FLUXTROL®

Advanced Induction Materials and Technology

Online Induction Heating Course

4. Computer Simulation for Induction Processes and Coil Design

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Opening Remarks

- First works on computer simulation of induction coils were made in 1960's. Due to a limited access to computers, their low memory, speed and poor programming methods the computer simulation did not receive significant industrial application until the 1980's
- Now computer simulation has become a practical tool for everyday use in the induction industry. It allows the user to design optimal systems, improve equipment performance, dramatically reduce development time and costs, better understand the process dynamics, etc.
- Though there are still difficulties in accurate simulation of non-linear and different mutually-coupled tasks, computer simulation is effectively used for design of induction heating coils and problem solution
- Material of this chapter is based mainly on experience of the author, his colleagues and his collaborators in development and use of computer simulation programs in different areas of induction heating

Special Features of Induction Heating Computer Simulation

- The induction heating market is small compared to other industrial sectors and there are only a few specialized simulation packages on the market that can be used for induction process and coil design
- Induction heating simulation involves a set of mutually coupled non-linear phenomena
- Many induction applications are unique and may require different program modules
- In addition to computer simulation software an extensive database is necessary for accurate results

Process Design & Coil Design

Process Design

- Optimal Frequency, Power and Time
- Heating style (Static, Scanning, Single-Shot)

In many cases we have limited control due to existing machines, dictating frequency and power range and heating style.

Coil Design

- Coil style selection
- Copper cross-section
- Magnetic flux controller
- Coil matching

This is something we can change to improve the process.

Computer Simulation vs. Experimental Method

Computer Simulation

Advantages
- Can work for any geometry and operating conditions
- Demonstrates the entire dynamics of the process
- Leaves records for future
- Limitless accuracy of calculations
- Does not require special equipment
- Less expensive and time consuming
- Future improvements expected

Limits and Disadvantages
- Requires special software and databases
- Not all the processes may be simulated (as of today)
- Does not provide physical samples

Experimental Method

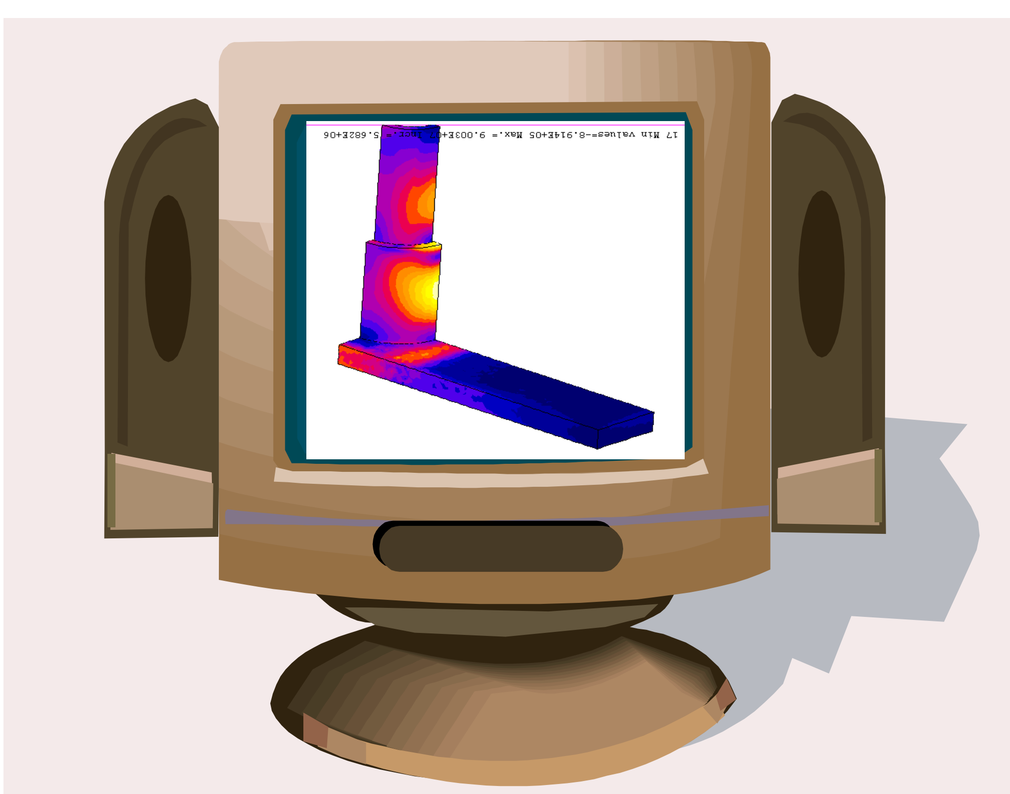
Advantages
- May provide the most reliable results
- Can show performance of the whole system including unexpected effects and troubles
- Does not require material property database
- Provides physical samples for properties validation

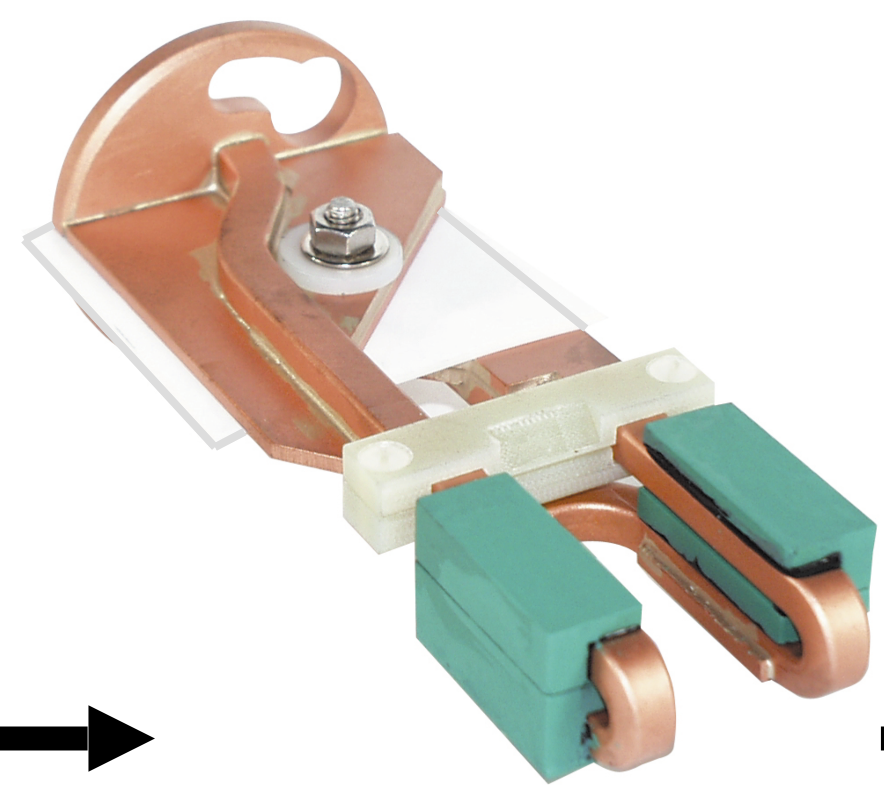
Limits and Disadvantages
- May require expensive equipment
- Does not provide a good understanding of the process
- Difficult to transfer knowledge
- Case dependent accuracy
- Limited access to production equipment (expensive)

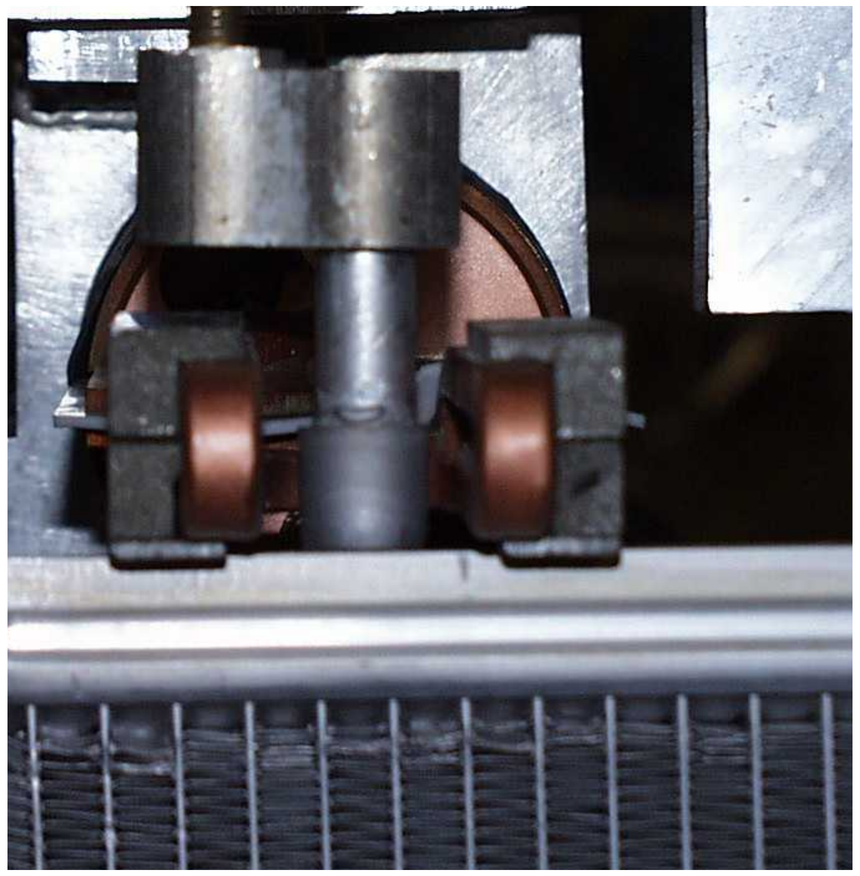
Induction Process and Coil Development via Computer

Typical stages of computer-assisted induction coil development:

- Induction process design (Power, Frequency, Time)
- Induction coil design
- Coil engineering and manufacturing
- Process set-up and performance validation
- Final modification of induction coil and process if required

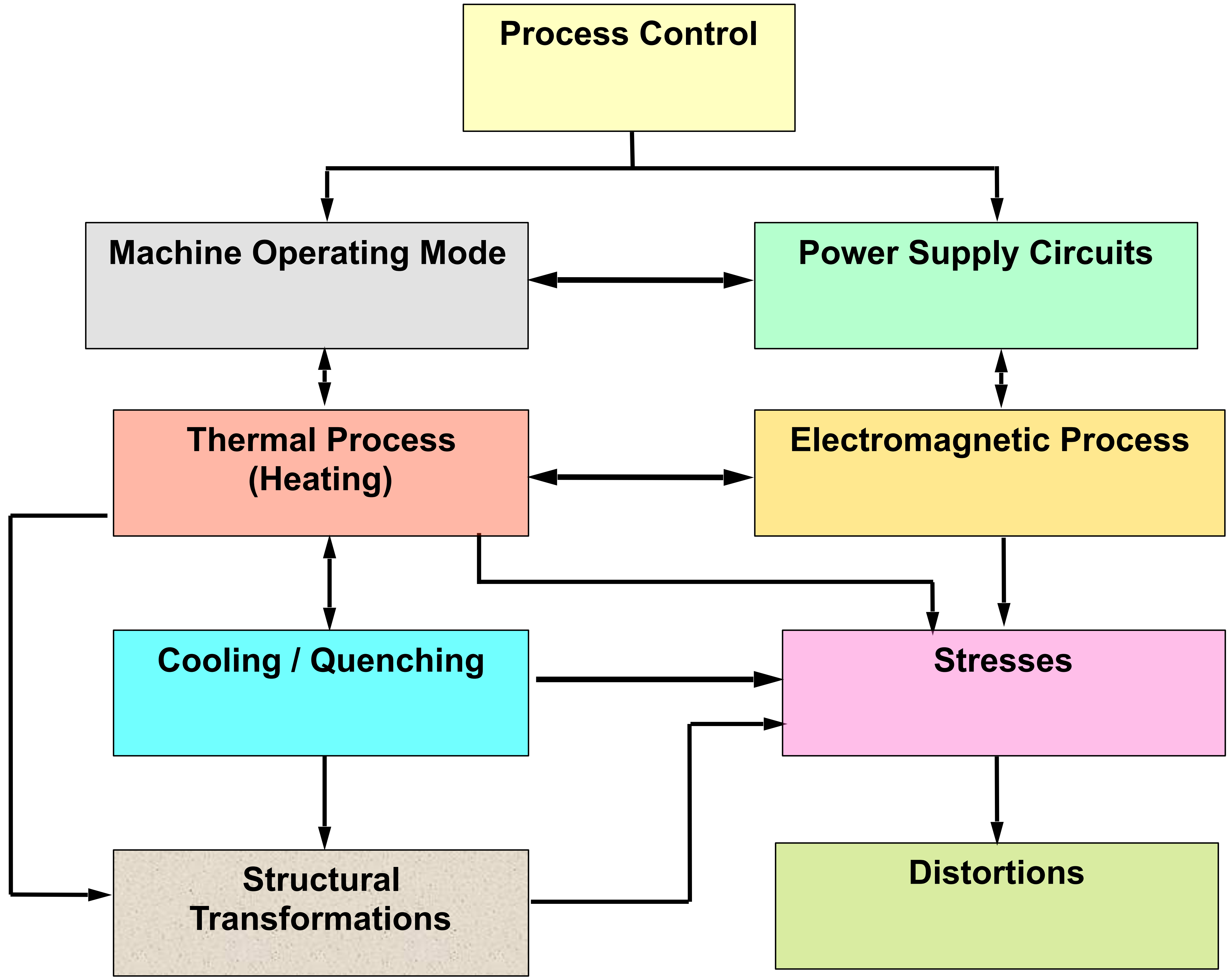






Example: Development of aluminum heat exchanger brazing and experimental validation

Interrelated Processes in Induction Heating Computer Simulation



Types of Programs for Induction Heating Computer Simulation at Fluxtrol Inc.

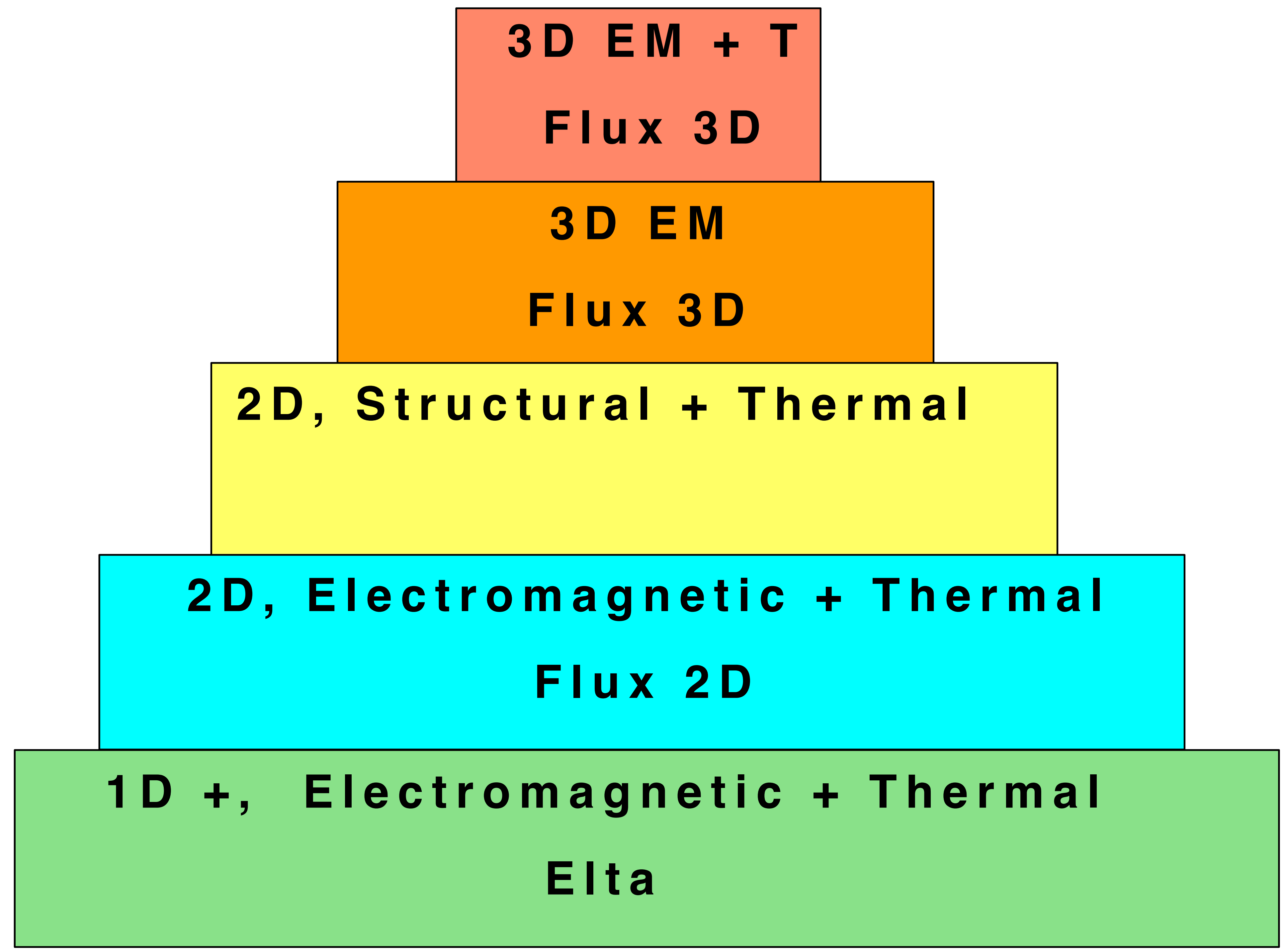
PC Computer Simulation

Type	Program
1D + Coupled	Elta
2D Electromagnetic	Flux2D
2D Thermal	Flux2D
2D Coupled	Flux2D
3D Electromagnetic	Flux3D
3D Thermal	Flux3D
3D Coupled	Flux3D

Rule of Pyramid

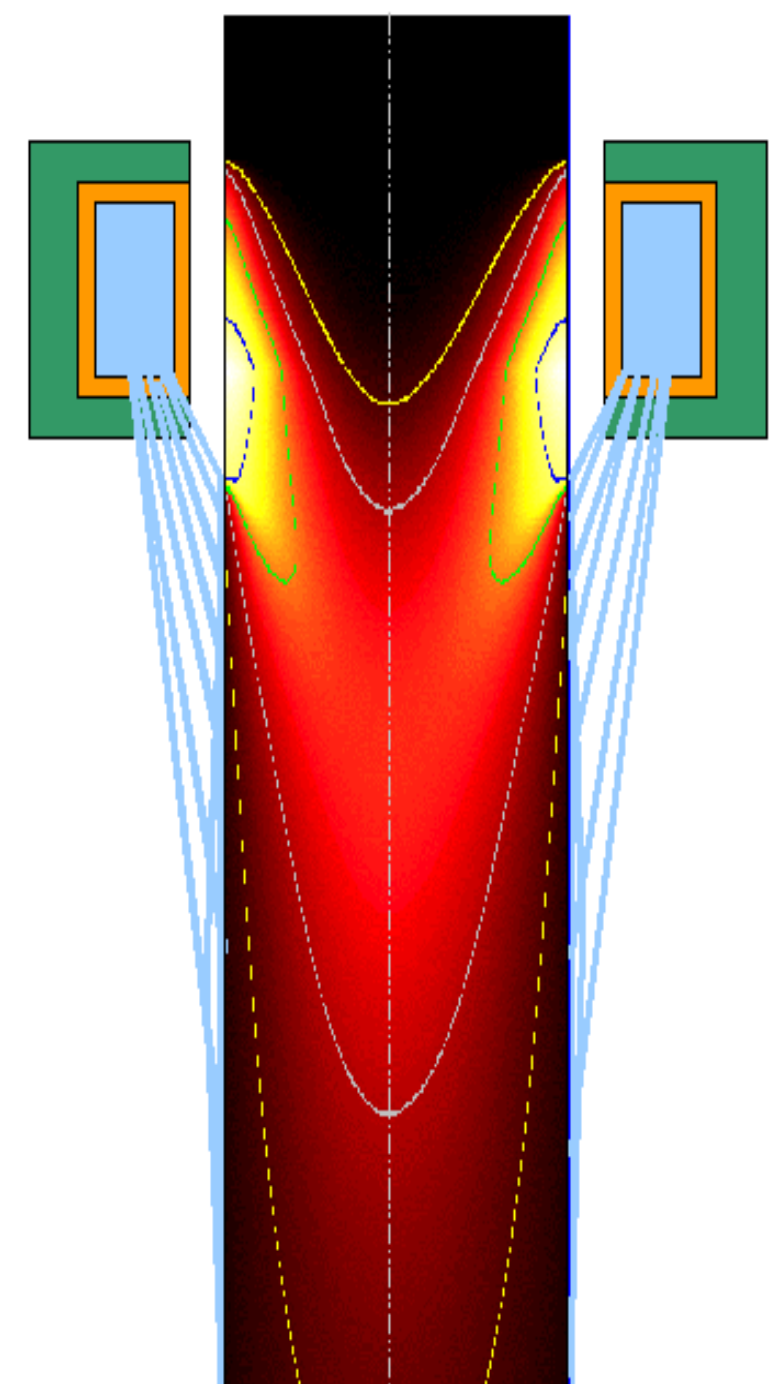
Guidelines:

- Use least complex software where possible; it can provide final solution in simple cases or reduce optimization area before using more complicated programs
- Analyze results to avoid mistakes in program input or setup
- There is no universal program that can solve all the problems of induction heating



ELTA Software Features

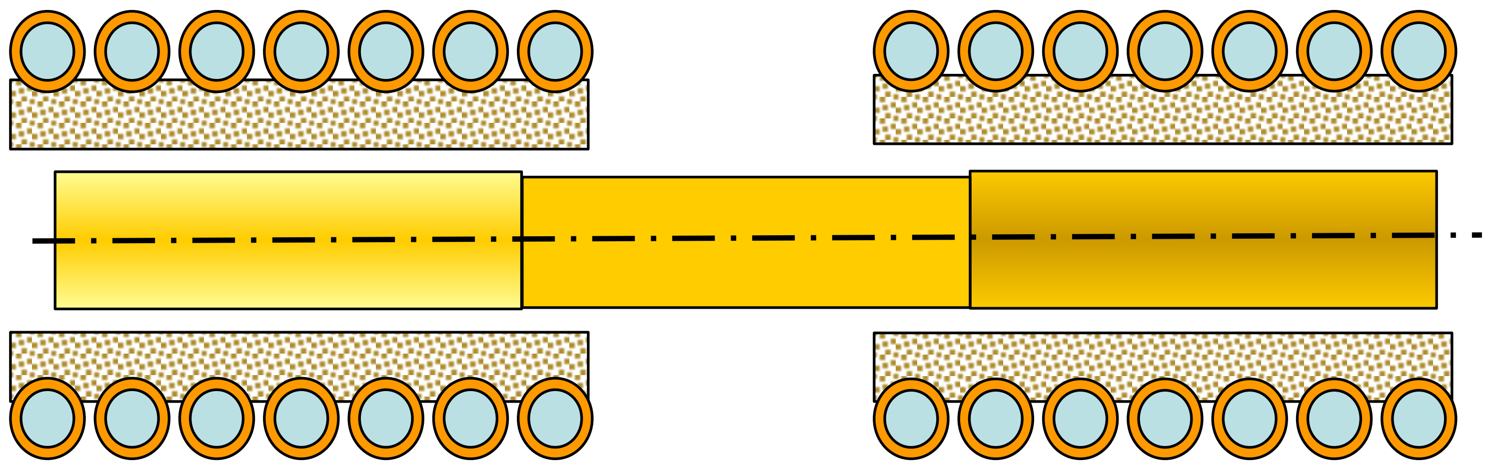
- User friendly interface with very fast solver
- Electromagnetic + Thermal
- Combines numerical 1D calculations with analytical account of the system length
- Axisymmetrical (OD & ID) & plane parallel geometries
- Module for simulating internal coils
- Possibility to simulate power supplying circuit (busswork, capacitors, transformer)
- Database with non-linear properties of materials
- Option of automatic frequency variation
- Automatic report generation according to selected or created template

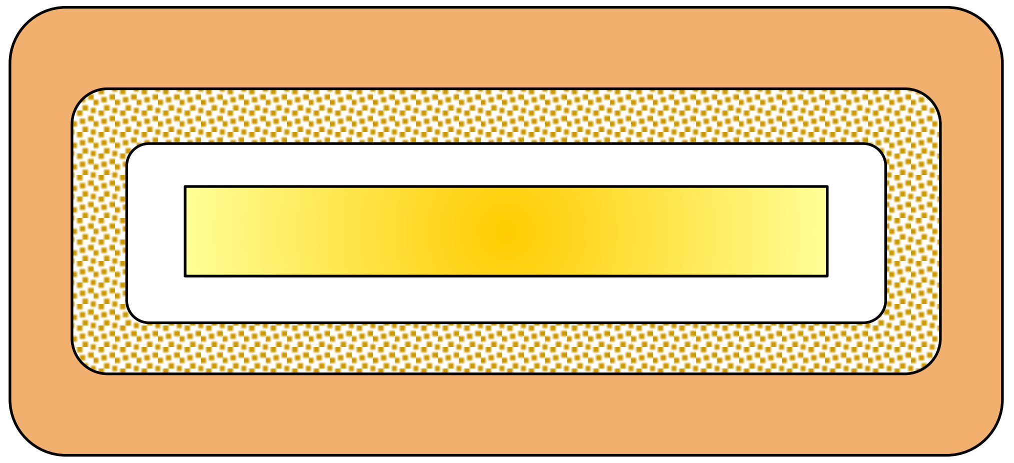


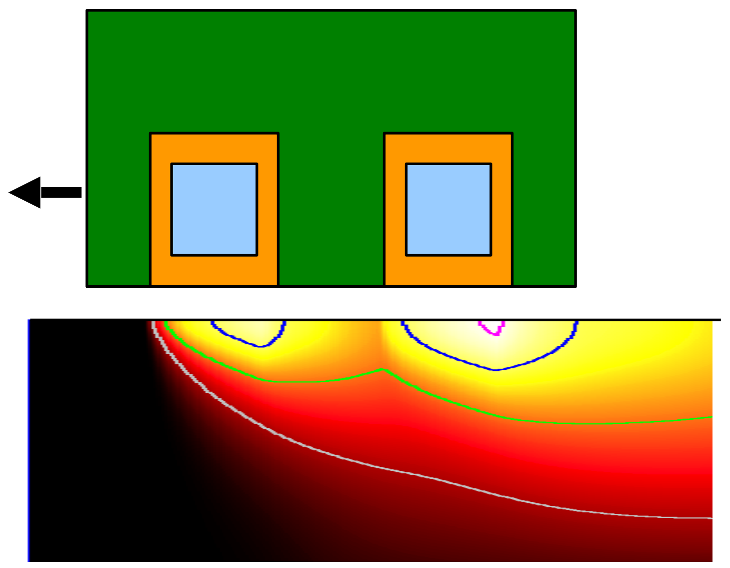
Scanning process simulation

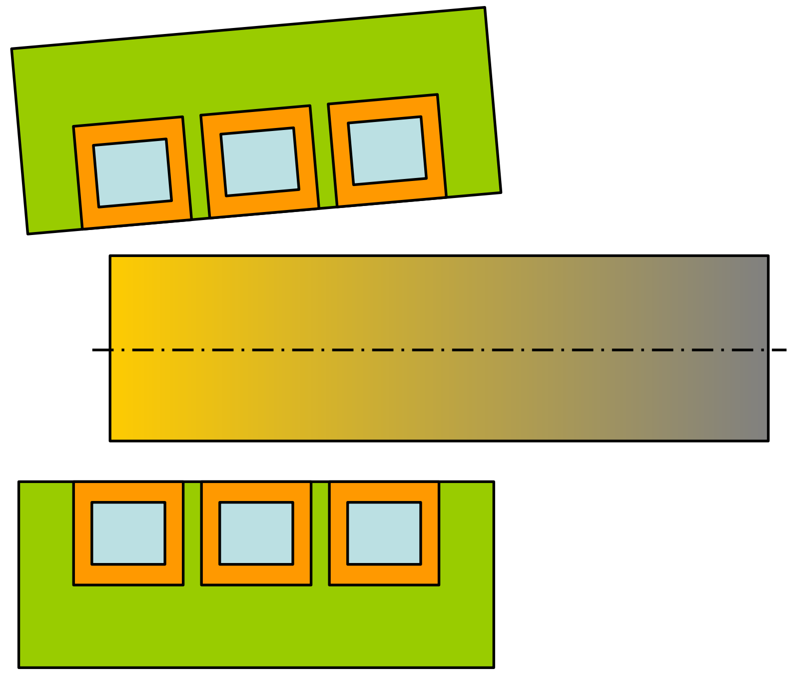
When to Use ELTA

- Valuable for almost all cases to determine optimal process parameters (P, f, t, Quenching) and coil style
- May be used for coil design
  - Determine number of turns for proper matching
  - Large (relative to part size), uniform heating areas
  - Scanning applications
- Very valuable for in-field support, new project evaluation and presentations
- Multi- stage and multi - inductor process simulation possible
- Valuable for learning and training

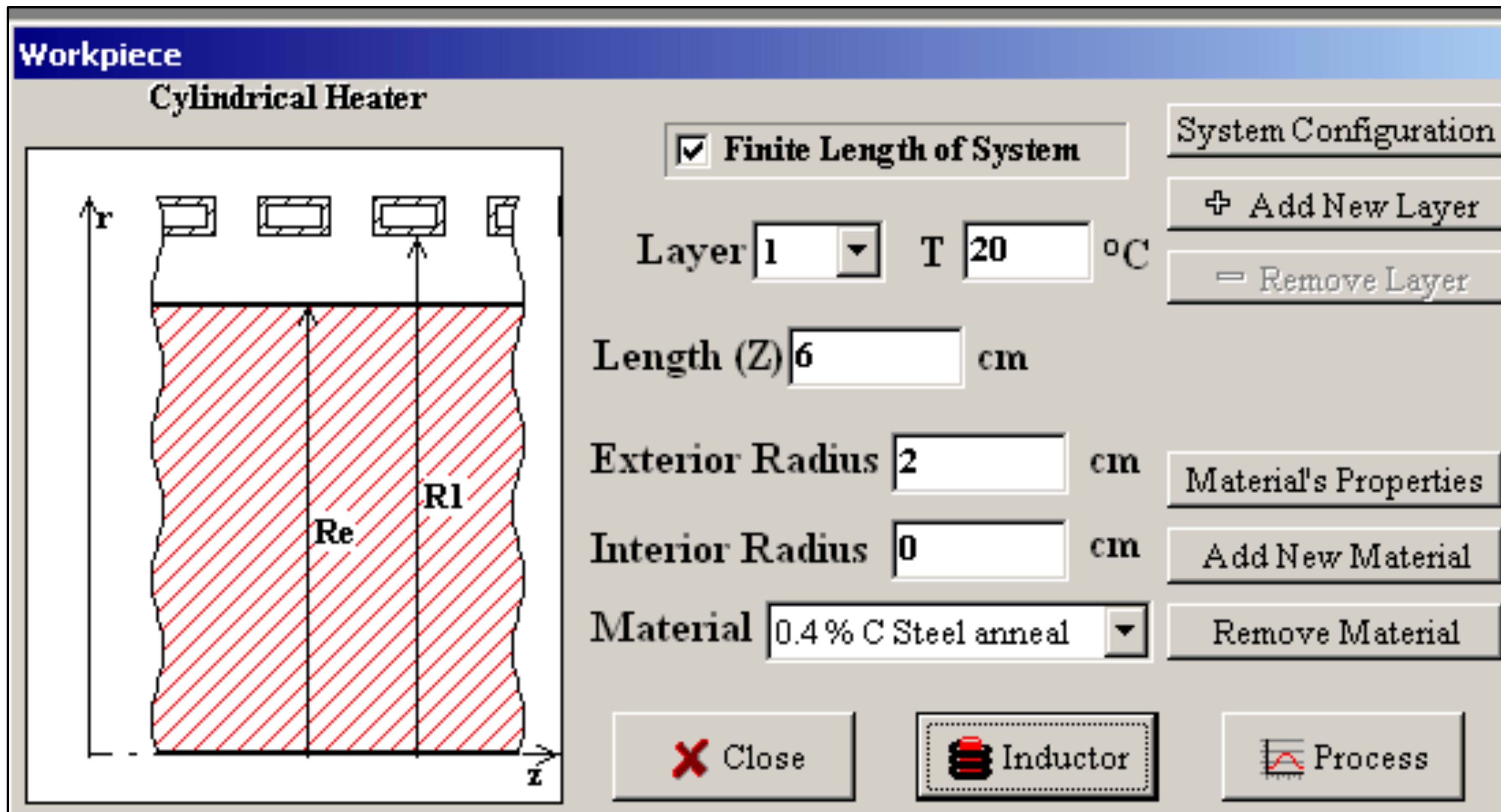






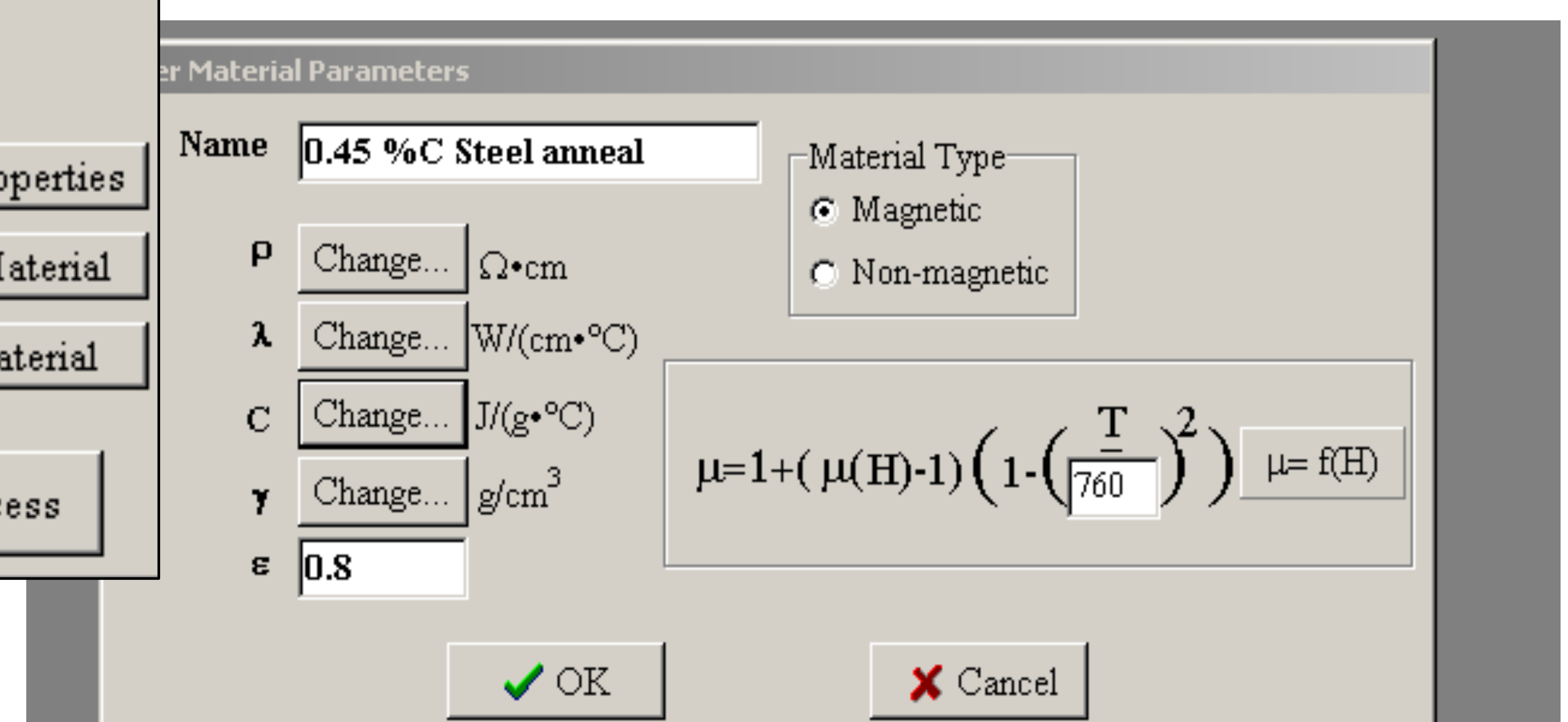


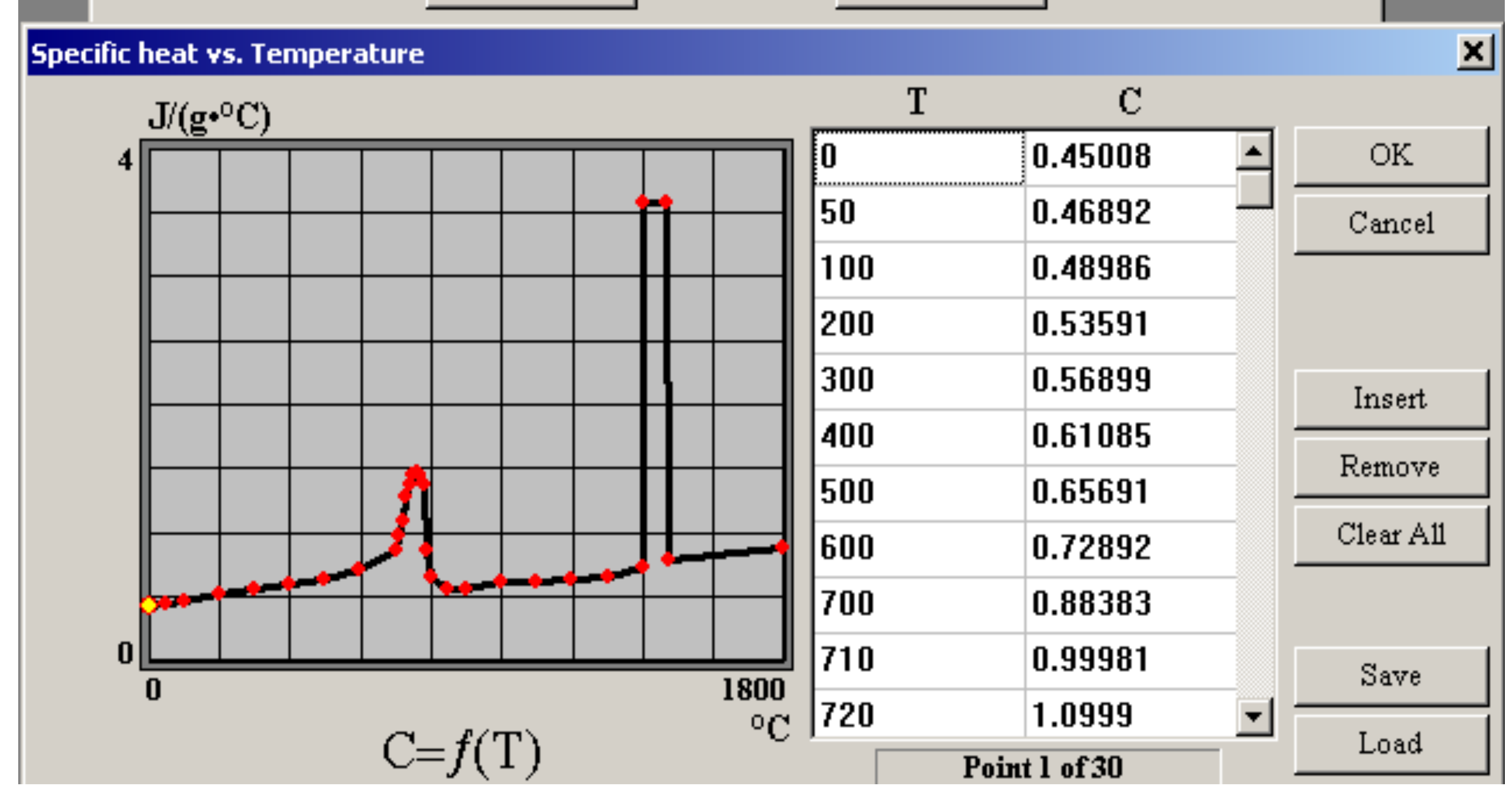
ELTA: Describing the Workpiece



Workpiece description screen

Material property database screen



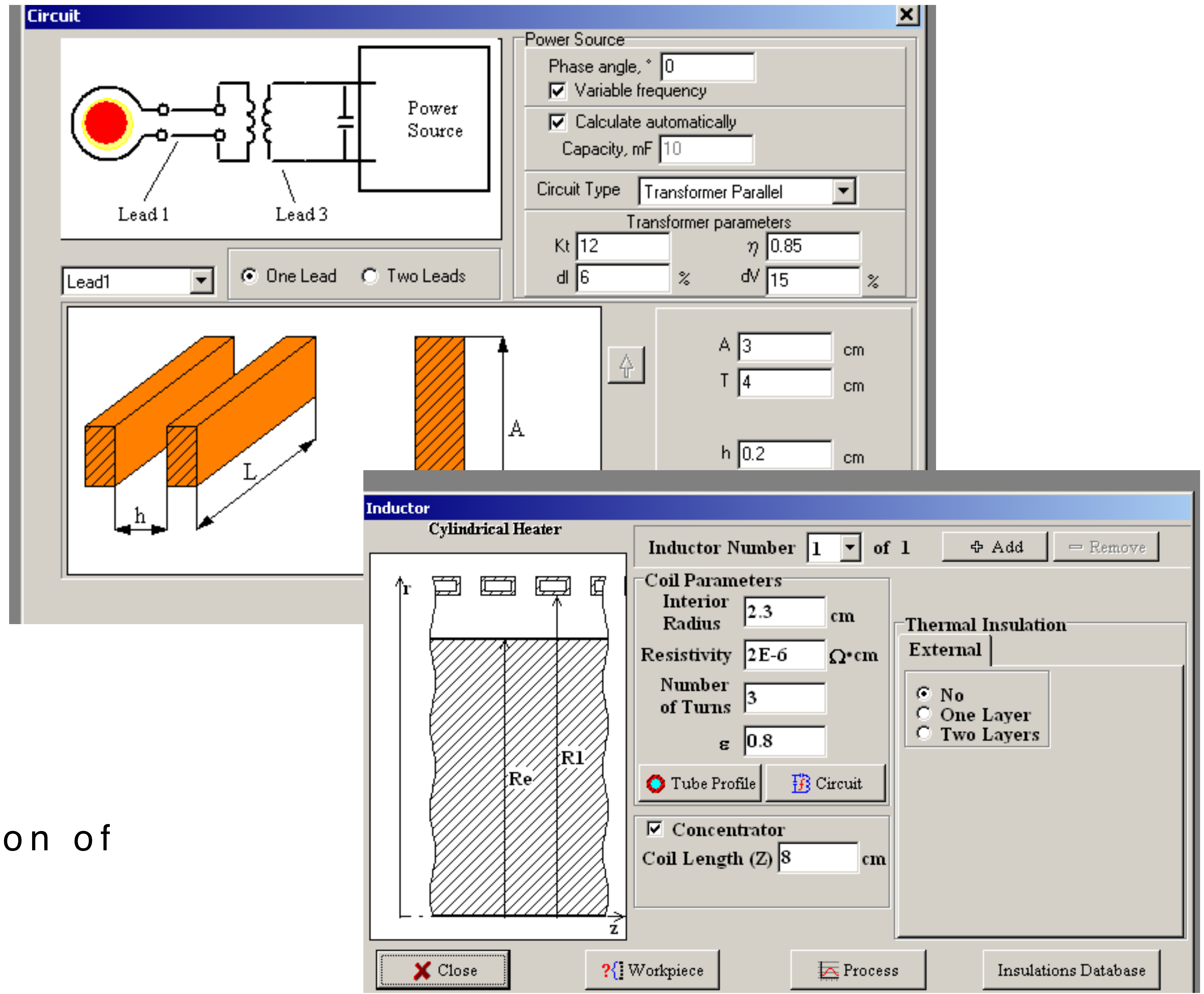


Specific heat vs. temperature for carbon steel

ELTA: Inductor and Tank Circuitry

Screen for description of **Tank Circuitry**

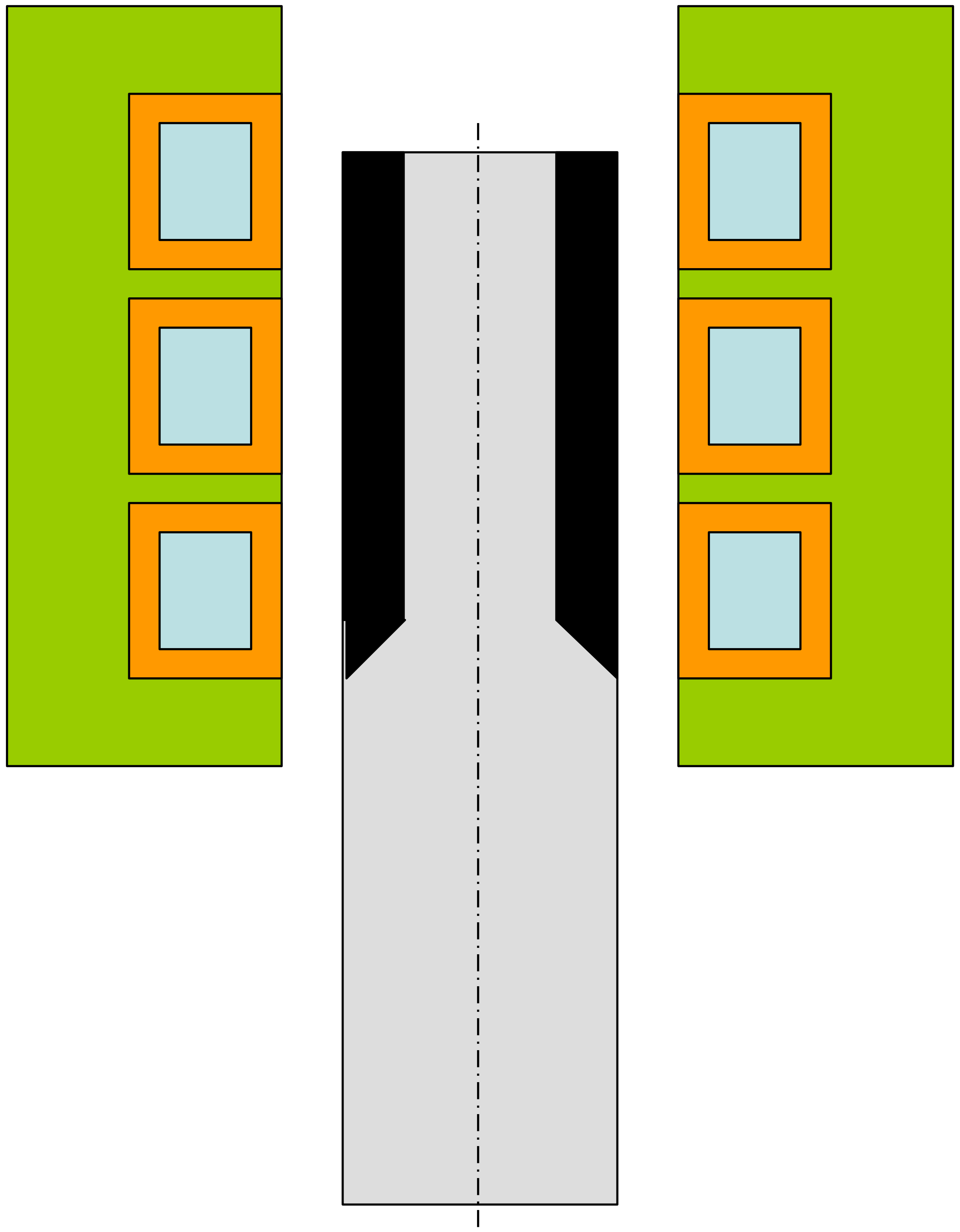
Screen for description of **Inductor**



Example: Design of In-Line Heat Treating Process

ELTA simulation program

- In-Line processes are more and more popular in industry
- Durations of all stages of in-line process (Austenization, Quenching, Tempering and Final Cooling) must be coordinated



Task: Hardening and tempering of the shaft end

- Diameter – 40 mm
- Length – 60 mm
- Case depth – 4 mm
- Steel 1040

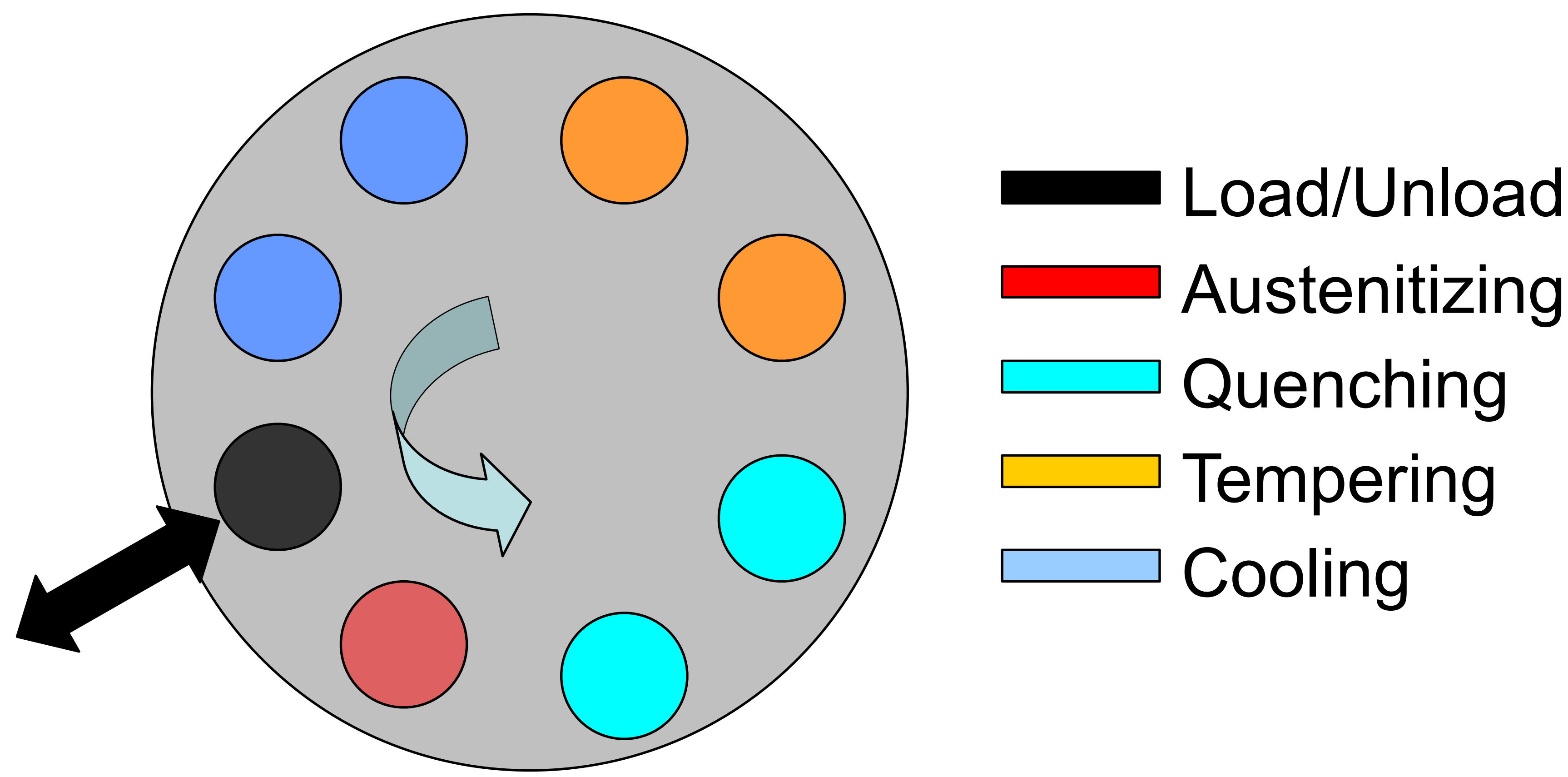
Design of In-Line Heat Treating Process (cont.)

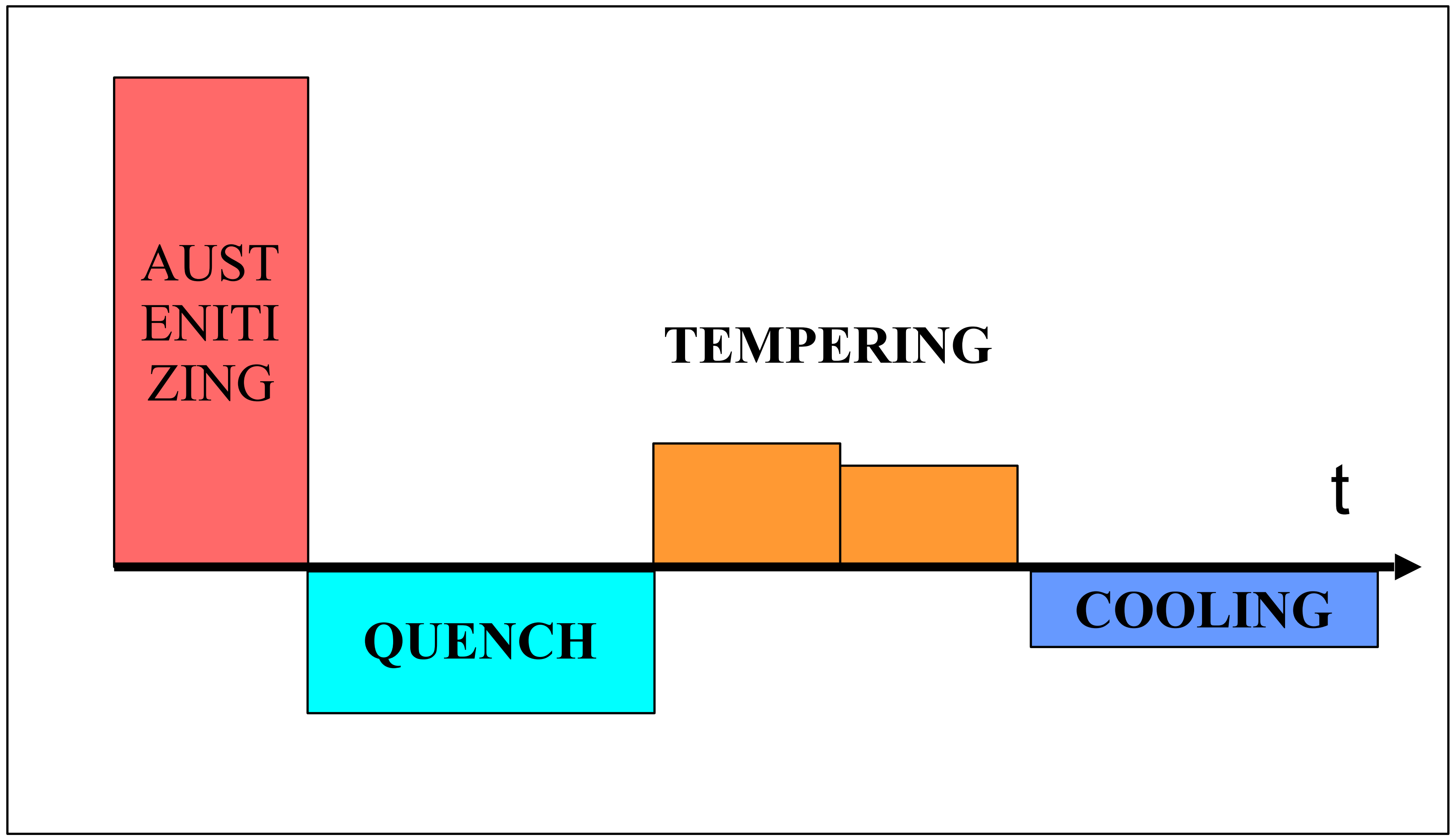
Simulation showed that minimum time for austenization heating is slightly under 4 sec. at optimal frequency 3kHz

This time was selected as a base for other stages:

- Austenization 4sec
- Quenching 8 sec
- Tempering 4 + 4 sec
- Final cooling 8 sec

Rotary table machine with 8 positions was selected for heat treating. Two positions were used for tempering





Design of In-Line Heat Treating Process (cont.)

Temperature evolution in optimized process:

Green – part surface

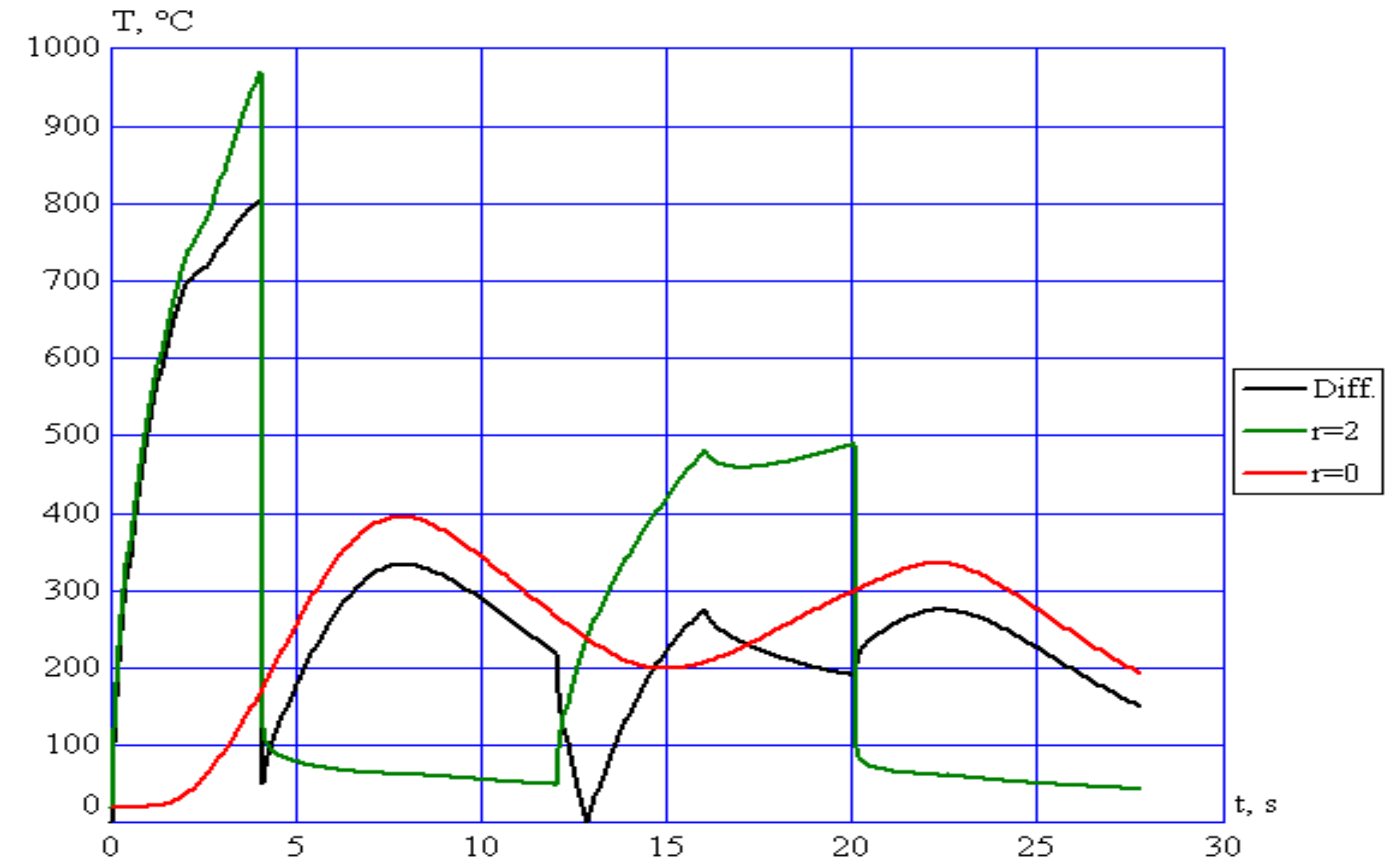
Red – center

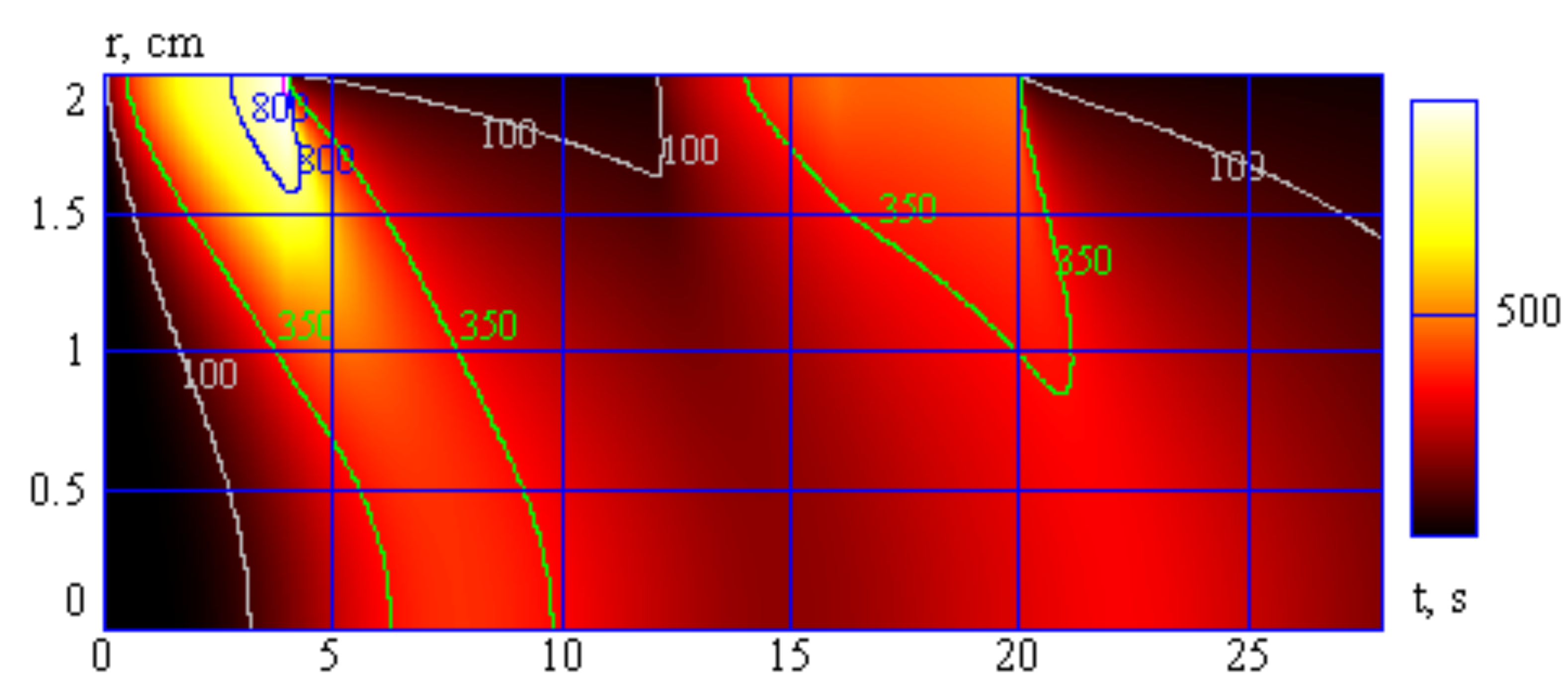
Black – temperature differential

Color Map of temperature distribution shows that at the end of the first stage a depth of austenitized layer (T> 800 C) is 4 mm as required.

After 8-second quenching, temperature at the depth of 4 mm dropped below 120 C, which is sufficient for complete martensite transformation, while temperature at the center remained around 300 C.

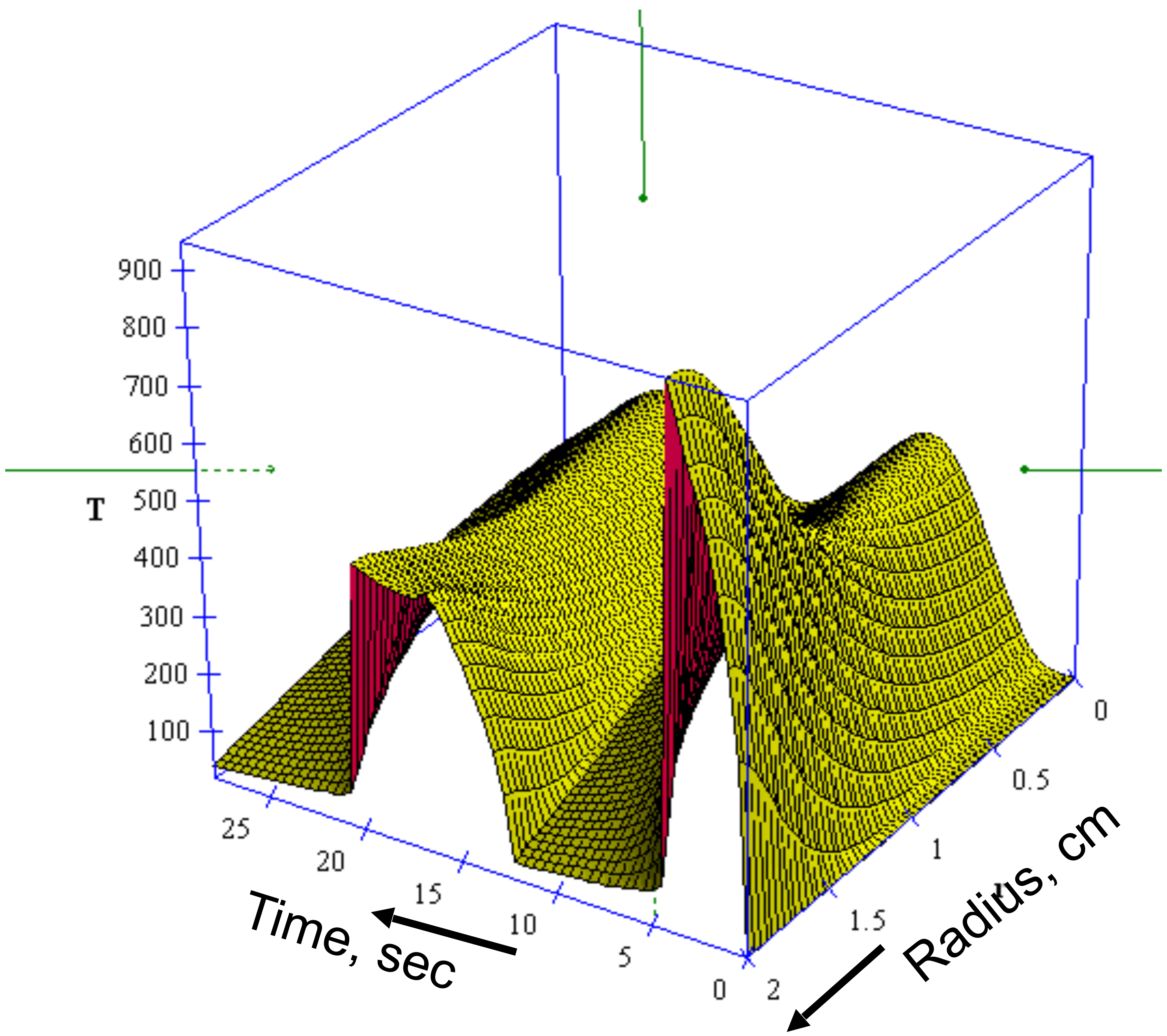
This residual temperature and two-stage heating for tempering provided very uniform temperature in hardened layer during tempering process.



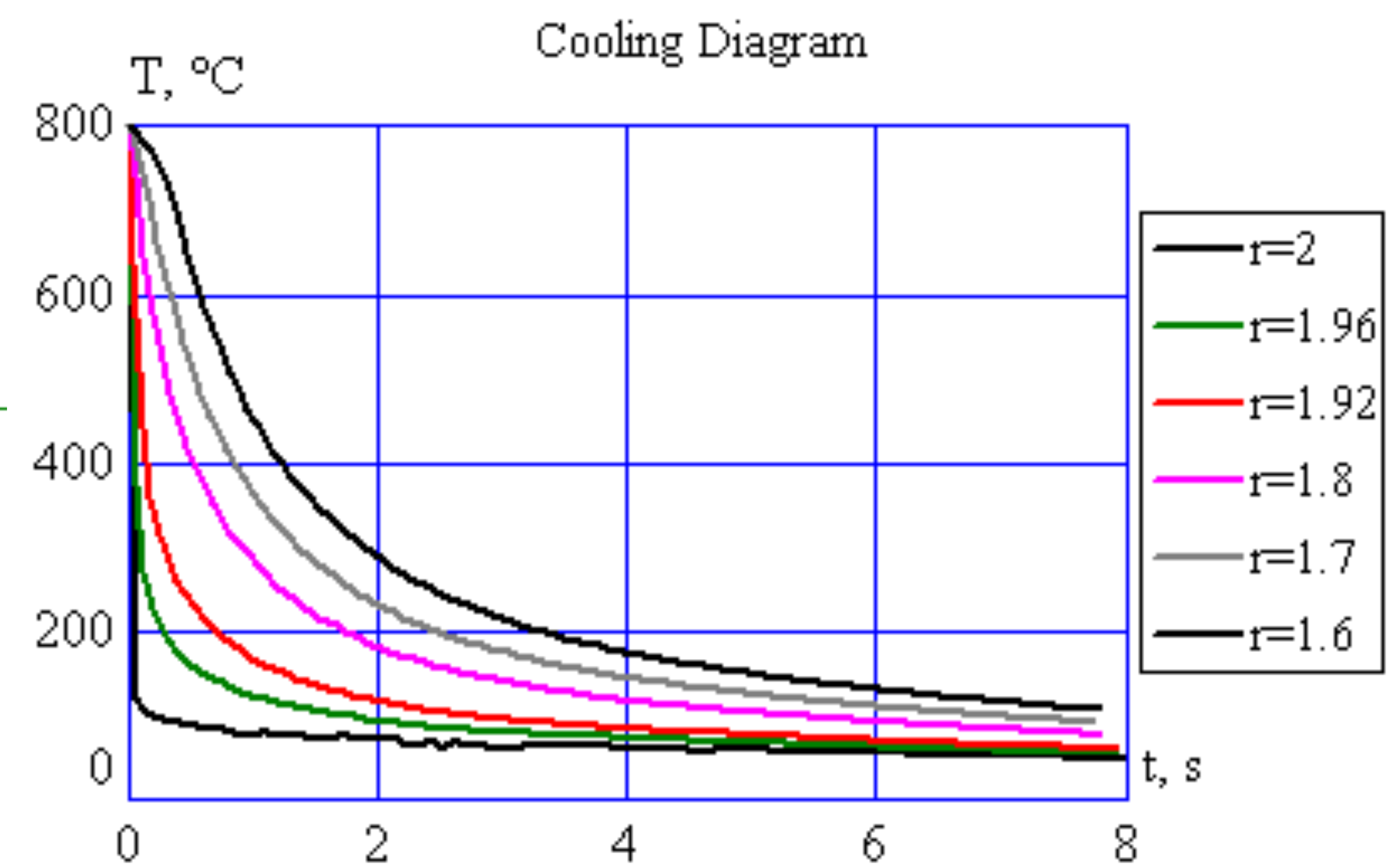


ELTA Software

Design of In-Line Heat Treating Process (cont.)



3D presentation of temperature evolution



Cooling curves for different radii

ELTA Software

Report Generated by ELTA

Version: 3.3

Date: 2/25/2006 3:27:50 PM

Project: Induction hardening

Project Information.
Quench hardening and tempering

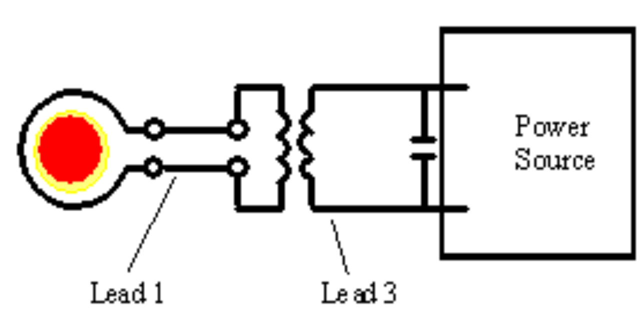
Input Data.

Workpiece:

Shape: "Cylinder". Length (Z): 6 cm, Finite system length.

Layers:
1. "0.4 % C Steel anneal", R_{int}= 0 cm, R_{ext}= 2 cm, T= 20 °C.

Inductor:



R: 2.3 cm.

Inductor length (Z): 8 cm.

Number of turns: 3.

Tube profile: rectangle
A= 2.2 cm; T= 1.6 cm; d= 0.4 cm.

Version: 3.3

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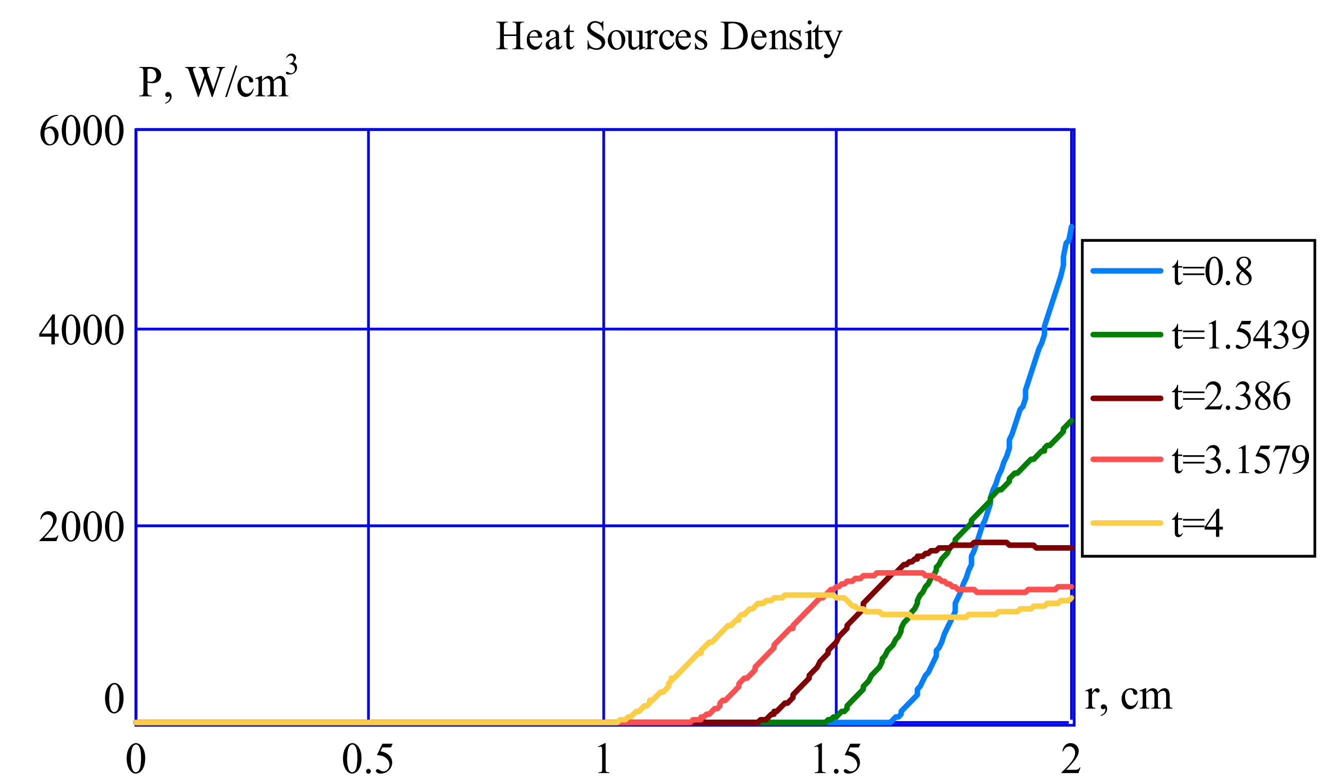
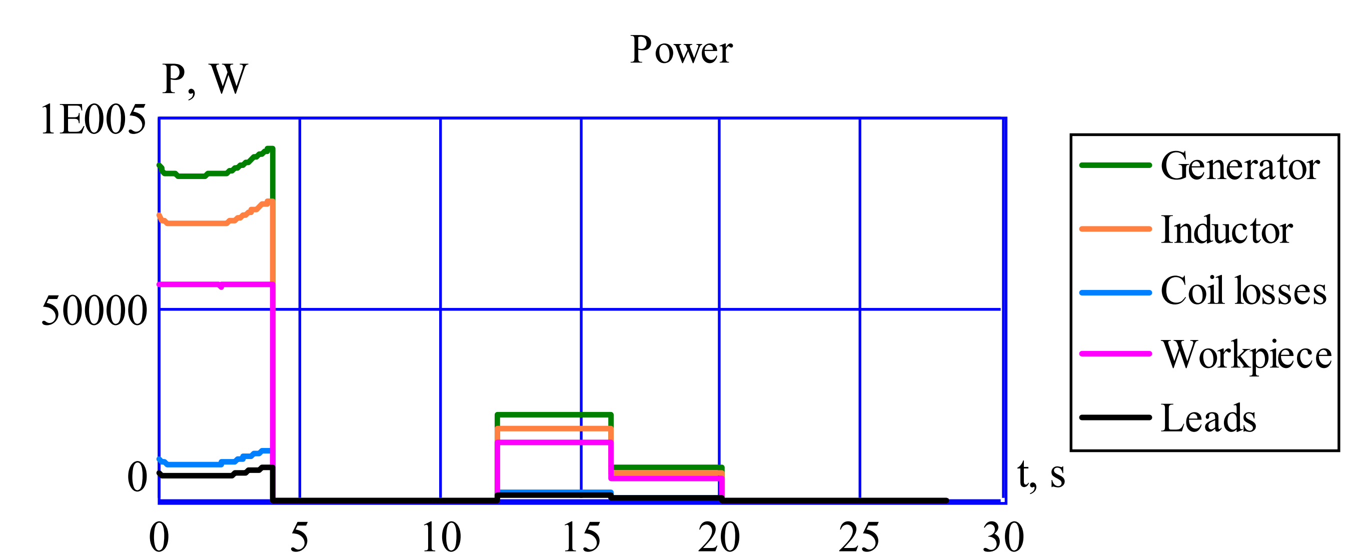
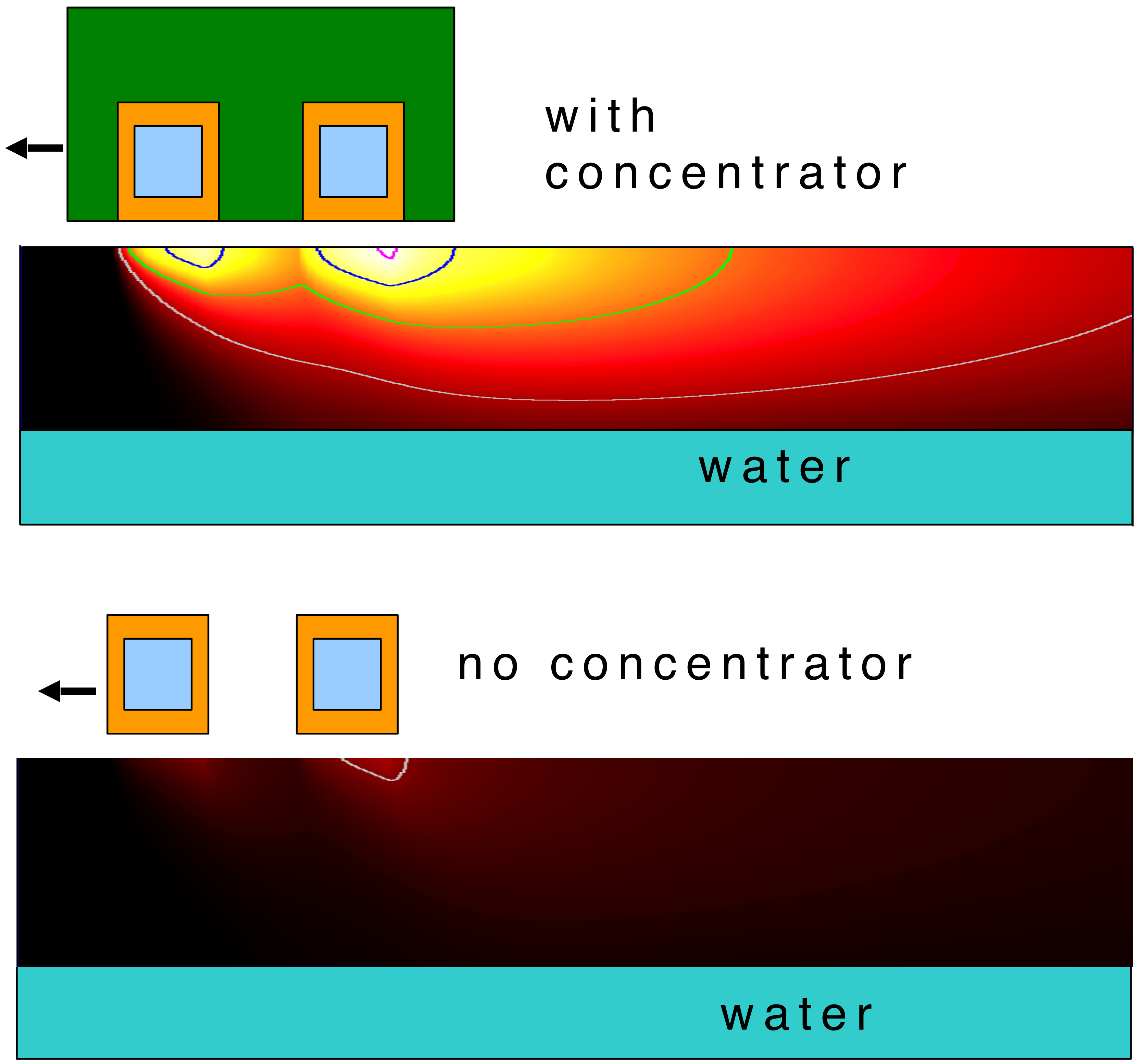
Project: Induction hardening



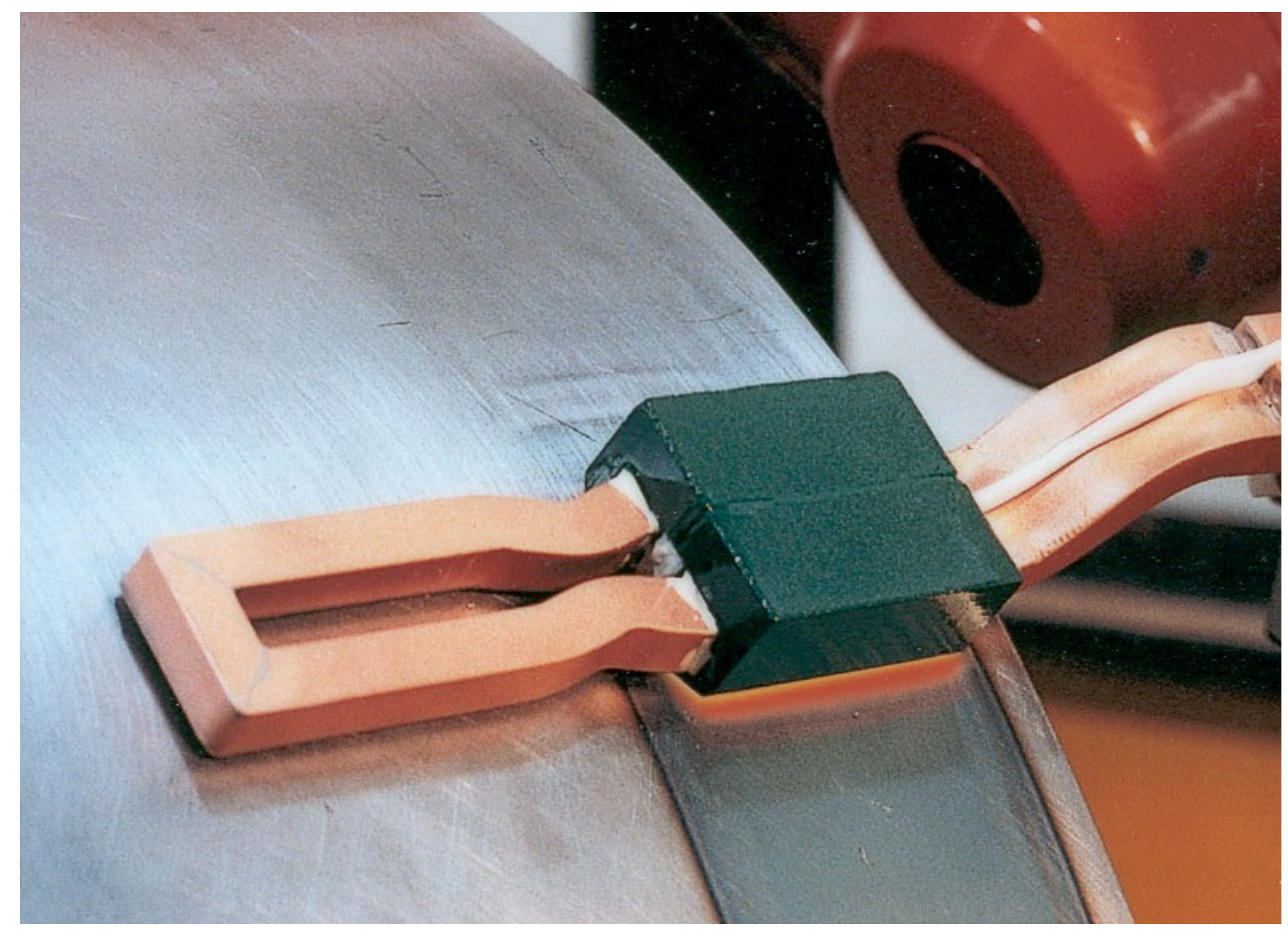
Heat source (power density) distribution in the workpiece



Scanning Simulation Using ELTA



Color map and isolines of temperature generated by the program

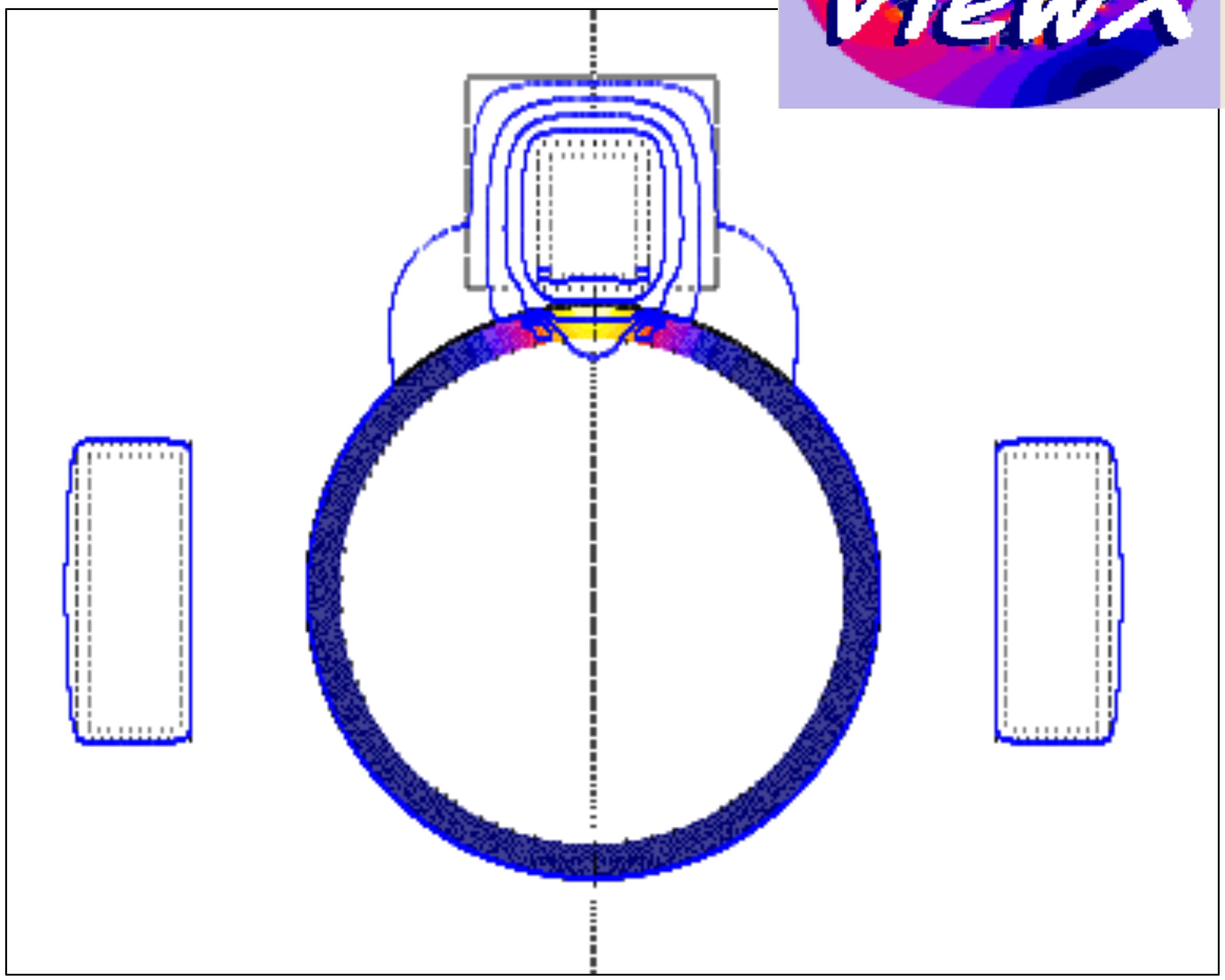


Scanning heating of water-cooled plate demonstrating effect of Fluxtrol Concentrator

See Robotic System video on next slide

Flux 2D Software

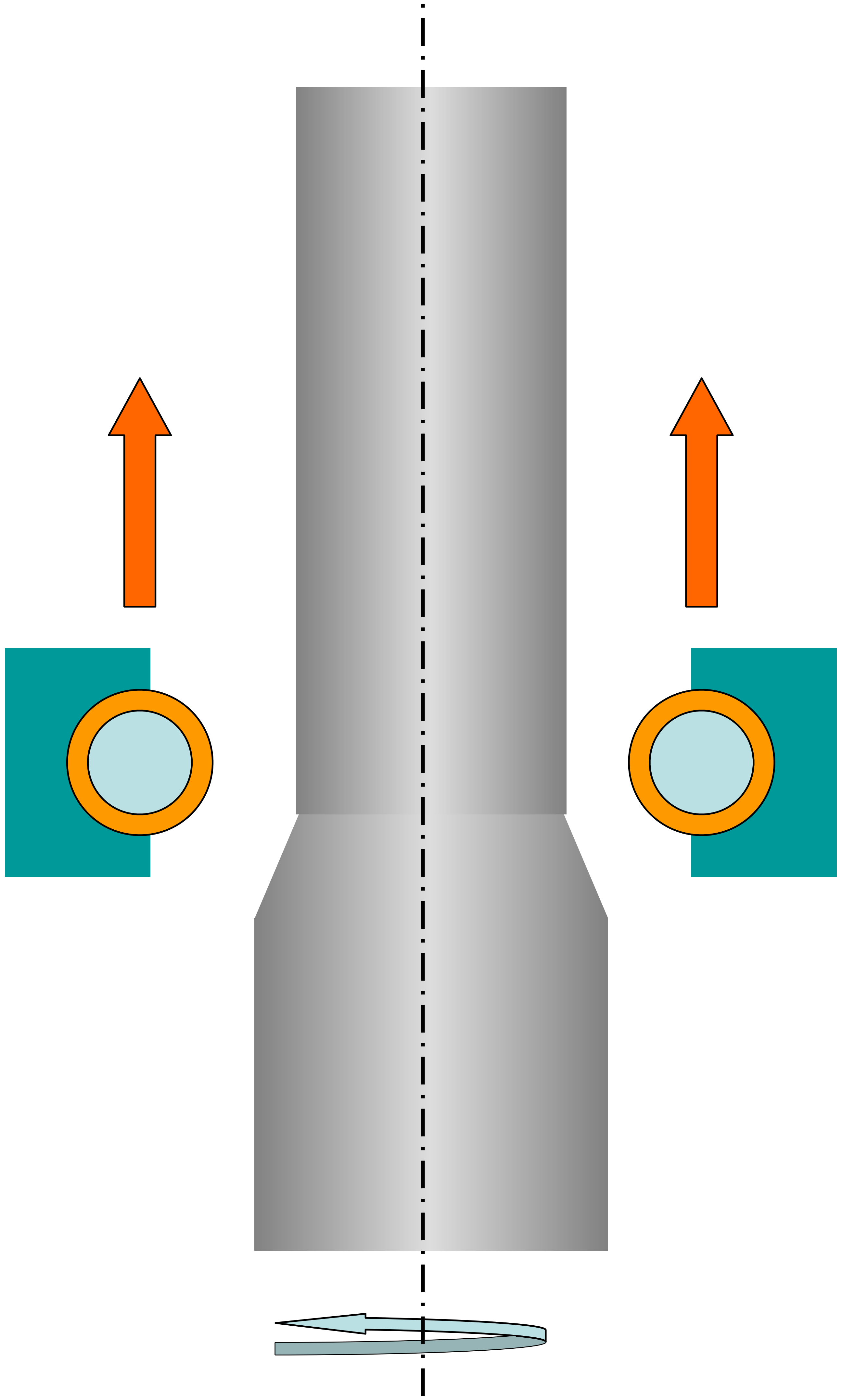
- Major software for precise analysis and optimization of induction coils with concentrators
- Electromagnetic + Thermal modules
- Material database with non-linear properties
- Scanning simulation possible
- Heating process animation available
- Can simulate external circuits
- Can work in conjunction with other software (AutoCAD, Mat Lab, Attila, etc.)



Temperature distribution and magnetic field lines of Split-n-Return coil in seam annealing application

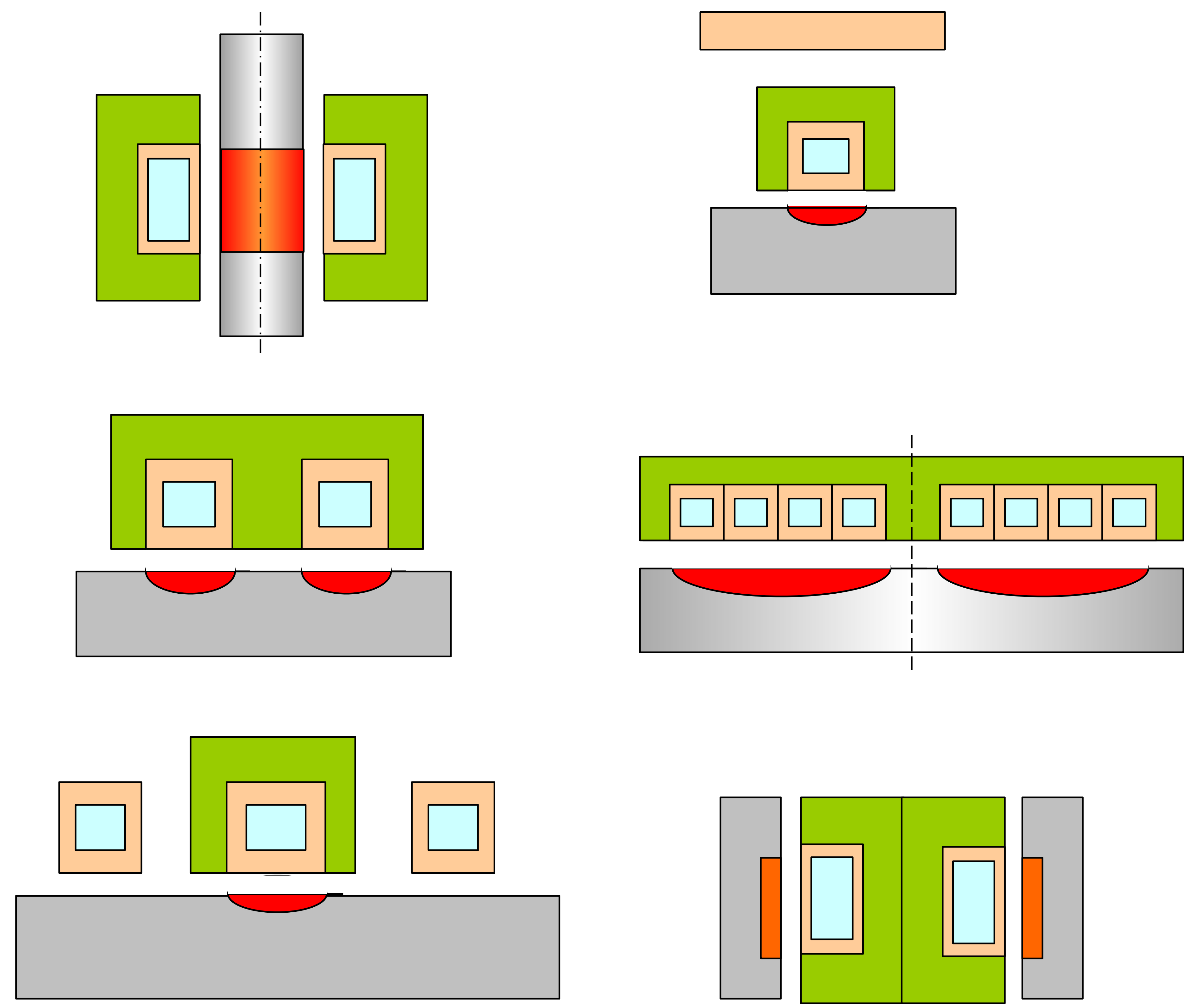
When to Use Flux 2-D Simulation

- Process and coil design
  - Part dimensions/heat pattern changes
  - Heat pattern is not uniform in length and the need exists to optimize distribution of temperature
  - Part & coil have rotational or planar symmetry (or partial symmetry)



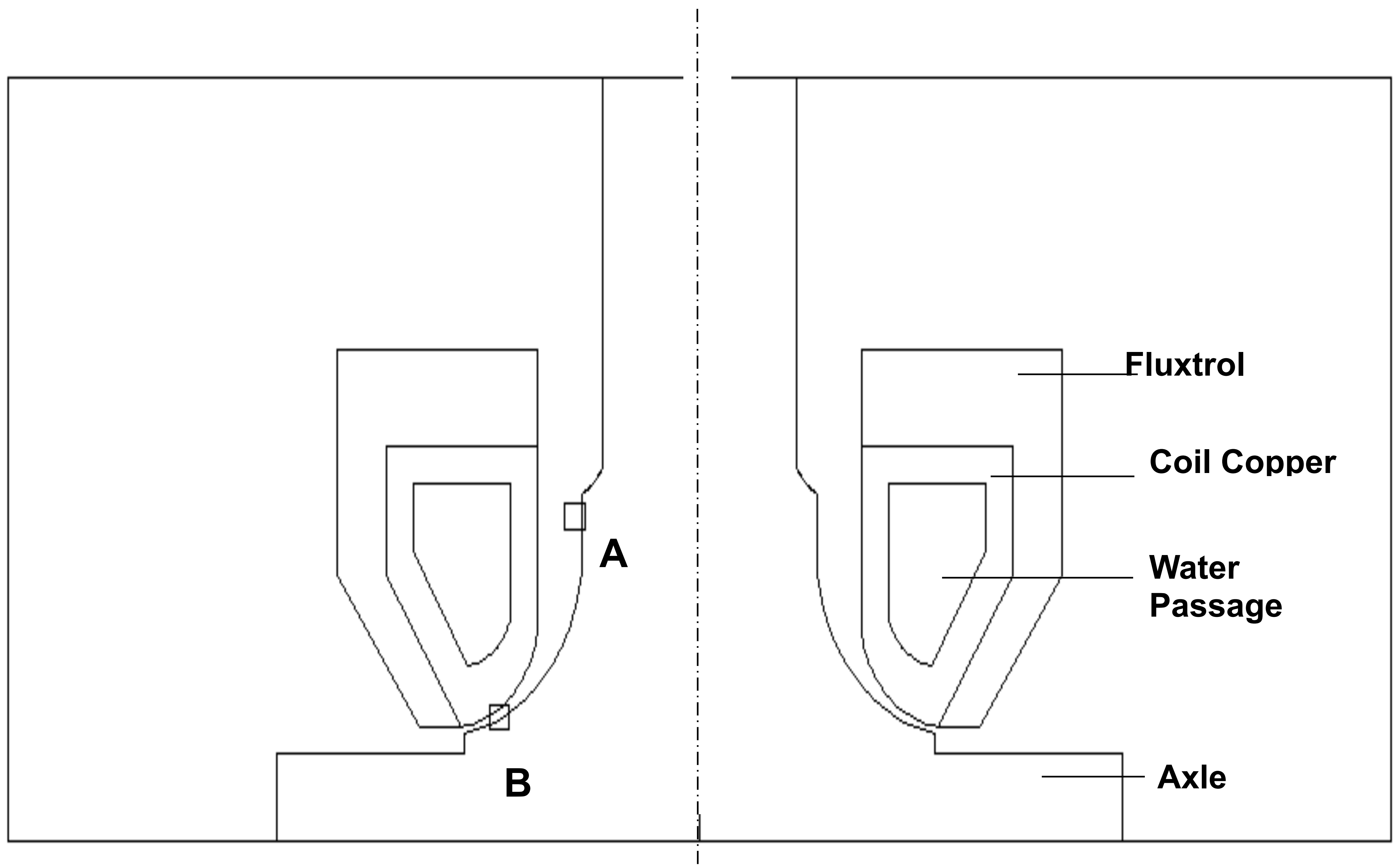
Coil Styles Favorable for Flux 2D Simulation

- Cylindrical Coils
- Vertical Loop Coils
- Hairpin Coils
- Cylindrical ID Coils
- Pancake Coils
- Split-n-Return Coils (partially)
- Channel Coils



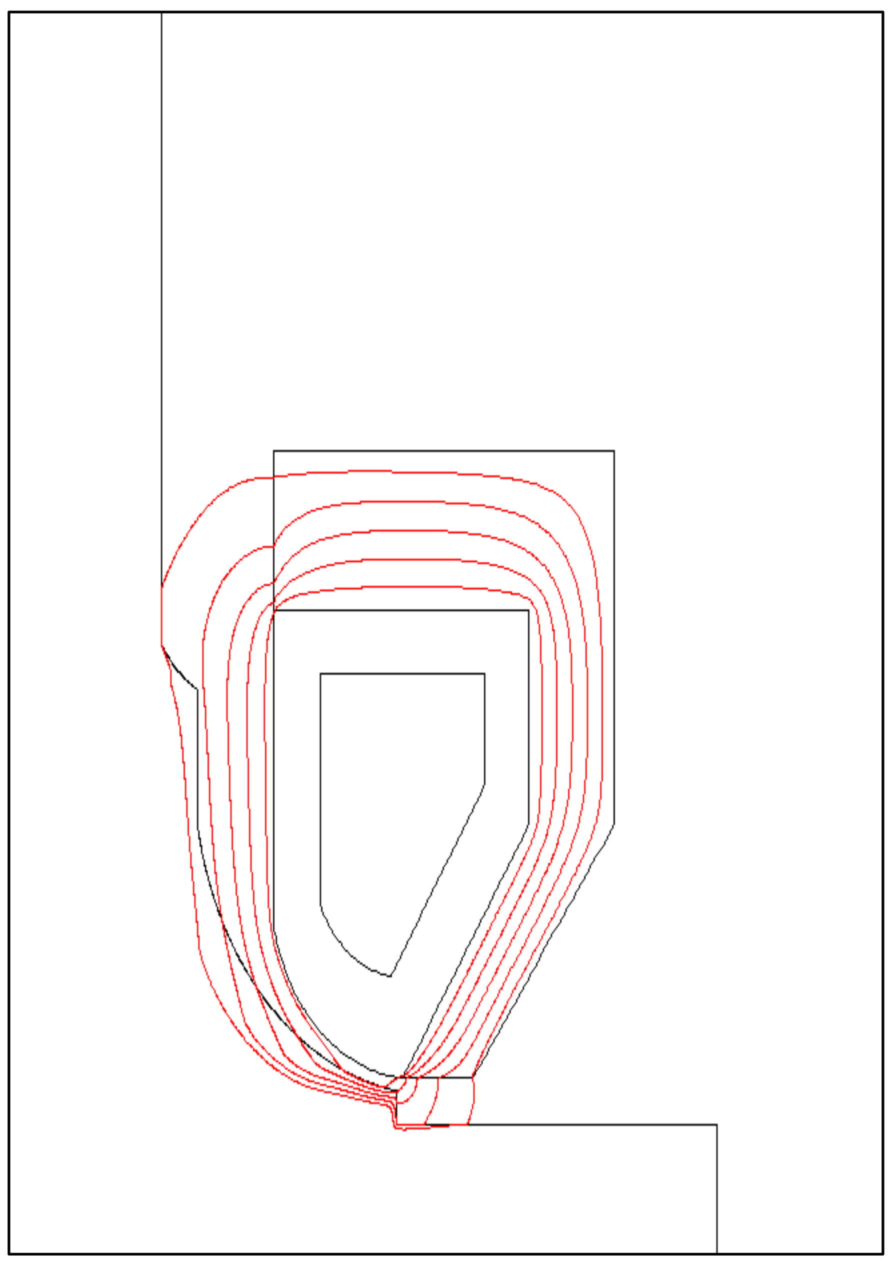
Ability to accurately simulate the system also strongly depends upon part geometry and motion mode (rotation, scanning etc.)

Axle Hardening Simulation with Flux 2D



Geometry of fillet area and induction coil

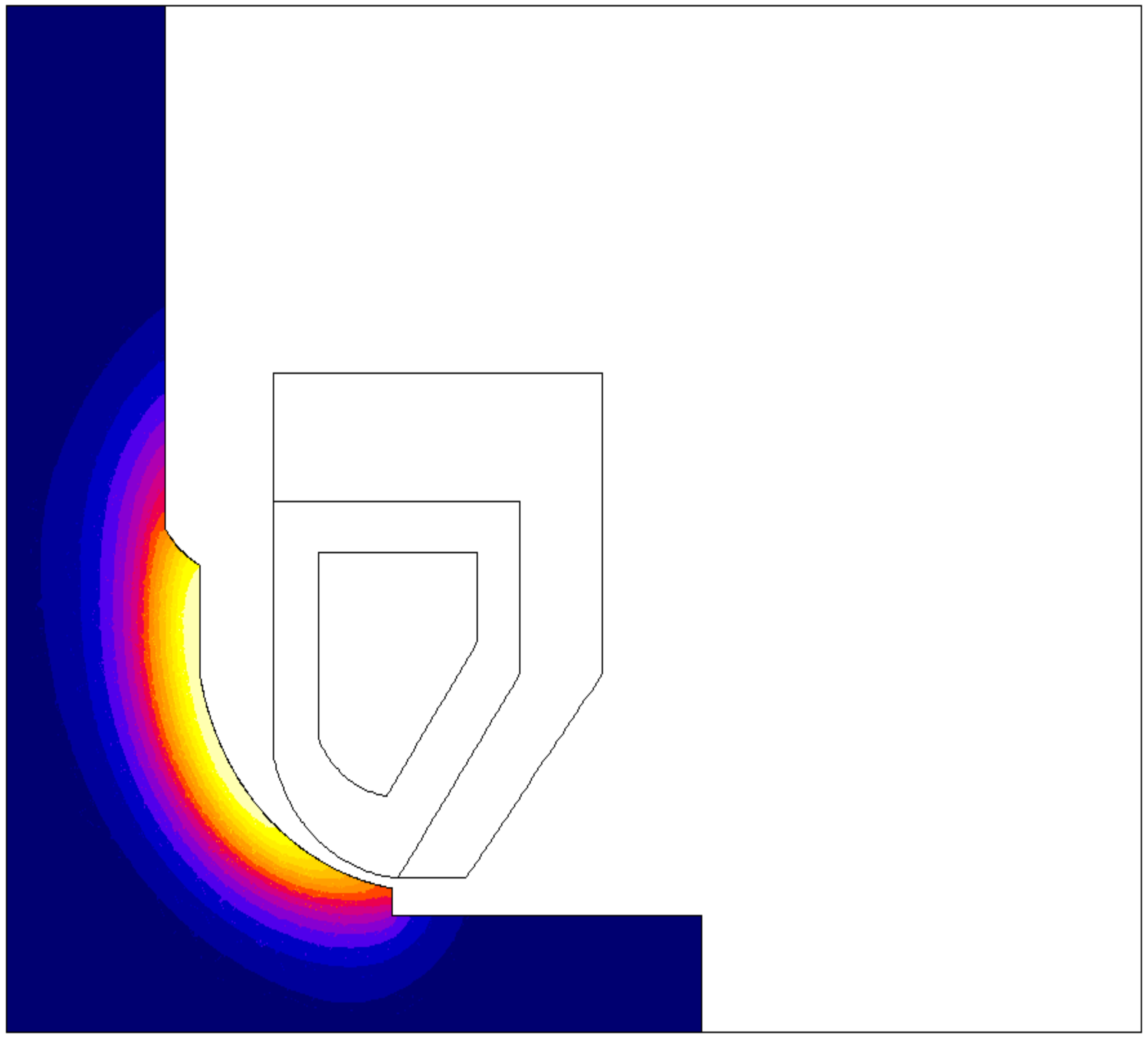
(Zone A – B must be hardened)



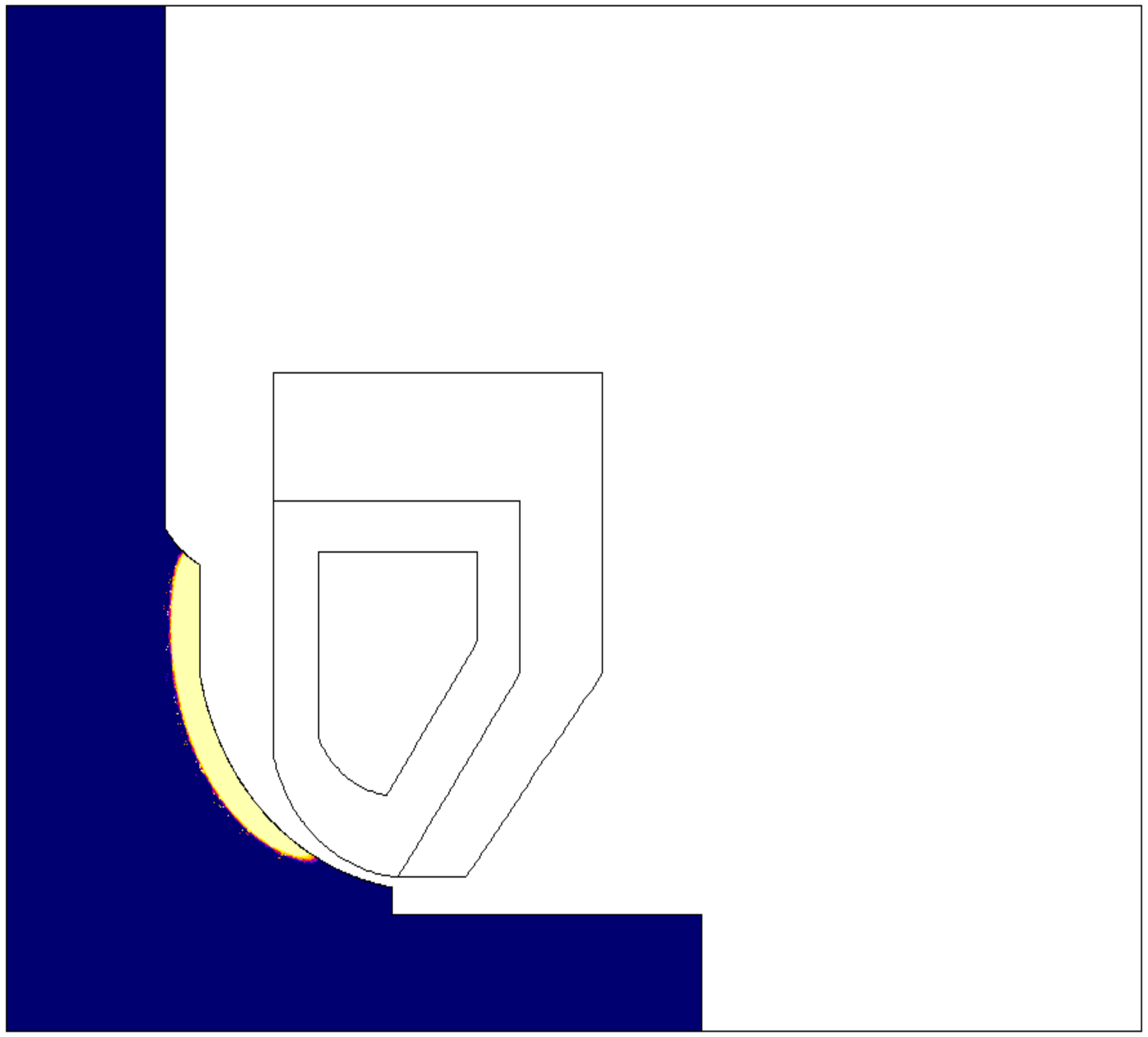
Magnetic field lines at 3kHz with Fluxtrol A concentrator

Temperature Profile and Austenitized Zone

Frequency 3 kHz



Final temperature distribution



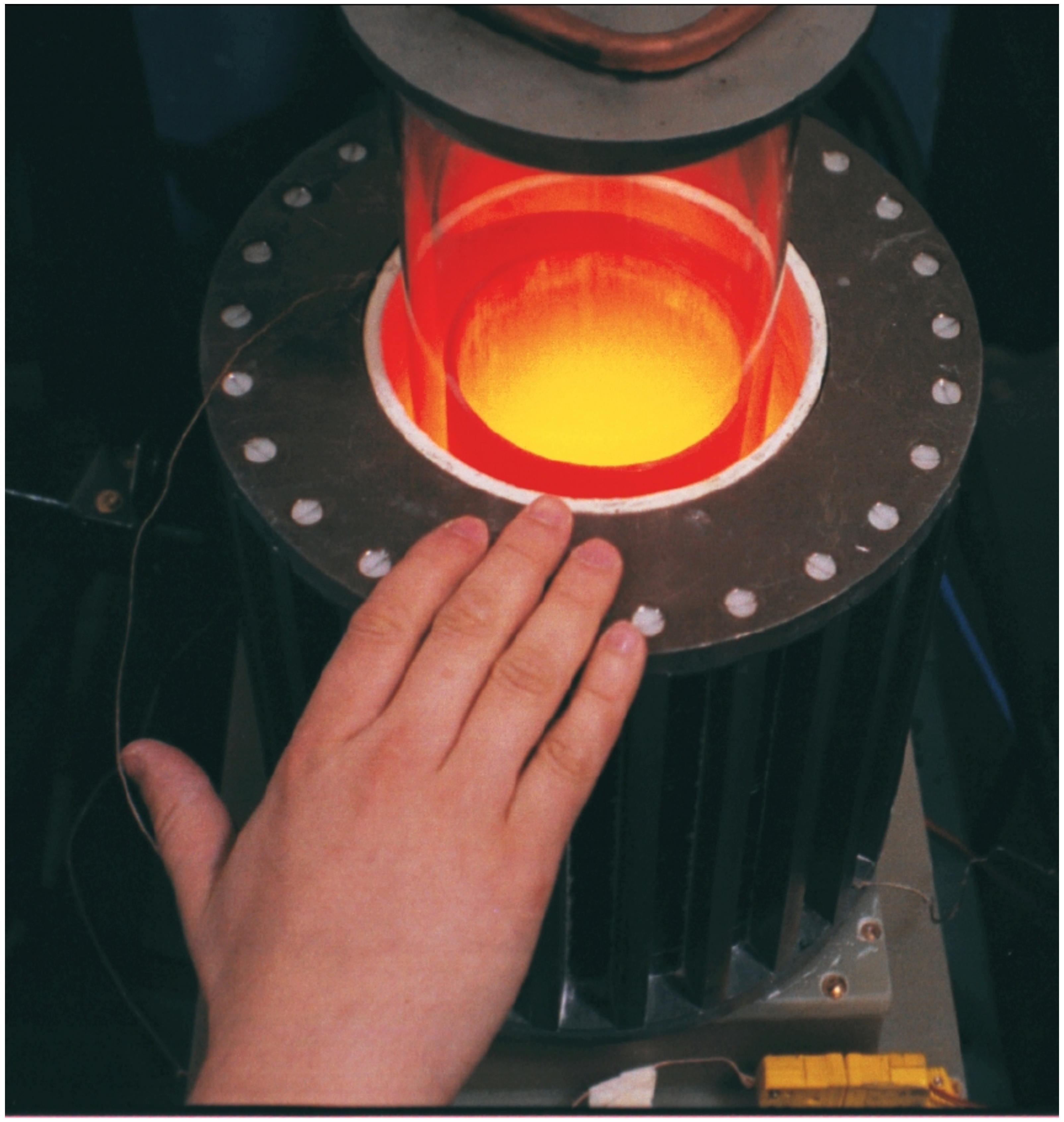
Austenitized layer, which will correspond to hardened zone after quenching

Example of Melting Furnace Designed with FLUX 2D Computer Simulation

Dry (air-cooled) induction furnace for special material melting.

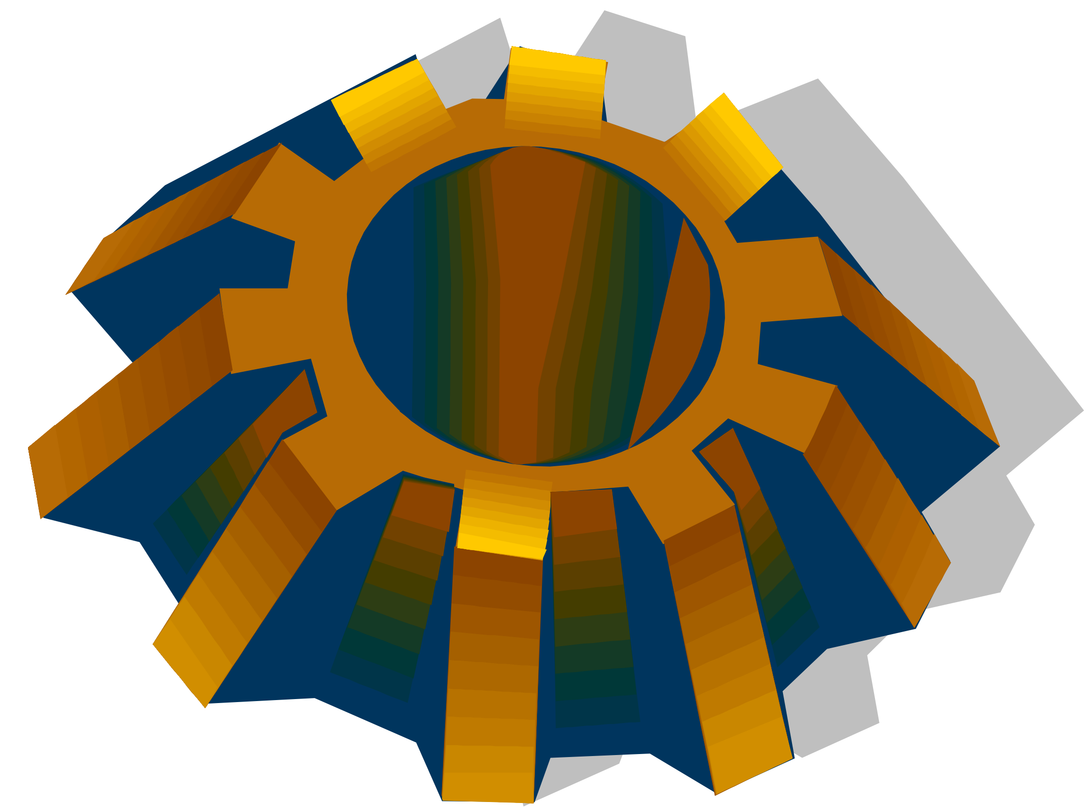
Coil is made of Litz cable and potted. Fluxtrol Concentrator plates are used to decrease current demand and improve efficiency.

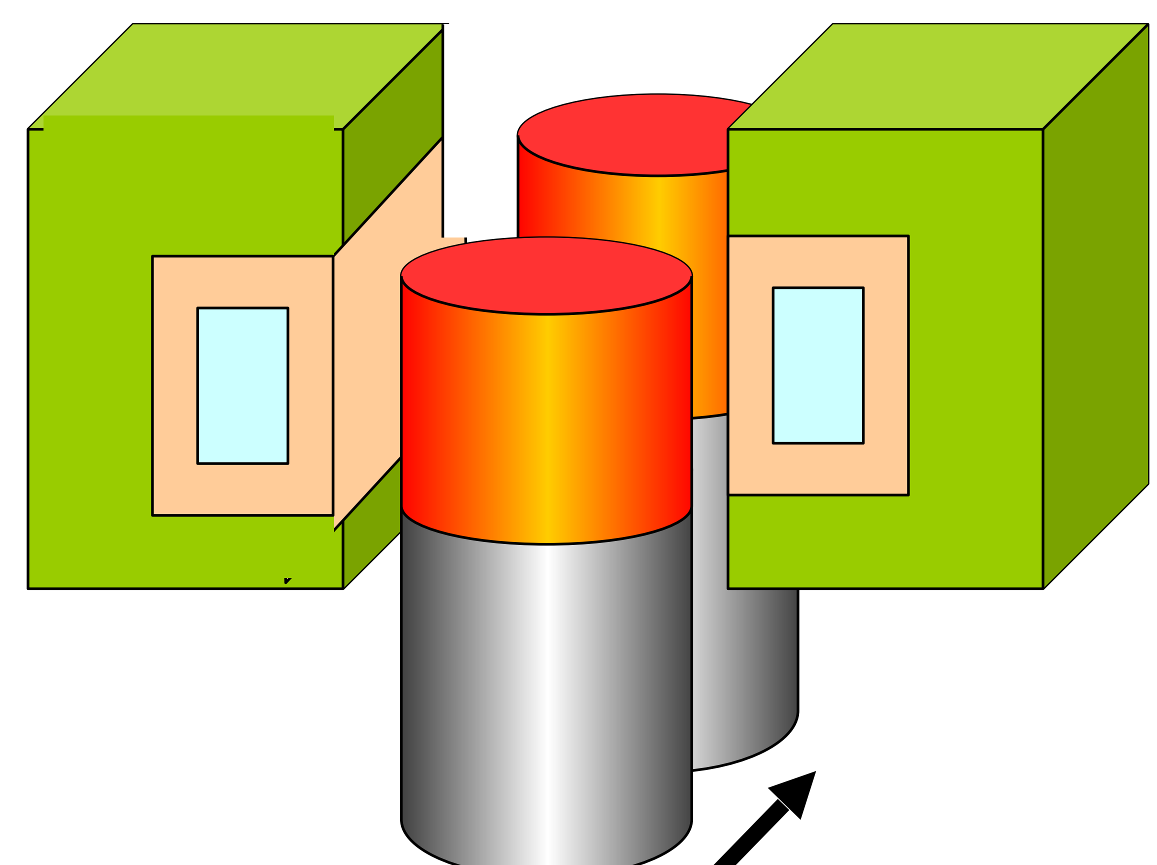
They are used also as radiators for heat transfer from the coil to inert gas in the chamber.



When to Use Flux 3-D Simulation

- When good information and results cannot be achieved using 2-D with reasonable approximations
- Evaluate 3-D effects for some systems where 2D is used with some assumptions (lead area in cylindrical coils, cross-over parts of single-short coils etc.)
- Understand some uncertain effects from experiments
- Simulation of strongly 3D systems/ processes such as gear hardening, welding, some brazing systems etc.



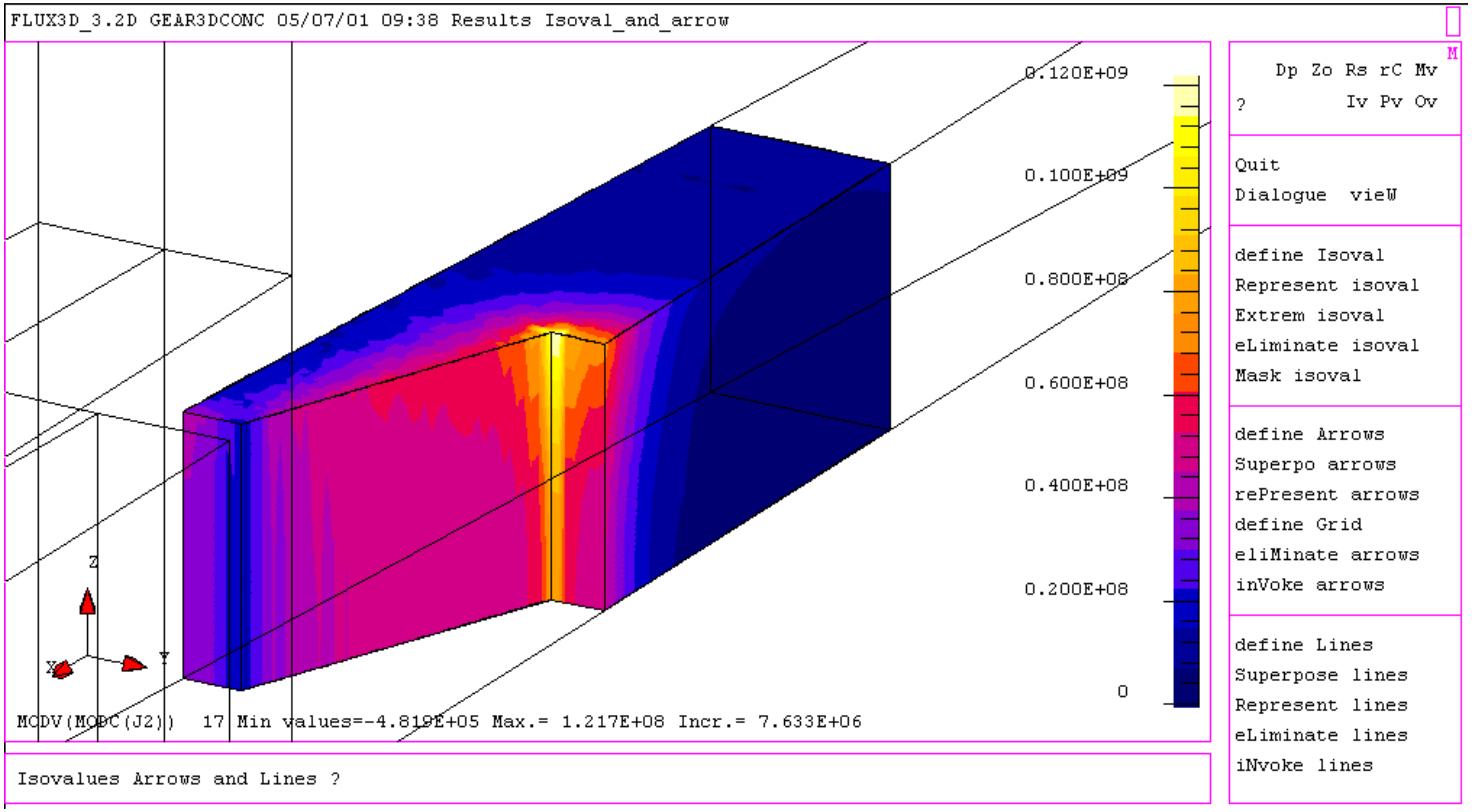


3D system composed from 2D coil and 2D parts

Flux 3D Software Features

- May be Electromagnetic, Thermal or Coupled
- Material database with non-linear properties is available
- Usage Considerations
  - More complicated and less user friendly than Flux 2D
  - Requires powerful computers for reasonable calculation times
  - Time and knowledge consuming for problem formulation, geometry description and calculation process setup (mesh building etc.)

Gear Heating Simulation Using Flux 3D

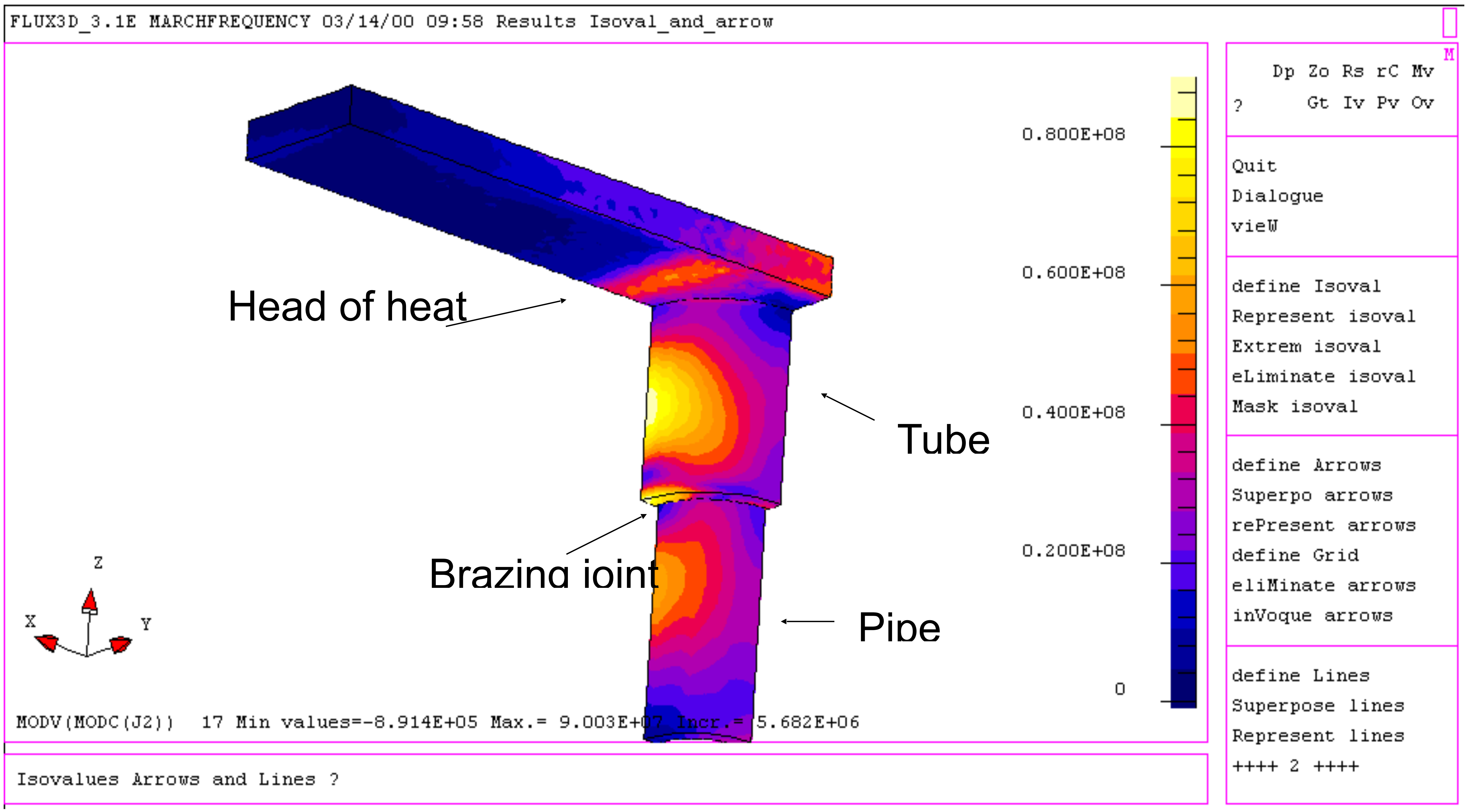


Eddy current density distribution in a quarter of a gear tooth

Frequency 50 kHz, concentrator - Ferrotron 559H; gear modulus is 5 mm.

Maximum current density is in root area near the tooth end.

Pipe-to-Tube Brazing Simulation



Color map of optimal power density distribution between the components of aluminum heat exchanger (see more details in Case Stories)

Accuracy of 2D and 3D Computer Simulation

Simulation accuracy depends upon:

1. Accuracy of system geometry description
2. Accuracy of description of material properties and processing parameters such as quenching intensity
3. Problem formulation; there are several options how to describe the electromagnetic field in 3D systems
4. Number, distribution and type of elements of simulation mesh
5. Algorithms used in the program and software quality

Position 1 is the most important for 2D simulation, when the user needs to neglect 3D effects of real induction systems (such as lead area in a cylindrical coil, "spirality" of multi-turn coils etc.).

Calculation errors may be reduced to negligible values by means of proper selection of mesh and calculation process parameters.

Accuracy of simulation also depends on experience and knowledge of the user especially in 3D simulation cases.

Conclusions

- At present time personal computers are powerful enough for simulation of most induction heating problems
- 1D and 2D simulation are well established in induction industry
- 3D simulation is an emerging technology
- Computer simulation is a powerful tool for:
  - Induction process and equipment design
  - Optimal design of induction coils
  - Research and development
  - Development of databases of processes, projects and coil designs
  - Troubleshooting
  - Advertisements and business presentations
  - Training, education and self-education

New advances in computers, software and data bases of material properties will lead to wider and more effective use of computer simulation in induction heating !

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