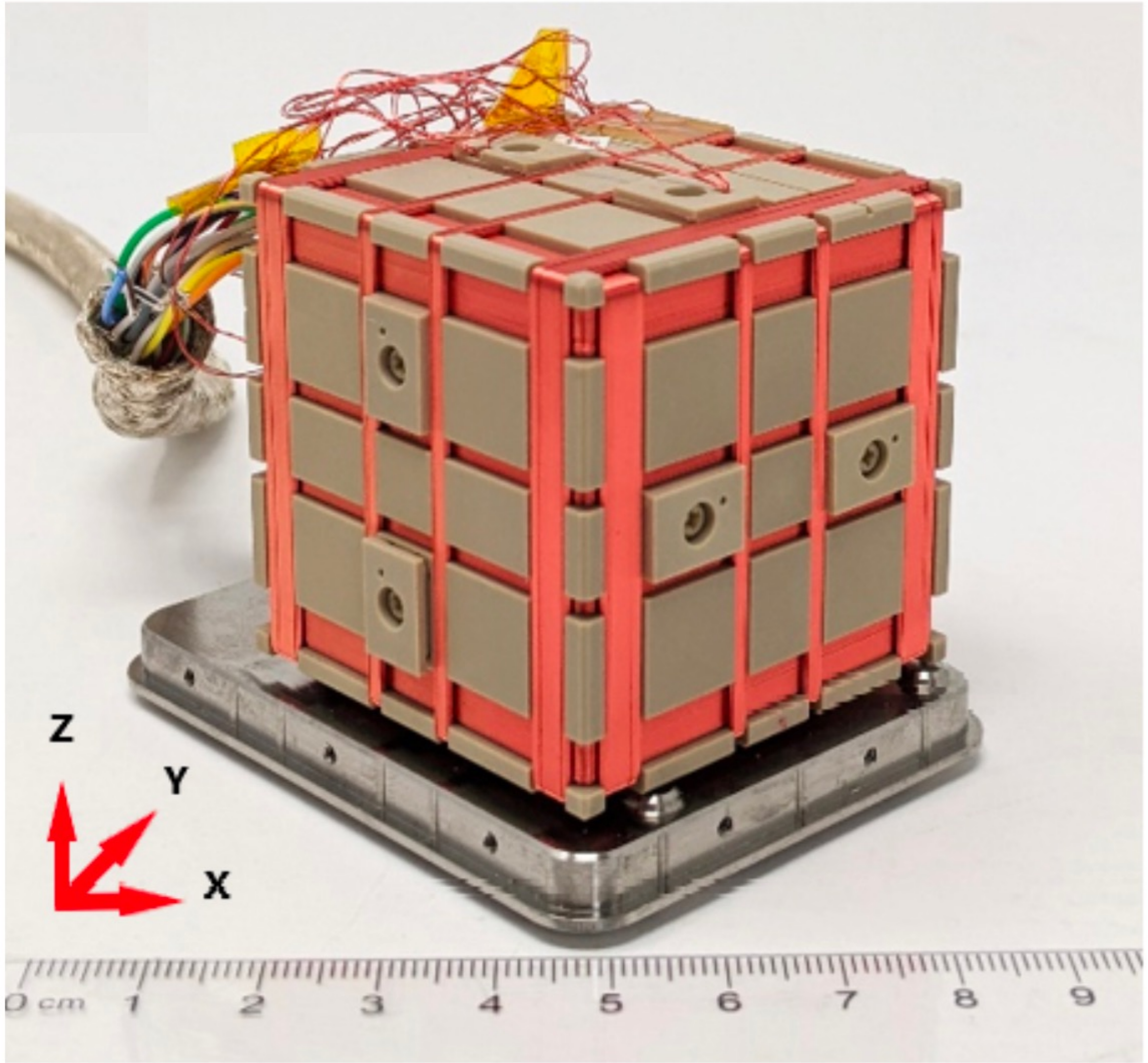
- Noise in Power Spectral Density [PSD] at 1Hz is 5 pT/rtHz [most likely]
- Noise PSD at 0.1 Hz is 8 pT/rtHz [most likely]
- Typical performance is well within INTERMAGNET 1 second standard



Tesseract sensor design

- 3 axis symmetric sensor design incorporating six racetrack cores
- 50 x 50 x 50 mm cube
- Merritt style feedback coil, requiring about 30 mW power
- Two racetrack cores per axis with an expected 3 dB further noise improvement with six cores

- Nov 20, 2022, two sensors flew successfully on ACES-II sounding rocket, reaching 188 km altitude.



Kenton Greene and others,
Geosci. Instrum. Method. Data Syst., 11, 307–321, 2022
https://doi.org/10.5194/gi-11-307-2022

Summary

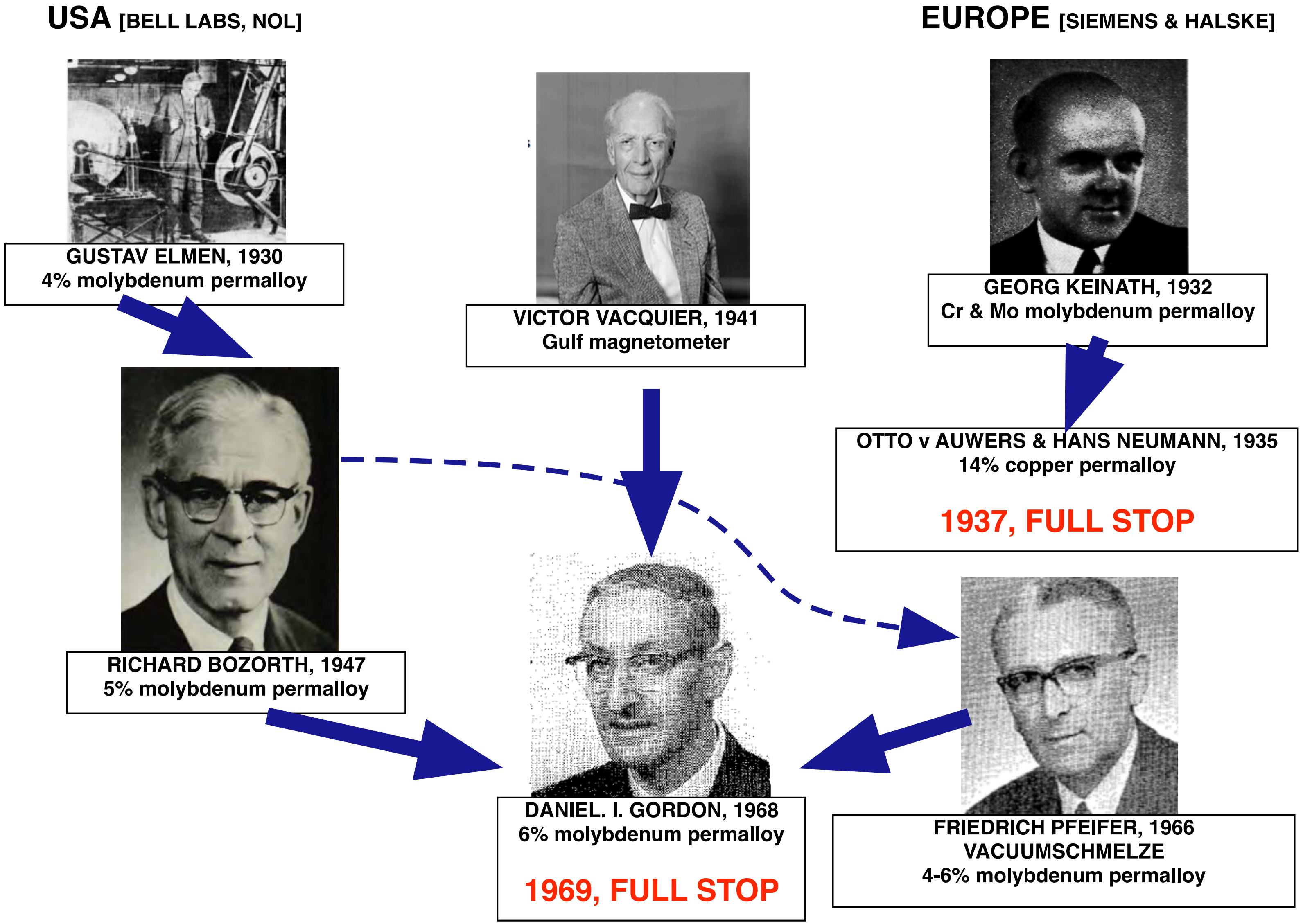
- Copper permalloy compares favorably to traditional 6-81 Mo in noise and power consumption for use in fluxgate magnetometers
- Potential for future optimization within the Molybdenum alloy range
- Current work enables cores that meet the recent INTERMAGNET requirement <10 pT/√Hz @ 0.1 Hz and further improvements are likely

This work is funded in part by:

- MAGnetometers for Innovation and Capability (MAGIC) Technical Demonstration 80GSFC18C0008
- CHIMERA: A hybrid search coil and fluxgate magnetometer for small spacecraft missions 18-HTIDS18_2-0010

History of permalloys: Why were Cu permalloys forgotten?

- In the USA the first Permalloys were invented by G. Elmen. These included 4% Moly’ Permalloy.
- Parallel developments occurred in the UK and in Germany
- By 1937 all work on Copper alloys had stopped.
- By 1969 all work on Moly’ alloys for fluxgates had also stopped. 6% Moly’ alloys became the preferred material.



Patented June 1, 1926. **1,586,884**

UNITED STATES PATENT OFFICE.

GUSTAF W. ELMEN, OF LEONIA, NEW JERSEY, ASSIGNOR TO WESTERN ELECTRIC COMPANY, INCORPORATED OF NEW YORK, N. Y., A CORPORATION OF NEW YORK.

MAGNETIC MATERIAL.

Application filed May 31, 1921. Serial No. 473,877.

This invention relates to the production and use of a new material or substance having certain desirable magnetic qualities, among which are high magnetic permeability, especially at low magnetizing forces, and low hysteresis loss. It is one object of this invention to provide a suitable loading material for signaling conductors to increase their range and speed of operation. Another object relates to applying this loading material to a conductive core in a manner to produce a highly efficient transmission line for long range, high speed signaling. These objects and other objects will become apparent on consideration of examples of practice thereunder which will be disclosed specifically in this specification, with the understanding that the definition of the invention will be given in the appended claims.

This application is in part a continuation of application, Serial No. 111,080, filed July 24, 1916.

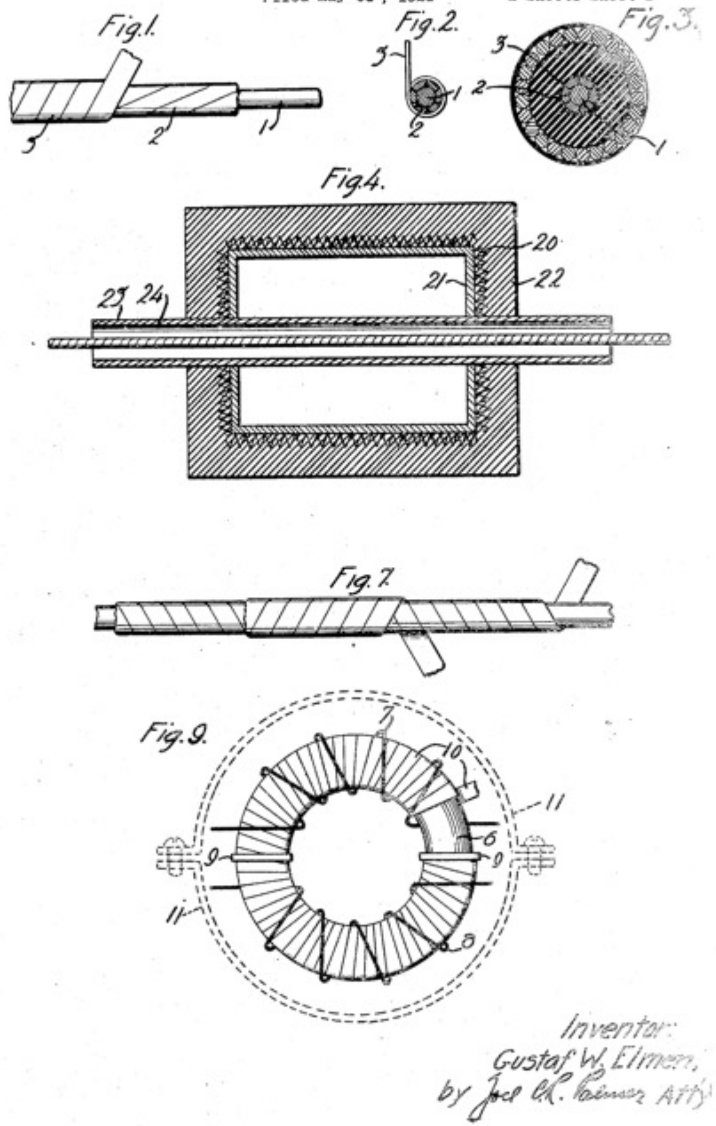
The importance of iron in the practical

Silicon steel exhibits magnetic qualities superior to ordinary iron in some respects, but its employment is limited by its comparative brittleness and the difficulty of working it. A good quality of soft iron has been commonly employed as the best magnetic medium for general use for tractive electromagnets. The principal possible rivals of iron, nickel and cobalt, are far below it in permeability at the magnetizing forces involved in such apparatus. With nickel and cobalt, in this respect, stands Heusler's alloy of aluminum, manganese, and copper. It has been found that a composition of about ⅔ nickel and ⅓ copper, when tested at low magnetizing forces, gives a permeability higher than that of iron alone. It will be seen that with the exception of aluminum, all these metals stand close together in their atomic weights and atomic numbers and in this specification the five elements, manganese, iron, cobalt, nickel and copper, having the consecutive atomic numbers 25, 26, 27, 28 and 29 will be re-

June 1, 1926. G. W. ELMEN 1,586,884

MAGNETIC MATERIAL

Filed May 31, 1921 2 Sheets-Sheet 1



UNITED STATES PATENT OFFICE.

WILLOUGHBY STATHAM SMITH, OF BENCHAMS, NEWTON POPPLEFORD, AND HENRY JOSEPH GARNETT, OF SEVEN OAKS, ENGLAND.

MAGNETIC ALLOY.

No Drawing. Original application filed January 10, 1924, Serial No. 685,432. Divided and this application filed May 2, 1925. Serial No. 27,593.

To all whom it may concern:

Be it known that we, WILLOUGHBY STATHAM SMITH, a subject of the King of Great Britain, residing at Benchams, Newton Poppleford, Devonshire, England, and HENRY JOSEPH GARNETT, a subject of the King of Great Britain, residing at Lymne, Solefields, Seven Oaks, Kent, England, have invented a new and useful Improvement in Magnetic Alloys, of which the following is a specification.

This application is a division of our application Ser. No. 685,432, filed January 10, 1924.

This invention relates to the production of alloys possessing a high magnetic permeability especially at low magnetizing forces.

It is well known that it is desirable to add inductance to telegraphic and telephonic cables and this has before been done by wrapping around the core of the cable an iron tape or wire.

Many research workers have been investigating the properties of various alloys, especially those of nickel and iron, with a view to discovering an alloy that should be

We also preferably include a small amount of manganese to render the alloy more easy to forge.

The following are examples of alloys made in accordance with our invention

No. 1.

An alloy consisting of:—

	Per cent.
Nickel	74.0
Iron	20.0
Copper	5.3
Manganese	0.7

has an initial magnetic permeability of 7000.

No. 2.

An alloy consisting of:—

	Per cent.
Nickel	73.0
Copper	5.4
Iron	20.7
Tungsten	0.6
Manganese	0.3

has an electrical resistance of 25 microhms per cubic centimetre and an initial magnetic permeability of 6600.

ATM Archiv für Technisches Messen | Z 913—3 November 1932

T 173

GEORG KEINATH, 1932
Cr & Mo molybdenum permalloy

Mißhandlung vermindert. Allen diesen ternären Legierungen ist eigen, daß ihr Sättigungswert niedriger liegt.

Eine Anzahl (Mumetall, die Nickel-Eisen-Manganlegierungen nach Gumlich) sind bereits in Z 913—1 erwähnt worden. Neue Ergebnisse liegen von Elmen[6] vor über die Eigenschaften von Permalloy, bei dem ein Teil des Eisens (normal 21,5%) durch Chrom oder

der Temperatur. Ohne Molybdänzusatz liegt der Curiepunkt, wo das Material unmagnetisch wird, bei 580° C, nachdem vorher bei etwa 450° C ein starkes Anwachsen der Permeabilität stattfand. Für 10% Mo liegt der

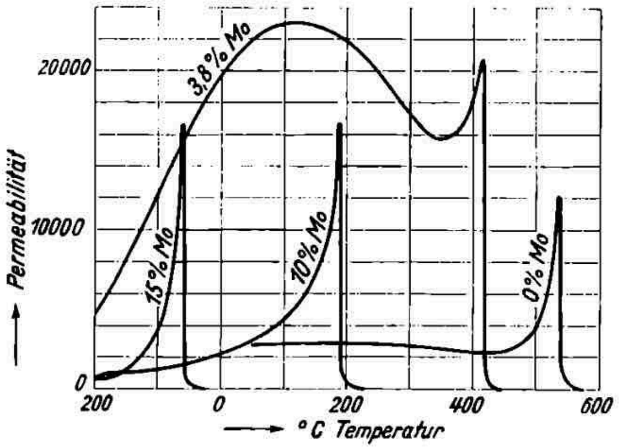


Bild 6. Permeabilität von Mo-Permalloy in Abhängigkeit von der Temperatur.

Neue magnetische Legierung „1040“
mit hoher Anfangs-Permeabilität

Z
913—5

Verfasser: Dr. Hans Neumann, Berlin-Siemensstadt

DK 681.2.03
669.144.24.018.58

Im folgenden werden ausführliche Angaben über eine neue hochpermeable Eisen-Nickel-Kupfer-Molybdän-Legierung von Siemens & Halske (Nr. 1040) mitgeteilt. Diese Legierung, die z. Z. die höchsten Werte der Anfangspermeabilität (μ_0...40000) besitzt, hat zwar eine gewisse Ähnlichkeit mit dem Mu-Metall (ATM Z 913—2), unterscheidet sich aber von ihm durch ihren niedrigeren Nickelgehalt, den Zusatz von Molybdän und den dreifach höheren Kupfergehalt. Dieser ist so hoch (14%), daß hohe Werte der Anfangspermeabilität nach den bisherigen Erfahrungen dabei nicht mehr zu erwarten waren. „1040“ besteht aus etwa 72% Ni, 11% Fe, 14% Cu, 3% Mo und ist gut walzbar; das spez. Gewicht ist 8,76, der spez. Widerstand 0,56. Die in den Bildern 1...10 gegebenen magnetischen Werte wurden an 0,35 mm starken Ringen von 60 mm Außen- und 45 mm Innendurchmesser gemessen. Gegenüber den höchsten magnetischen Werten des Mu-Metalls, der bisher besten Legierung für kleine Induktionen, wurden Anfangspermeabilität, Koerzitivkraft und Hysteresisverluste um den Faktor 2...3 verbessert. Die hohe Anfangspermeabilität der Legierung hängt zusammen mit ihrer niedrigen Magnetostriktion, die um eine Größenordnung tiefer liegt als beim Permalloy und etwa 5×10^{-7} beträgt. Die Hysteresisverluste (Bild 4) sind so gering, daß sie bei 0,35 mm Blech nur 25% der Gesamtverluste ausmachen, wie aus der für die Wirbelstromverluste typischen elliptischen Schleifenform (Bild 5) hervorgeht.

Die Alterungsbeständigkeit ist sehr hoch, eine 600stündige Erwärmung auf 100°C hat keinen nachweisbaren Einfluß auf die magnetischen Werte.

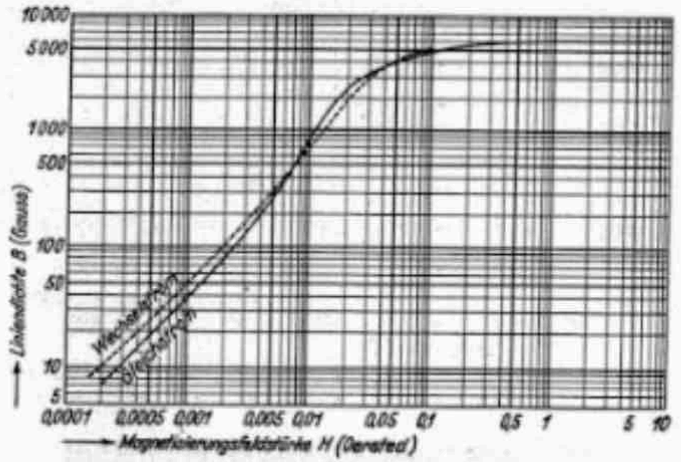


Bild 1. Magnetisierung für Gleichstrom, ballistisch gemessen, und für 50 Hz (bei vorwiegend sinusförmiger Spannung) mit dem

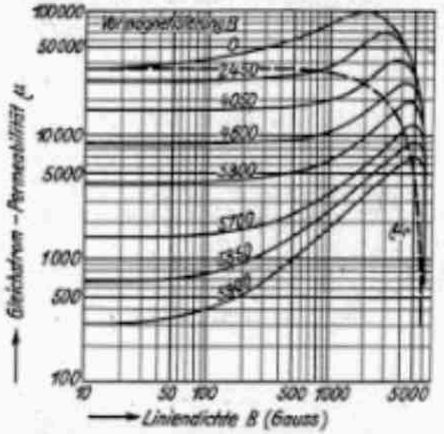


Bild 3. Gleichstrom-Permeabilität als Funktion der Induktion und reversible Permeabilität bei verschiedenen Dauervormagnetisierungen:

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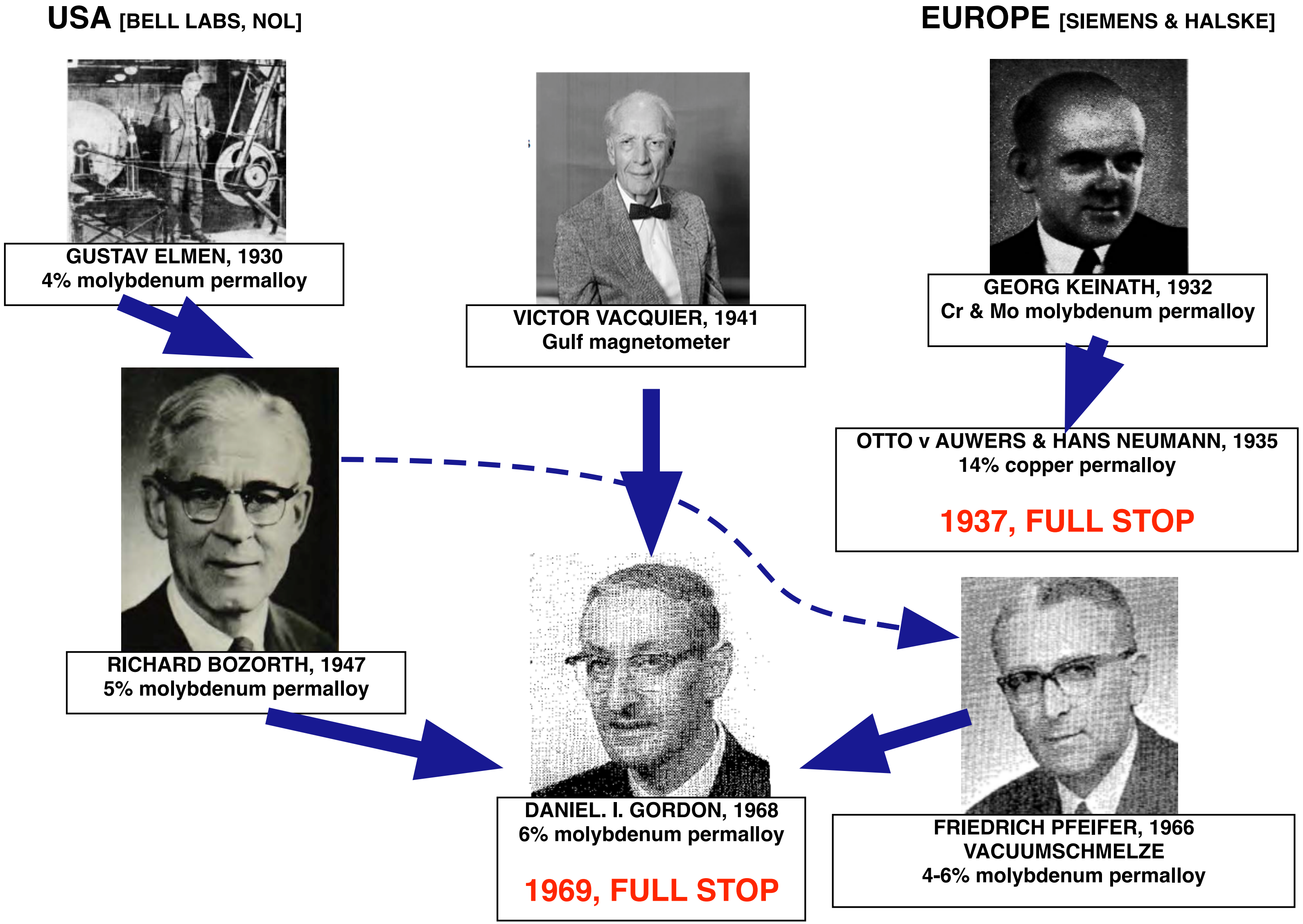
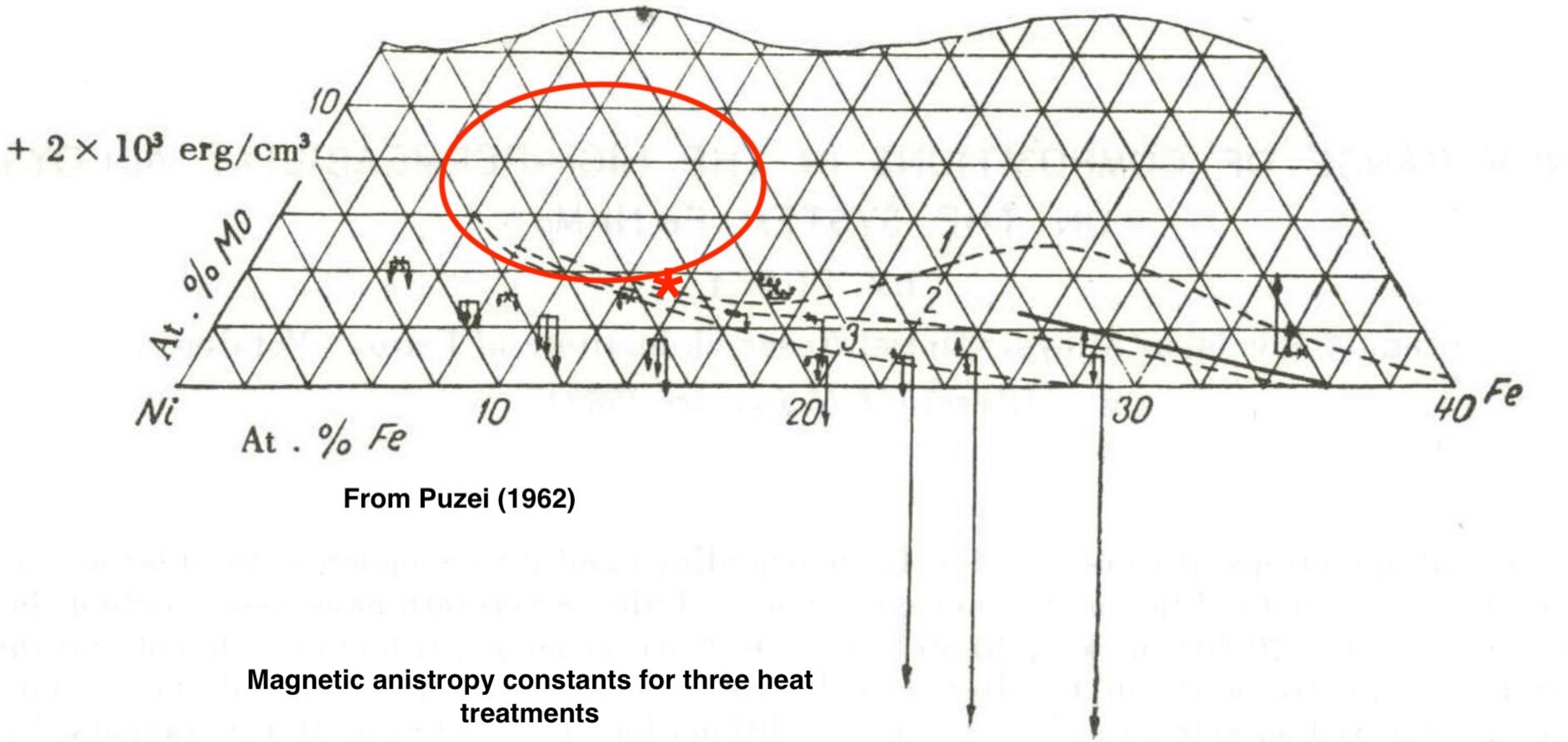


Future work – Moly permalloys

- Additional historical examinations have found that Moly’ permalloys lack a similar study of high Mo content alloys, a deficit which we intend to correct.
- The red oval indicates our expected region of interest.
- The red star locates the well known 6%Mo permalloy composition.



From Puzei (1962)

Magnetic anistropy constants for three heat treatments

I.M. Puzey, 1962, A New Range of Compositions in the High-permeability Alloys on the System Fe-Ni-Mo.
Fiz. Metal. Metalloved., 14, No. 3, 347-377