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Advanced Induction Materials and Technology
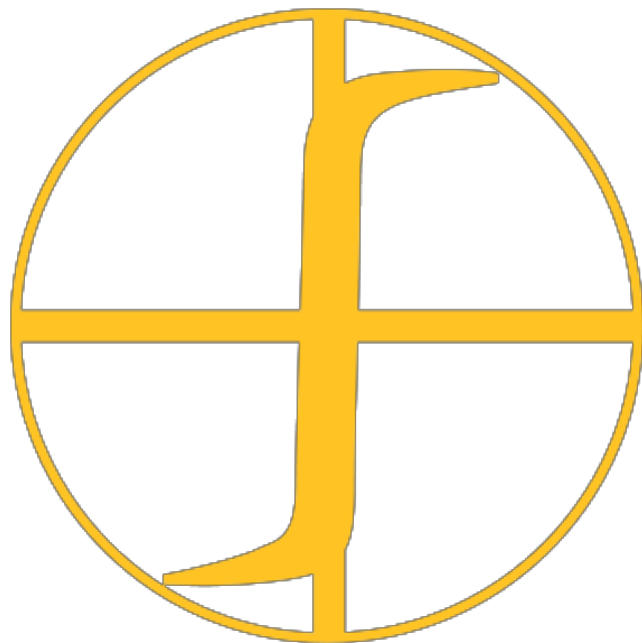
1b. Basics of Induction Technique Part 2

by. Dr. Valentin Nemkov

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Introduction

- Part 1 of Basics dealt mainly with electromagnetic phenomena in induction heating systems

- Part 2 of Basics deals with heating effects, dynamics of temperature distribution and coil parameter variation in the process of heating as well as with electrodynamic forces created by magnetic field

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Power, Time & Frequency Ranges

A combination of **Power**, **Time** & **Frequency** defines an

"Induction Process"

Typically heating of larger parts requires more power at low frequency and heating time is longer (or the process is continuous)

Frequency Ranges:

Though there is no standard for frequency ranges in induction heating, it is a common understanding that:

Low Frequency - 50/60 Hz to 3 kHz (melting, forging, deep hardening)

Middle Frequency - 3 to 50 kHz (surface hardening, brazing, small forging, tempering, shrink fitting etc.)

High Frequency - 50 to 500 kHz (shallow hardening, brazing, soldering, HF welding etc.)

Radio Frequency - above 500 kHz (packaging, crystal growth, low temperature plasma and other special technologies)

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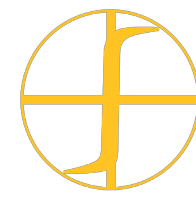
Modern Induction Power Supplies

Modern power supplies cover all industrial demand in power for a very wide range of frequencies.

If necessary, several power supplies may be used in one installation with same, different or dual frequencies.

Examples of very big and very small:

-Melting installation 80 MW@60 Hz

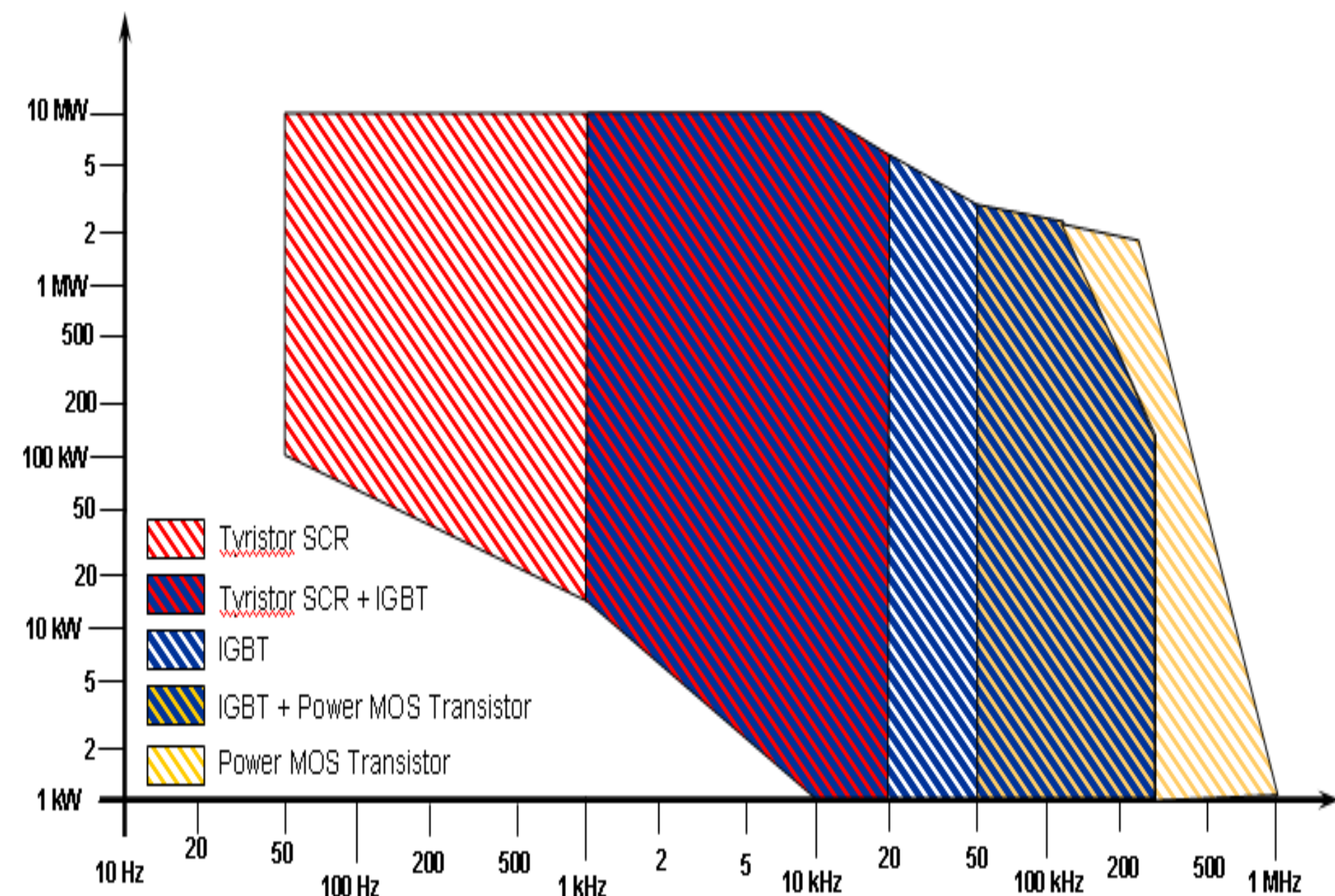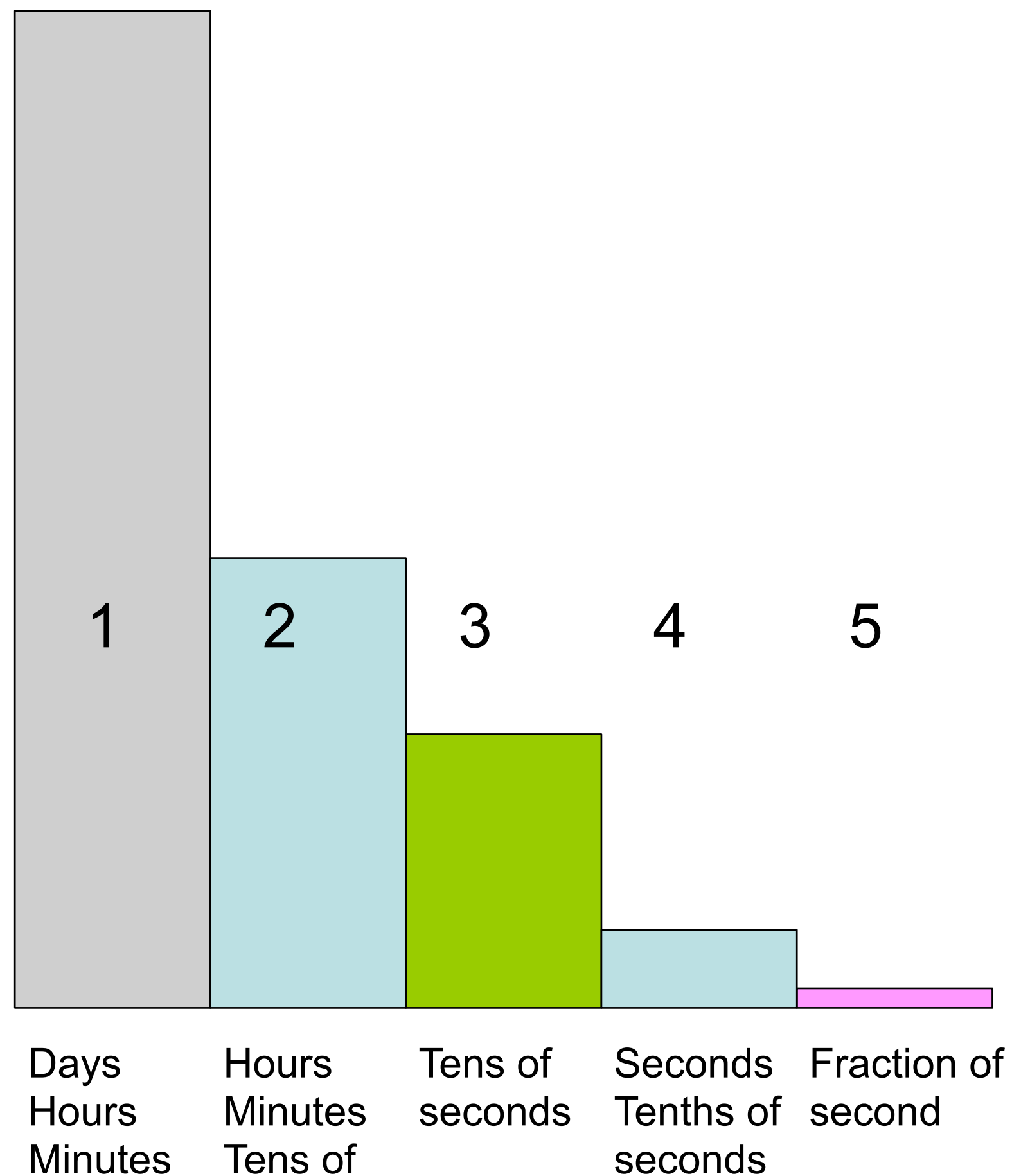- Soldering installation 250W@300 kHz
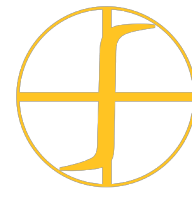

Chart Courtesy of EFD Induction

Heating Time

1	2	3	4	5
Days Hours Minutes	Hours Minutes Tens of	Tens of seconds	Seconds Tenths of seconds	Fraction of second

Typical processes

1. Continuous processes (wire, rod, billet and strip heating, tube welding, crystal growth etc.)

2. Semi-continuous processes (melting, scan hardening and tempering etc.)

3. Single-shot heating

4. Local surface hardening

5. Pulse heating (gear hardening, sealing etc.)

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Frequency Selection

Frequency selection is very important for optimal induction process design.

Criteria and factors for frequency selection:

- Efficiency of inductor and installation in general

- Power factor of the inductor, characterizing reactive power of installation and, therefore, dimensions of matching transformer and capacitor battery

- Heating time and corresponding production rate

- Hardness depth and heat pattern control

- Electrodynamic forces, causing vibration of inductor and machine components and acoustic noise

- Cost of equipment and its size

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Power Density Curves for Induction Surface Hardening Process

Effectiveness of induction surface hardening strongly depends on frequency selection.

At the end of heating cycle when utilizing the optimal frequency the maximum value of power density must be just beyond the required hardness depth (5 mm in the case on right).

For simple cases of flat and round pieces and traditional steels, there are graphs and formulae for frequency selection. However, computer simulation is a much more powerful, universal and accurate design tool.
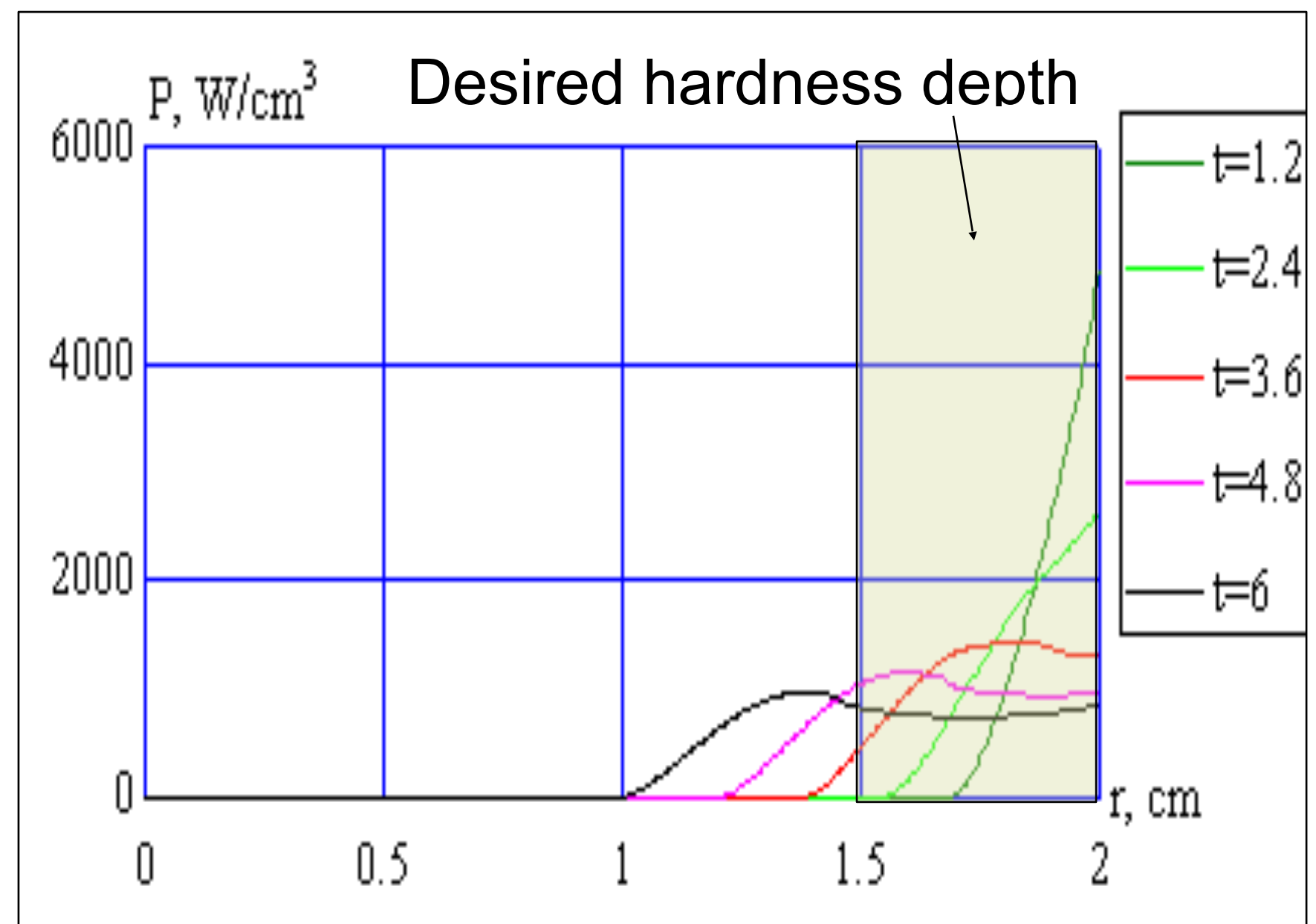
Part diameter 1.6" (4 cm), frequency 4 kHz,

Required hardness depth – 0.2" (5 mm)

ELTA simulation program

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Recommended Frequency for Different Case Depths

Optimal frequency corresponds to Case Depth = 0.5 δ

Good frequency range corresponds to 0.3 δ < Case Depth < 1 δ

| Case Depth	Frequency, kHz					
	1.0	3.0	10	30	100	300
Min mm	5.0	2.7	1.5	1.0	0.6	0.5
Opt mm	8.0	4.5	2.5	1.6	1.0	0.8
Max mm	15	9.0	5.0	3.0	1.6	1.2

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Temperature Evolution During an Induction Hardening Process

Compared to furnace heating induction hardening provides much faster heating when optimal frequency is used.
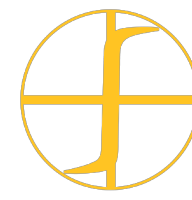
Using direct flame method, in order to achieve required temperature at a needed depth, surface must be strongly overheated. ------>

When using induction, temperature inside the case depth is much more uniform resulting in better quality.

With induction, process may be well controlled and automated.
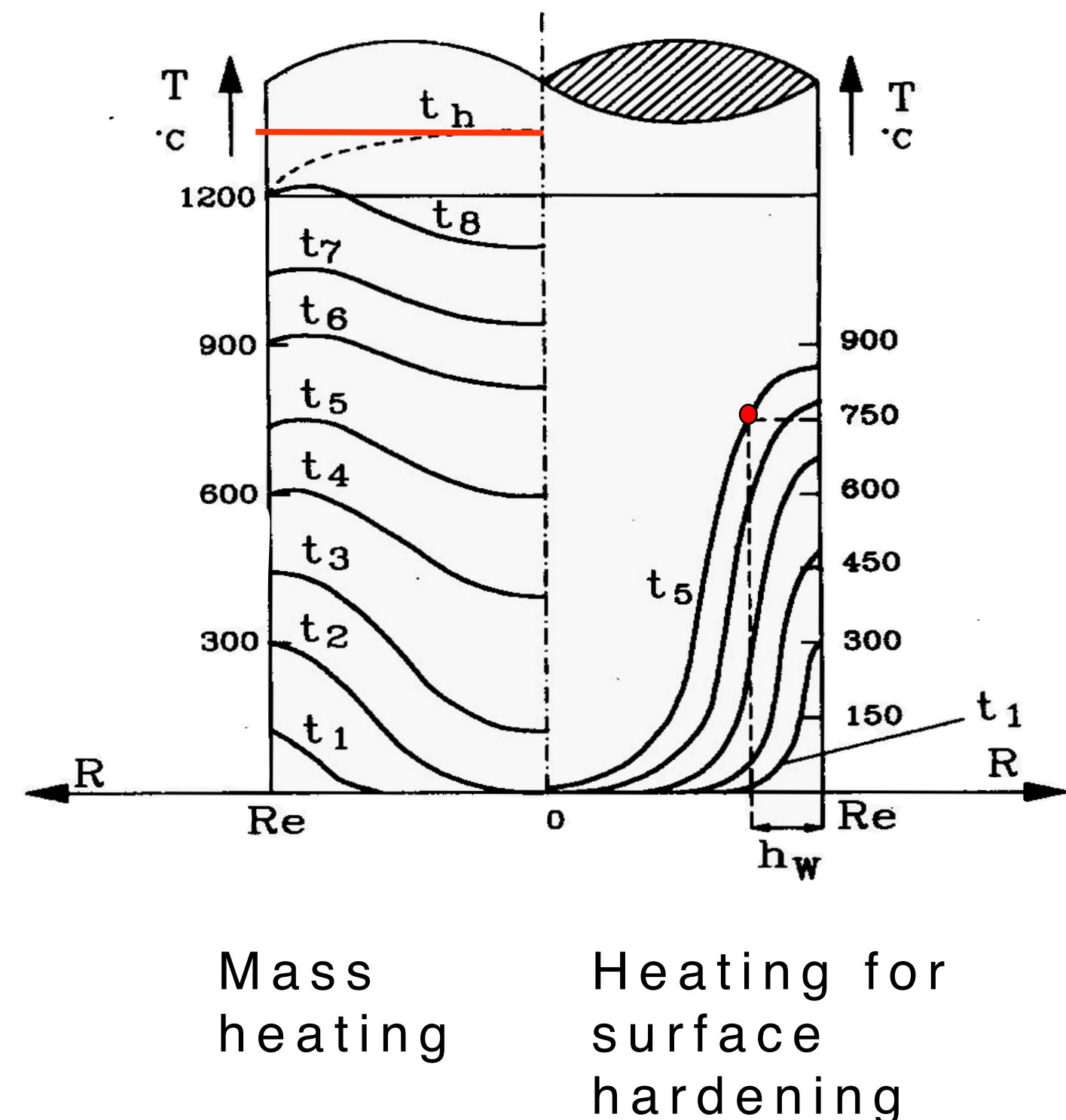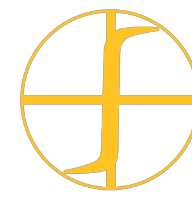

ELTA simulation

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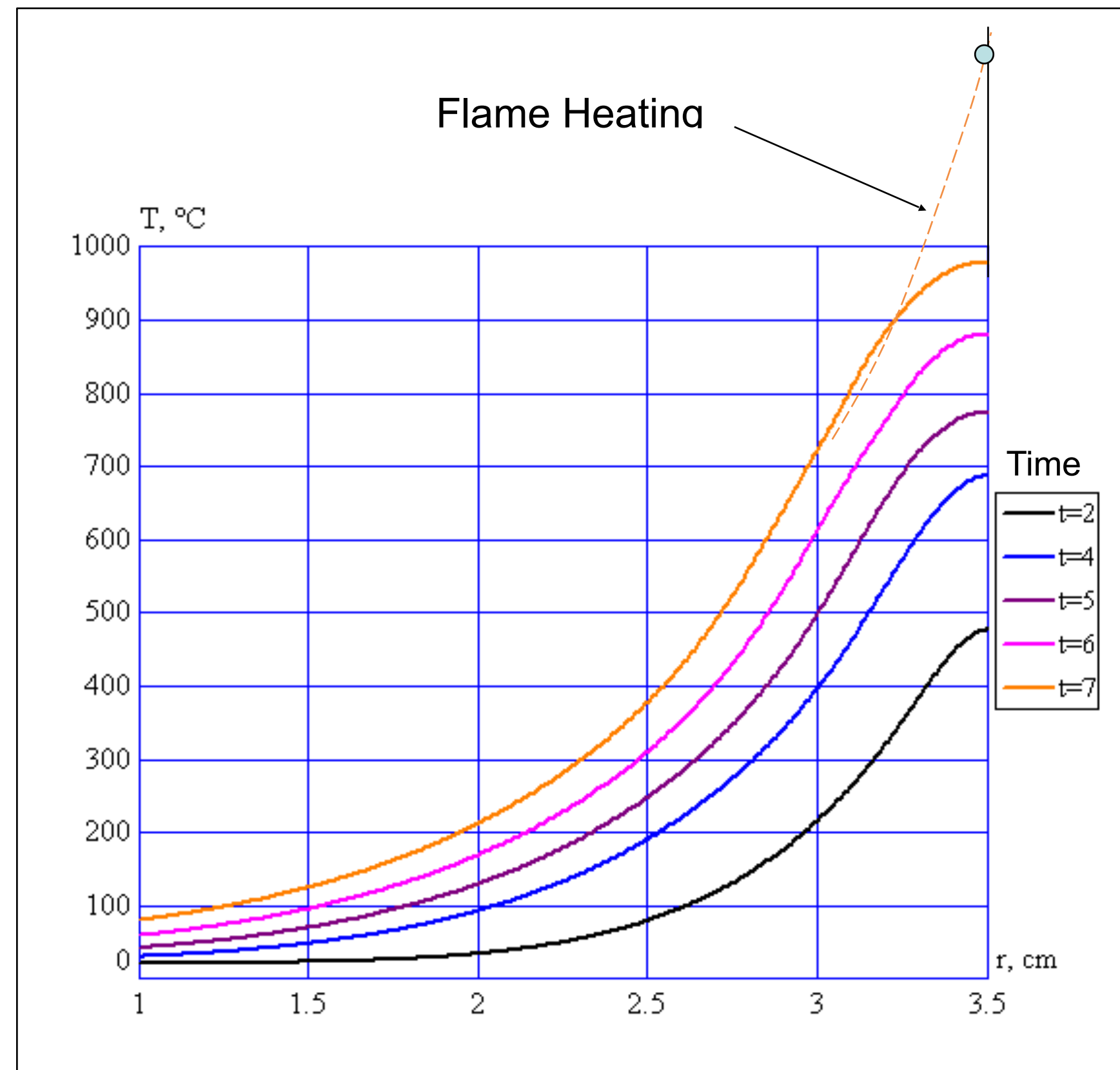
Comparison of Temperature Evolution for Mass Heating and Surface Hardening

Induction heating can provide almost uniform cross-section heating (such as in the case of mass heating) or selective surface heating.

Typical temperature distribution at the end of mass heating corresponds to time t_8. If the workpiece is held inside of inductor with constant surface temperature control (for example during the forge operation pause), temperature inside the billet may be higher than on the surface (curve t_h).

In surface hardening, frequency must correspond to the desired case depth (h_w). Typical final temperature distribution for case hardening of a big shaft corresponds to time t_5. Final curve is flat on the part surface and temperature is close to constant inside the major part of expected case depth, leading to more uniform hardness.

Mass heating

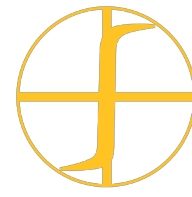Heating for surface hardening

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Temperature Color Map for Induction Hardening Process

Computer simulation allows us to predict temperature distribution in the part and optimize the process of heating (power, frequency, time) and quenching (quenchant type, time). Case depth, microstructure and hardness may be predicted for a particular steel.

For typical steels such as 1040, hardness depth corresponds to temperature isoline 800 degrees C
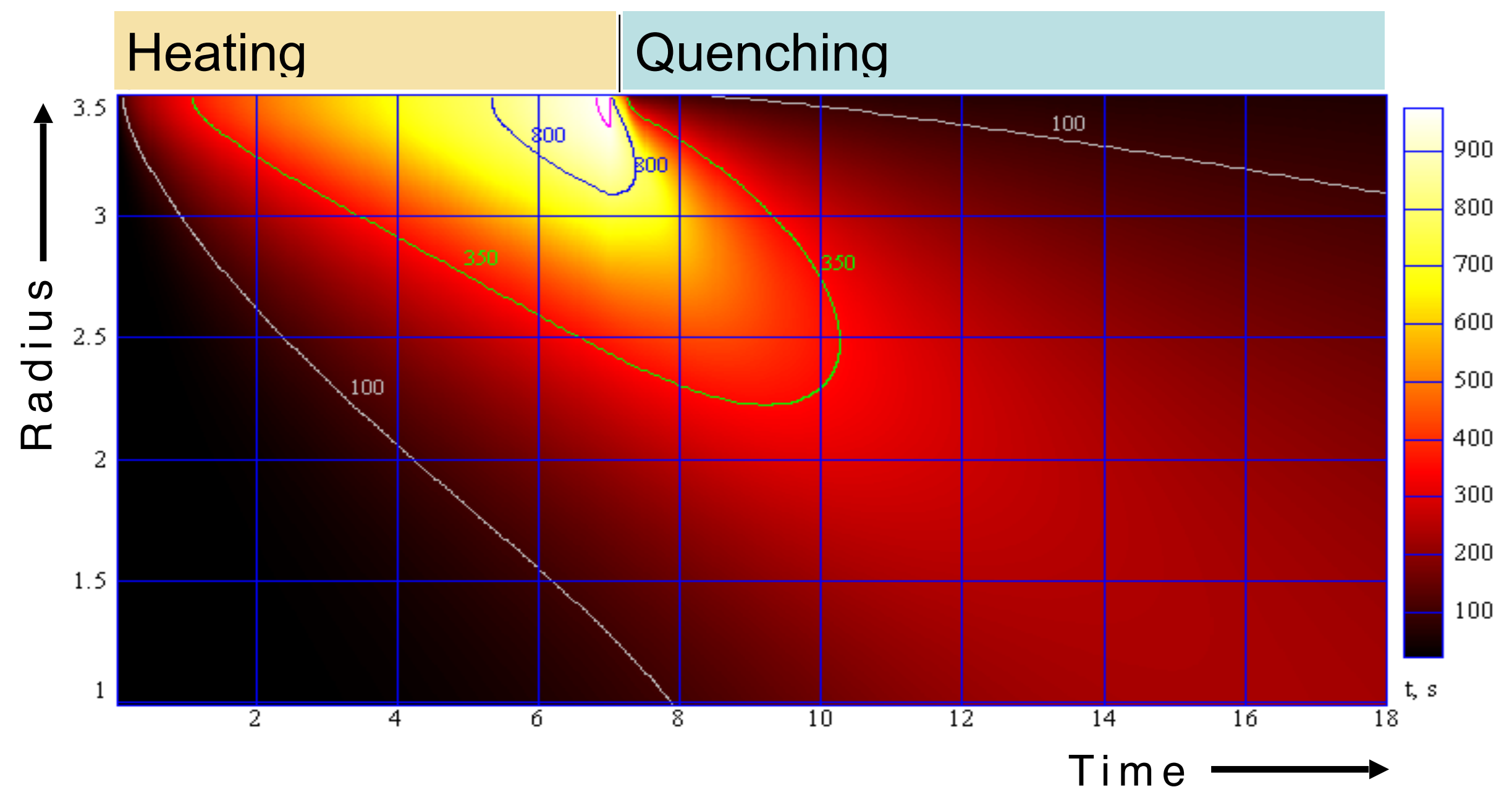
ELTA simulation program

Resistivity and Permeability Variation with Temperature

- Electrical resistivity of metals grows with temperature. For carbon steels it grows approximately 6 times from room temperature to typical hardening temperature 850 - 950 C (1550 – 1750 F). For graphite resistivity is almost constant in a wide range of temperatures. Salts, glasses, oxides and some other materials are non-conductive at low temperature

- Magnetic permeability of steels remains almost constant until temperature 400 C (750 F). After that it begins to drop and at a certain temperature (called Curie point) material becomes completely non-magnetic (μ = 1). Curie temperature is 710-750 C (1300 – 1380 F) depending on steel type. Alloyed steels may have much lower Curie point

- Permeability at room temperature depends on steel type and magnetic field strength, i.e. heating power at a given frequency. For surface hardening μ may be 5-10 while for through heating – 30 and more. It means that penetration depth may change 10-40 times resulting in different coil parameters and heating intensity

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Variation of Reference Depth with Temperature

Material – magnetic steel

Tc – magnetic transformation or Curie temperature. Below this temperature steel is magnetic ($\mu \gg 1$); above – non-magnetic ($\mu = 1$). For carbon steel Tc is close to 750 C (~1400 F).

Permeability drops when temperature approaches to Curie point.

Due to variation of μ, ρ and reference depth δ, the coil parameters vary in the process of heating.

Material and coil parameter variation is much smaller when heating non-magnetic materials or magnetic material below Curie temperature (tempering, stress relieving etc.).
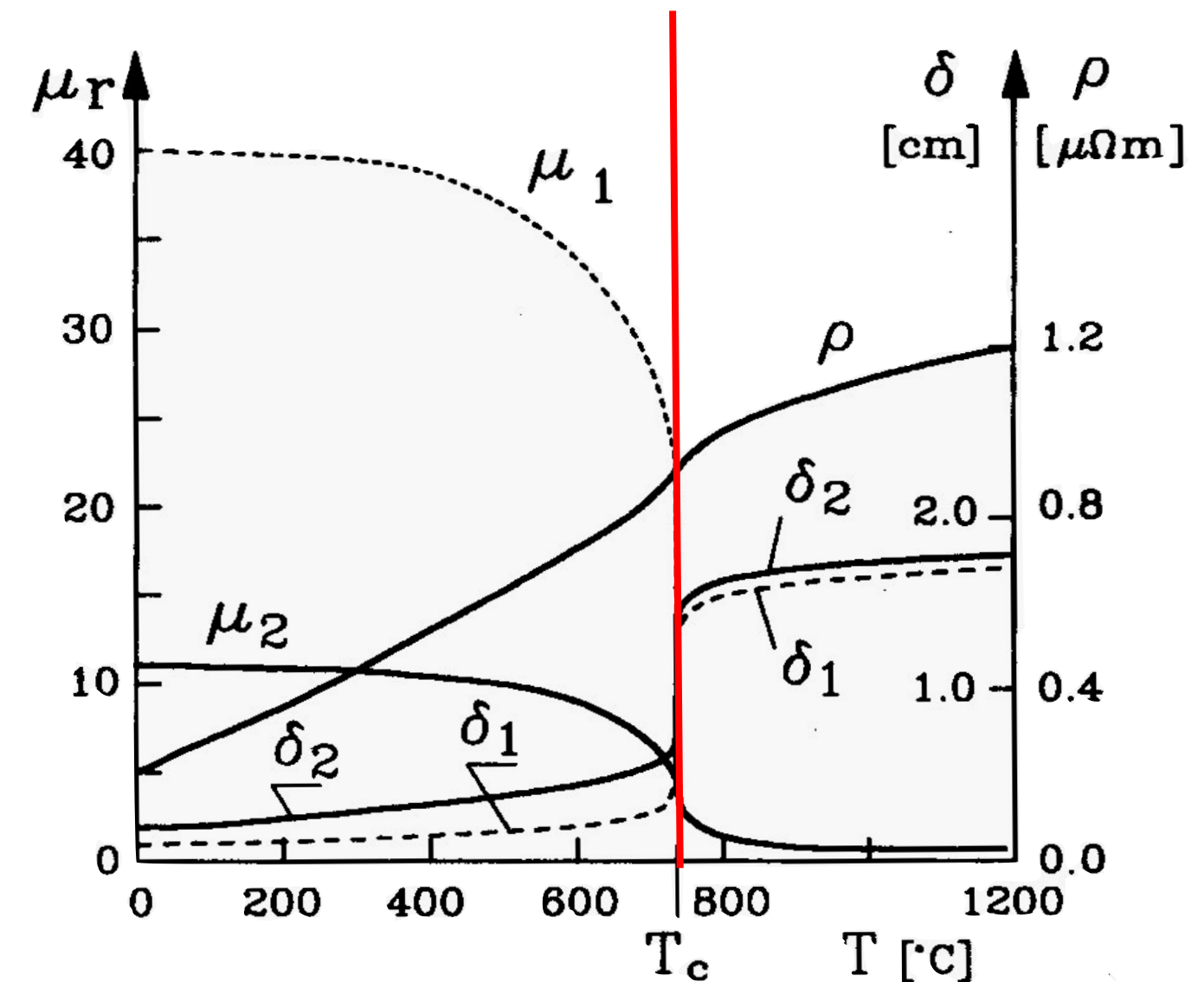
Resistivity, permeability and reference depth variation with temperature for carbon steel.

High permeability μ_1 corresponds to weaker magnetic field (typical for mass heating); much lower value of μ_2 is typical for surface hardening when magnetic field is much stronger.

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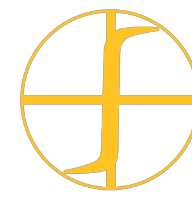# Typical Power Variation in Surface Hardening

Case of constant coil voltage

In a static or single-shot heat treating process, the coil power may drop and then significantly increase when the surface layer gets non-magnetic.

If generator controls are set for constant output current, power dynamics will be very different.

Parameter variation is essential for optimal process and coil design. It may be predicted by computer simulation.
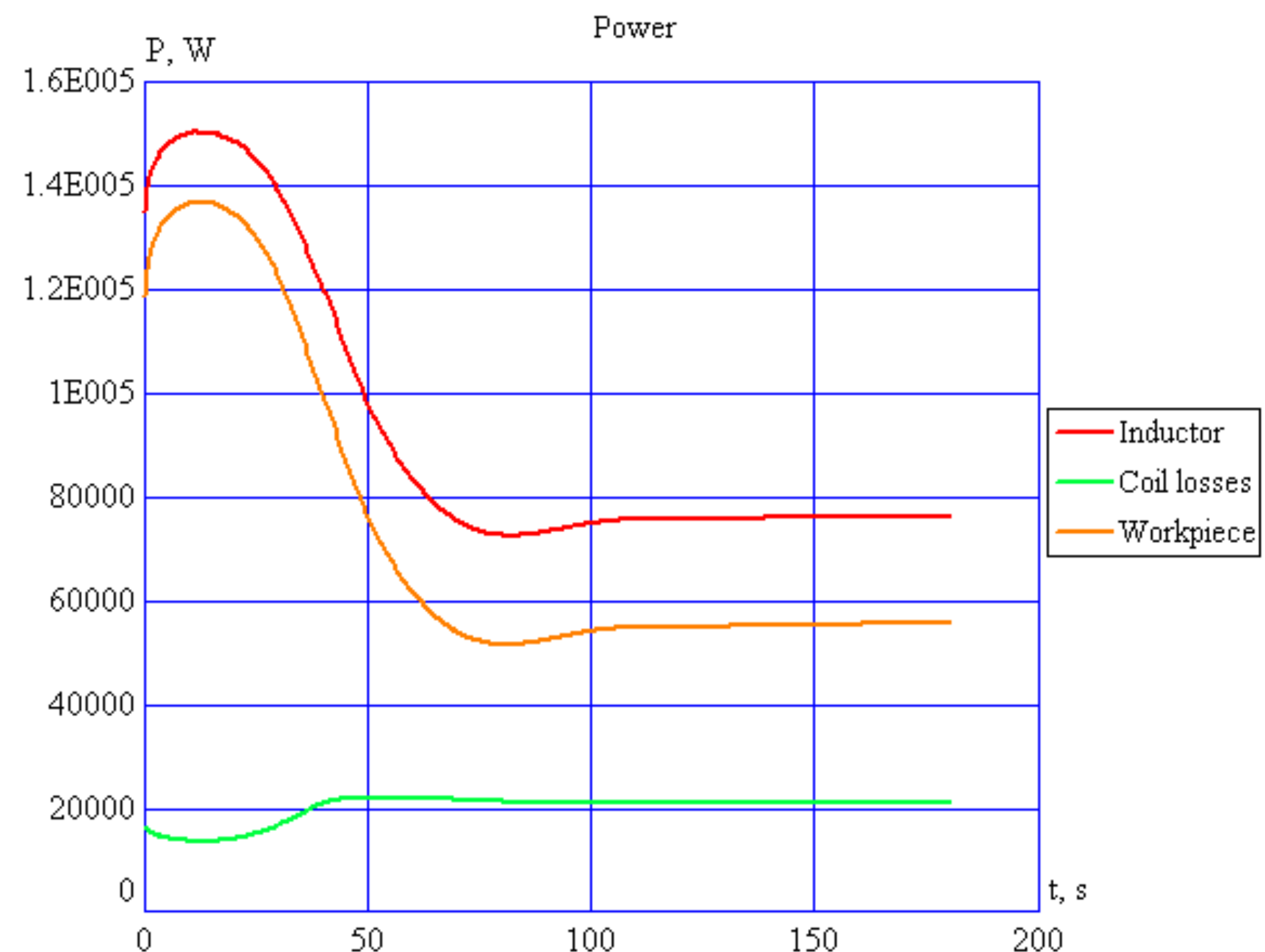

ELTA simulation program

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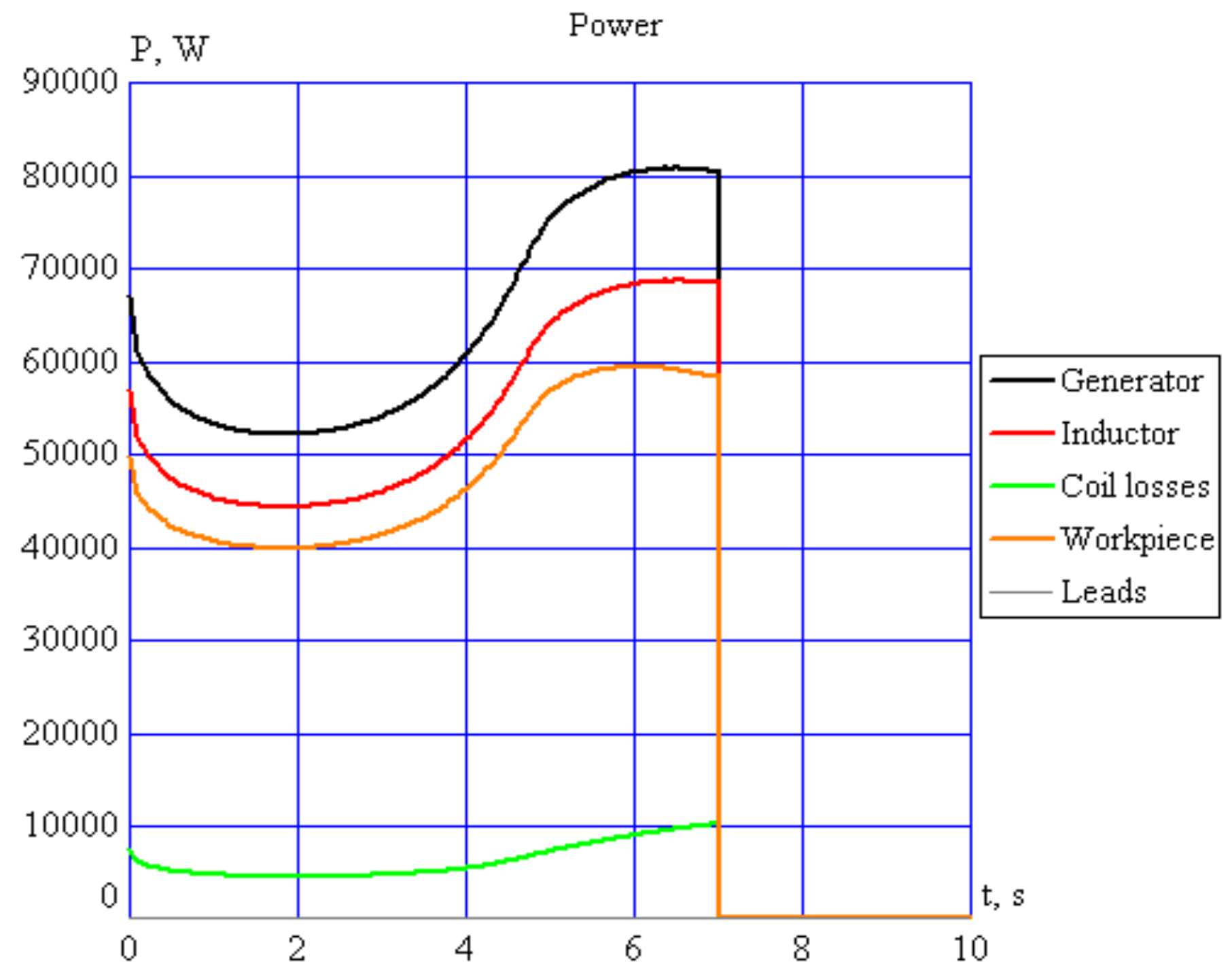
Example of Power Variation in Mass Heating Process

Case of constant coil voltage

Maximum power corresponds usually to a thickness of non-magnetic surface layer of 0.5-0.7 of the reference depth in hot metal.

After that coil losses gets higher while the workpiece power drops, i.e. coil efficiency dramatically drops.

Part Dia. 7 cm; frequency 3 kHz

ELTA simulation program

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Electrodynamic Forces

In induction heating processes Electrodynamic forces usually play a negative role causing coil and part vibration. Vibration can generate harmful noise and also reduce coil lifetime.

Electrodynamic forces are distributed between the system components. At high frequency forces are applied to the coil component surfaces.

The coil copper face always experiences repulsion from the workpiece. The concentrator poles experience attraction to the workpiece. Resulting force applied to the coil may be either attractive or repulsive (more typical).

For the same workpiece power, the electrodynamic forces become lower with higher frequency.

Electrodynamic forces vary in time.
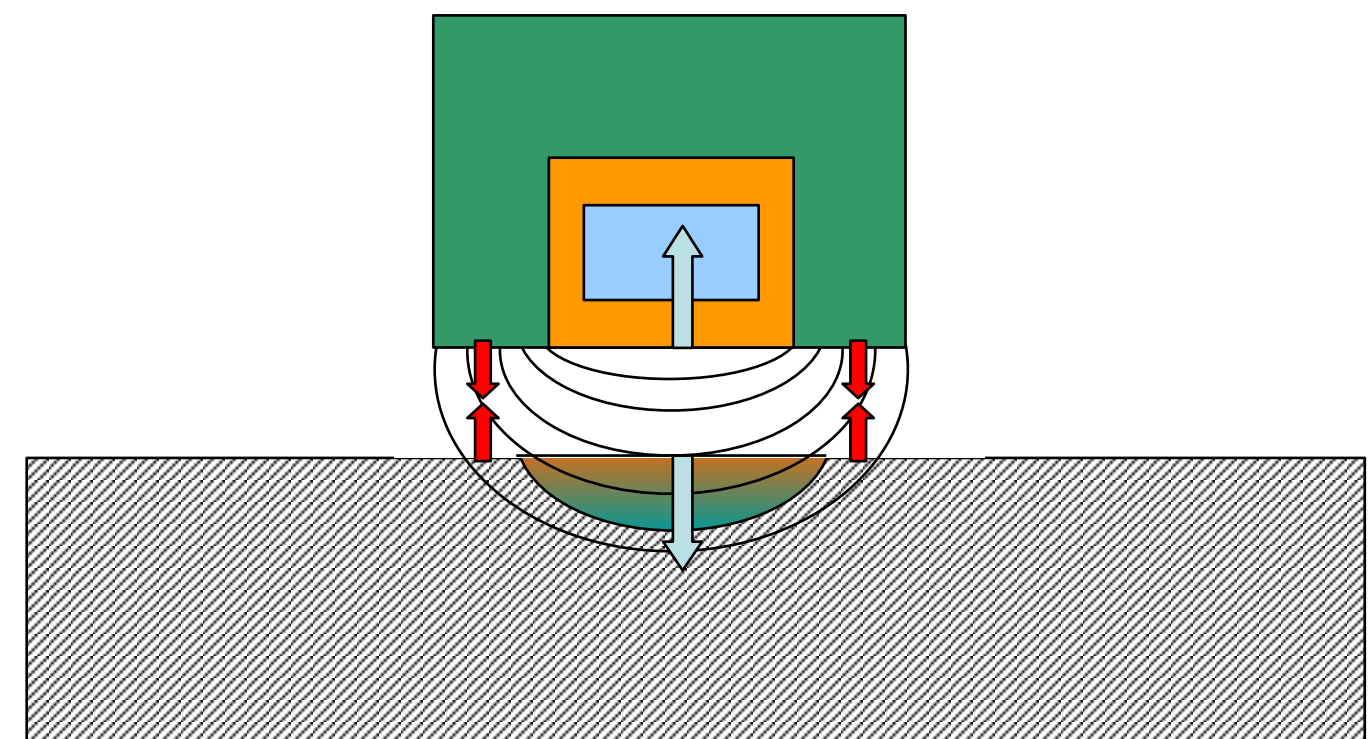
Electrodynamic forces applied to the coil copper and concentrator poles. Workpiece is a magnetic steel with a locally austenitized (non-magnetic) zone under the coil face.

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Time Variation of Electrodynamic

If coil current waveform is sinusoidal, electrodynamic forces are also sinusoidal but with **twice the frequency**.

If current frequency is 1 kHz, force and vibration frequency will be 2 kHz, which corresponds to maximum sensitivity of the human ear. Resulting noise may exceed the **Max Permissible Level** in the work place.
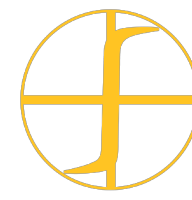
At current frequency 10 kHz and higher acoustic noise is inaudible (except of some "subharmonics").

Application of Fluxtrol concentrators can reduce noise compared to laminations.
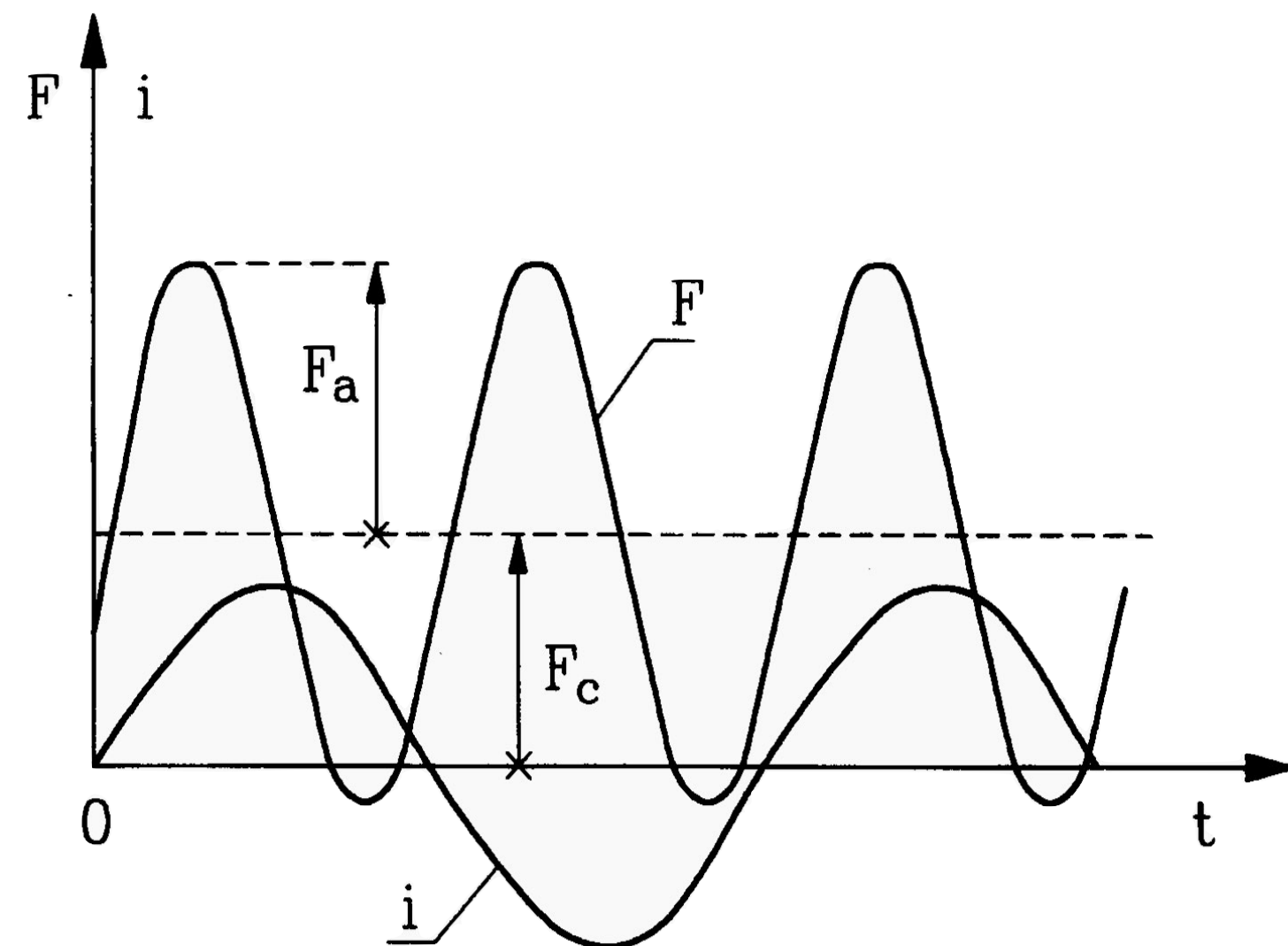
In addition to the oscillating force Fa there is a constant component Fc of a total force F.

Fc produces permanent pressure on the coil and part, which can cause their deformation.

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Melt Stirring by Electrodynamic Forces

When applied to molten metal (melting, brazing), electrodynamic forces cause material flow.

In a crucible induction furnace maximum pressure is applied to the metal surface in the middle of the coil where magnetic field is stronger.

Metal flows inside the crucible (stirring effect). Stirring is positive effect that provides better melt composition and temperature uniformity. When the force is too big, it can cause a big meniscus or even squeeze metal out of crucible.

Magnetic concentrators may be useful for electrodynamic force control in molten metal treatment (melting, brazing, casting etc.).

MENISCUS

I_1

COIL

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CERAMIC CRUCIBLE

I_1

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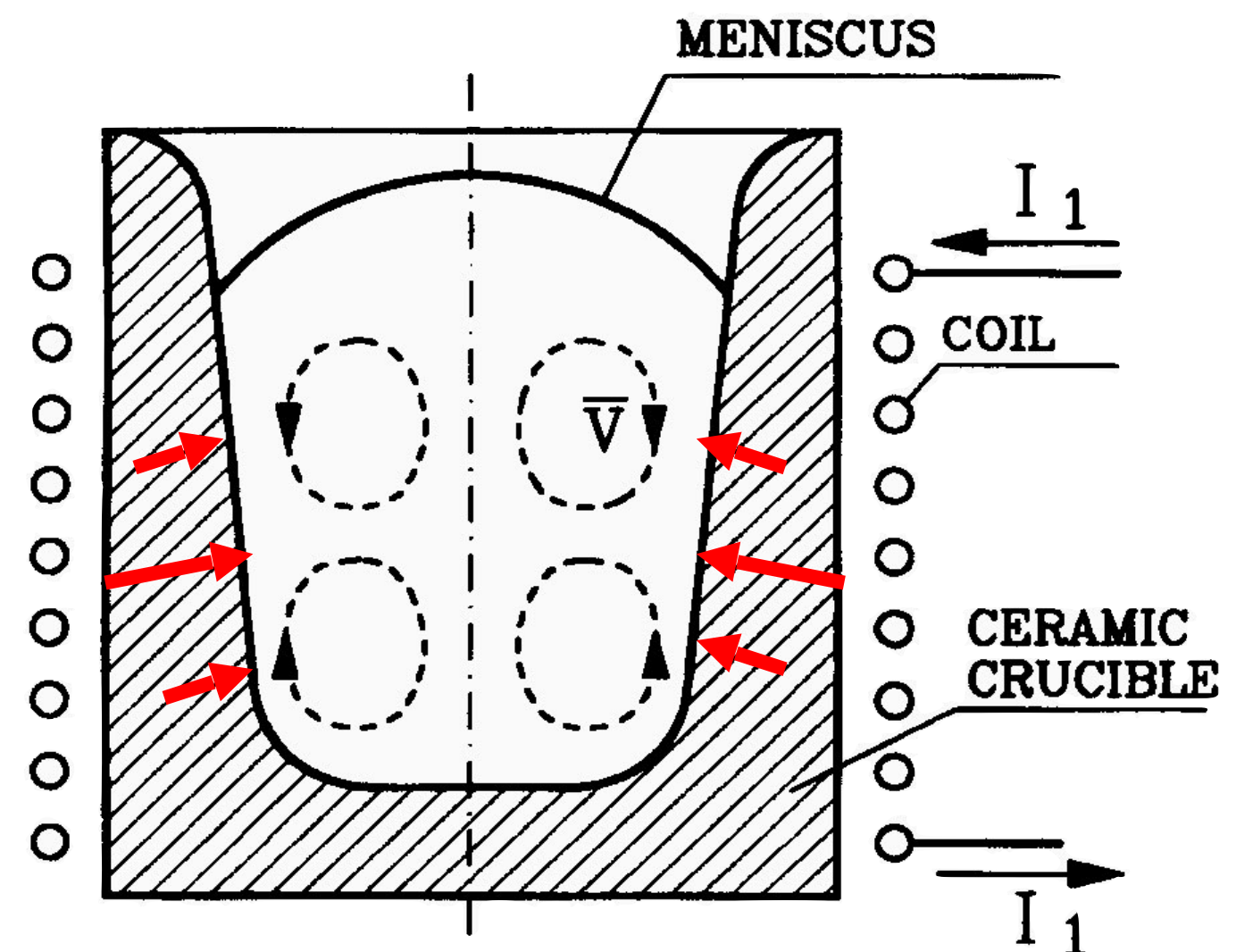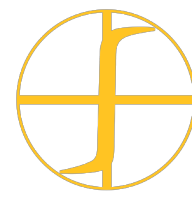
Excessive Electrodynamic Forces

At high and middle frequency, the electrodynamic forces are usually not high and may be well managed. Forces may be very high when heating large slabs at low or line frequency resulting in damage to induction coil and equipment.
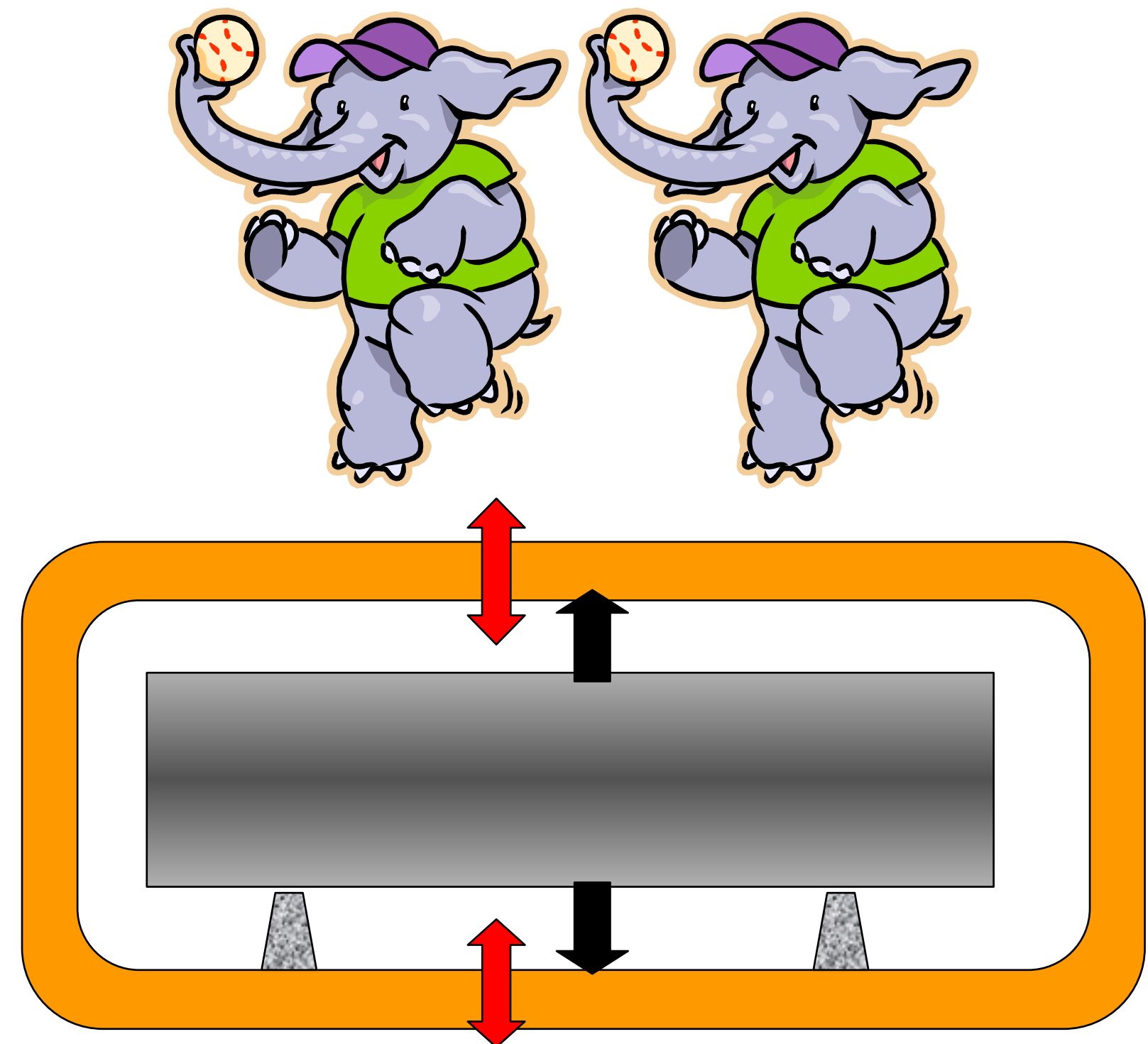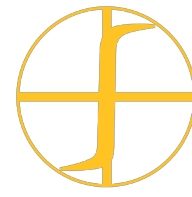
Example:

Aluminum slab 0.3 x 1 x 3 m

(2.5 tons)

Power 600 kW, 50 Hz

Constant force - 7 tons (black arrows)

Oscillating forces acting on each side of the coil are 7 tons @100 Hz (red arrows)

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Electrodynamic Forces Summary

Possible positive effects:

- Melt stirring in the bath resulting in uniform temperature and metal composition

- Possibility to control liquid metal flow in casting and other processes

- Possibility to hold small quantity of molten material levitated inside the inductor without touching coil or crucible walls

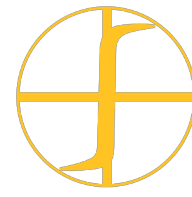Negative effects of electrodynamic forces:

- Attraction of magnetic particles to the coil and concentrator poles (magnetic chips move into the areas of the strongest field)

- Coil vibration, which in addition to static force and thermal stresses can result in coil deformation or failure of brazed joints

- Separation of concentrators from copper and possible shift of loose pieces

- Loud noise exceeding Max Permissive Levels on work places

- Deformation of heated parts (distortions) especially of thin non-round profiles

- Unintended or excessive movement of molten metal or parts of assembly in brazing and melting

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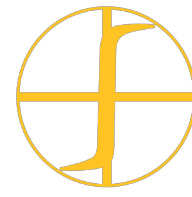
Electrodynamic Forces Summary (cont.)
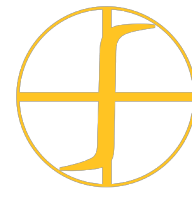
Measures for reduction of electromagnetic forces influence:

- Coil style and design selection to account for forces

- Frequency selection (avoid too low frequency!)

- Mechanical design of the coil and concentrator; frequency of mechanical resonance of the coil assembly must be far from double value of current frequency

- Reliable manufacturing of coil and concentrator

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Conclusions to Basics

- There are many mutually coupled phenomena in induction heating systems (electromagnetic, thermal, electrodynamic etc.). Their understanding is essential for a proper design and maintenance of induction coils and installations

- Induction coil parameters depend on the workpiece dimensions and temperature distribution. This effect may be used for real-time process monitoring and quality control systems

- Absorbed power and temperature distribution in the part may change during the heating time

- Magnetic flux control can improve the coil performance

- Computer simulation can predict a system behavior and is a powerful tool for study and design of induction heating systems

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Questions and Answers

- An induction Process can be defined by a combination of?

  Power, Time, Frequency

- Curie, is the temperature at which a magnetic material becomes ....?

  Non-Magnetic

- Induction heating effectiveness is strongly dependant on....?

  Frequency

- Temperature inside the case depth is much more uniform when using flame or induction heating?

  Induction Heating

- Computer Simulation can predict: Coil parameter variation? Power and temperature distribution? Case depth?

  All

- Which material properties affecting coil parameters change with temperature?

  Electrical Resistivity, Permeability

- Resistivity of what materials drops significantly when temperature grows?

  Glass, Ceramics, Oxides

- In a static or single shot surface hardening application, coil power may drop and then significantly increase when the surface layer of the workpiece....?

  Reaches Curie temperature and becomes non-magnetic

- For the same workpiece power, electrodynamic forces become lower with?

  Higher Frequency

- If coil current frequency is 3 kHz what will be a main frequency of acoustic noise?

  6 kHz

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