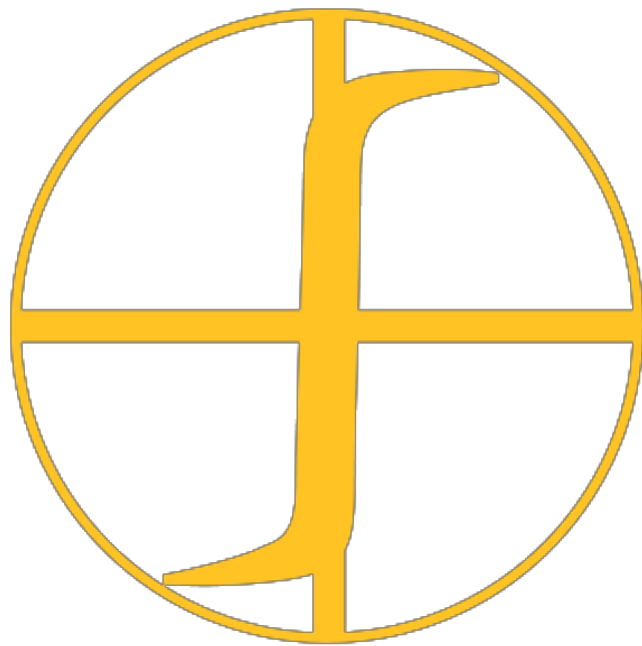




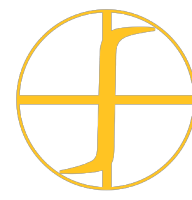
Advanced Induction Materials and Technology



O n l i n e I n d u c t i o n H e a t i n g C o u r s e

6. Fluxtrol Materials on Induction Coils

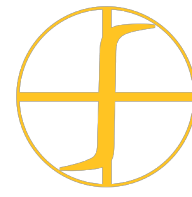
by. Dr. Valentin Nemkov



Materials Manufactured by Fluxtrol Inc.

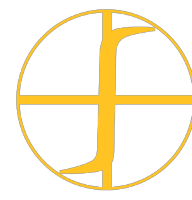
- Fluxtrol Inc. is a world leading manufacturer of magnetodielectric materials for induction heating controllers
- Primary materials:
 - **Fluxtrol A**
 - **Fluxtrol 50**
 - **Ferotron 559H**
- Fluxtrol Inc. also manufactures other standard and custom materials:
 - **Ferotron 119**
 - **Fluxtrol 25**
 - Custom materials
- Fluxtrol Inc. manufactures a big variety of sizes and shapes. Special shapes may be made on request
- Materials in the Fluxtrol and Ferotron families, which are designed primarily for induction heating, may be used in many other applications (as sensors, antennas etc.)





Fluxtrol Material Features

- Fluxtrol and Ferrotron materials cover the whole frequency range used in induction heating
- Magnetic permeability is sufficient for induction heating applications
- All materials have excellent machinability and good mechanical strength; they may be used as structural components of the coil
- Ferrotron materials have good electrical strength and may withstand applied voltage up to several hundred volts
- Temperature resistance is high enough; in critical applications additional measures of thermal management may be used
- Losses may be removed by quenchant, by contact to the coil tubing, by special cooling plates or water channels machined directly into the material
- All materials are resistant to oil, hot water and polymer quenchants; small surface rusting may be prevented by etching or coating



Uses of Fluxtrol Materials in Induction Heating

Major applications:

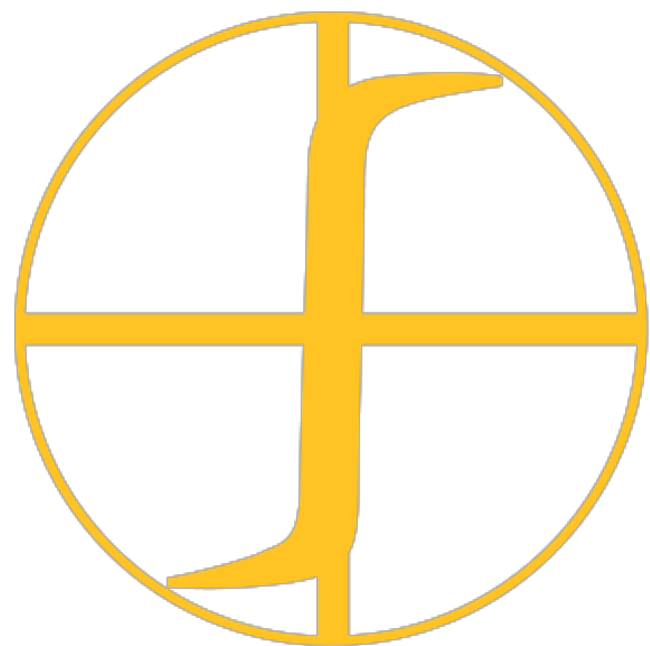
- Cylindrical OD coils for static hardening
- Single-turn OD scan coils (parts with a sharp fillet)
- Complex coils (wheel hubs, CVJ stems, etc.)
- ID coils (cylinder liners, ID gears, etc.)
- Channel coils (fasteners, machine tool brazing, etc.)
- Gear heat treating coils (single and dual frequency, tooth by tooth etc.)
- Local heating for bending and other deformation
- Brazing and soldering

Emerging applications:

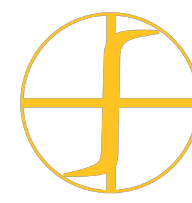
- Single shot coils for axles and shafts
- Rotational crankshaft coils
- Seam annealing coils
- Induction tempering
- Packaging technology
- Shielding of workpiece and equipment parts
- Inductive coupled low temperature plasma
- Impeders for tube welding



Induction coil for CVJ
hardening with Fluxtrol
concentrators



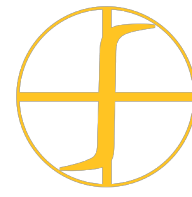
Properties of Fluxtrol and Ferrotron Materials



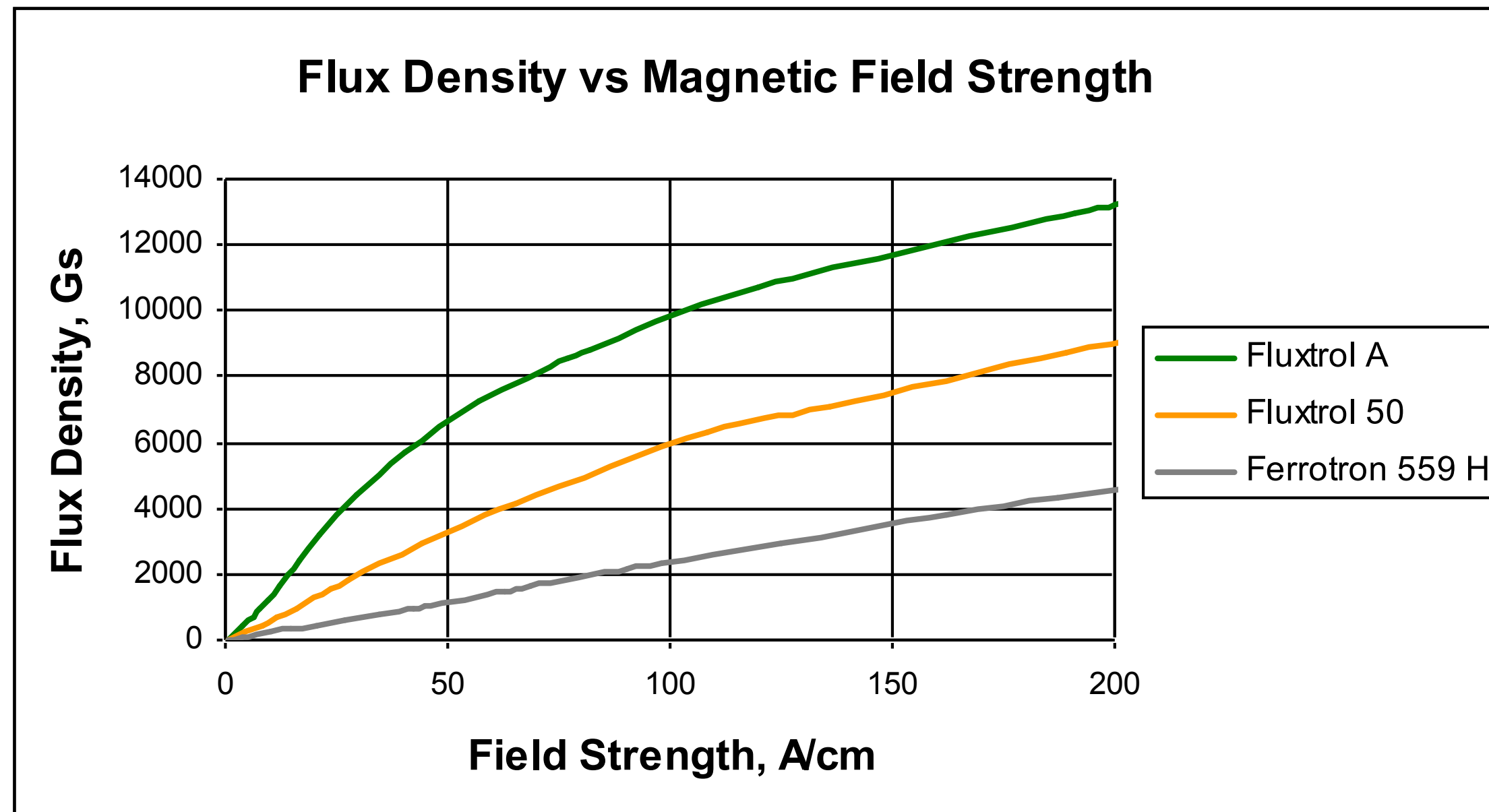
Fluxtrol Primary Products

Physical Characteristics Chart							
		Primary Products			Specialized Products		
Properties	Units	Fluxtrol A	Fluxtrol 50	Ferrottron 559H	Fluxtrol 25	Ferrottron 119	
Product Identification Color		Green	Yellow	Grey	Red	Black	
Density $\pm 2\%$	g/cm ³	6.6	6.1	5.9	5.5	4.8	
Operating Frequency Range	kHz	1–50	10–1000	10–3000	10–3000	10–5000	
Major Frequency Area	kHz	3–30	50–500	50–1000	50–500	100–1000	
Initial Permeability	None	63	36	16	23	7	
Maximum Permeability	None	120	55	18	28	8	
Saturation Flux Density	Tesla	1.6	1.5	1.0	1.3	0.8	
Temperature Resistance	Centigrade	250 Long Term 300 Short Term	250 Long Term 300 Short Term	250 Long Term 300 Short Term	250 Long Term 300 Short Term	250 Long Term 300 Short Term	
Resistivity	kOhmcm	0.5	10.0	>15	>100	>100	

Note: frequency ranges and resistivity values are only for reference

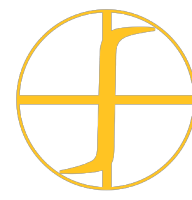


Magnetization Curves for Fluxtrol Products



Compared to laminations and ferrites, Fluxtrol materials are almost linear. This means that Fluxtrol controllers do not generate distortions in coil currents or voltage waveforms. Distortions result in additional reactive power of the coil and additional losses in transformer and capacitor battery.

Permeabilities were measured at 10 kHz for a favorable direction of magnetic flux flow. These data remain valid for all frequency ranges specified for particular materials.

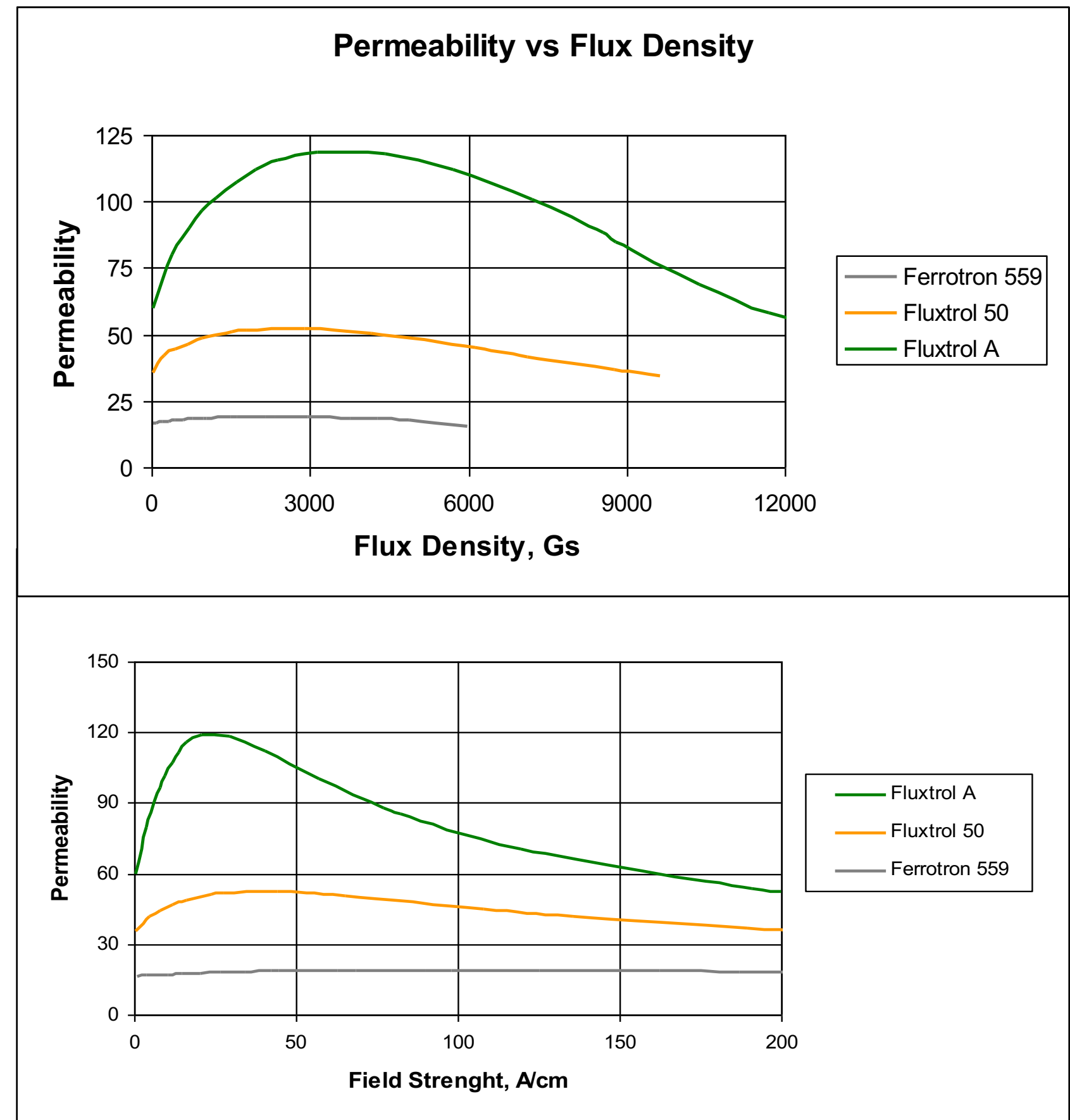


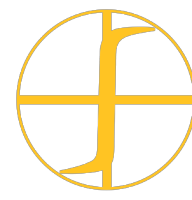
Magnetic Permeability of Fluxtrol Products

Fluxtrol A material can support permeability above 50 at high magnetic loading (flux density up to 14000 Gs), which is essential for high power and low frequency applications.

Range of flux density in measurements is sufficient for majority of applications. Materials may be used even at higher load at proper conditions (short heating cycle, intensive heat removal).

Permeabilities were measured at 10 kHz for a favorable direction of magnetic flux flow. These data remain valid for all frequency ranges specified for particular materials.





Material Anisotropy

When material has different properties in different directions they say that material is Anisotropic.

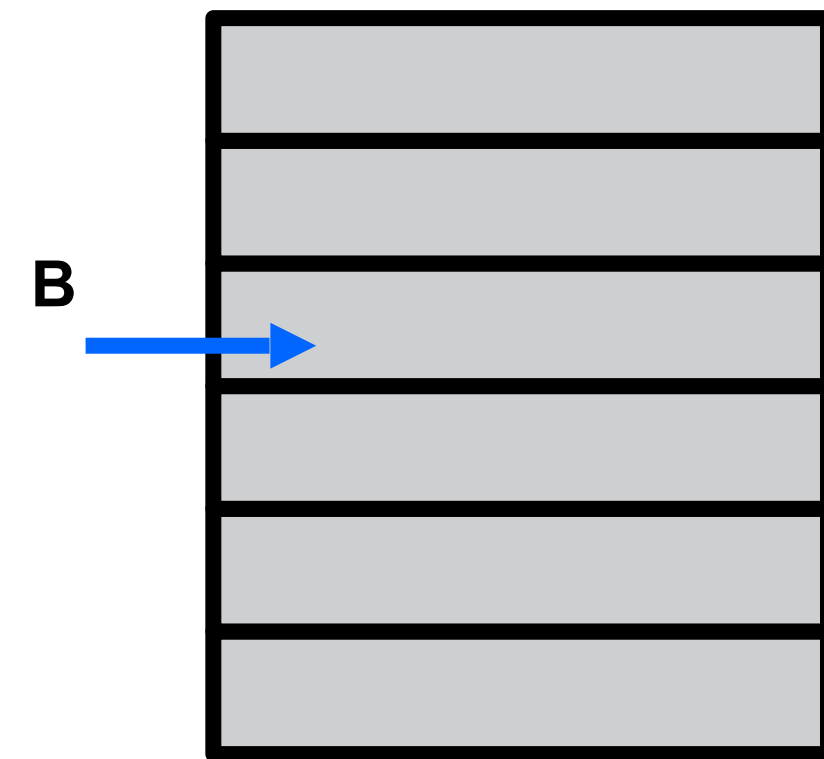
Laminations are highly anisotropic because all properties in the plane of a sheet are very different than in perpendicular direction of the stack.

Ferrites have low anisotropy except in special types of material.

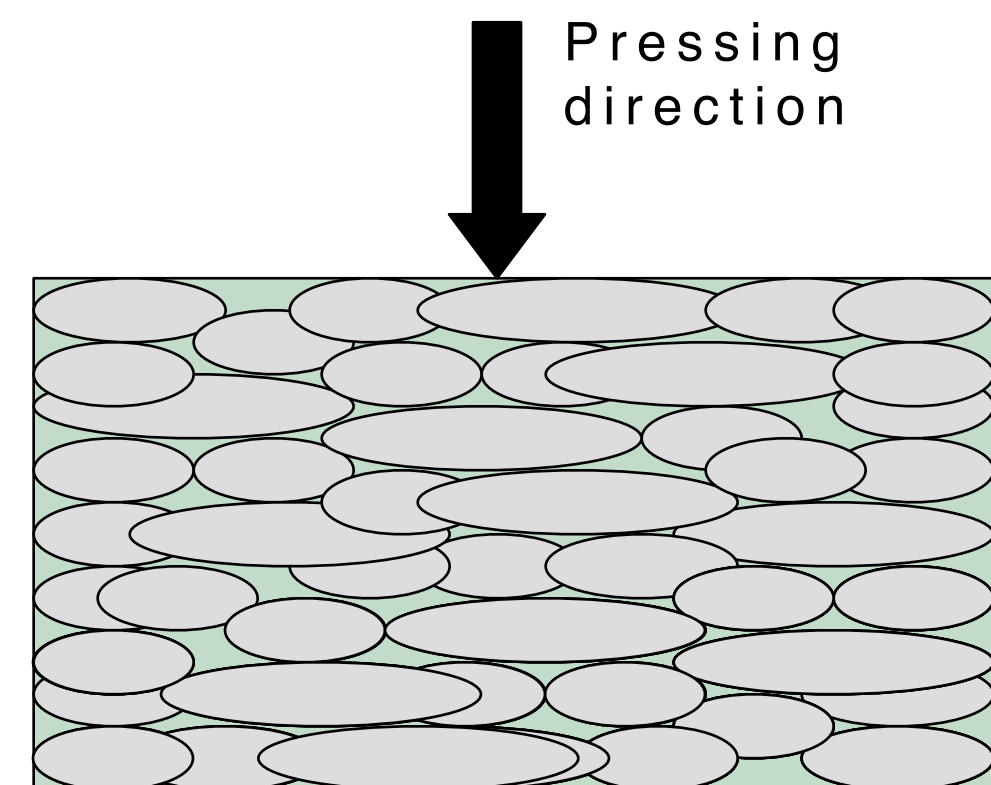
Fluxtrol composites are pressed materials and therefore have certain anisotropy, which depends on material composition, size and shape of particles and manufacturing technique.

Magnetic and thermal properties are higher in the direction perpendicular to pressing.

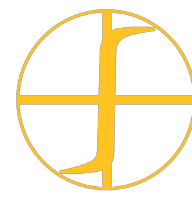
Anisotropy must be taken into account in concentrator design and manufacturing in heavy loaded applications (high power density, high frequency, long heating time.



Anisotropy in lamination stack



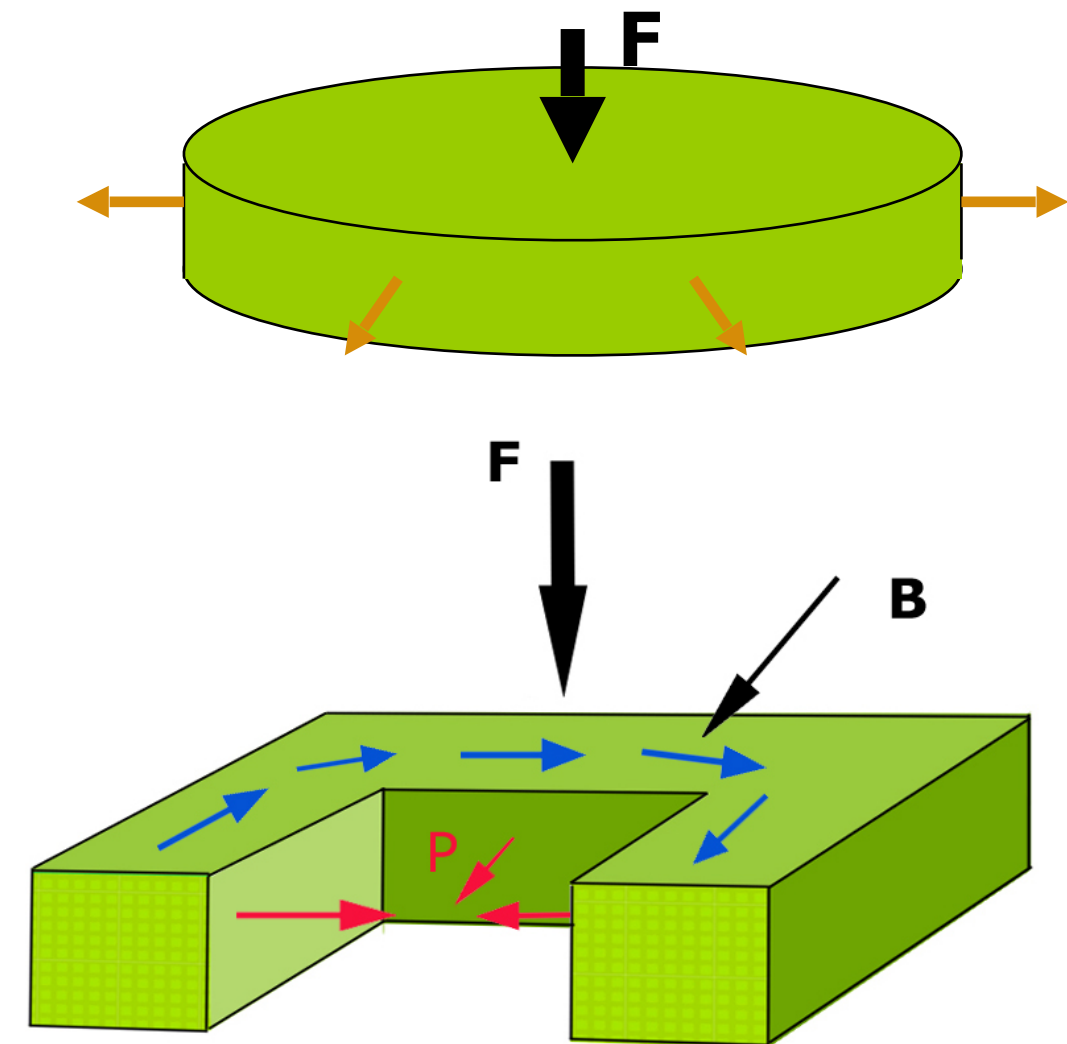
Structure of **Fluxtrol A** material



Anisotropy of Fluxtrol Materials

Anisotropy of **Fluxtrol** and **Ferrotron** materials:

- **Fluxtrol A** has significant anisotropy due to its structure. In a plane perpendicular to the pressing direction permeability and thermal conductivity are significantly higher. Also losses are lower in a plane perpendicular to pressing direction
- **Ferrotron 559H** has low anisotropy due to higher content of binder and different material structure
- **Fluxtrol 50** has anisotropy in between that of **Fluxtrol A** & **Ferrotron 559H**
- Anisotropy of **Fluxtrol A** allows this material to have an exceptional combination of high electrical resistivity, thermal conductivity and permeability with proper orientation

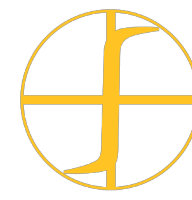


Optimal orientation of material in C-shaped concentrator provides high permeability, lower losses and good heat transfer from material to the coil copper

F – Pressing direction

B – Magnetic flux density

P – Heat transfer to the coil

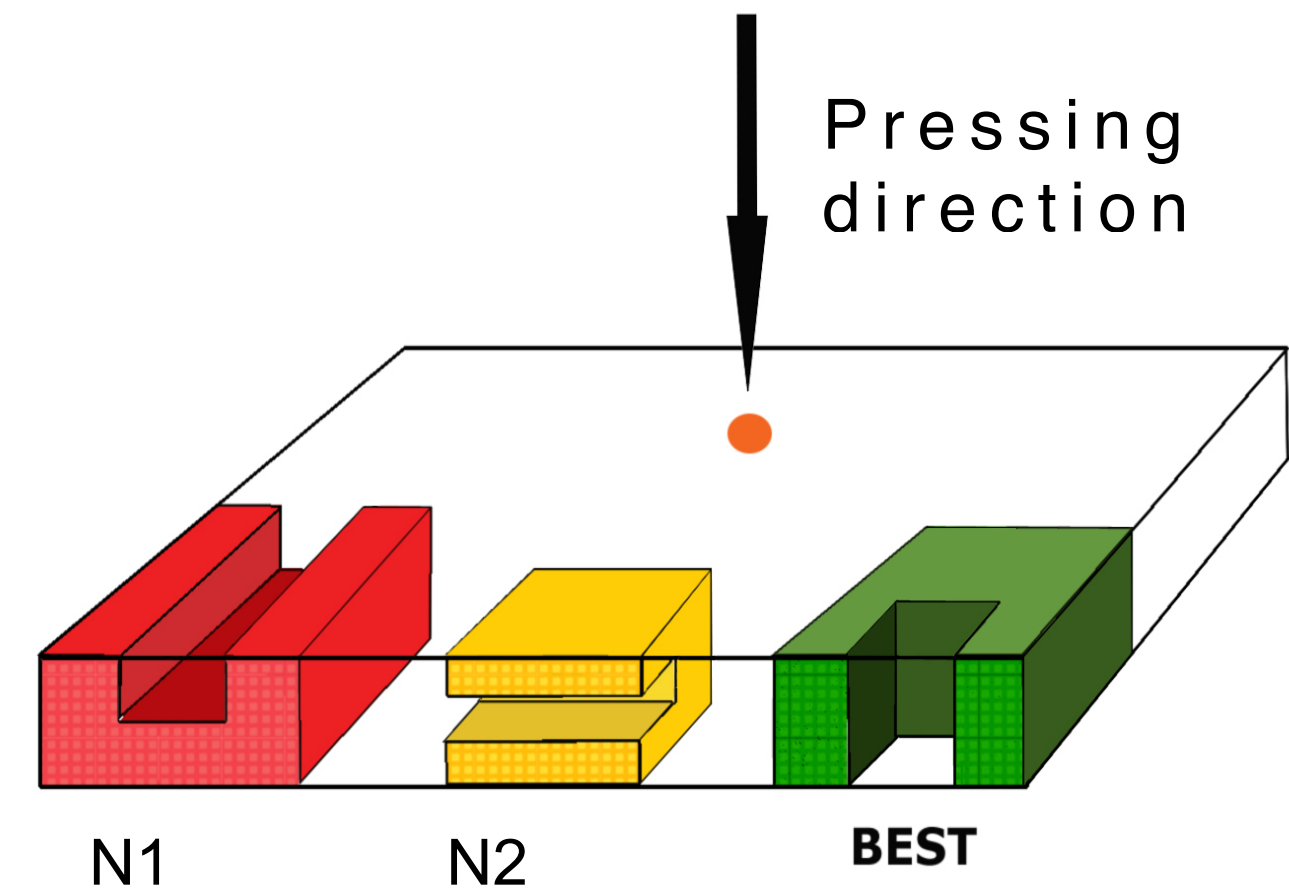


Optimal Cutting of Fluxtrol Material from Blank Stock

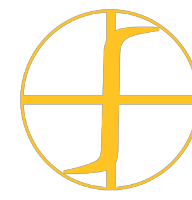
As shown in Chapter 5, for the majority of applications, permeability values above 30-50 do not change the controller performance. Main reasons for optimal material orientation is control of the concentrator temperature, which depends on losses, heat removal conditions and duty cycle.

Material orientation is mostly essential for heavy loaded applications such as scanning or single-short hardening when concentrator losses are removing continuously by heat transfer to the copper in the process of heating. For these cases orientation best is strongly recommended with orientation N1 as a second choice. It is because the highest value of thermal conductivity is more important than slightly higher magnetic losses in the poles.

For short heating cycles such as contour gear hardening, orientation N2 is the second choice after **best** because of lower losses in the poles than in the case N1 and lower influence of thermal conductivity on concentrator temperature.



Parameter	Orientation		
	N1	N2	Best
Losses	Max	Min	Min
Heat transfer (thermal conduct.)	Max	Min	Max



Electrical Resistivity and Resistance

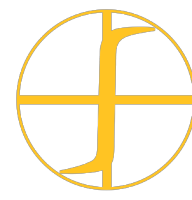
Resistivity:

- Strongly depends on material type
- Is higher in direction of pressing (material anisotropy)
- Can drop after long-term exposure to temperature above 250 C

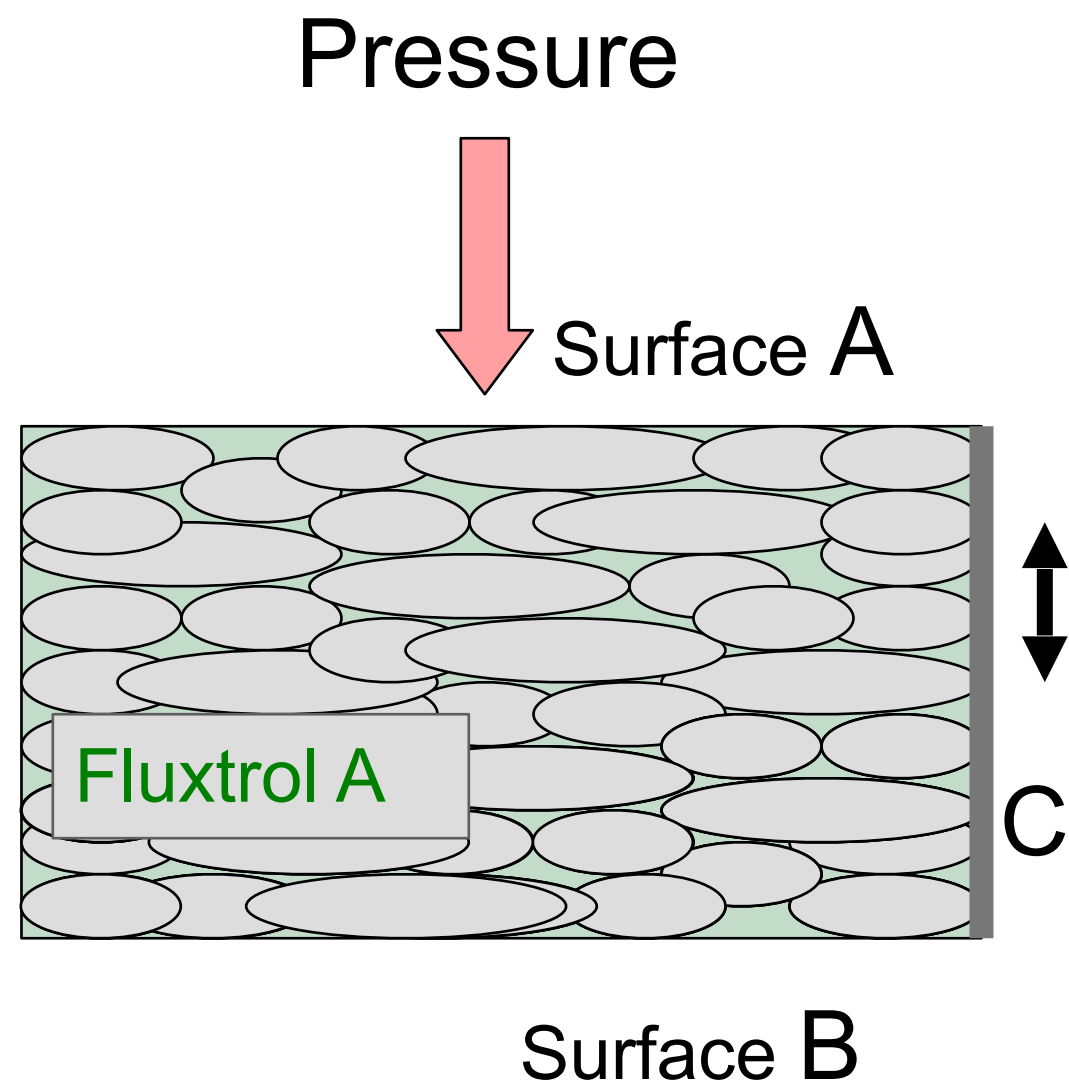
Resistivity is not a major material performance parameter; **only a level of resistivity should be controlled.**

- HF materials require higher resistivity to withstand higher voltages induced inside the concentrator or applied to it
- **Fluxtrol A** is a unique material, which has high permeability and internal electrical resistivity but it can form conductive surface layers when machined

Material	Resistivity Ohmcm	Typical touch resistance on broken or etched surfaces, kOhm
Fluxtrol A	> 500	∞
Fluxtrol 50	> 10000	10
Ferrotron 559H	> 15000	∞



Touch Resistance of Machined Parts



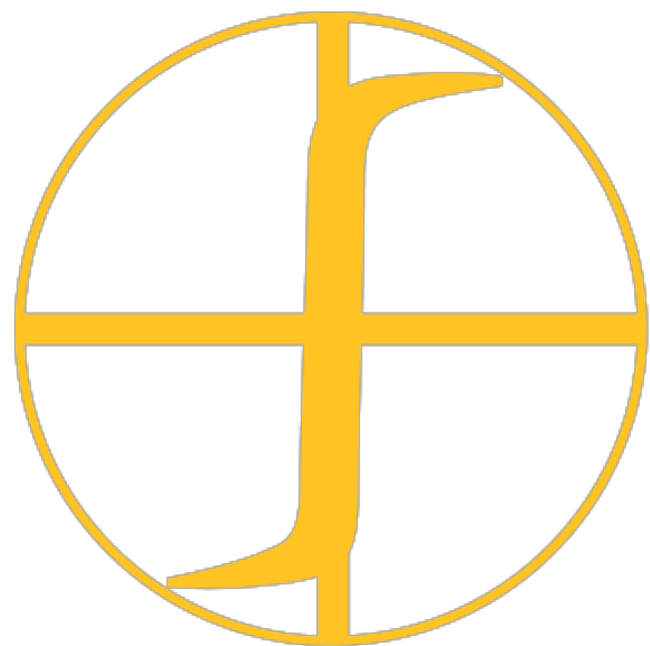
Machining may cause particle smearing on the surface and lead to formation of a conductive layer.

Resistance of this layer may depend on material type, machining method (grinding, milling, saw cutting etc.) and on machining direction.

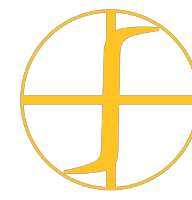
Ferrotron 559H has very high touch resistance and does not form a conductive surface layer. No etching is required for this material except in cases when we expect relatively high voltage being applied to material (several hundred volts).

Fluxtrol 50 has good touch resistance (up to 30 k Ohms) on broken and machined surfaces but forms a thin conductive layer on side pressed surfaces. Etching is recommended for high frequency applications.

Fluxtrol A has very high internal resistivity but can easily form a conductive layer when machined. Machining of surfaces A and B causes much less conductive layers (if any) than of side surface C, where touch resistance may be as low as 10 - 30 Ohms. Etching is recommended in this case.



Material Selection



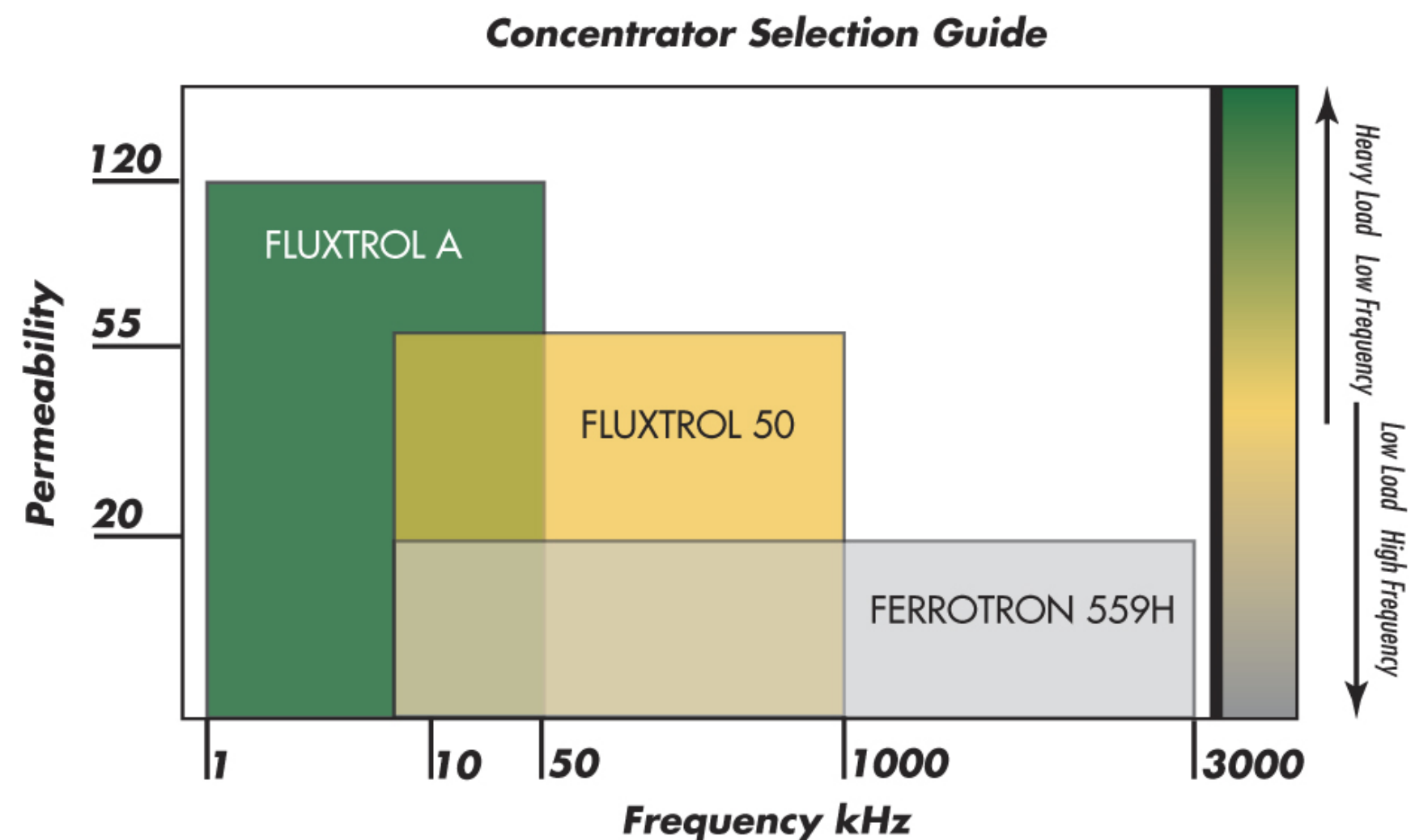
Guidelines for Fluxtrol Material Selection

Several factors must be taken into account in Fluxtrol material selection for particular applications:

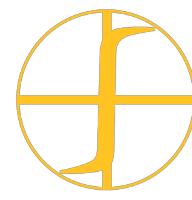
- Frequency range
- Expected maximum voltage that may be applied to concentrator (required electric strength evaluation)
- Coil style and geometry
- Concentrator loading (required density B of magnetic field)
- Duty cycle and heat transfer conditions
- Prior experience and individual preferences

Notes:

- Frequency ranges of material overlap and two or even all three materials may be used for the same or similar application
- All materials can work at frequencies lower than indicated in recommendations; for example Ferrotron 559 may be used at 10 kHz and even below
- Low frequency materials may be used at frequency higher than specified if intensive cooling provided

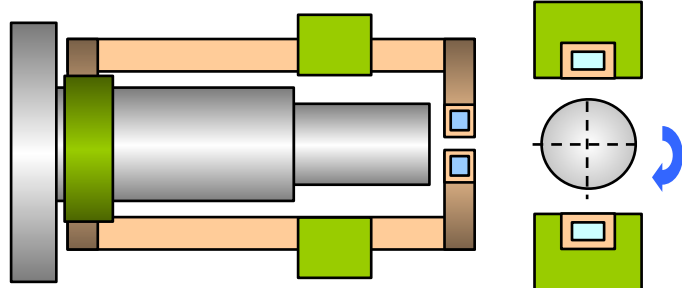
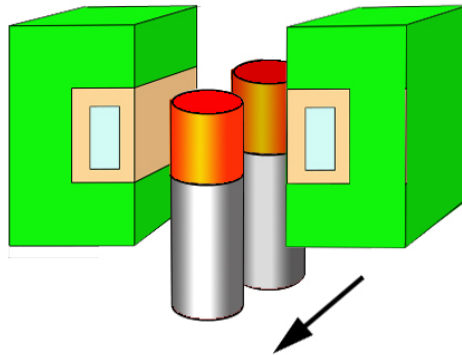
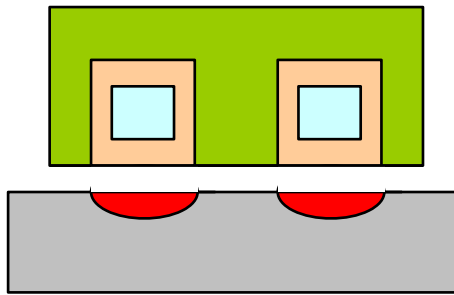
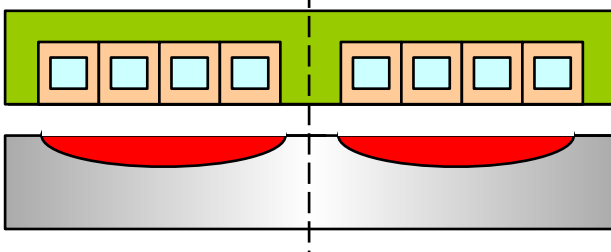


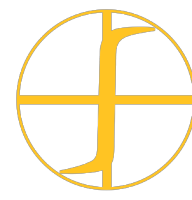
General chart for material selection



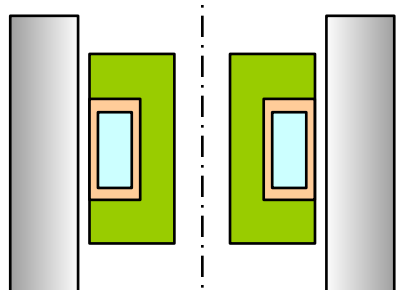
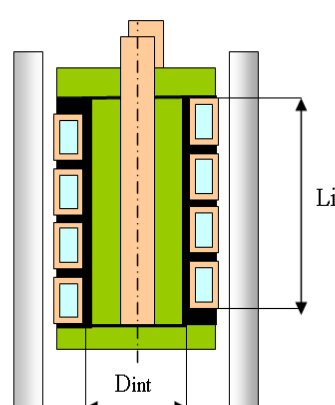
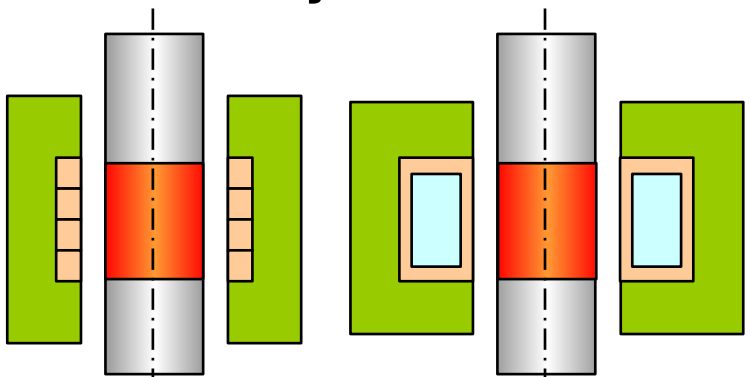
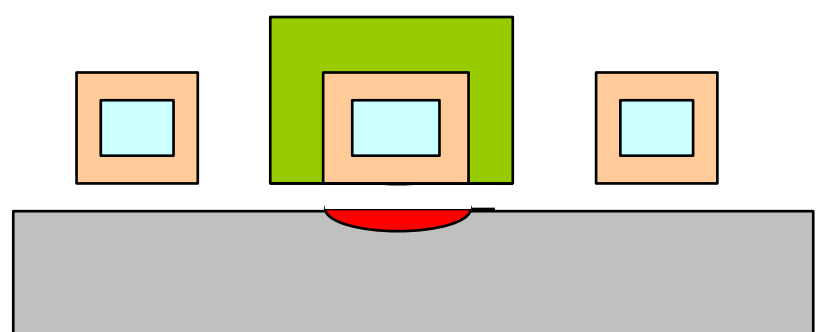
6 Fluxtrol Materials on Induction Coils

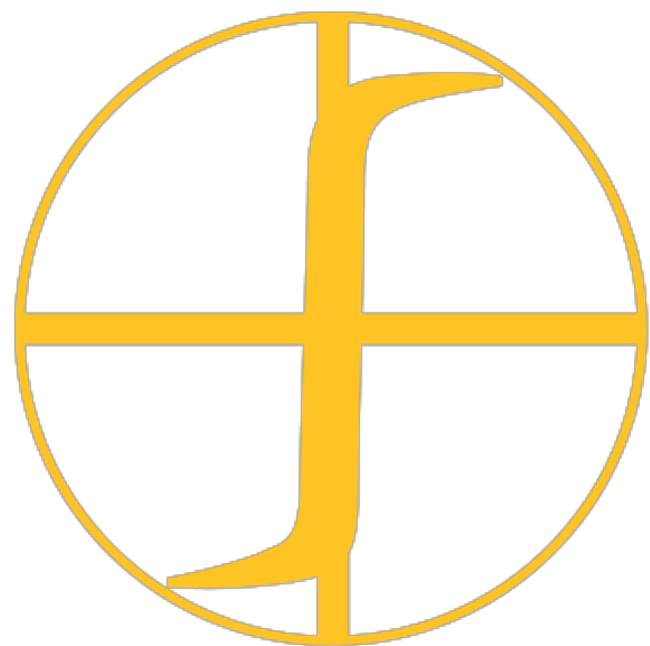
Fluxtrol Products General Selection Guide

Coil Style	Frequency	Fluxtrol Material
Single Shot 	<10kHz 10-50 kHz >50 kHz	Fluxtrol "A" Fluxtrol "A" or "50" Fluxtrol "50"
Channel 	All Frequencies	Fluxtrol "50"
Hair Pin 	<50kHz >50kHz	Fluxtrol "50" Ferrotron 559H
Pancake 	<50kHz >50kHz	Fluxtrol "50" Ferrotron 559H

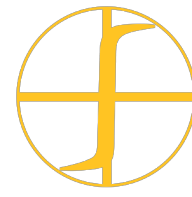


Fluxtrol Products General Selection Guide

Coil Style	Frequency	Fluxtrol Material
I.D. Single Turn 	<10kHz 10-50 kHz >50 kHz	Fluxtrol "A" Fluxtrol "50" Fluxtrol 559H
I.D. Multi Turn 	<50kHz >50kHz	Fluxtrol "50" Fluxtrol 559H
O.D. Cylindrical 	<10kHz 10-50kHz >50kHz	Fluxtrol "A" Fluxtrol "A" or "50" Fluxtrol "50"
Vertical Loop and Split & Return 	<10kHz 10-50kHz 50-100 kHz >100 kHz	Fluxtrol "A" Fluxtrol "A" or "50" Fluxtrol "50" Ferrotron 559H

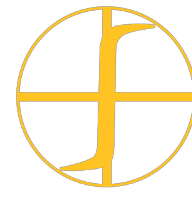


Fluxtrol Materials Application Technique



Etching

- **To Etch Or Not To Etch? That Is The Question!**
- **Main Goal:** To remove or modify conductive surface layer for better electrical resistance and electrical strength to applied voltage
- **Additional possible benefits:**
 - To prevent rusting
 - To improve glue or coating adhesion
- **Disadvantage:**
 - Additional chemical operation
- **Recommendations:**
 - Etching is always useful but in majority of applications not required
 - Etching with Nitric or Chloric acids does not provide good results; it can damage material and the process is not safe
 - Phosphoric acid may be used with success for etching and rust prevention
 - Special iron-phosphoric agent CrysCoat 187 provides the best results according to Fluxtrol Inc. experience
 - Contact Fluxtrol Inc. for more information

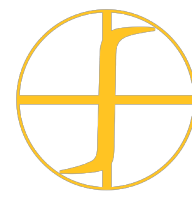


Machining

- Fluxtrol materials may be machined using various methods (drilling, milling, turning, grinding, etc.)
- No special tools required
- It is not necessary to use cooling or lubricating liquids
- General rules:
 - Use sharp tools with slow feed and fast speed
 - When drilling pay attention to chips removal from the drill bit; clogged bit channels can result in material breaking or incorrect dimensions
 - Make pilot holes for drilling large bores
 - Drill material on strong support (wooden or plastic block) to avoid chipping at the exit

Fluxtrol A may give chipping on sharp edges due to layered structure. Machined surface may look different on different surfaces due to grain orientation.

Ferrottron 559H and **Fluxtrol 50** may be machined into parts having sharp angles and thin (less than 1 mm) areas

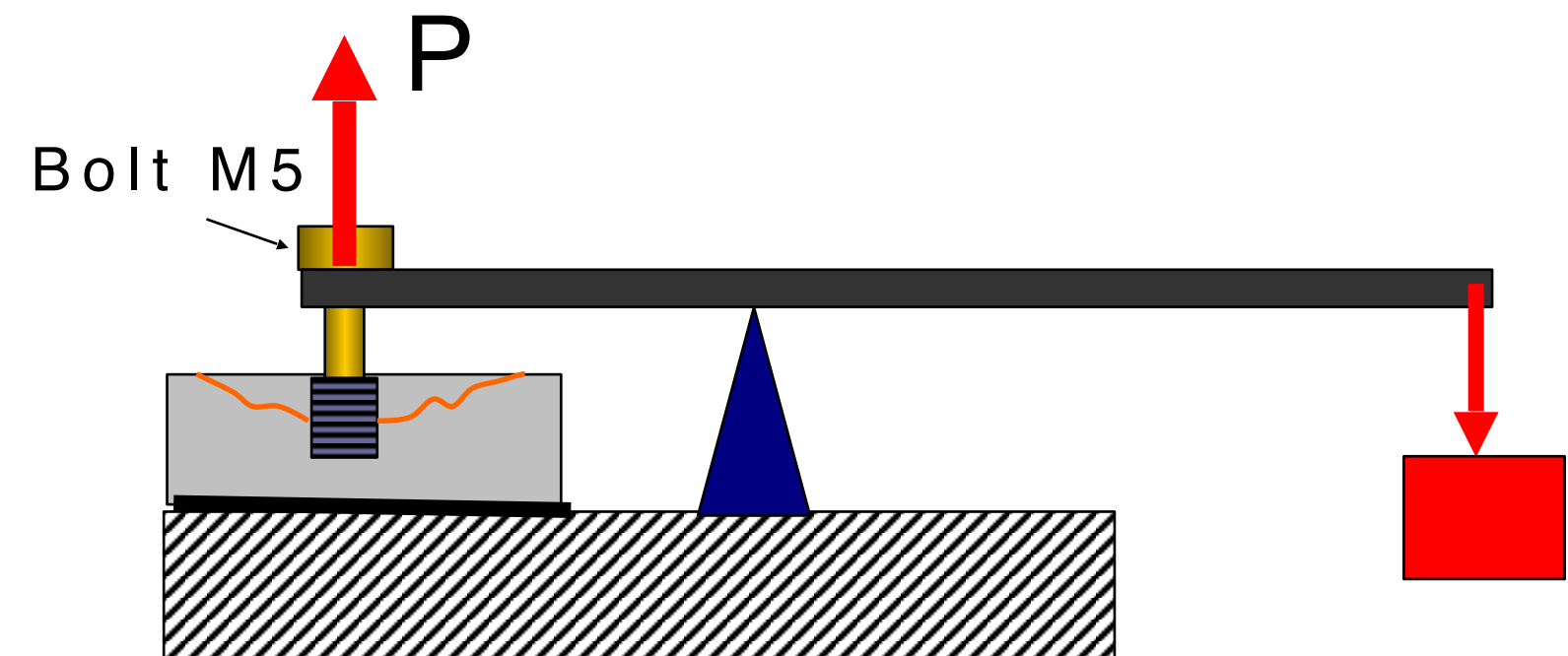
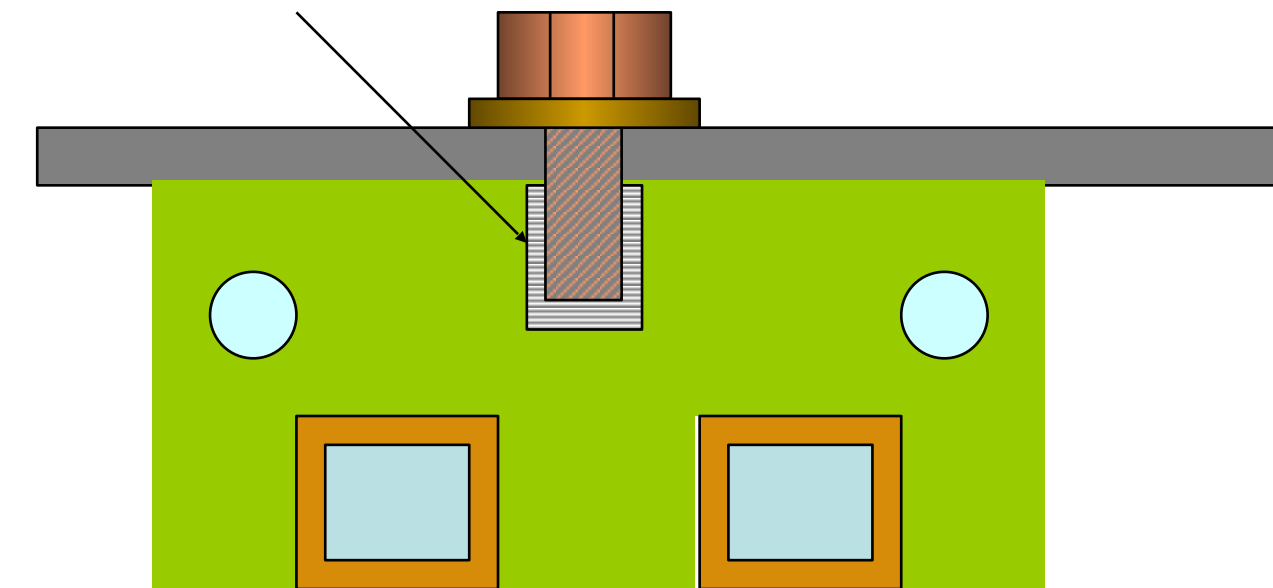


Mechanical Properties

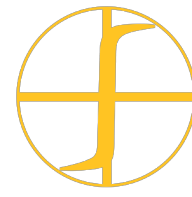
Fluxtrol materials:

- Strong in compression, less strength in tension or bending loads
- May be machined to any shape, drilled for coolant, quenchant supply or mechanical attachments
- Threads may be cut directly in material for fastening
- For example **Fluxtrol 50** withstands a torque of 11 Nm when applied to a M8x8 bolt screwed directly into the material
- Non-magnetic (brass or stainless steel) helicoils or other inserts are recommended for heavy mechanical loadings

Helicoil or insert

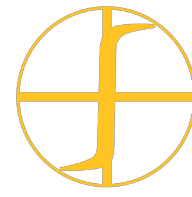


Example of tension strength test for Fluxtrol 50. Bolt M5 with 7 mm long stainless steel insert withstands loading $P = 450 \text{ lbs}$ (220 kg)



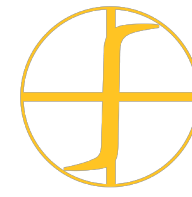
Fluxtrol Material Coating

- Coating is not necessary for general applications
- Some users apply paint or varnish for cosmetic reasons to concentrator together with the copper (whole coil) or separately
- Ceramic coating can protect against electric contact to the work piece, magnetic chips and radiation from hot part. Coating may be applied to the whole coil face. Two layers (pre-coating and final) are the best
- There are special requirements for a “clean” environment in some high frequency high tech applications (semiconductor industry, food packaging etc.). Special coatings for these purposes are available (contact Fluxtrol Inc.). These coatings also increase electric strength of materials



Attachment Methods

- **Mechanical attachment** using bolts is the most precise and reliable method. A thermally conductive agent is strongly recommended for use in-between Fluxtrol and the coil copper. For permanent installation use epoxy glue. A thermal conductive paste or silicone rubber may be used if ease of removal is required
- **Fasteners** must be isolated from Fluxtrol concentrator when it is attached to multi-turn coil
- **Adhesive fastening:** Use a thermally conductive, high temperature resistant media. Epoxy composites with oxide or metal filler are the best. For thin layers (up to 0.2 mm) we recommend black Duralco 4525 epoxy from Cotronics. It is thin, has good adhesive properties and high temperature resistance. For thicker layers (higher tolerances etc.) thicker epoxy compounds are recommended such as Dexter Hysol 1C from Loctite Corp.
- Use clean or copper-loaded **silicone rubber** for multi-turn coils to insulate controller from the coil turns. If controller overheats, use additional methods of temperature control (cooling plates, water spray, forced air)

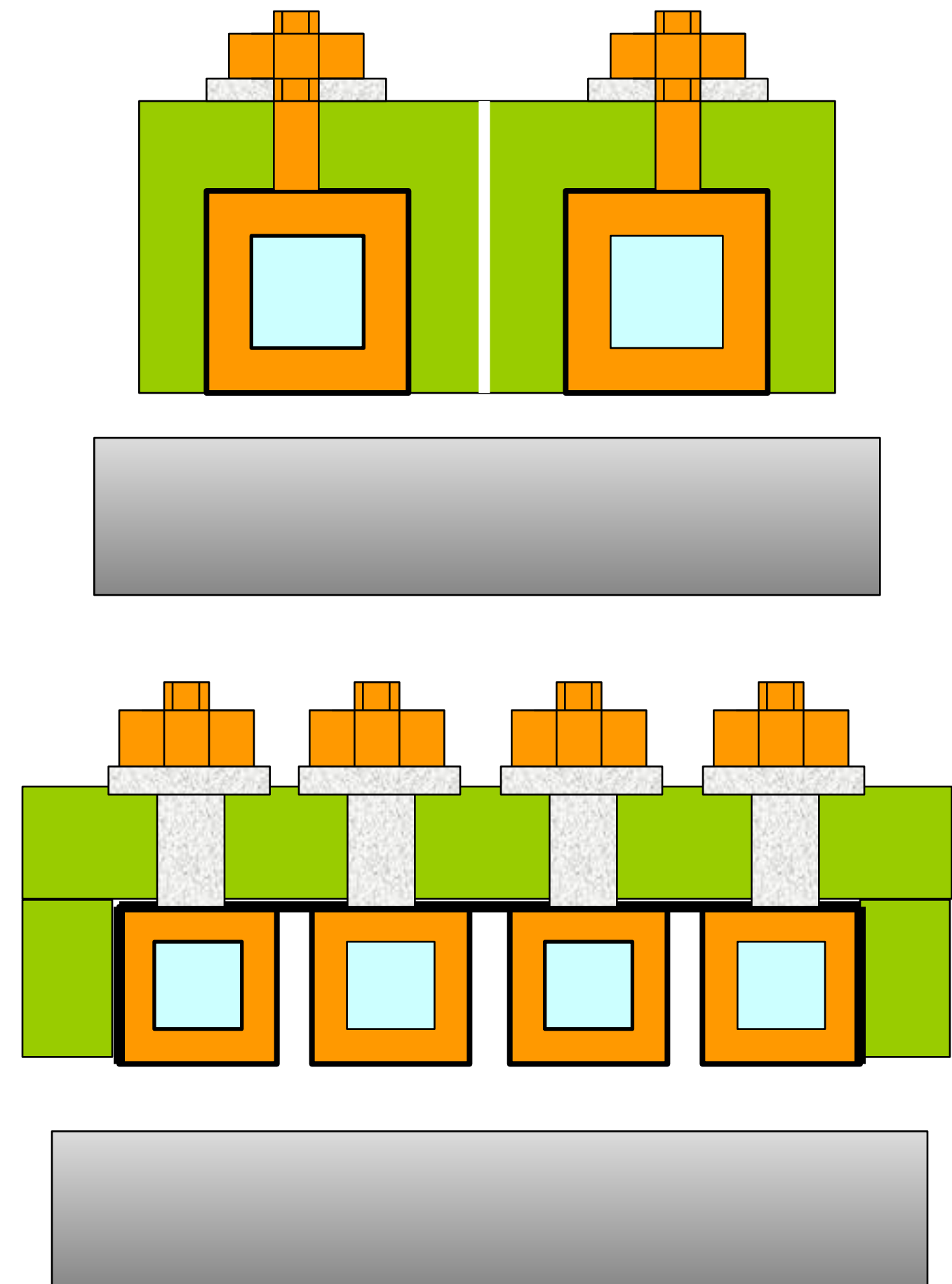


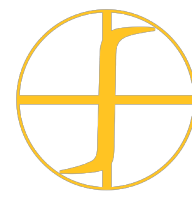
Mechanical Attachment

Mechanical application of concentrator in combination with a thermally conductive adhesive is the most reliable method. If E-shaped concentrator is broken into two isolated C-shaped sections, no electrical insulation between coil tubing, studs and concentrator is necessary

For multi-turn coils it is necessary to insulate concentrator from turns and studs to avoid current leakage through the concentrator which can result in damage

Though controllers made of **Ferrottron 119** or **559H** can withstand applied voltage, electrical insulation is still recommended

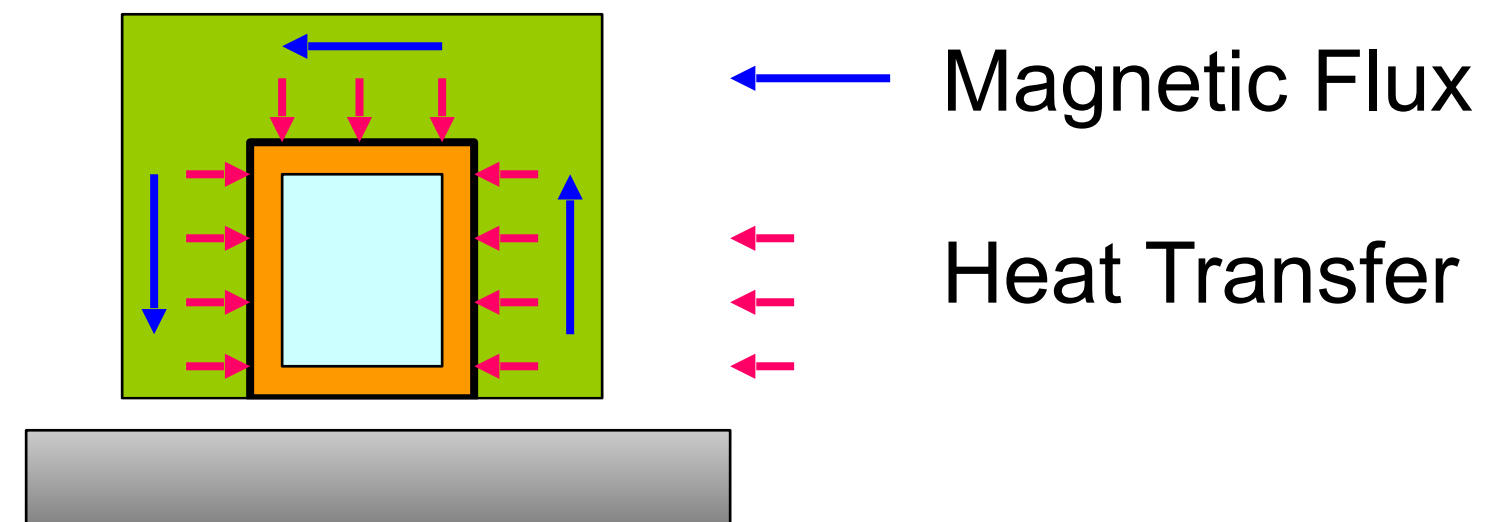




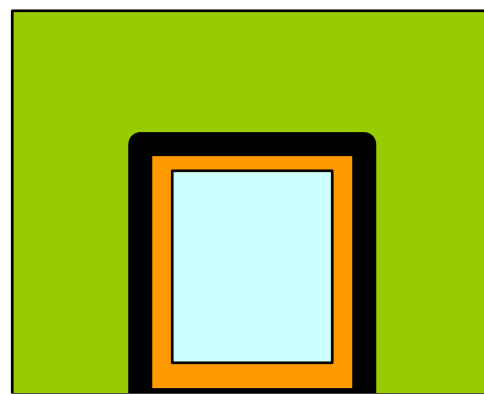
Application Technique for Heavy Loaded Coils

Correct Application:

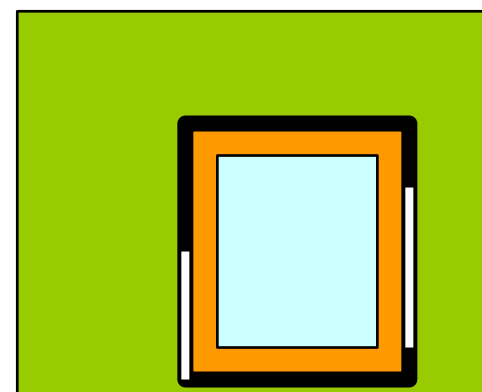
Uniform gap 0.1-0.2 mm (5-10 mils)
filled with thin layer of Duralco
epoxy or similar material



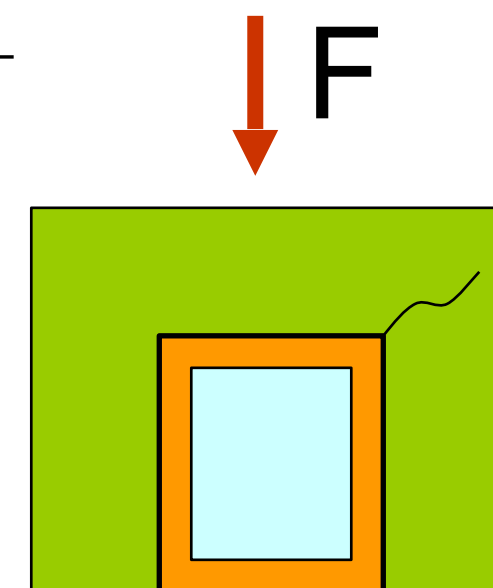
Incorrect Application Technique



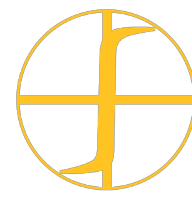
Too thick glue layer



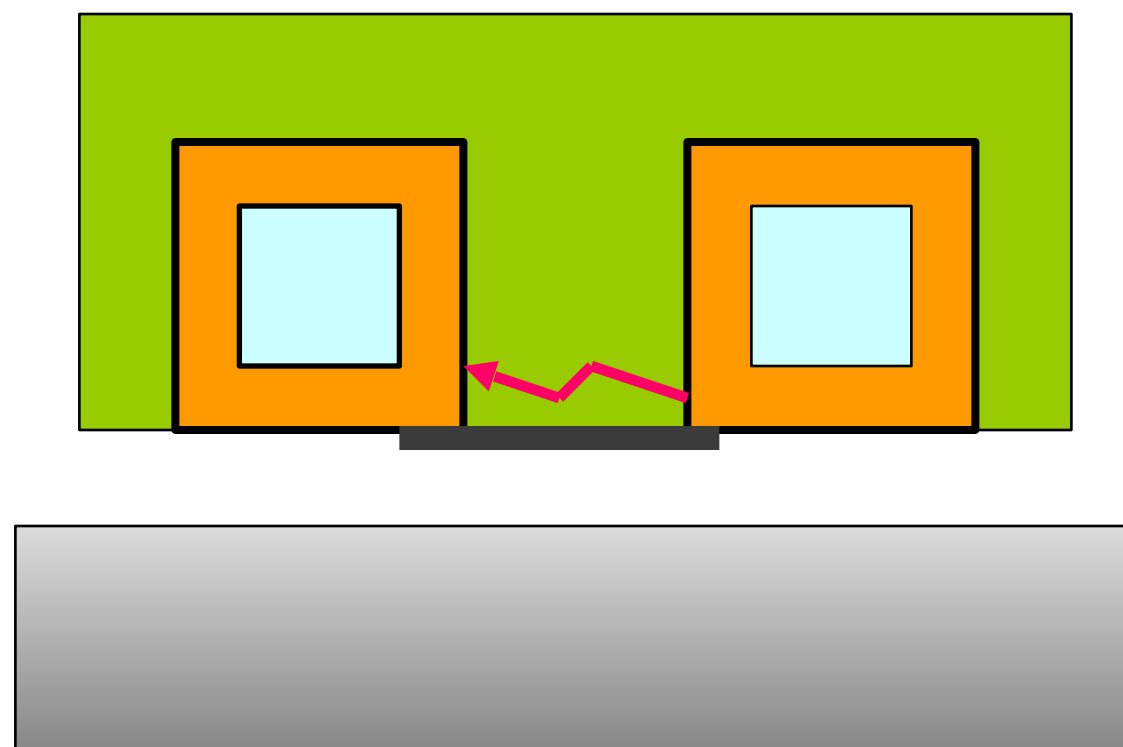
Air pockets



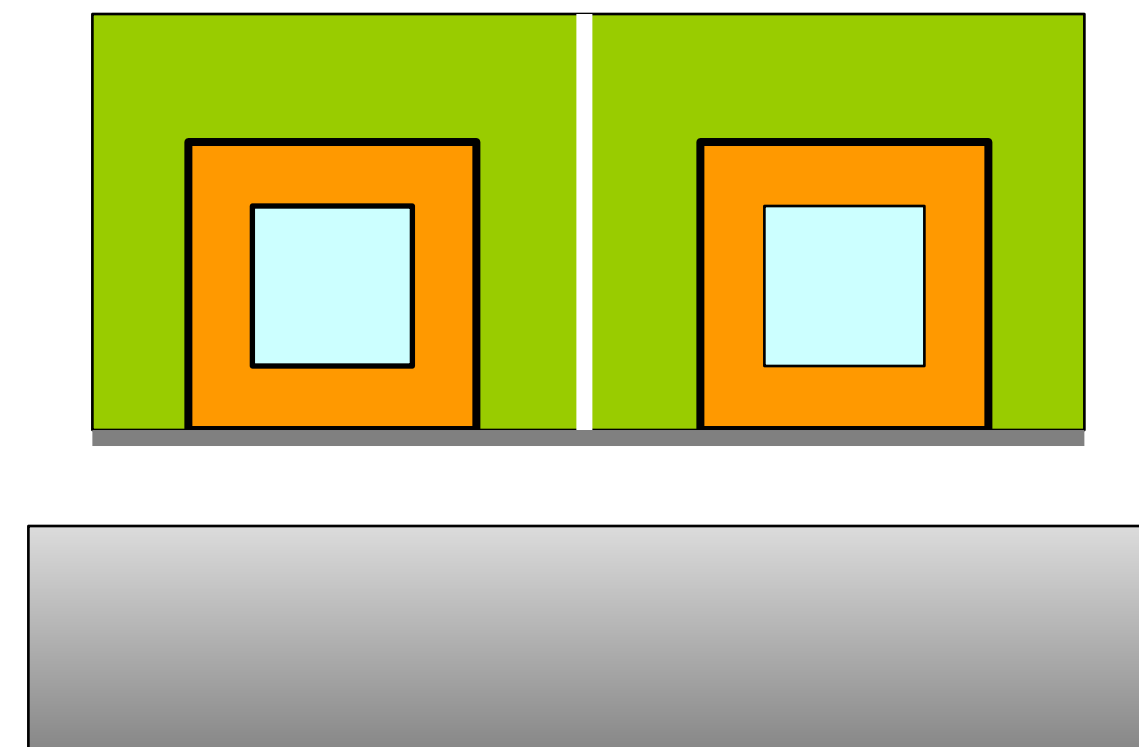
Forced installation of
material having
insufficient clearance



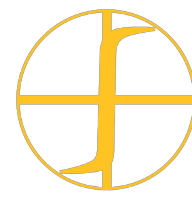
Example of Concentrator Application to Hairpin Coil



Possible concentrator failure due to metal chips on the face and significant voltage between copper legs



Ceramic coating and thin isolation sheet solve the problems



Concentrator Temperature Control

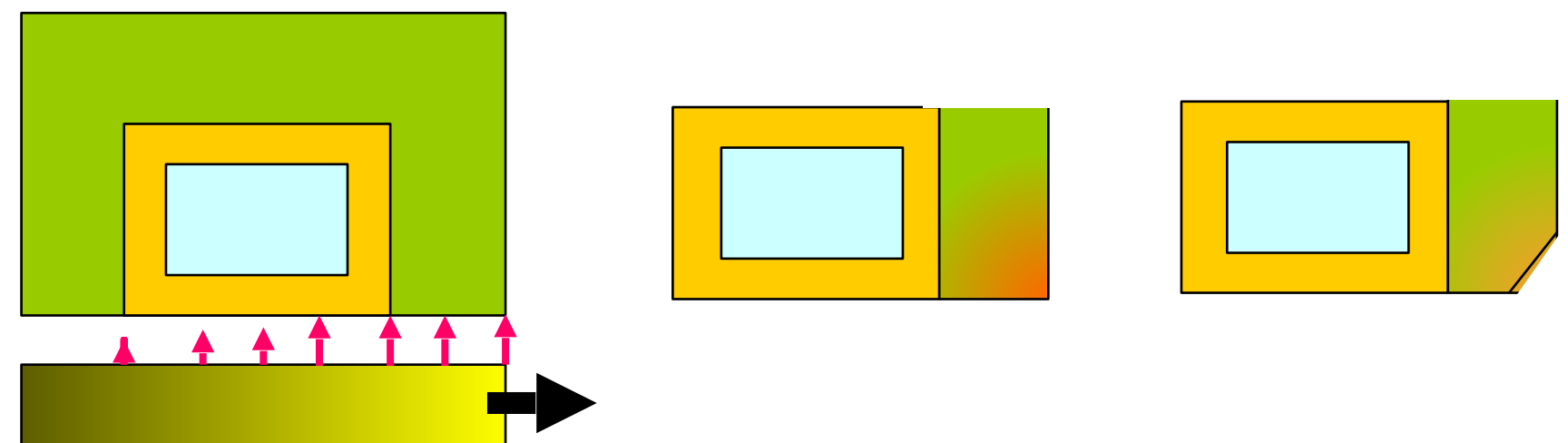
Methods of concentrator temperature control to prevent its overheating:

- Correct selection of material and its orientation
- Correct selection of glue and concentrator application technique
- Coil design with improved heat transfer from the concentrator material and reduced concentrator exposure to hot part surface
- Intensive coil copper cooling; in short cycle applications copper may reach higher temperature than concentrator
- Cooling plates
- Ceramic coating of the coil surface
- Additional cooling with quenchant, water channels, forced air etc.
- In short-time static applications heat may be removed from the concentrator between the heating periods



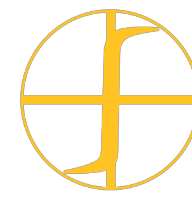
Example of concentrator temperature control in heavy longitudinal scanning operation (seam annealing):

Magnetic flux density is higher in end areas (A) than in a regular zone resulting in higher material temperature. Copper side plates reduce 3D effects and provide additional heat transfer from the concentrator.



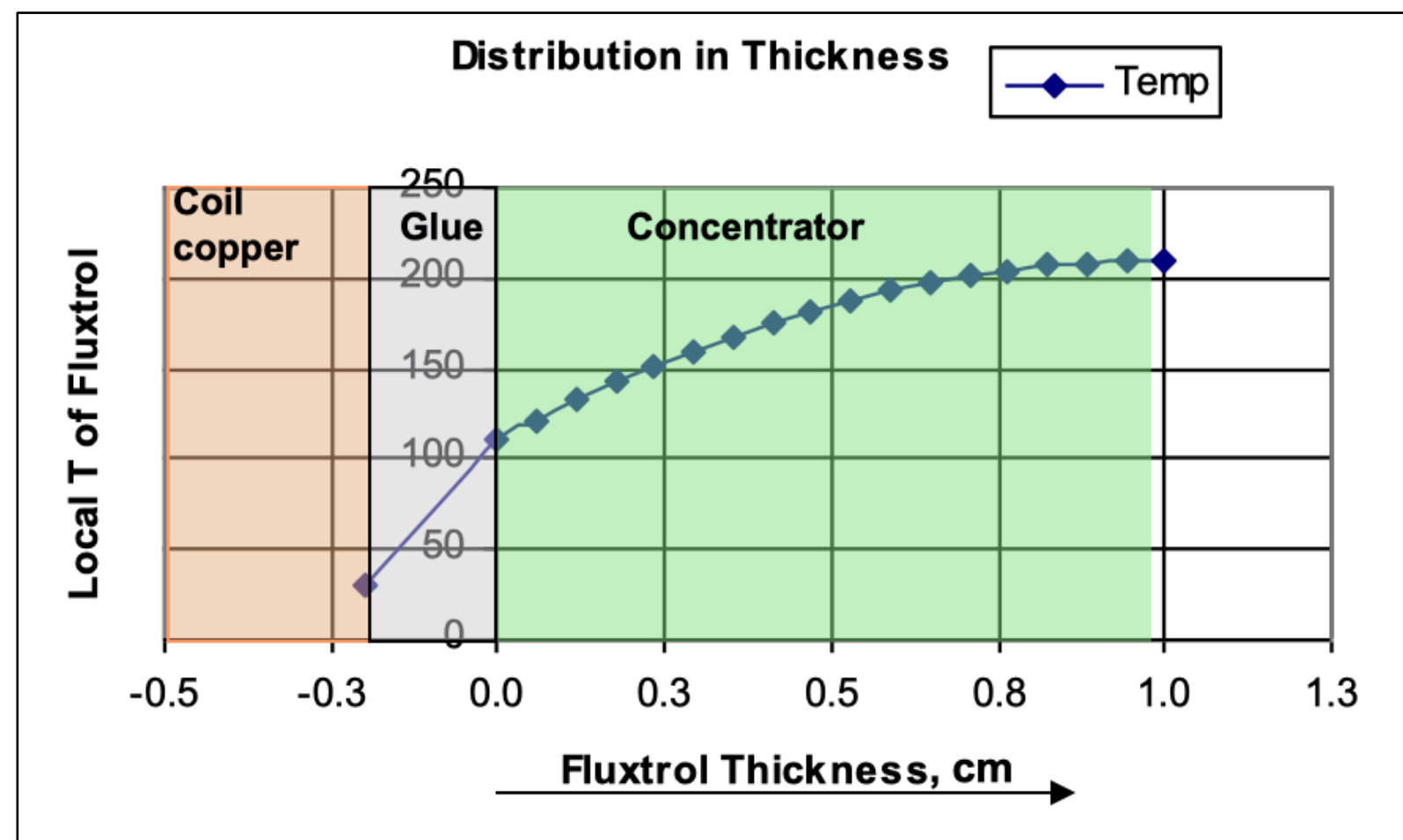
Example of concentrator temperature control in transversal scanning operation:

Chamfering of concentrator pole on the coil exit side reduces absorption of radiation from the heated part (right).



Temperature Distribution in Fluxtrol Controllers

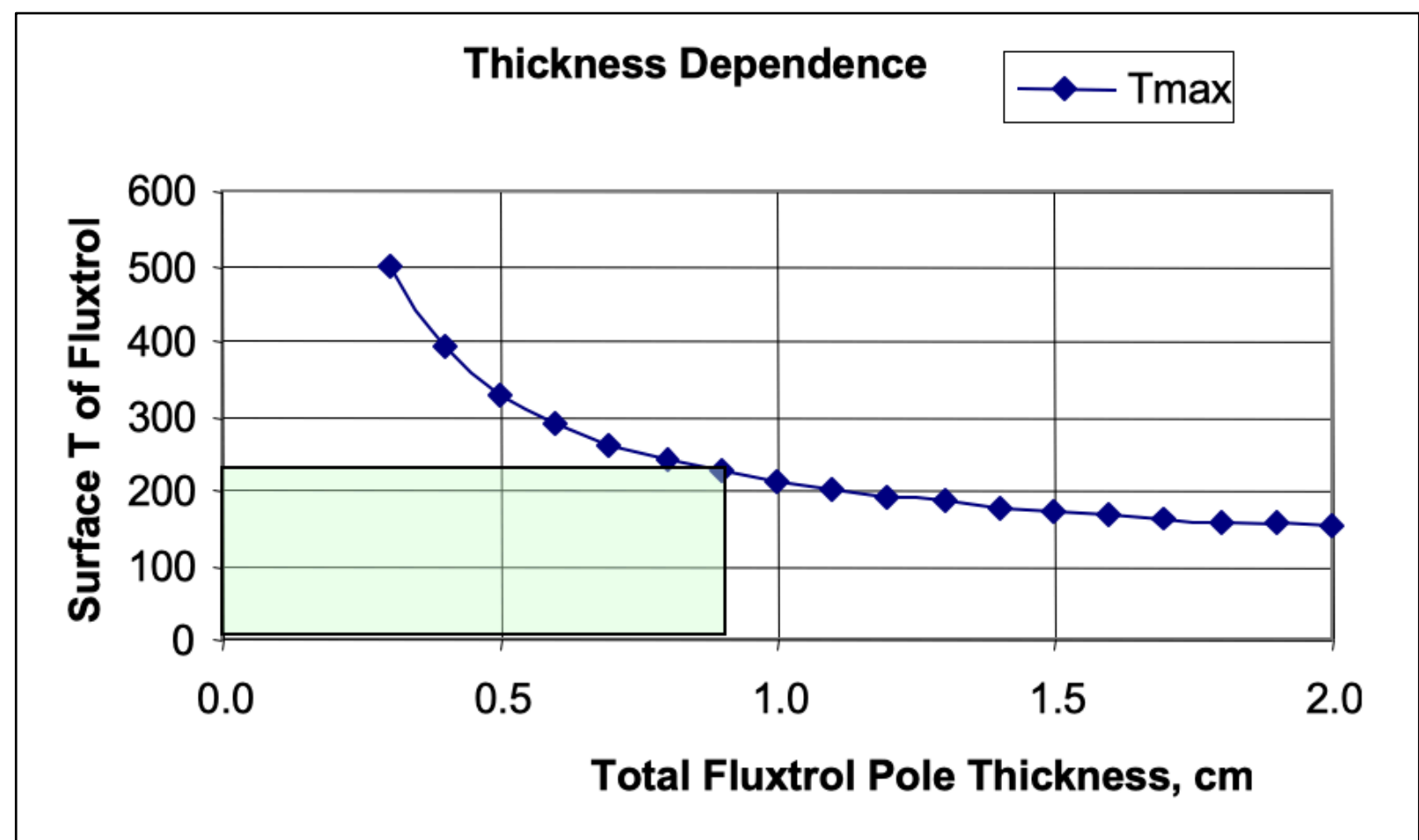
Typical temperature distribution in thickness of the concentrator pole for continuous regime.



Temperature distribution in glue layer (gray) and Fluxtrol pole (green).

Temperature differential in glue is too big (80 C). Adhesive must be thinner or more heat conductive.

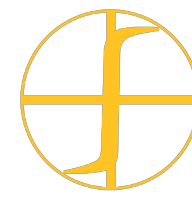
In other applications temperature distribution may be strongly influenced by duty cycle, additional cooling on the external surface or radiation losses from the heated part.



This graph shows what would happen if we change the pole thickness with the same coil power.

For thinner pole magnetic flux density is higher but a path to a cold copper shorter and these factors compensate each other. However thermal resistance of glue layer remains the same and maximum temperature grows.

In this particular case the pole size reduction below 0.8 cm results in significant increase of Fluxtrol temperature.



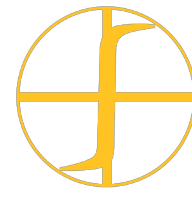
Thermal Conductivity for Fluxtrol & Adhesive Materials

Units: W/(cm Degree C)

Value	Fluxtrol A	Fluxtrol 50	Ferrotron 559H	Duralco 4525	Dexter Hysol 1C	Epoxy (pure)
						Epoxy plus Metal
Optimal direction	0.20	0.10	0.04	0.019	0.005	0.002
						0.01 – 0.2
Non- optimal	0.04	0.05	0.025	N/A	N/A	N/A

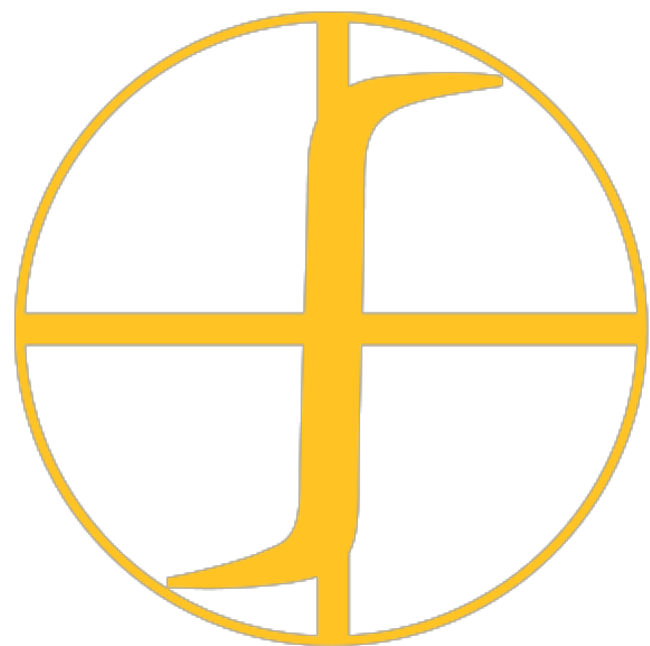
Max thermal conductivity of **Fluxtrol A** is close to that of stainless steel and is 5 times less in direction of pressing

Thermal conductivity of epoxy adhesives and compounds may vary in a wide range depending on glue and filler materials

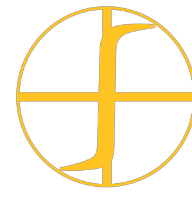


Maintenance of Coils with Fluxtrol Concentrators

- In many applications Fluxtrol concentrators can work longer than copper
- Mechanical damage is one of the main factors causing coil failure and proper preventive measures must be taken
- Visual control of Fluxtrol concentrators:
 - Check concentrator integrity, attachment (loose parts, cracks in glue, mechanical damage) and insulation conditions when applicable
 - Periodically clean concentrator from metallic chips and scale
 - Restore damaged coating when applicable
 - Dark surface may be due to smoke and quenchant residue buildup. Gently scratch the surface with knife or other sharp tool. Cleaned surface must have grey metallic color typical for a particular type of material
- Dark and crumbling surface shows that concentrator material was overheated. Concentrator must be replaced. If the coil lifetime is not sufficient, provide additional cooling or change the coil design
- In some applications, especially in installations with tube generators, sparking from a concentrator to the part or fixture may occur. If there is a ground protection, the generator turns OFF quickly however there might be small areas on the concentrator damaged by sparking. Remove damaged volumes with a sharp tool and eliminate a factor that caused sparking (too small gap, metal particles etc.). Concentrator can continue to work if damage was small.



Examples of Applications



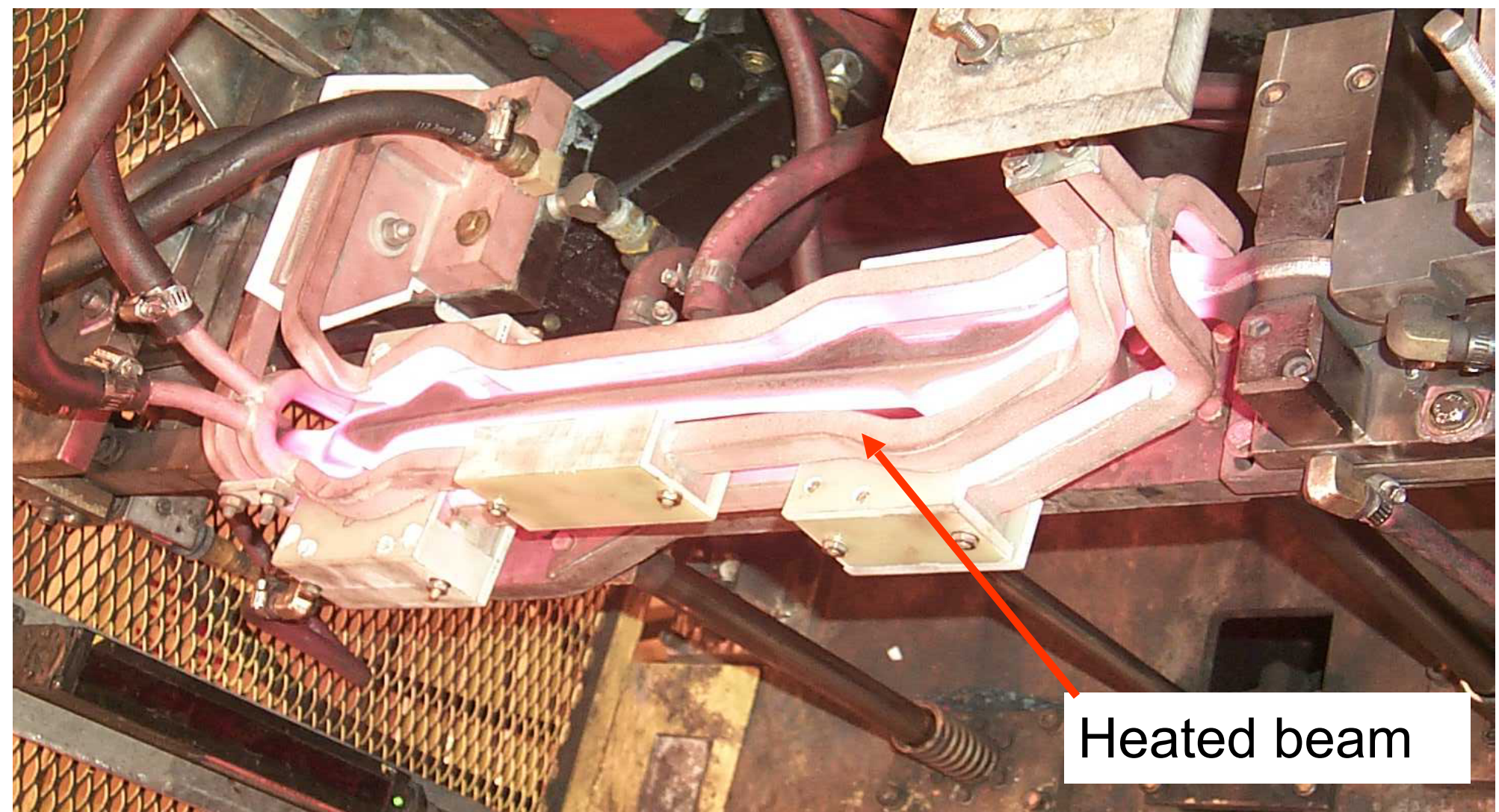
6 Fluxtrol Materials on Induction Coils

Mass Heating Inductor for Bending Operation

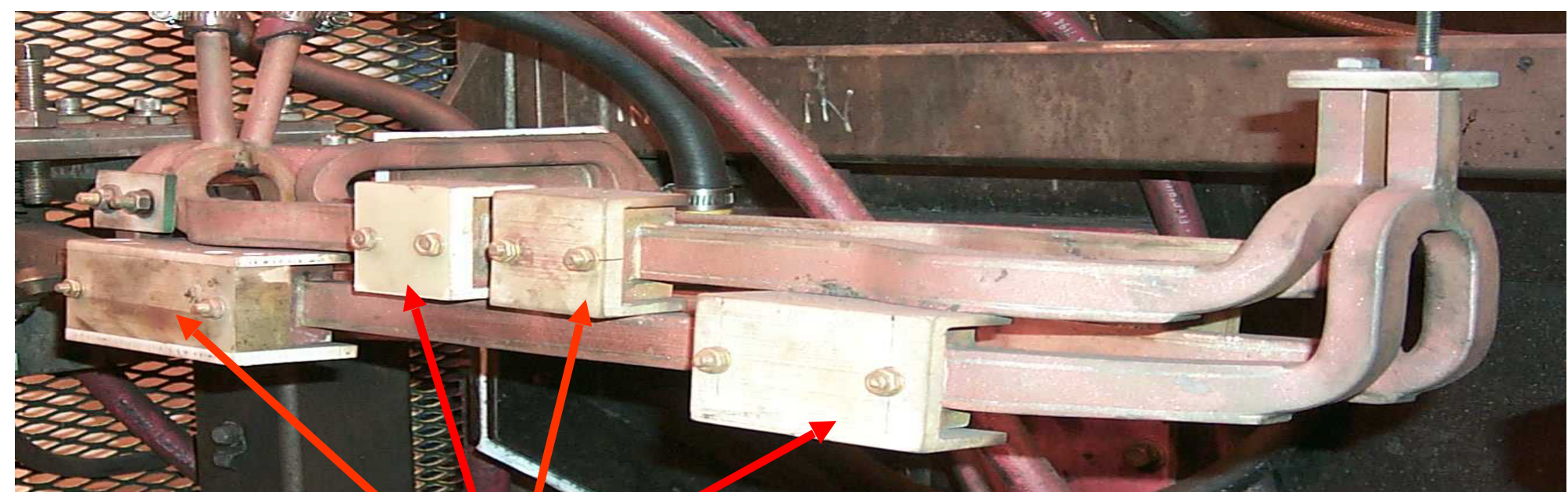
Heating of a beam with variable cross-section in a two-turn coil was non-uniform.

Local concentrators placed in strategic points solved the problem.

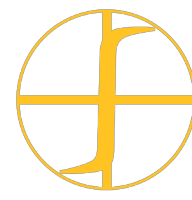
Top view



Side view



Mechanically fastened **Fluxtrol A** concentrators with fiberglass casings for better mechanical protection



Replacement of Laminations with Fluxtrol Materials

Fluxtrol A and **50** materials may be effectively used instead of laminations.

Benefits of Fluxtrol controllers:

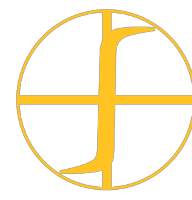
- Possibility to work at any frequency
- Good performance in 3D fields resulting in longer lifetime of Fluxtrol concentrator compared to lams
- Longer coil copper lifetime due to lower current concentration at the concentrator corners
- Possibility to make controller of any geometry
- Possibility of In-Field adjustment of concentrator to modify heat pattern
- Much lower labor time and costs especially for complex geometries



Example: Laminations were initially applied to a single-short induction hardening coil working at 3 kHz.

Due to local overheating from 3-D field lams started to expand resulting in losing pattern; after 13,000 hits the coil completely failed (above).

Coil with Fluxtrol A concentrator produced over 50,000 hits and remained in working conditions.



C-shaped Concentrators Matching to Standard Copper Tubes

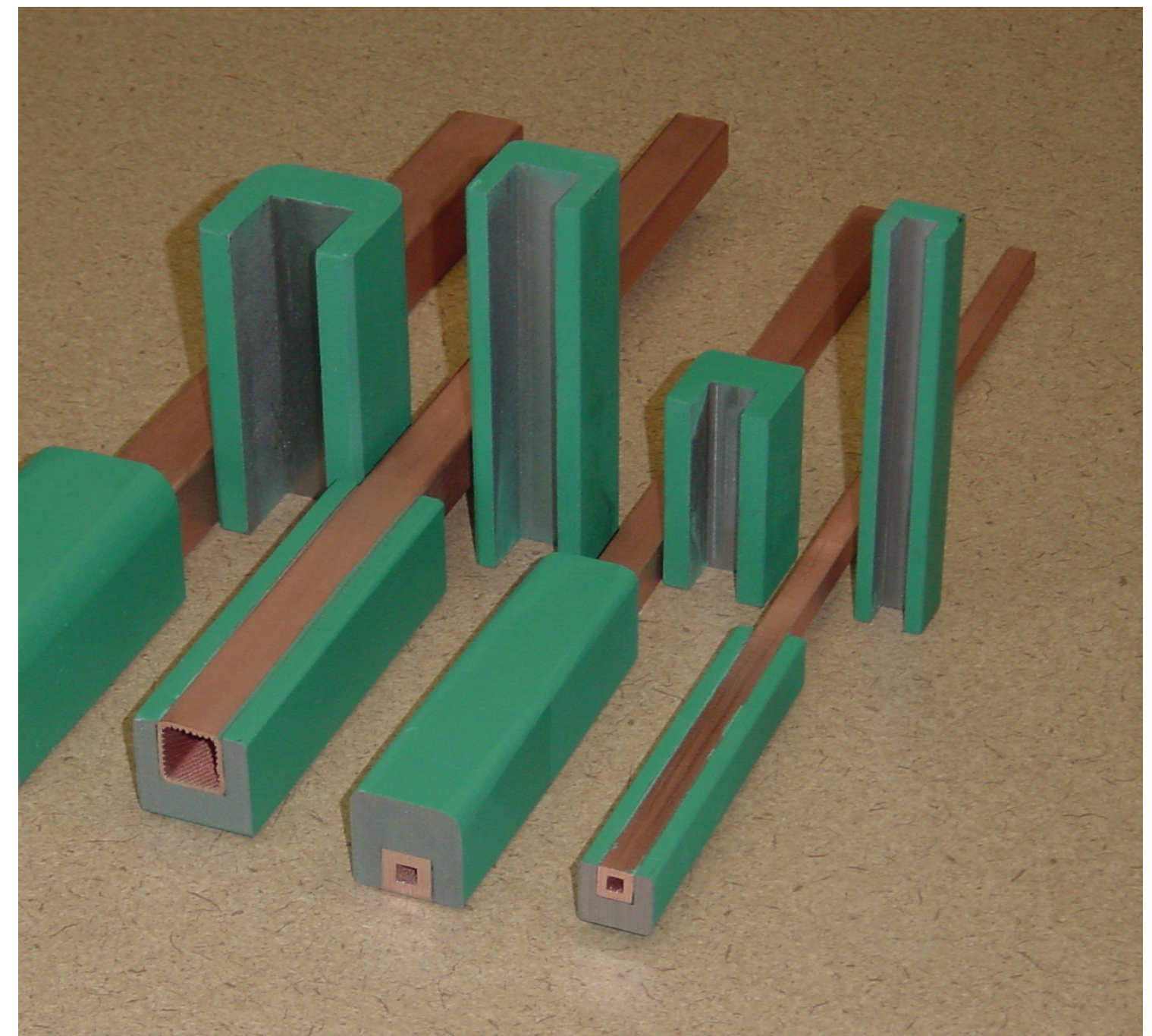
Netshape concentrators are designed for straight coil areas.

C-shape concentrators have optimal material orientation and dimensions that fit majority of standard tube sizes.

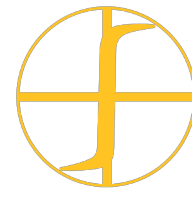
With small additional machining concentrators may be adjusted to fit more tube dimensions.

They may be used at low frequencies instead of laminations or at high frequencies where concentrators are not used at all (fastener heating etc.).

Application of these concentrators minimizes installation time and is very cost effective.



Examples of netshape Fluxtrol concentrators



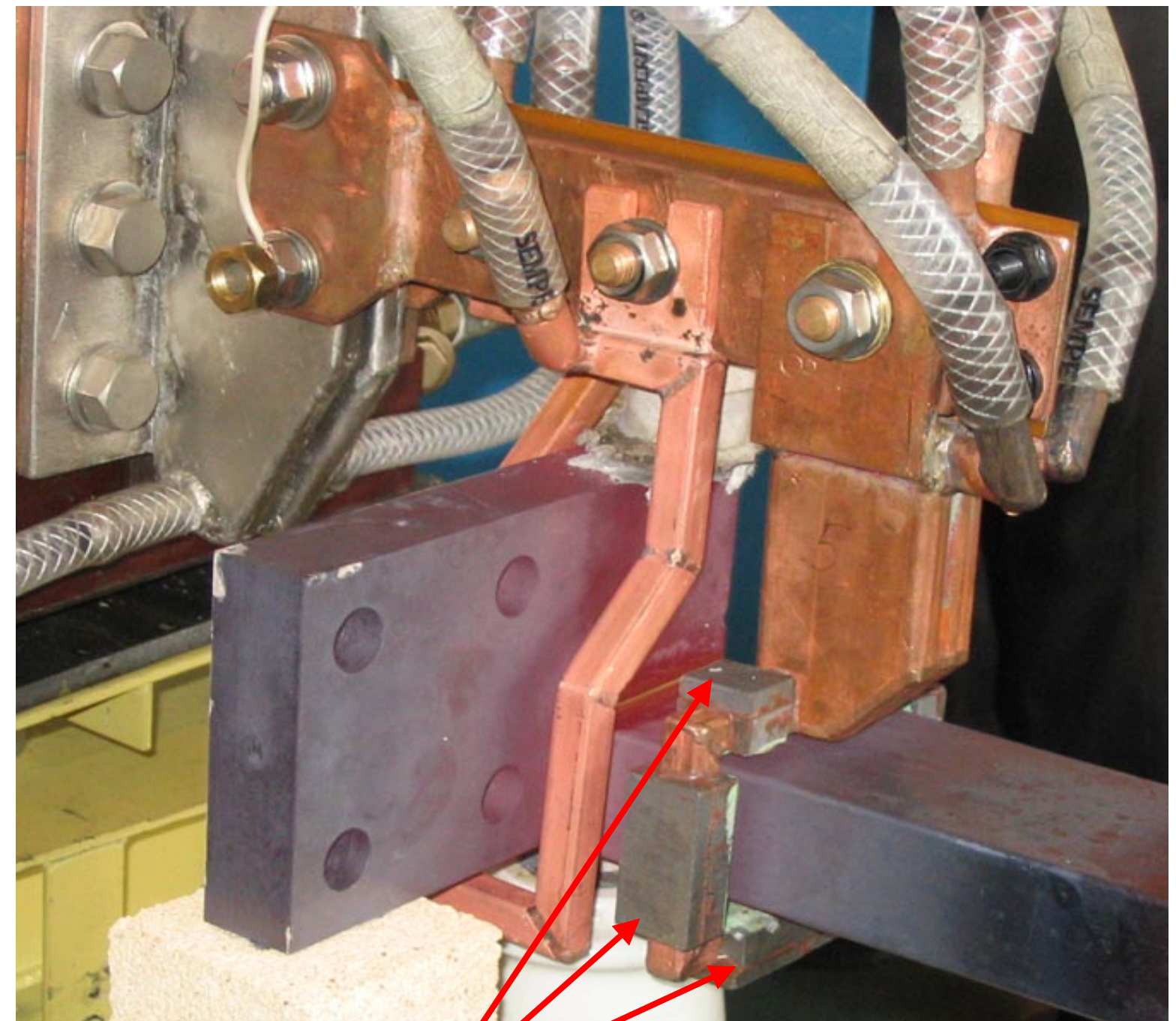
6 F L U X T R O L M A T E R I A L S O N I N D U C T I O N C O I L S

Brazing of Heavy Copper Bars for Nuclear Plants

Brazing of big copper bussbars for nuclear plants is a difficult task. Two inductors connected to the same power supply solved the problem. Application of Fluxtrol controllers to one of the coils provided balanced temperature distribution.

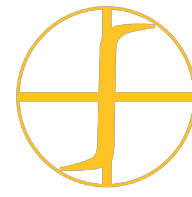
Power 100 kW

Frequency 10 kHz



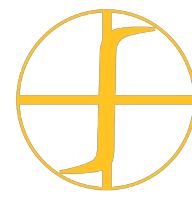
Fluxtrol concentrators

Courtesy Freal Co., Russia



Conclusions

- Magnetic flux controllers made of Fluxtrol and Ferrotron materials are used in a large variety of induction applications ranging from soldering of small conductors at 2 MHz, to food packaging, to automotive parts heat treating, to melting of special materials and inductively coupled plasma
- Due to unique combination of properties Fluxtrol materials are also used in electrophysics, material research and other special areas
- Magnetic flux controllers improve heating quality, boost production rate and coil lifetime, save energy and manufacturing costs
- Fluxtrol materials cover a whole frequency range of induction heating applications providing a variety of permeabilities from 7 to 120
- Computer simulation gives a possibility to predict concentrator performance and optimize induction coil design
- Correct application technique is essential for effective use of Fluxtrol controllers especially in heavy loaded cases
- Fluxtrol Inc. provides extensive technical support to customers and continues to improve materials for magnetic flux control



Questions

- Is permeability of Fluxtrol A and 50 materials sufficient to provide the same heating intensity as laminations?
Yes
- Losses in Fluxtrol materials may be removed by?
Quenchant, Coil Tubing, Cooling Plates, Channels / passages in the material
- When a material has different properties in different directions it is said to be?
Anisotropic
- The Fluxtrol material with the highest level of Anisotropy is?
Fluxtrol "A"
- Permeability and thermal conductivity of Fluxtrol materials are highest in what direction?
In direction perpendicular to pressing direction during manufacturing
- What Fluxtrol material is most likely to develop a conductive surface layer after machining?
Fluxtrol "A"
- What is the best method for removing the conductive layer formed during machining?
Etching
- Other than removing conductive layers, etching also provides...?
Better surface area for adhesive bonding, Rust prevention
- Are lubricants and or coolants required for machining Fluxtrol materials?
No
- Can threads be cut directly into Fluxtrol materials?
Yes
- What is the recommended gap size for the application of adhesives when bonding Fluxtrol materials to coils?
0.1-0.2mm

