Fast Whole-Engine Stirling Analysis

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Thermal Energy Conversion Branch

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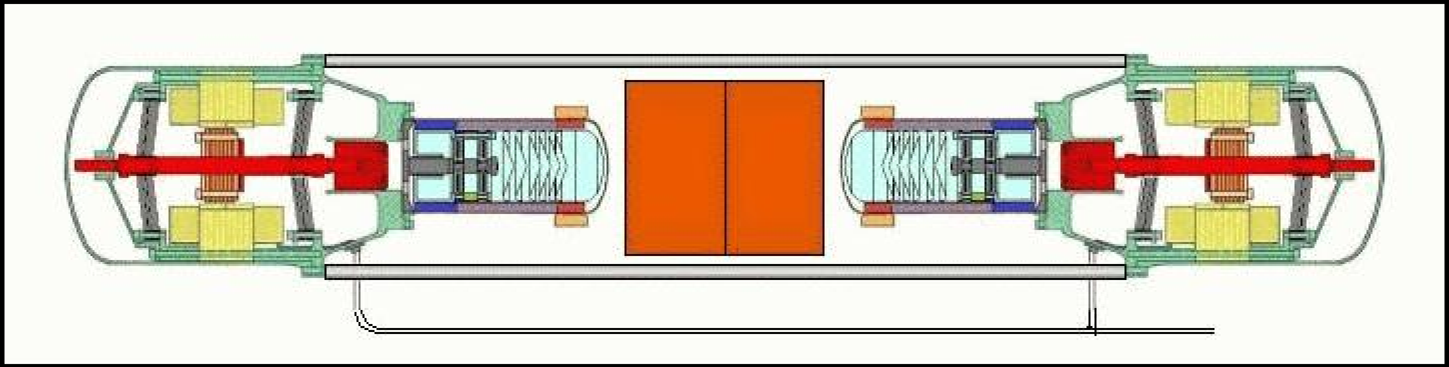
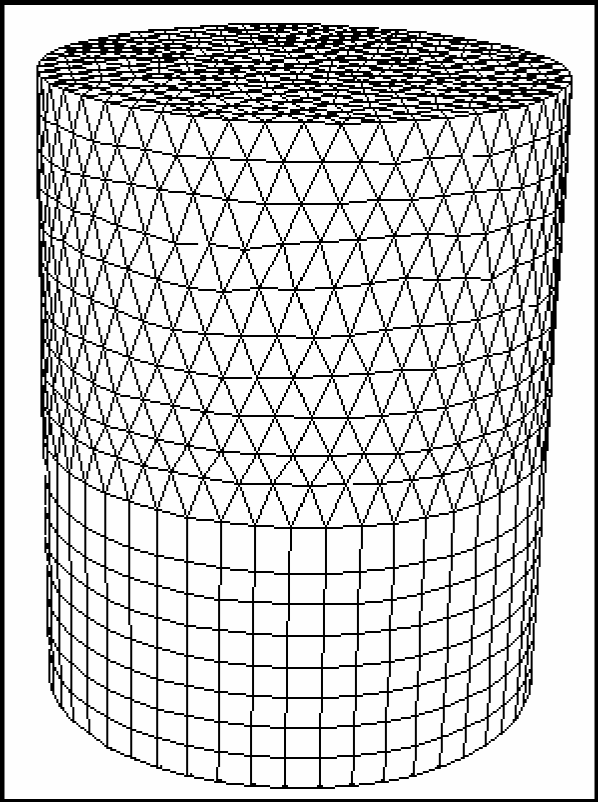
Glenn Research Center at Lewis Field

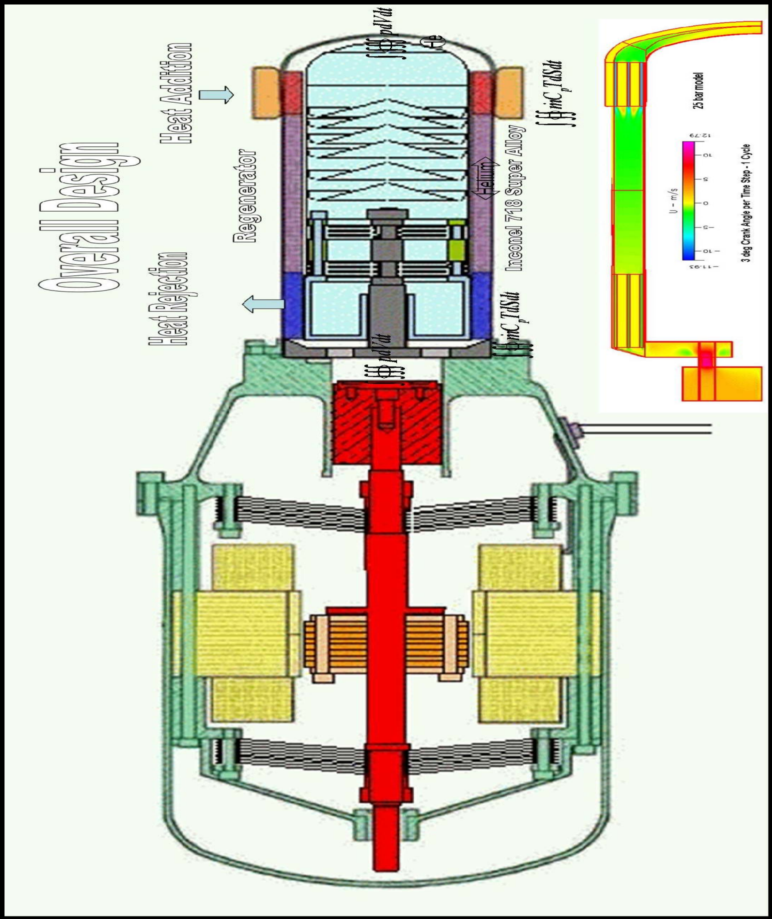
Dual Opposed Stirling Convertors

- High Efficiency, Low Mass Space Power



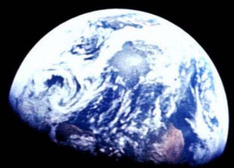
Simulate Engine Only



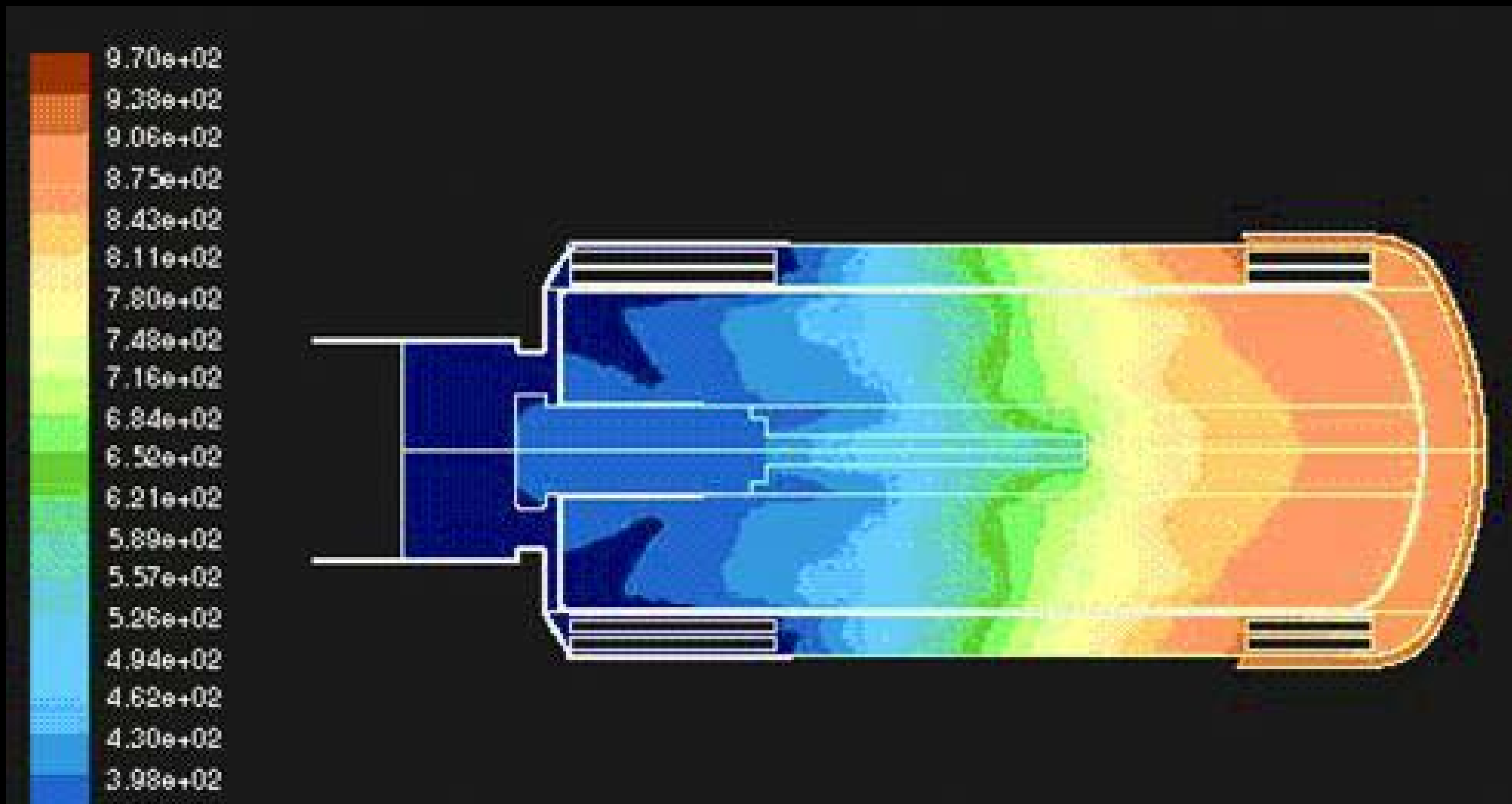


Operating Conditions

Hot-End Temperature, K	923
Cold-End Temperature, K	353
Ambient Temperature, K	293
Frequency, Hz	80
Mean Pressure, Pa	2.429E+6
Power Piston Amplitude, mm	6.0e-3



Whole-Engine Simulation



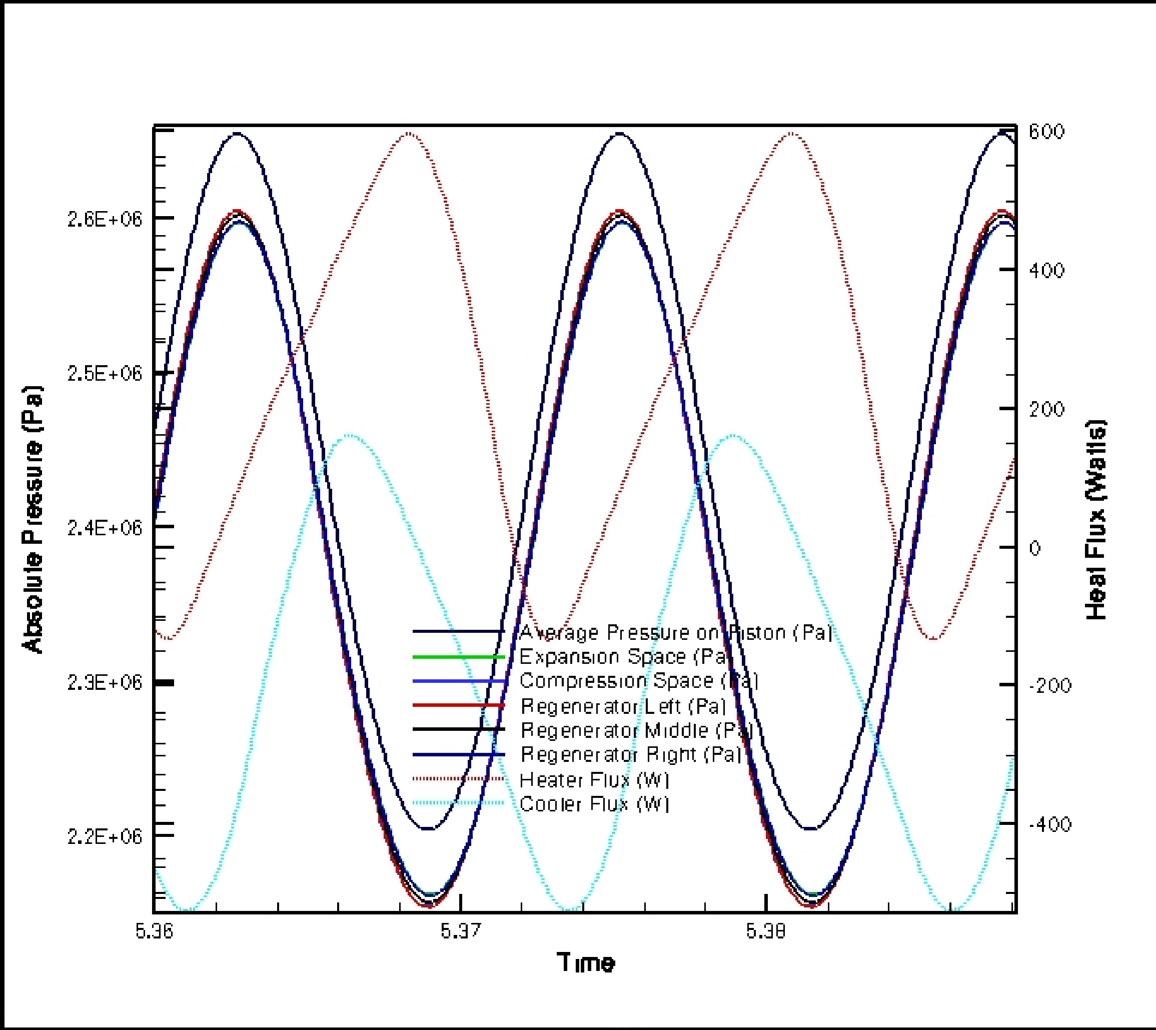
Comparison with Sage 1D Results

	Axisymmetric Simulation	Sage 1D Ambient	Sage 1D No Ambient
PV Power, W	79.65	68.77	70.14
Heat In, W	247.315	260.94	193.8
Heat Out, W	168.313	191.9	123.7
PV Efficiency	.322	.264	.362
Pressure Ratio	1.209	1.187	1.187
Regen. ΔP., Pa	10466.3	15888	15790
Heater P, Pa	682	194	192
Cooler P, Pa	896	316	315
Pressure Amp., Pa	225269	203100	203200
Mean Pressure, Pa	2429130	2378000	2378000

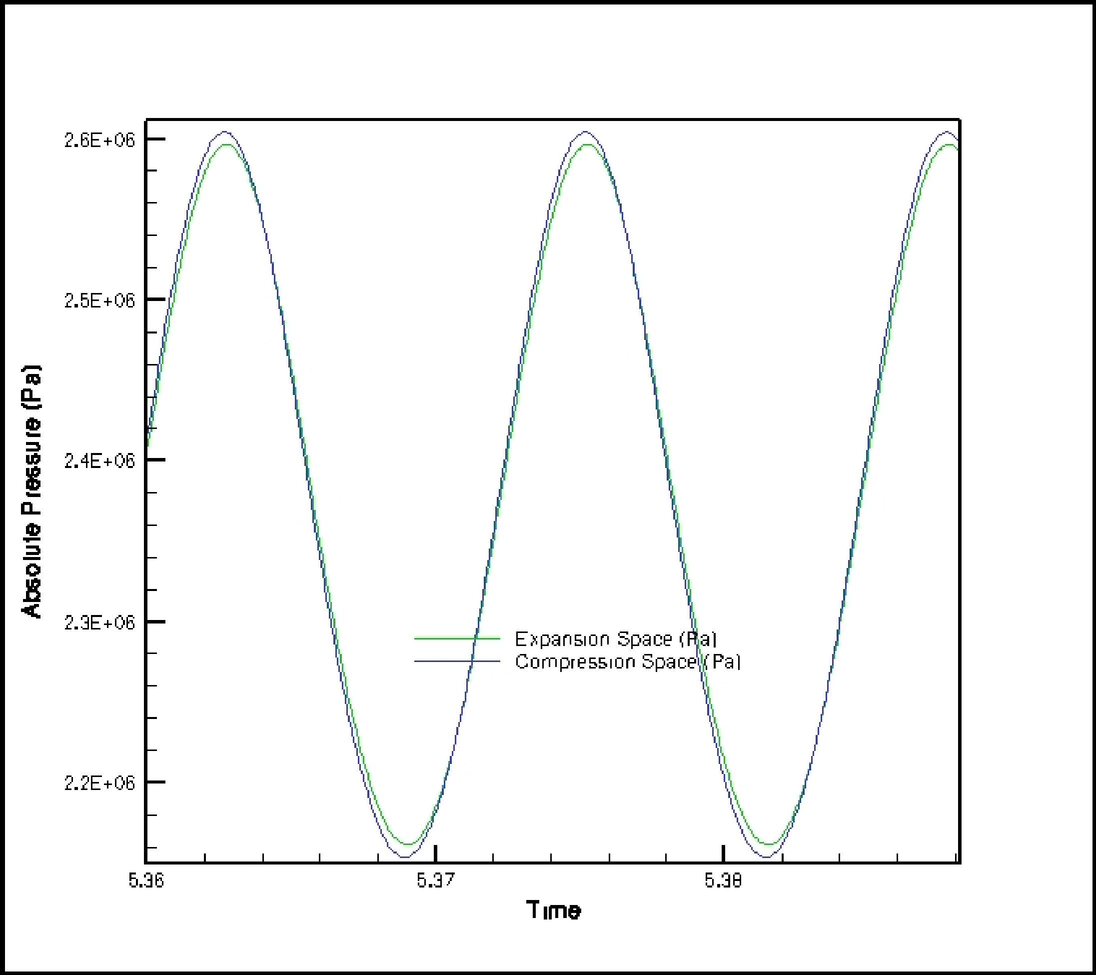
Comparison with Experiment

	Thot C	Tcold C	Freq. Hz	Qin W	PV W	Qout W
TDC #13	646.0	80-92.4	81.4	242.1	78.2	163.9
TDC #14	646.5	80-94.4	81.4	250.4	79.6	170.8
Simulation	650.0	80	80	247.3	79.7	168.3
%Err-AVE	100.6	?	98.2	100.4	100.9	100.6

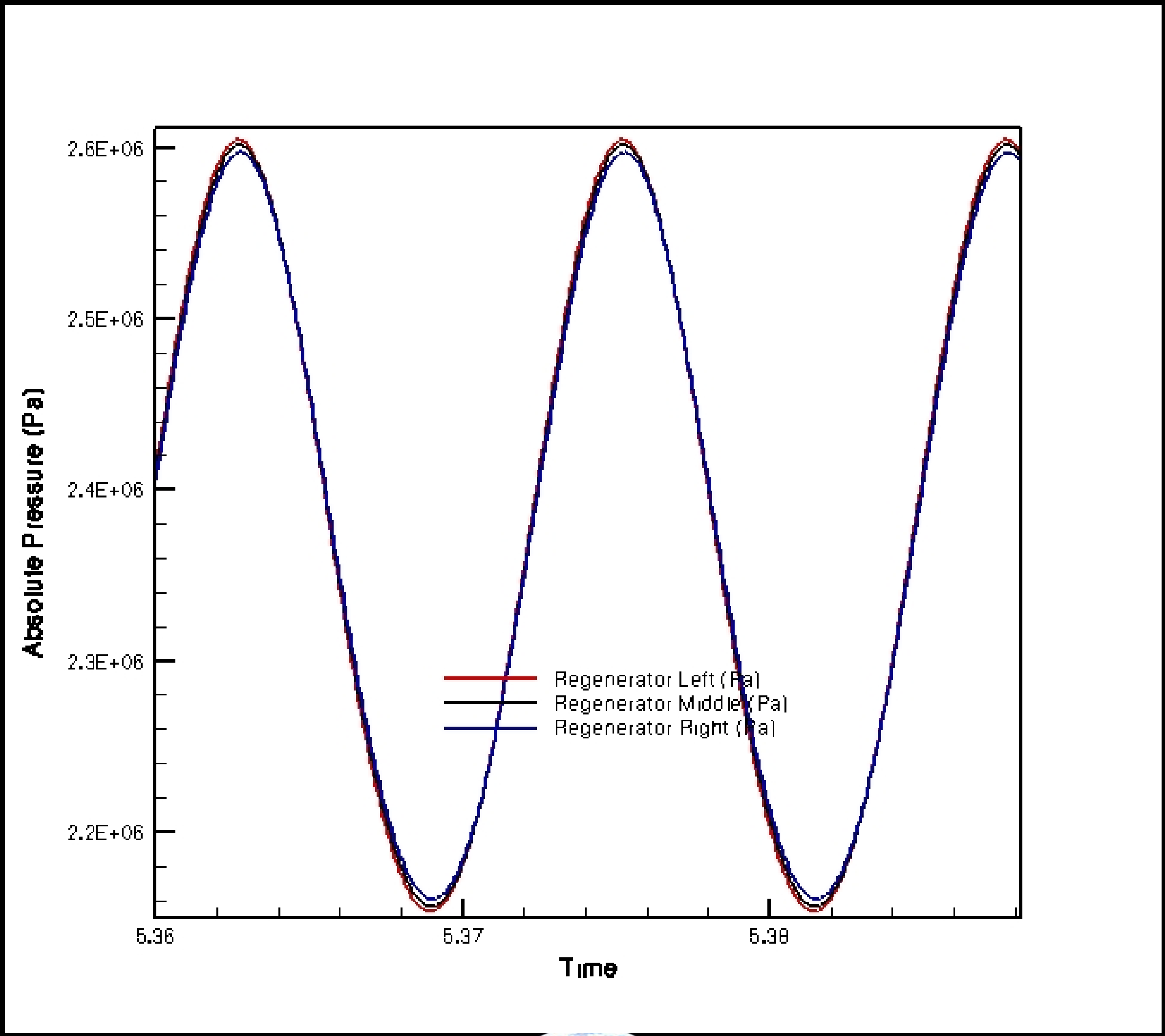
Pressure and Heat Transfer over Cycle



Expansion and Compression Pressure



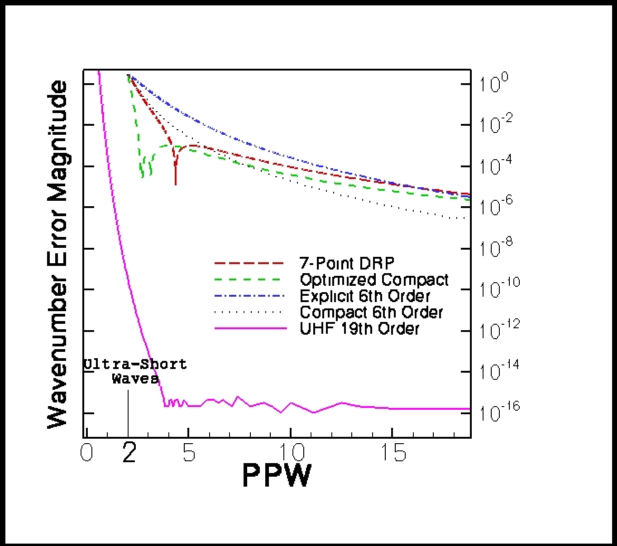
Regenerator Pressure Drop

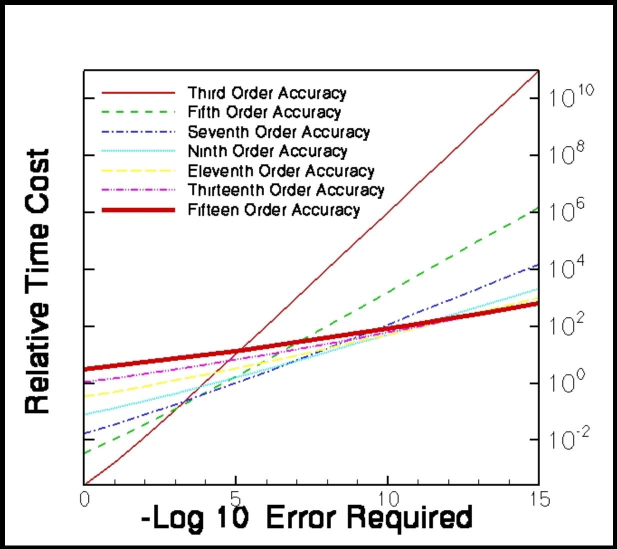


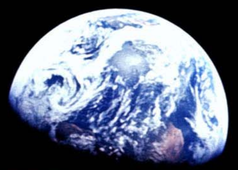
Solved Whole-Engine On 32 Processor Cluster

Multidimensional Analysis Tools

- Modified CAST, CFD-ACE, Fluent, STAR-HPC, CFX/ANSYS, others …
- All low order SIMPLE/PISO based
- New high-order codes being developed

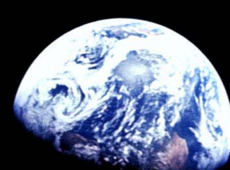




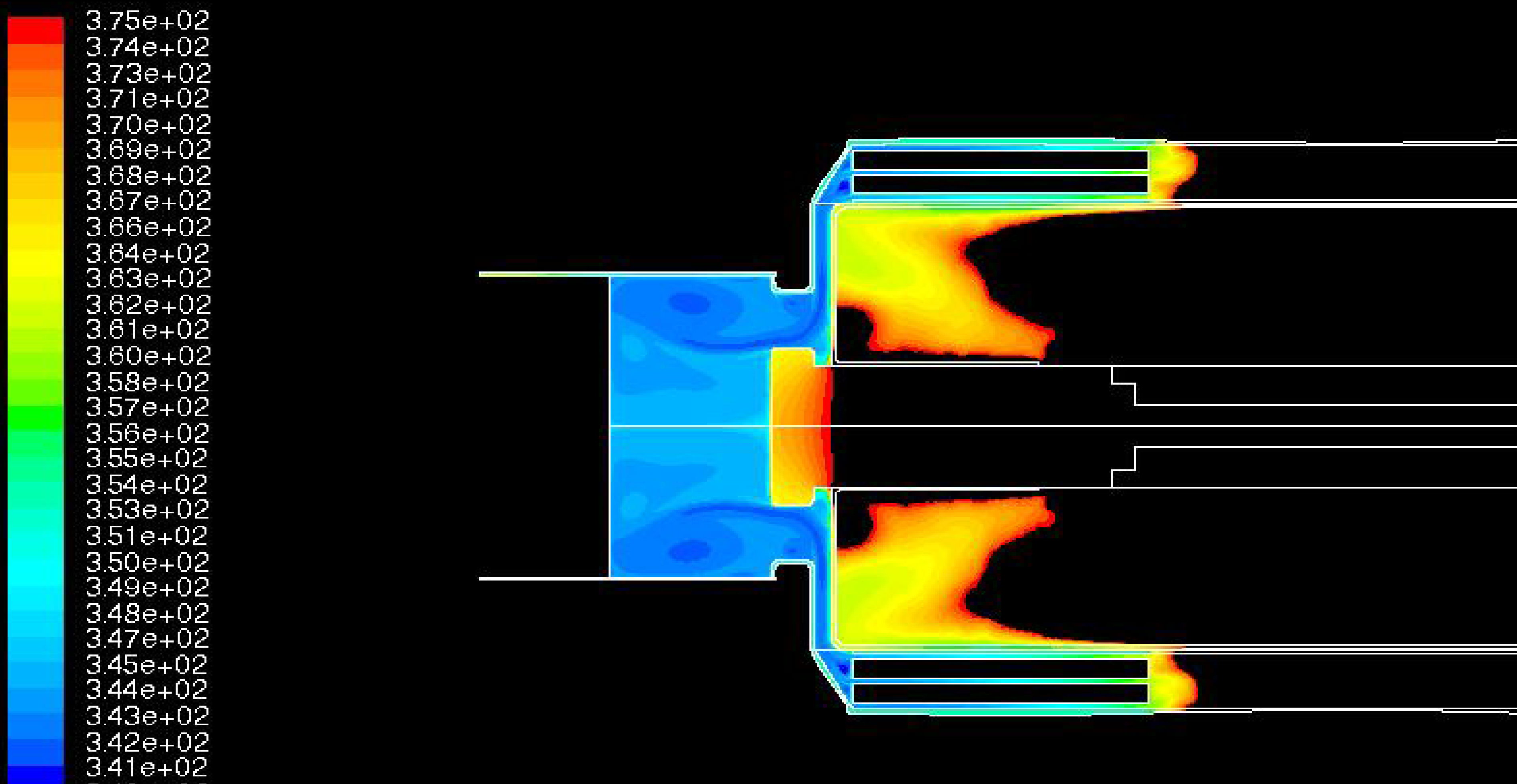


Multidimensionally Enabled Capabilities

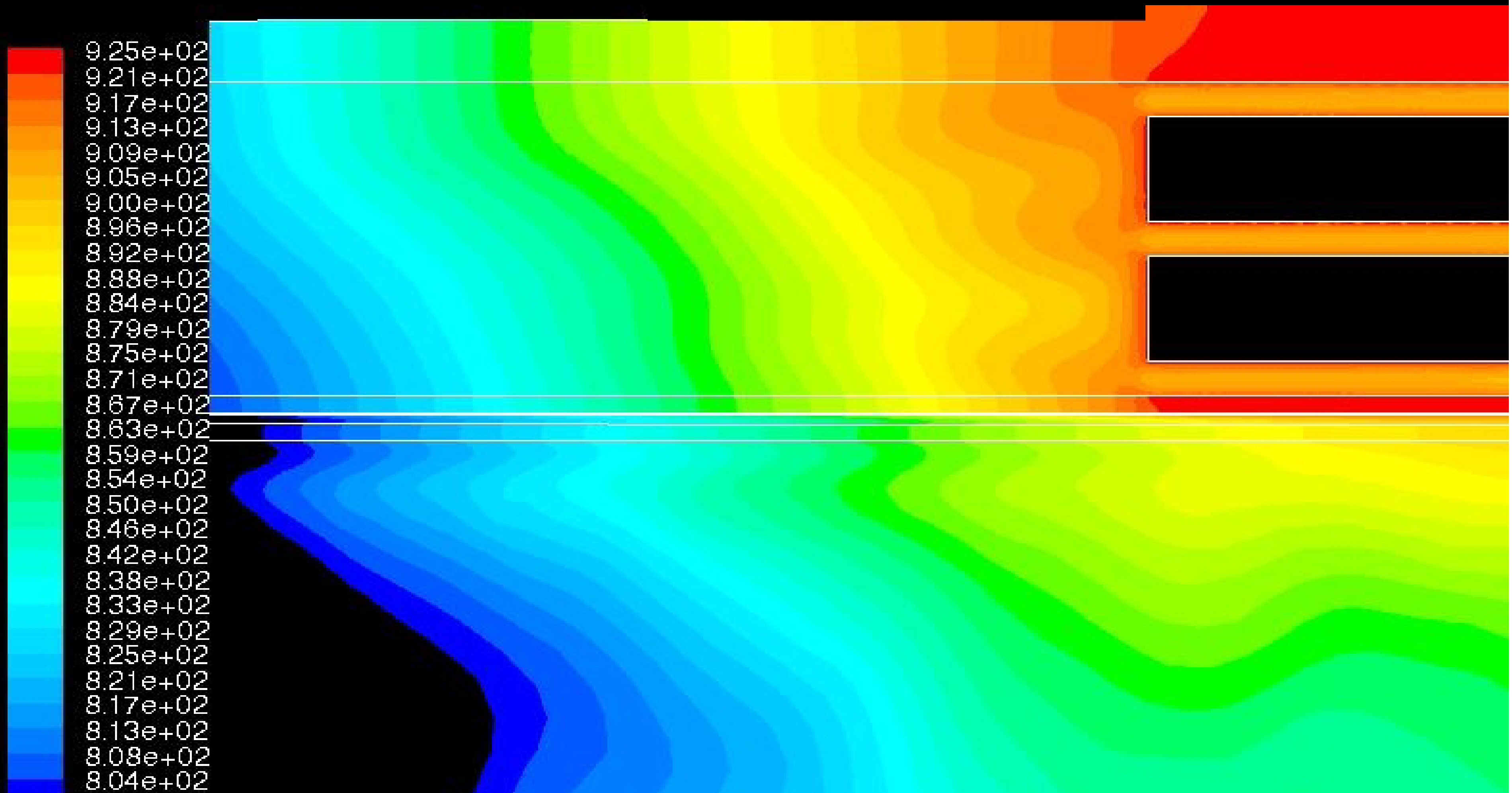
- Structural, thermal, fluid, electromagnetics, and coupled physics.
- 1 hour per cycle axisymmetric simulation
- Seal & appendix gap phenomena
- HX end effects
- Effect of vortices in expansion & compression
- Flexure temperatures for reliability analysis
- Effects of slight geometrical variations

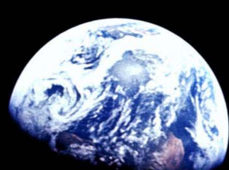


Cool End Heating

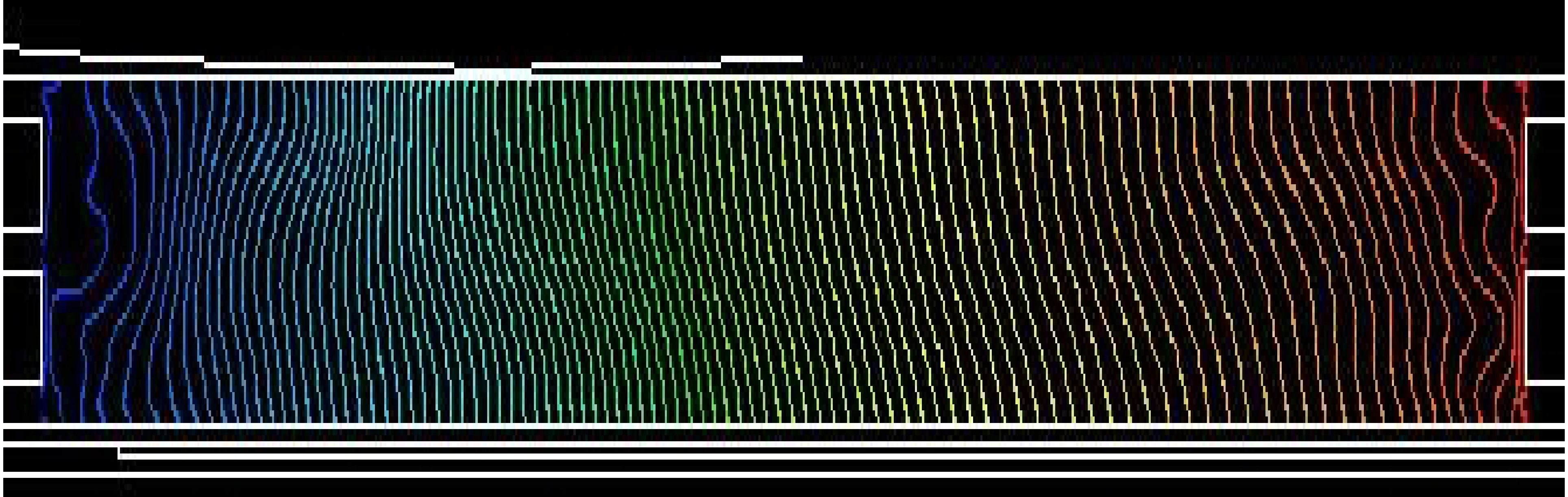


Radial Heat Transfer Effects

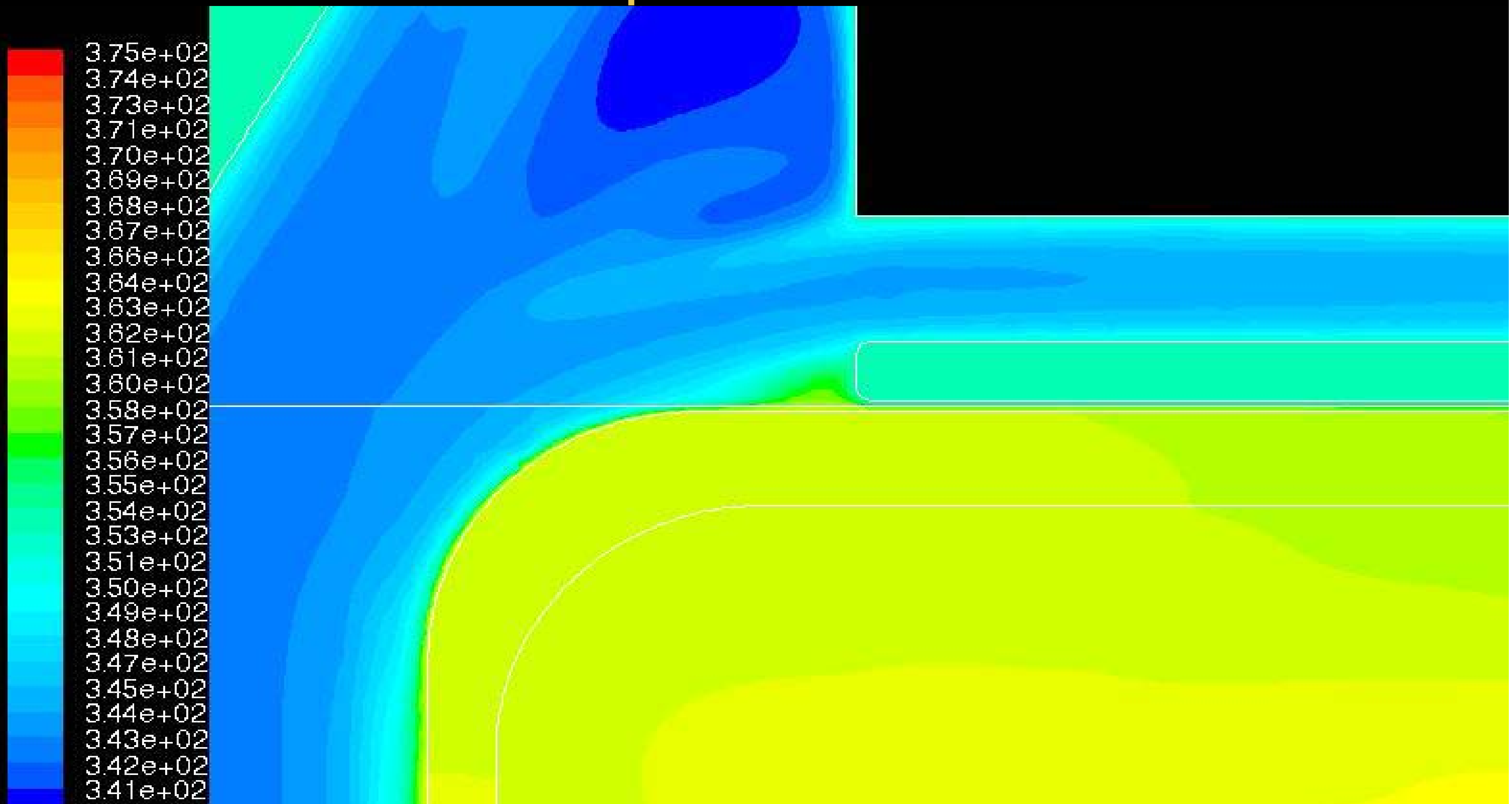




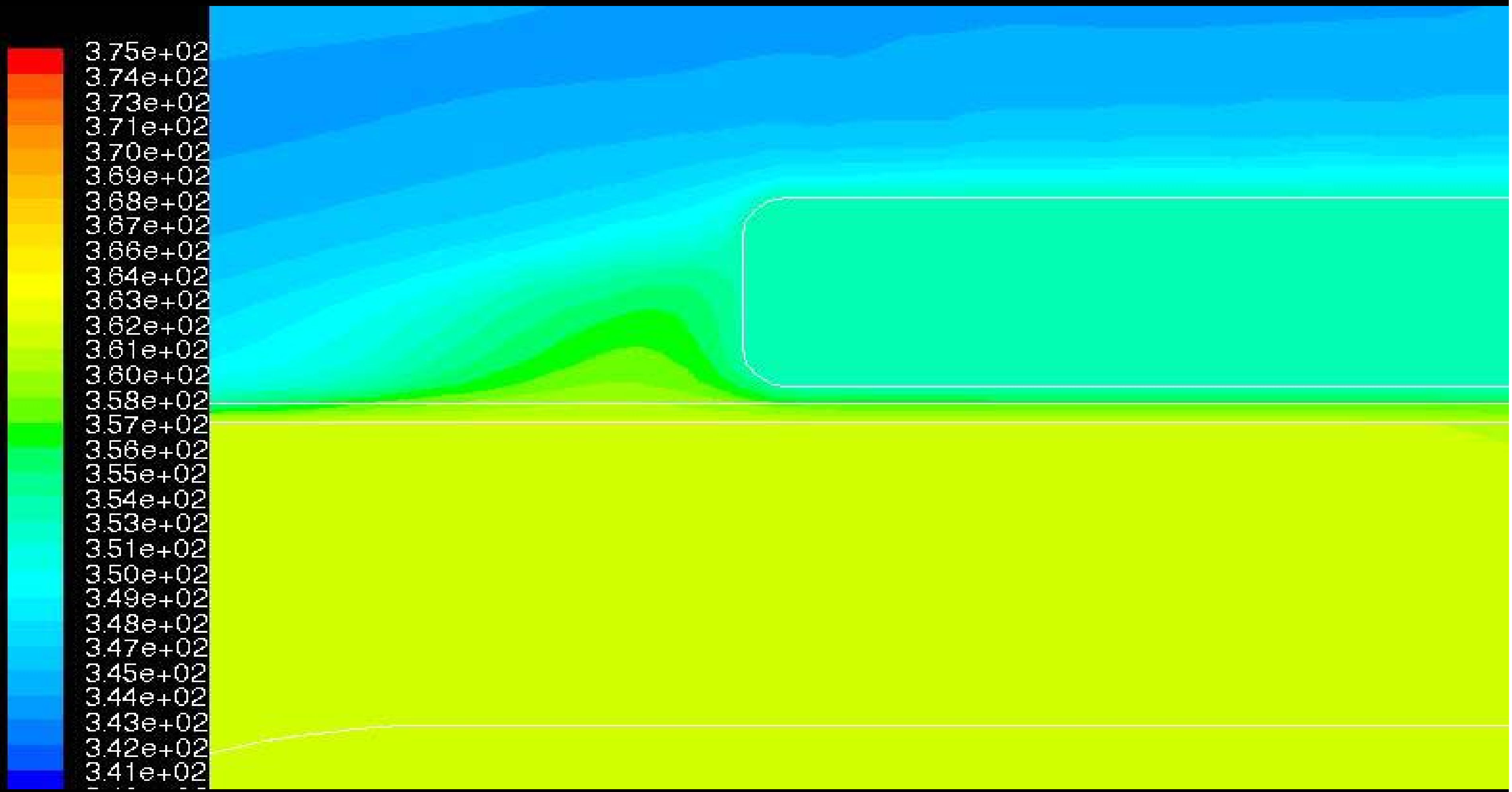
Radial Heat Transfer Effects



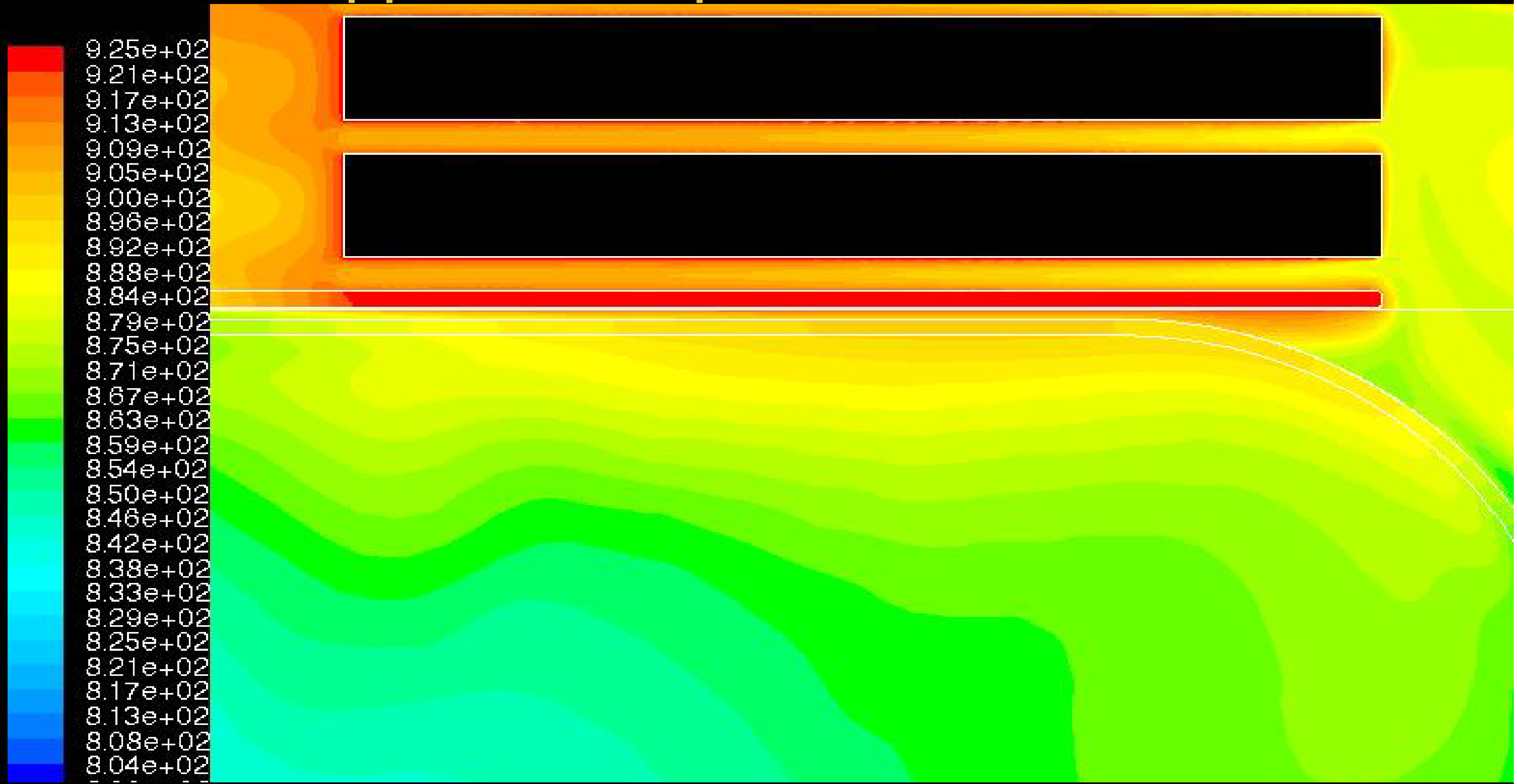
Displacer Seal



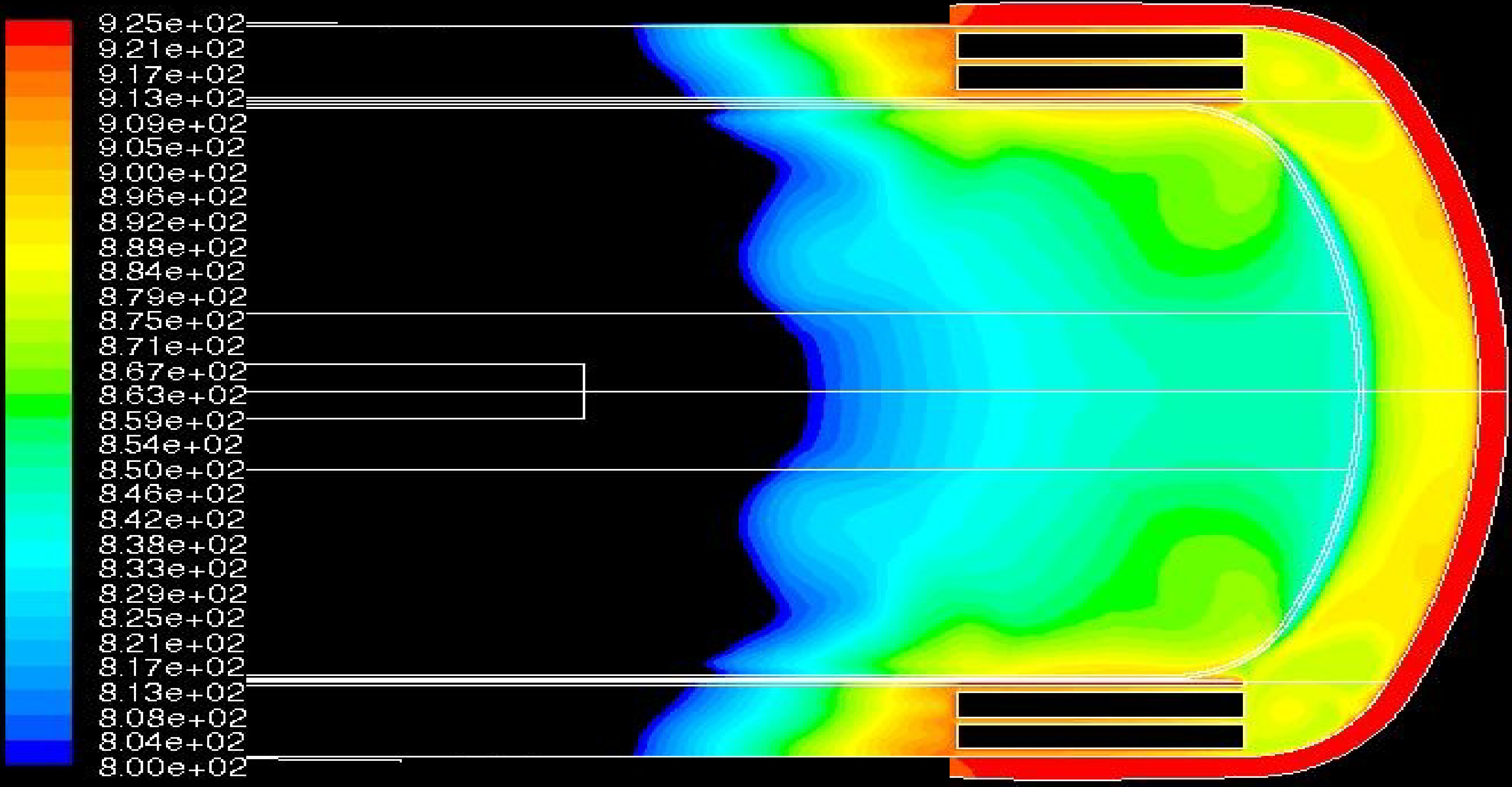
Displacer Seal Close-up



Appendix Gap Shuttle Losses

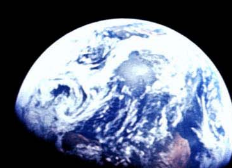


Effects of Vortices in Expansion

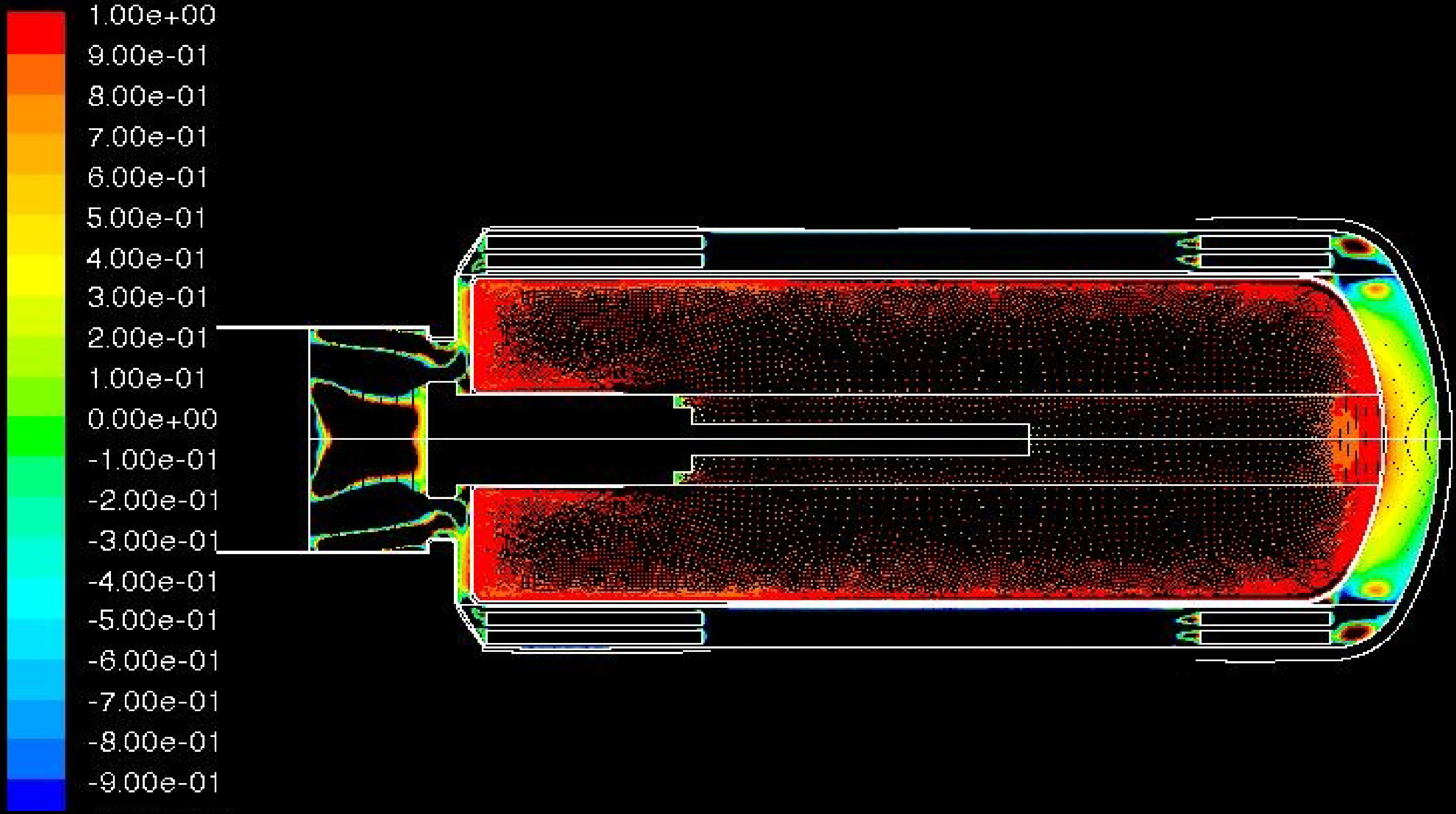


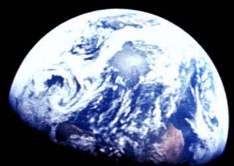
Simulation Approach

- Whole-engine for physical consistency
- REV Regenerator Modeling
- Grid Layering, Smoothness, and Quality
- Conjugate heat transfer method adjustment
- High-speed Low Cost Parallel Cluster
- Lot’s of debugging….

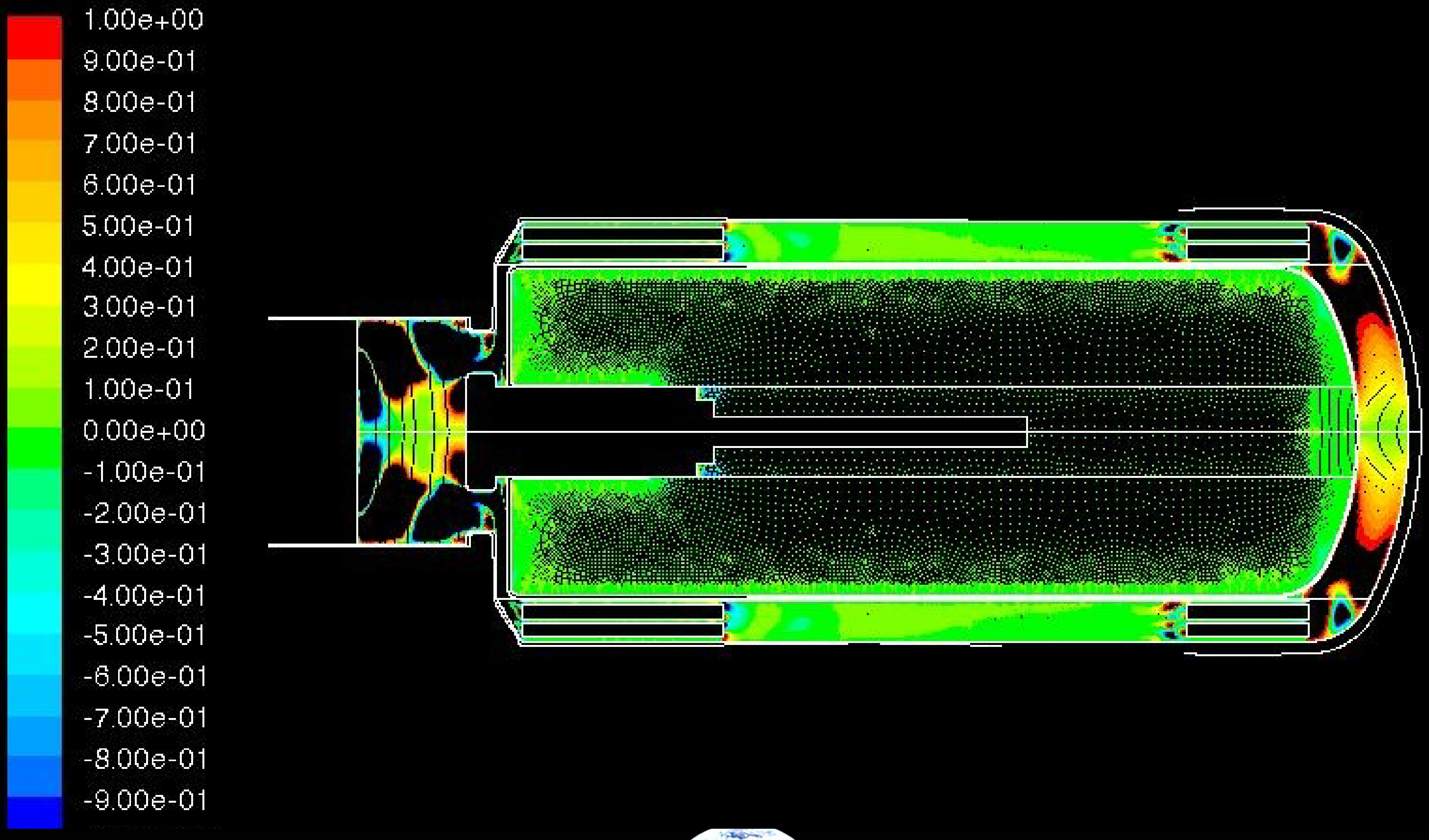


Dangers of Component Modeling: Axially Oscillating Boundaries

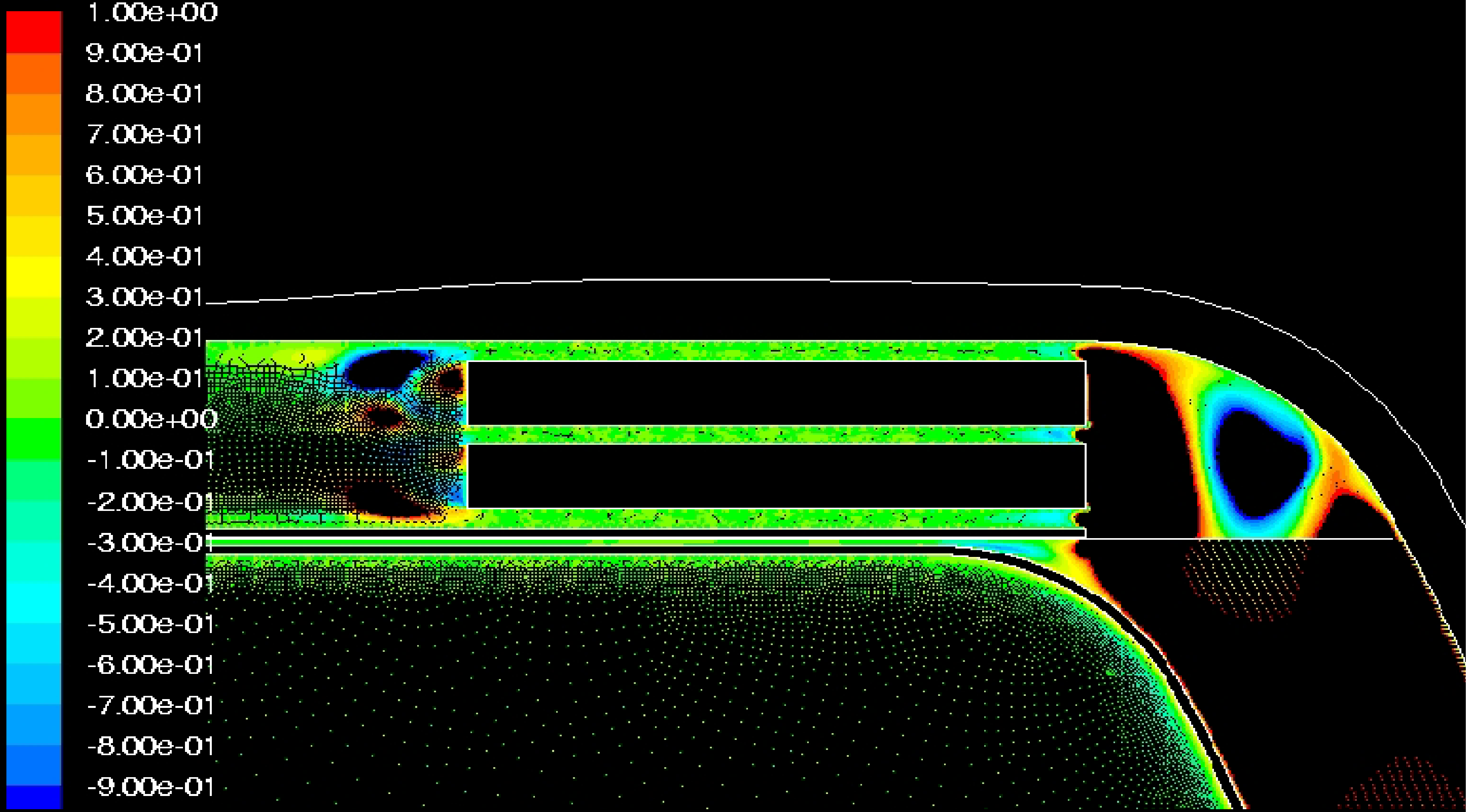


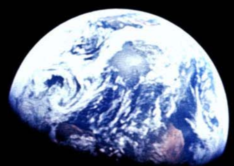


Radially Oscillating Boundaries

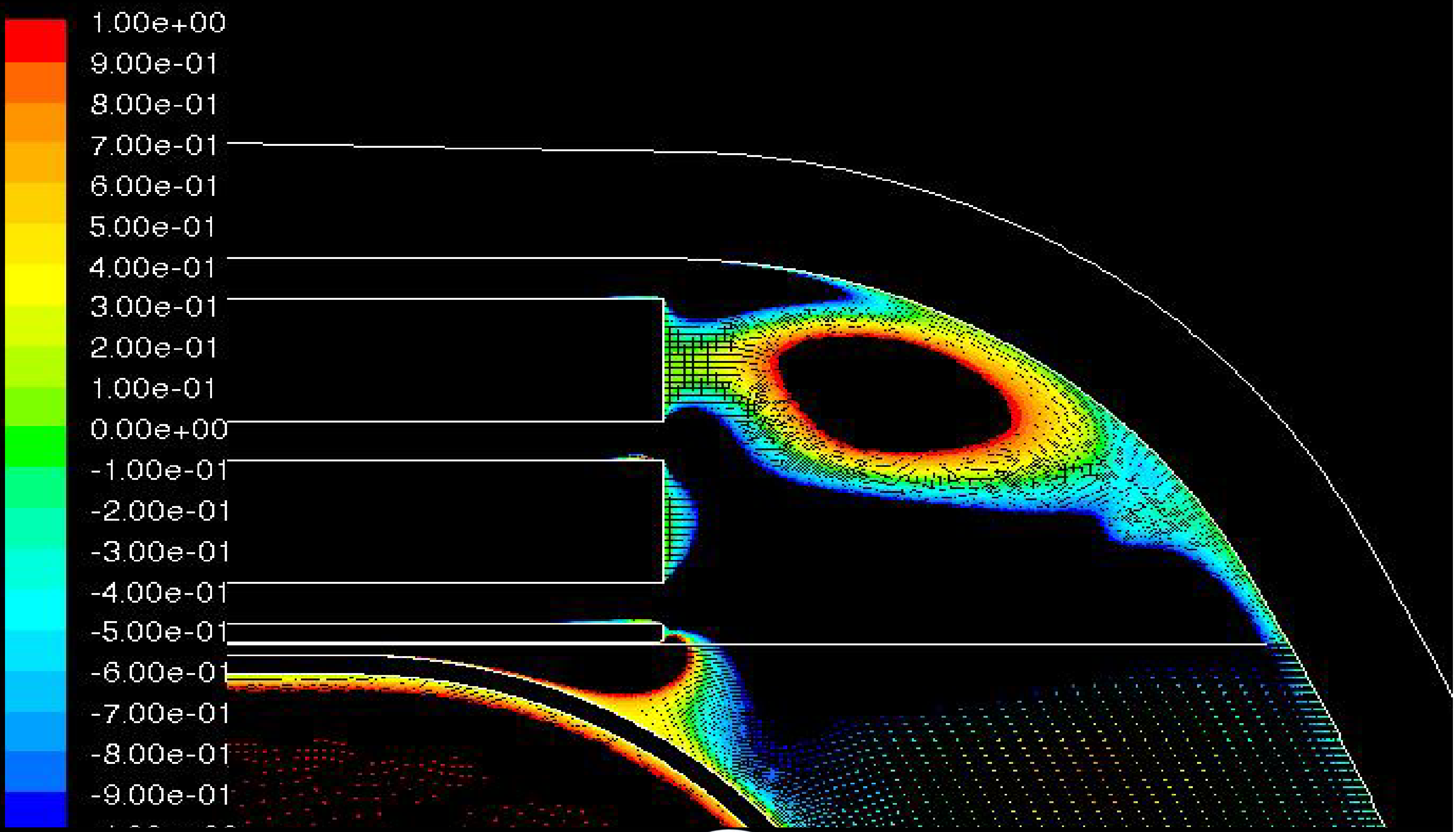


Heat Exchanger Oscillating Boundary

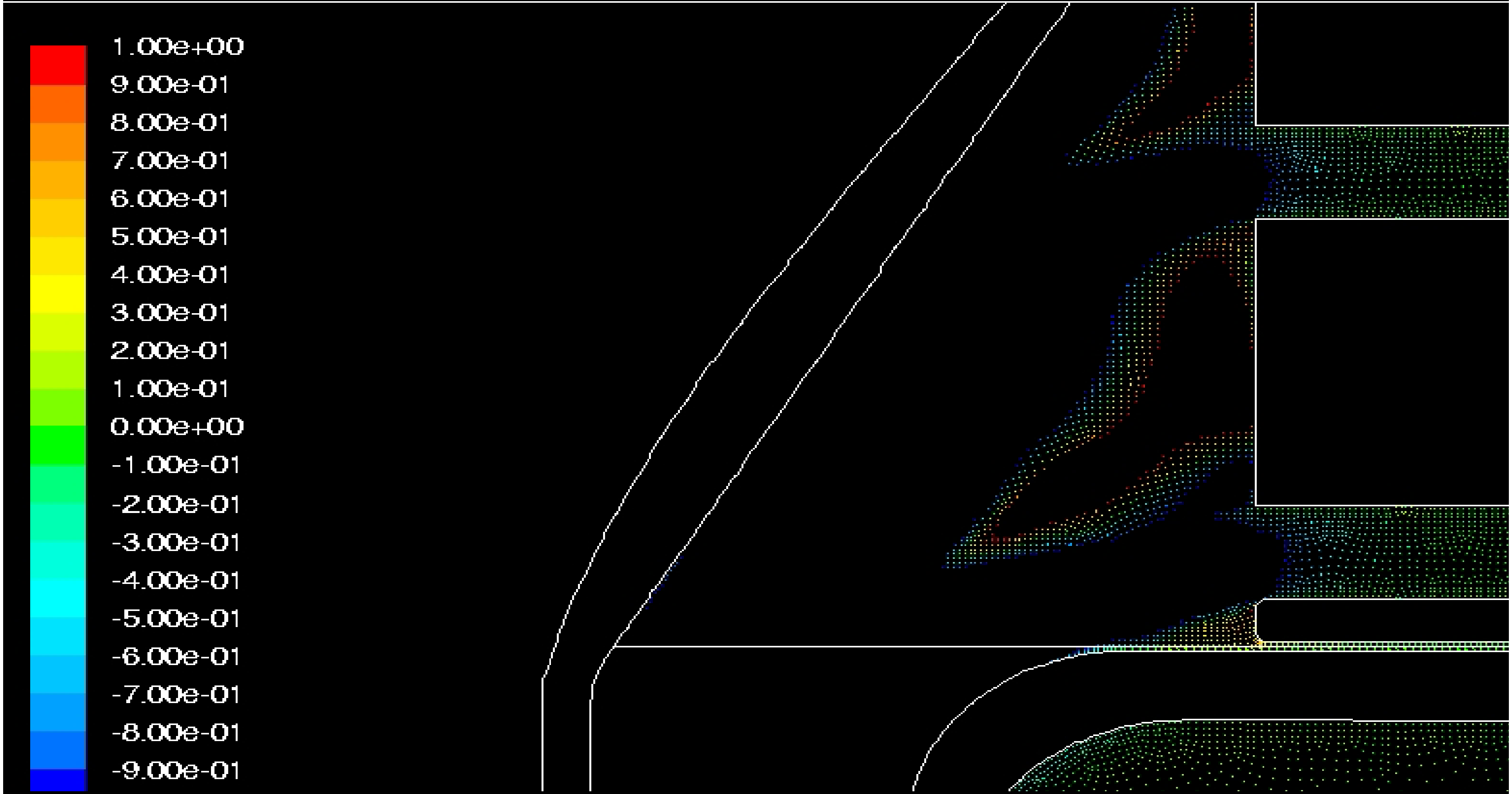




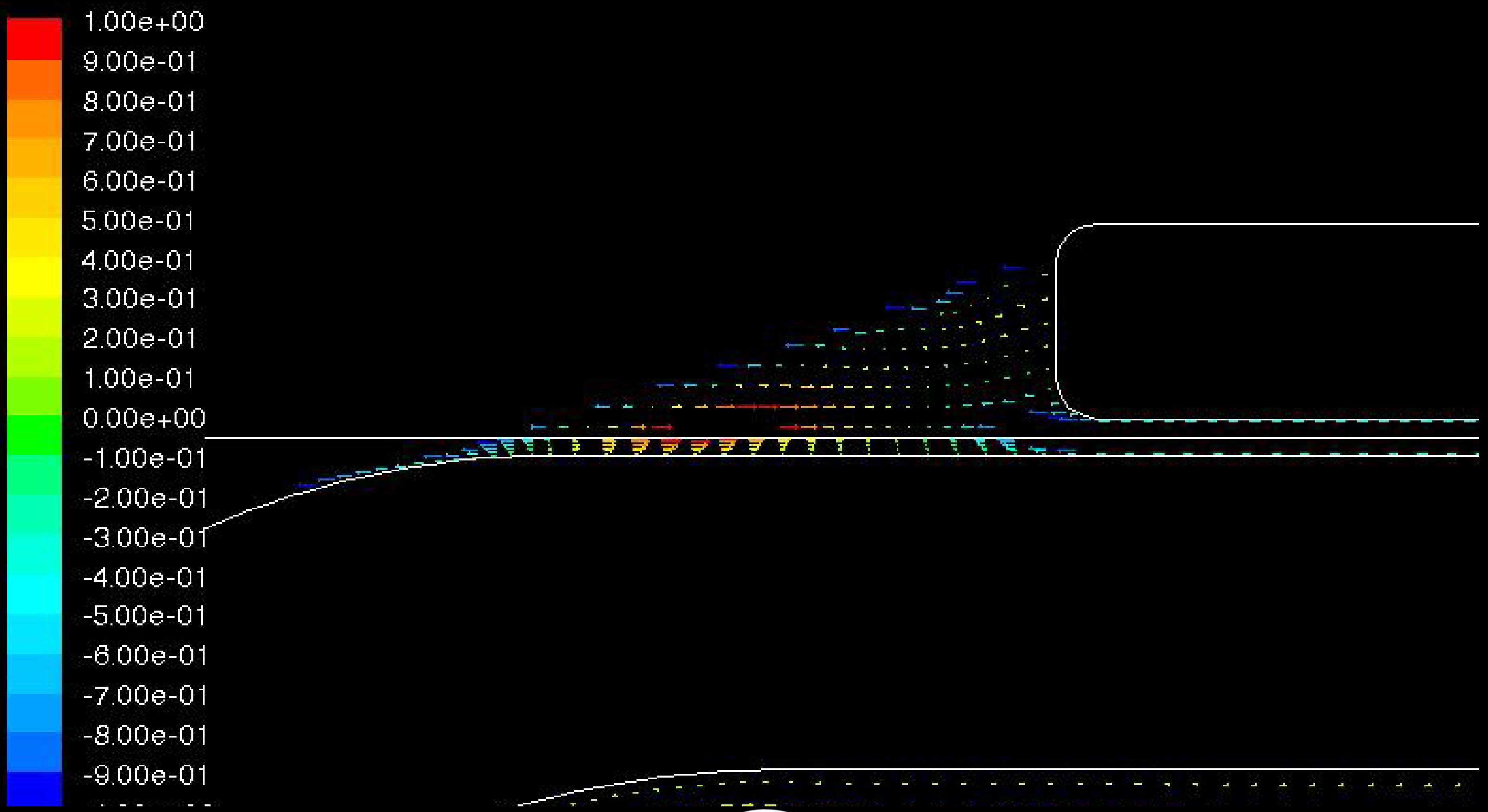
Manifold & Appendix Gap O.B.



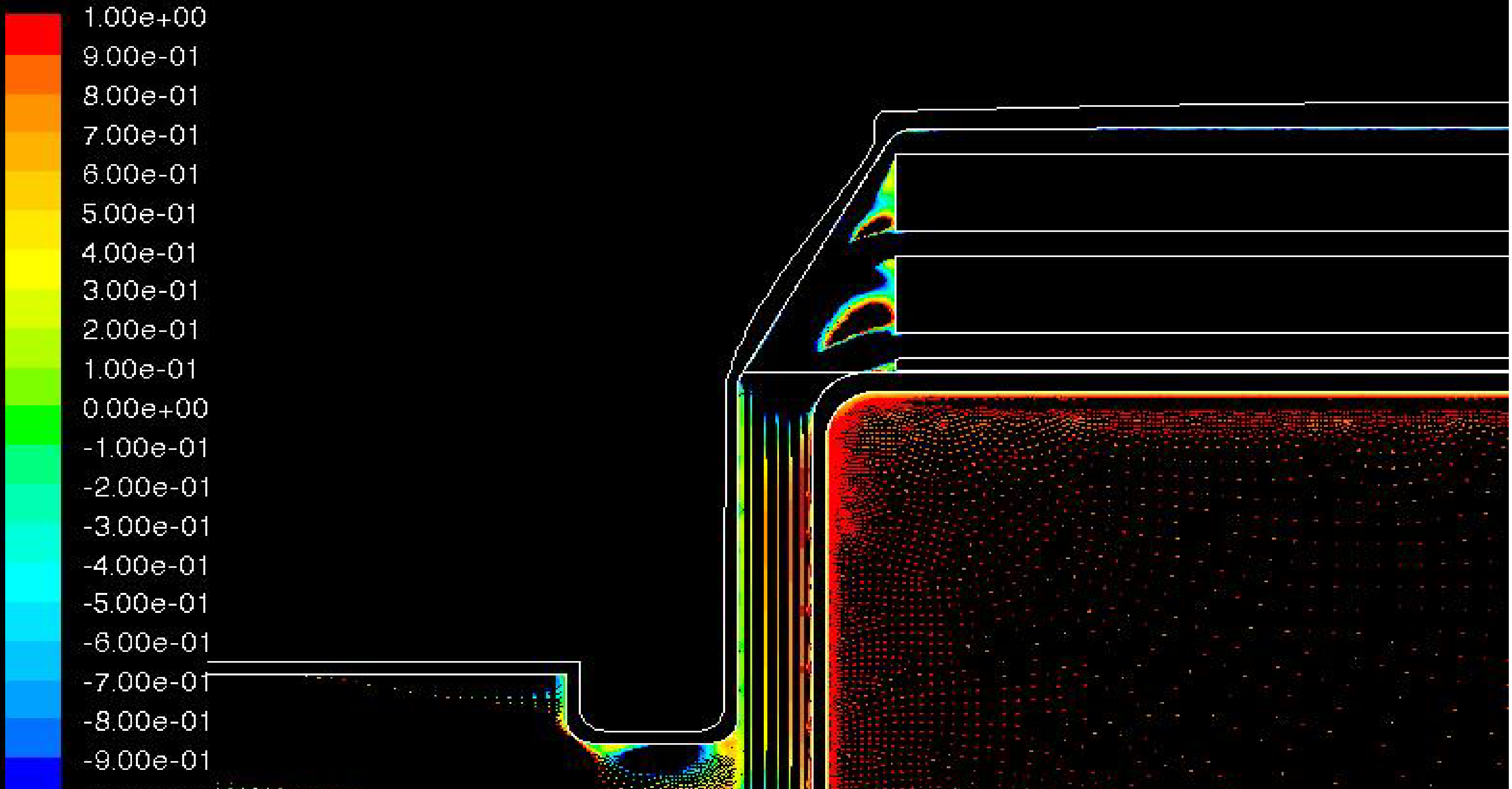
Cooler Manifold O.B.



Seal Region O.B.



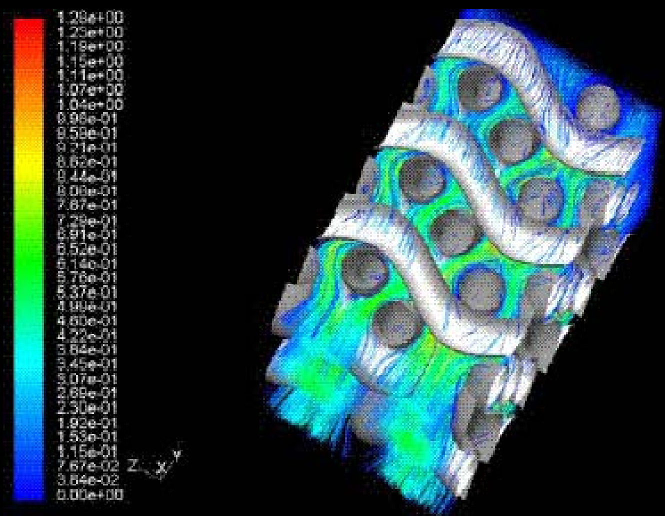
Compression Manifold O.B.

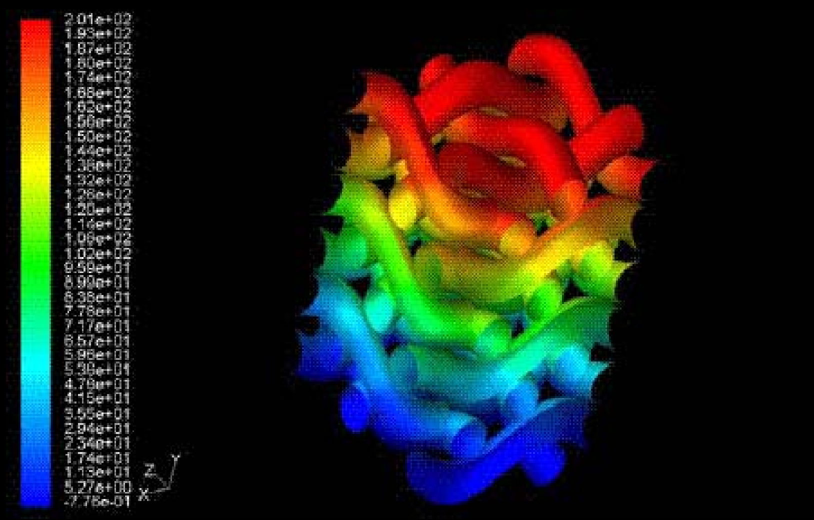


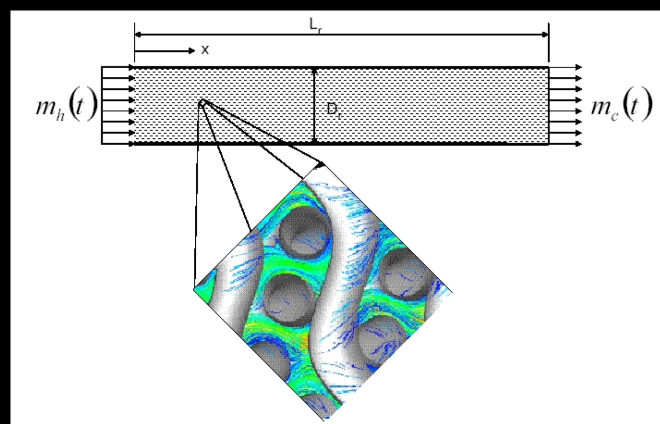
Regenerator Modeling

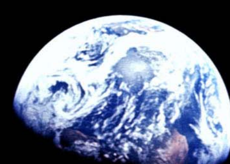
- Geometrical Shapes Affect Complexity
- High Efficiency Regenerators Permit Thermal-Equilibrium Assumption/Usage
- Add source terms to governing equations
- Darcy-Forcheimer equation is used on momentum, Coefficients from experiment
- Single Energy equation (fluid/solid averaged) with averaged conductivity and energy

Regenerator Modeling in More Detail Later

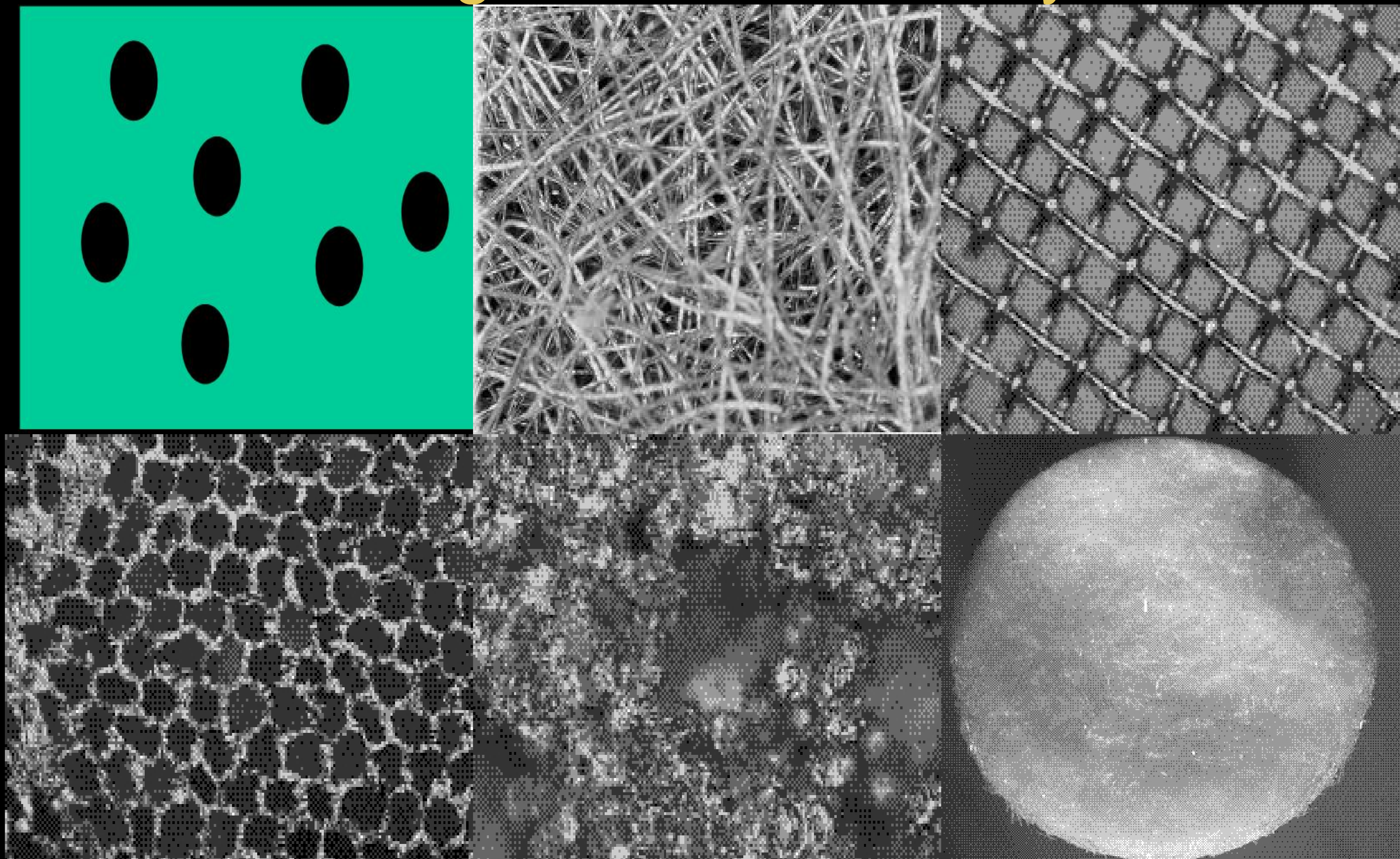








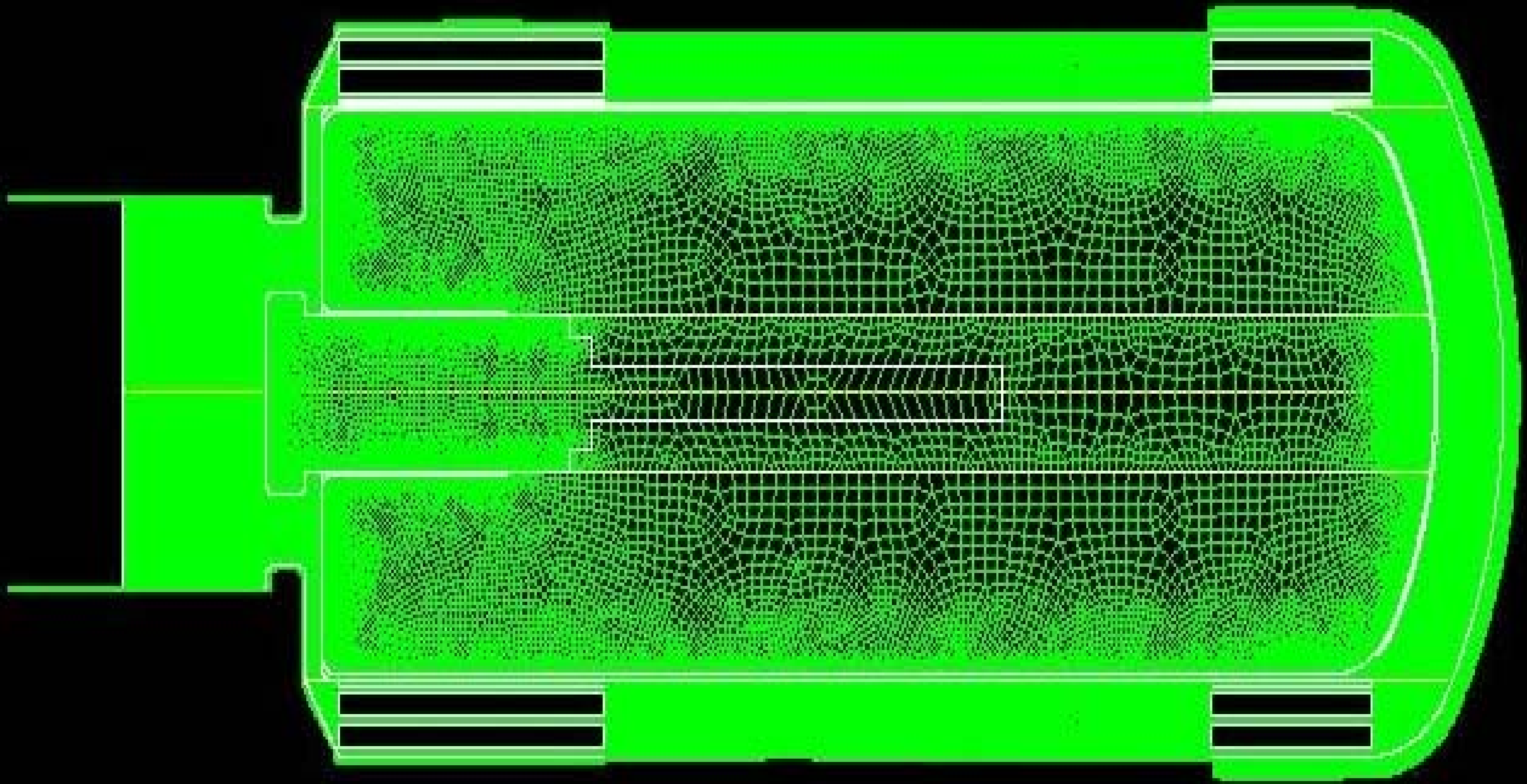
Regenerator Geometry



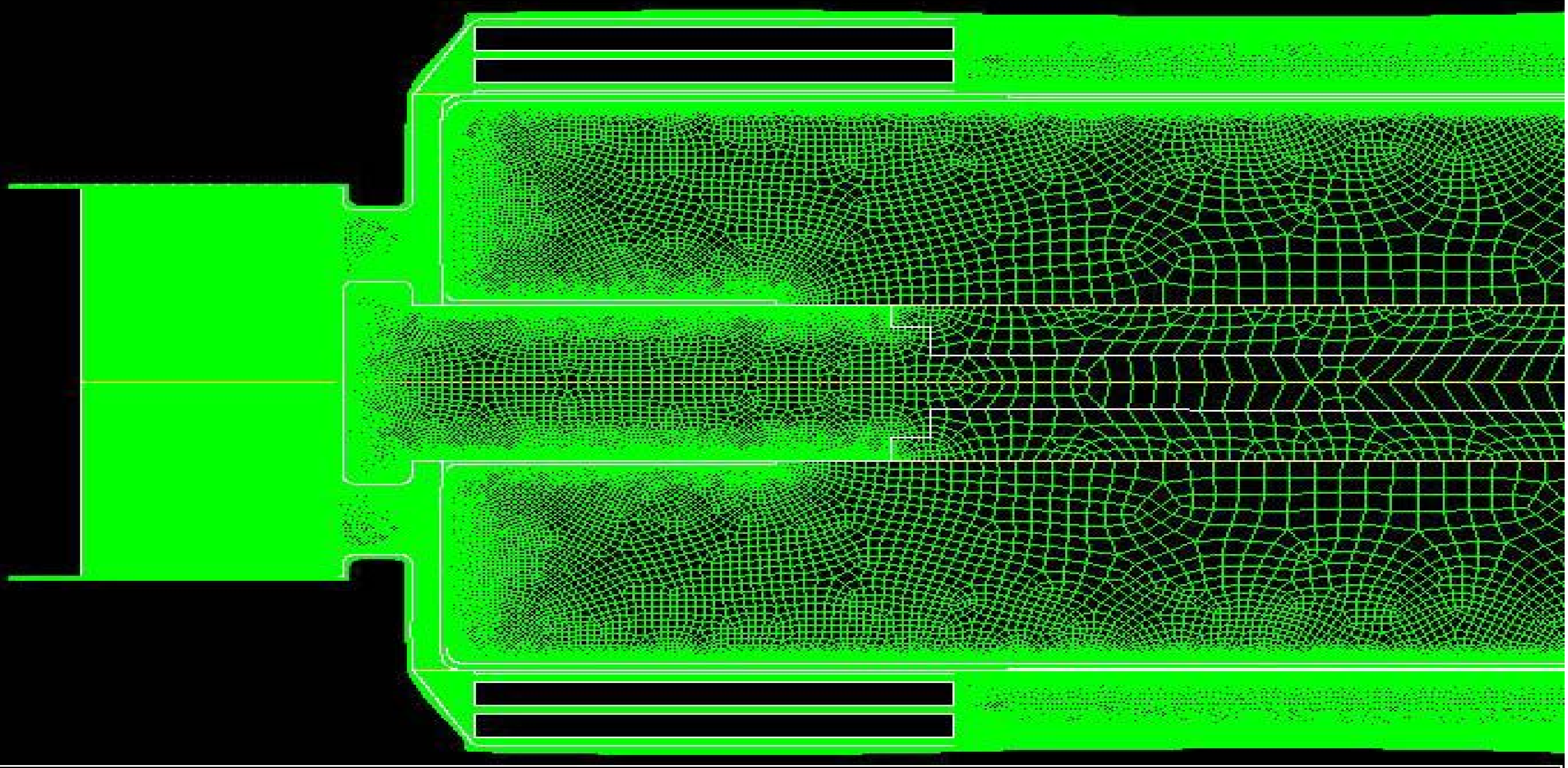
Gridding Approach

- Scale geometry to compensate for 32-bit
- Avoid tetrahedrals, use unstructured quads
- Match cell sizes across sliding regions
- Smoothly expand/shrink cell sizes throughout
- Use layering, avoid adaption/remeshing
- Utilize moving and double-sided boundary layers
- Include as much geometry as practical
- Clean up geometry in CAD, avoid virtual geometry
- Over-converge the steady solution to improve grid

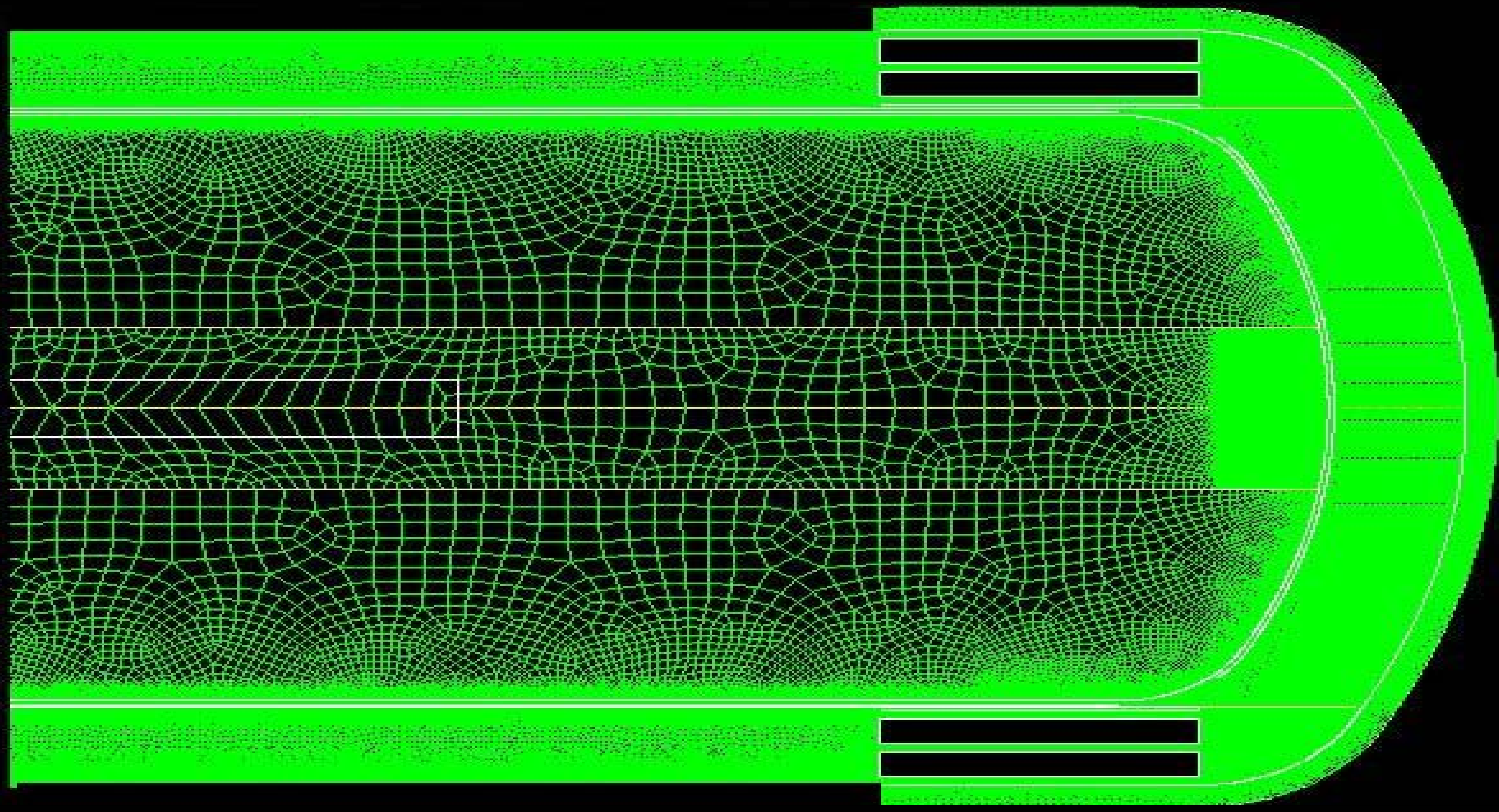
Whole Engine (700K cells)



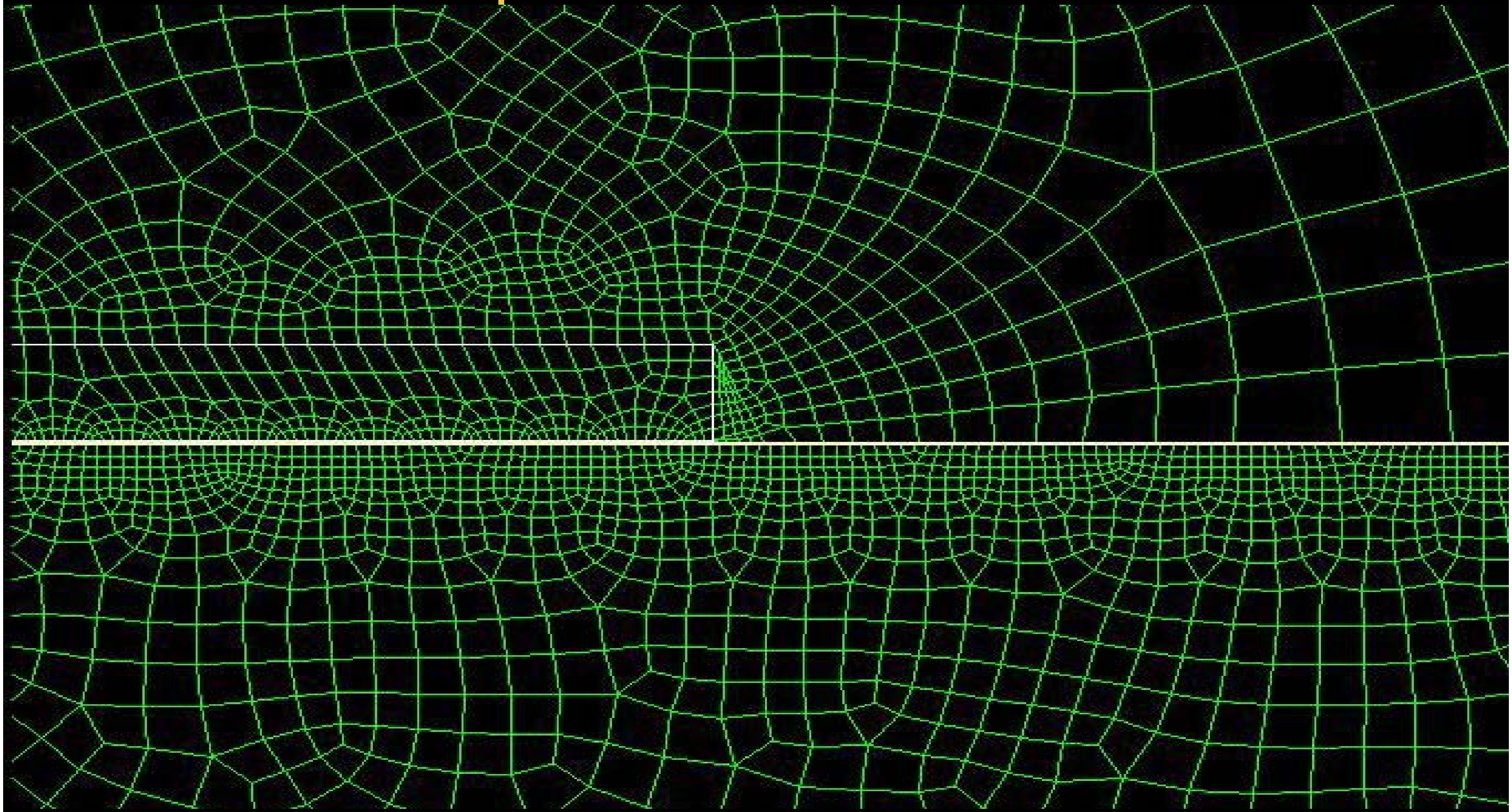
Left Half Grid



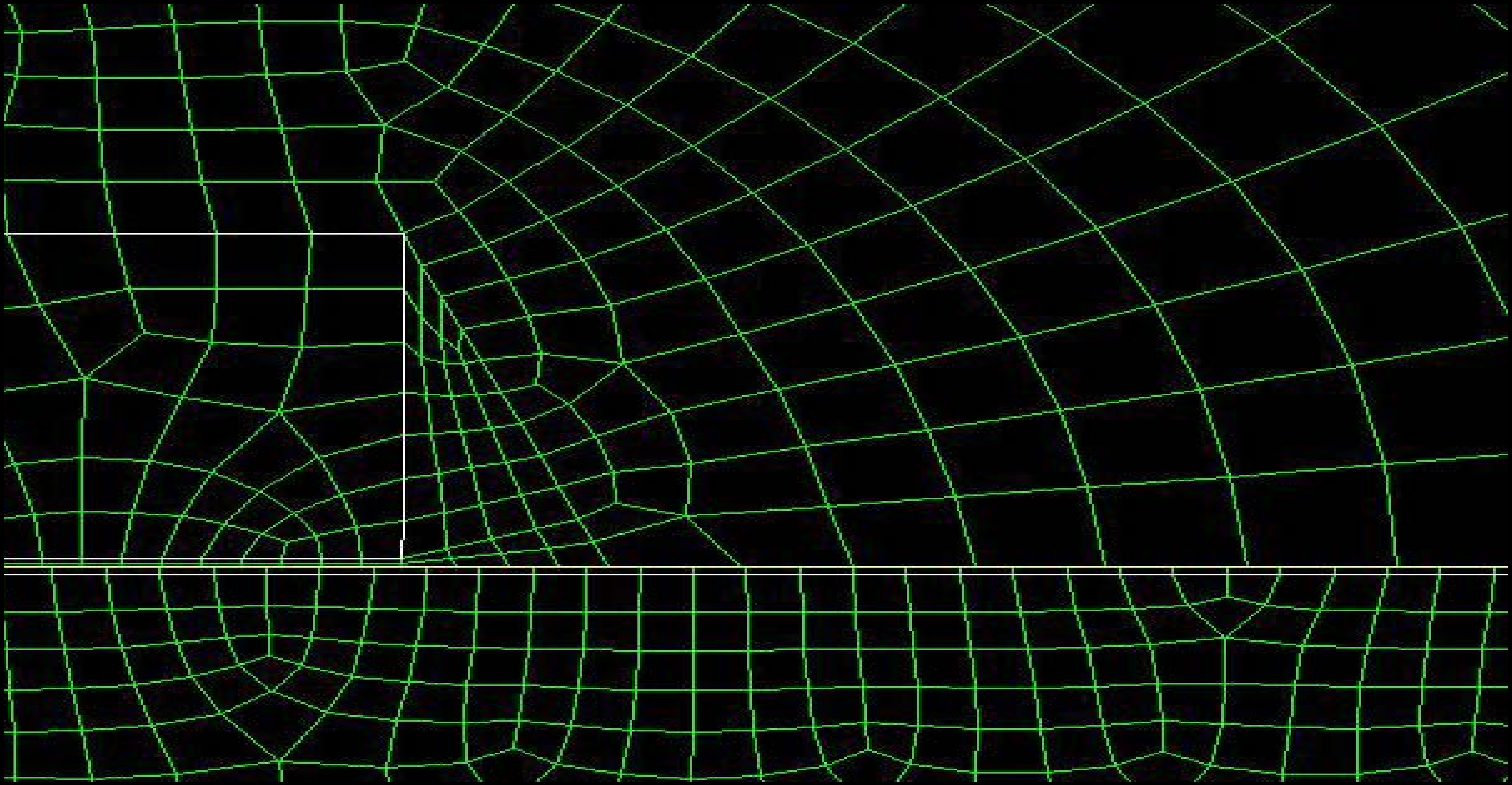
Right Half Grid



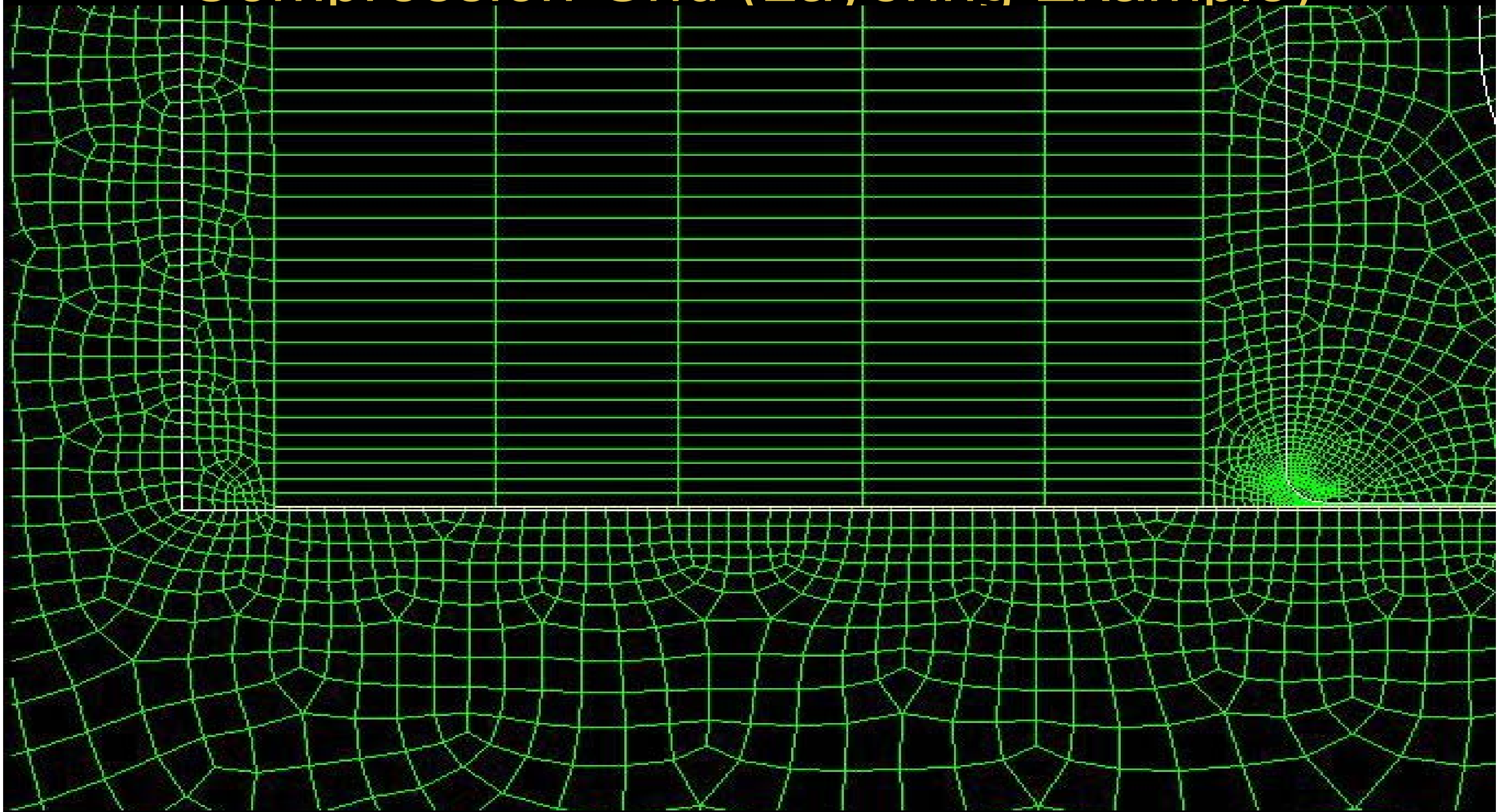
Displacer Rod Seal Grid



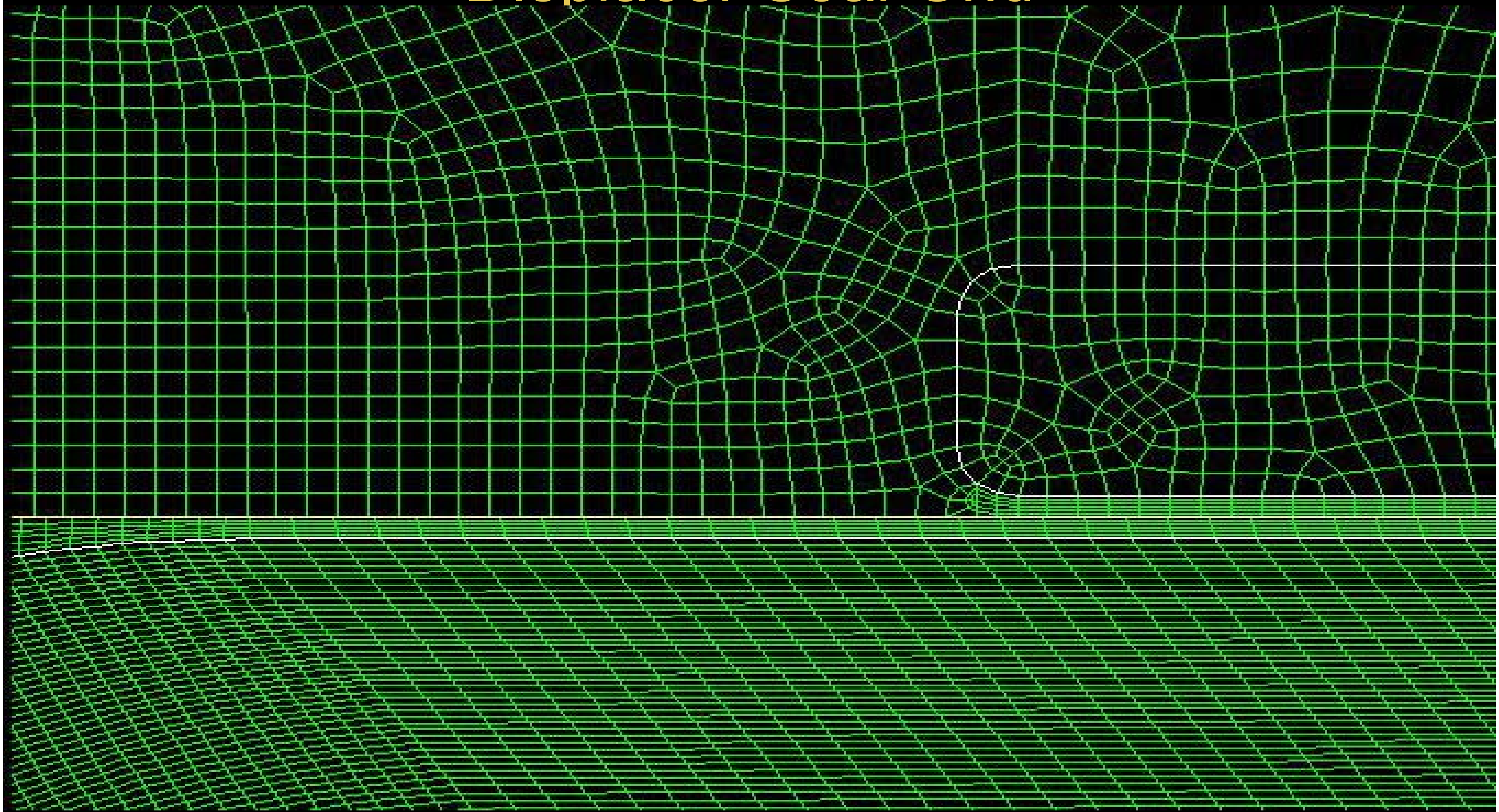
Displacer Rod Seal Grid (Close-Up)



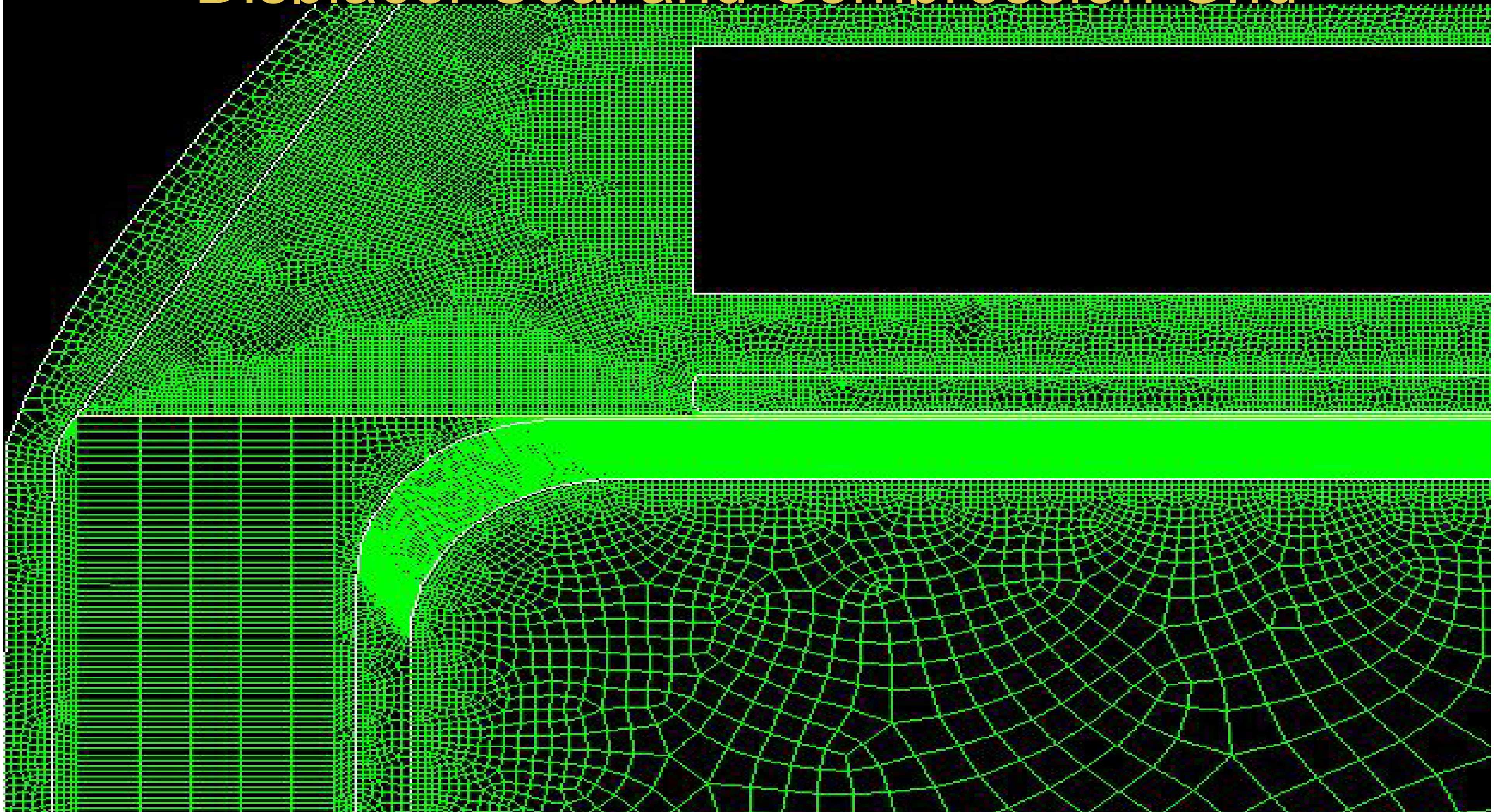
Compression Grid (Layering Example)



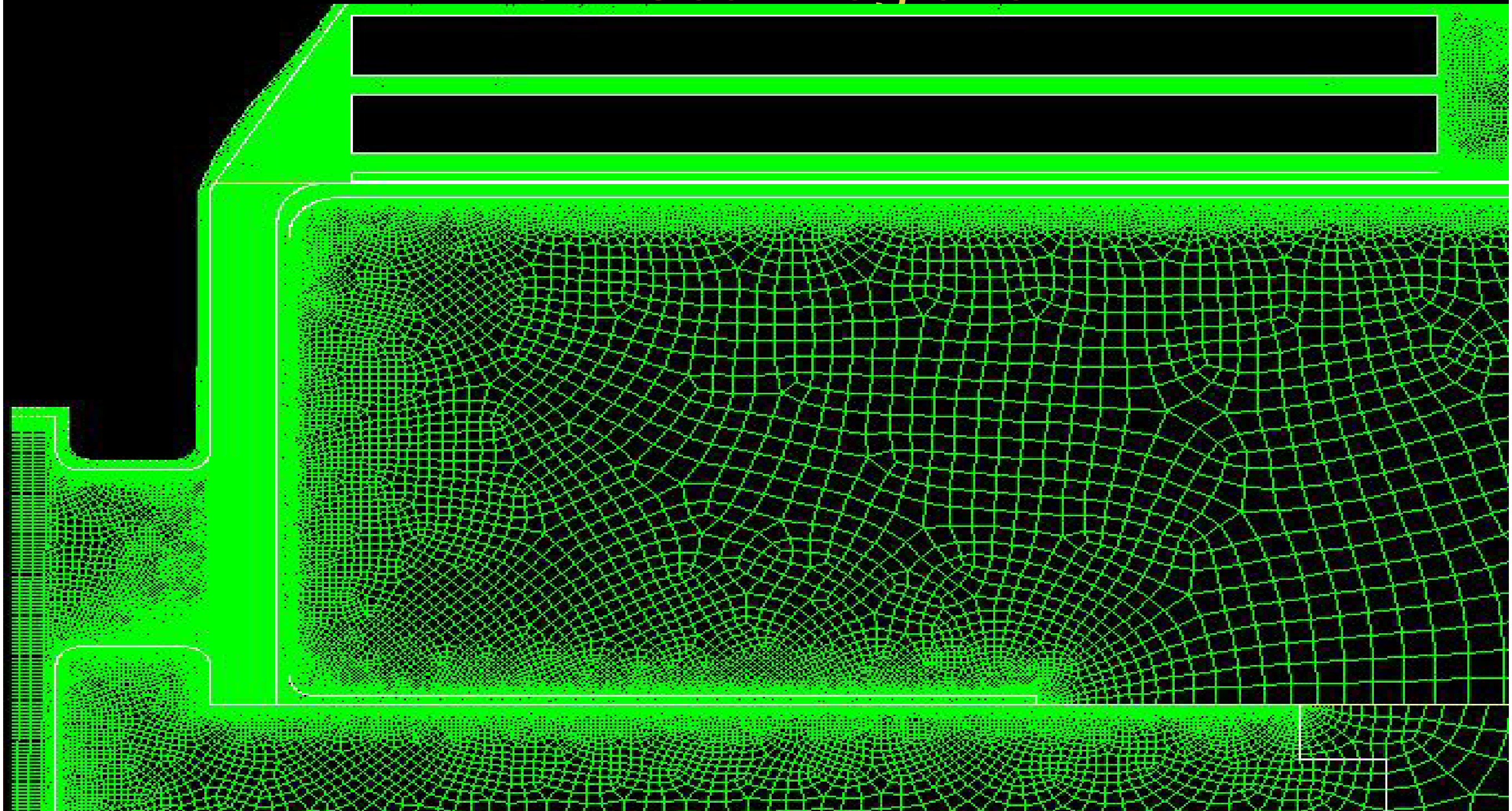
Displacer Seal Grid



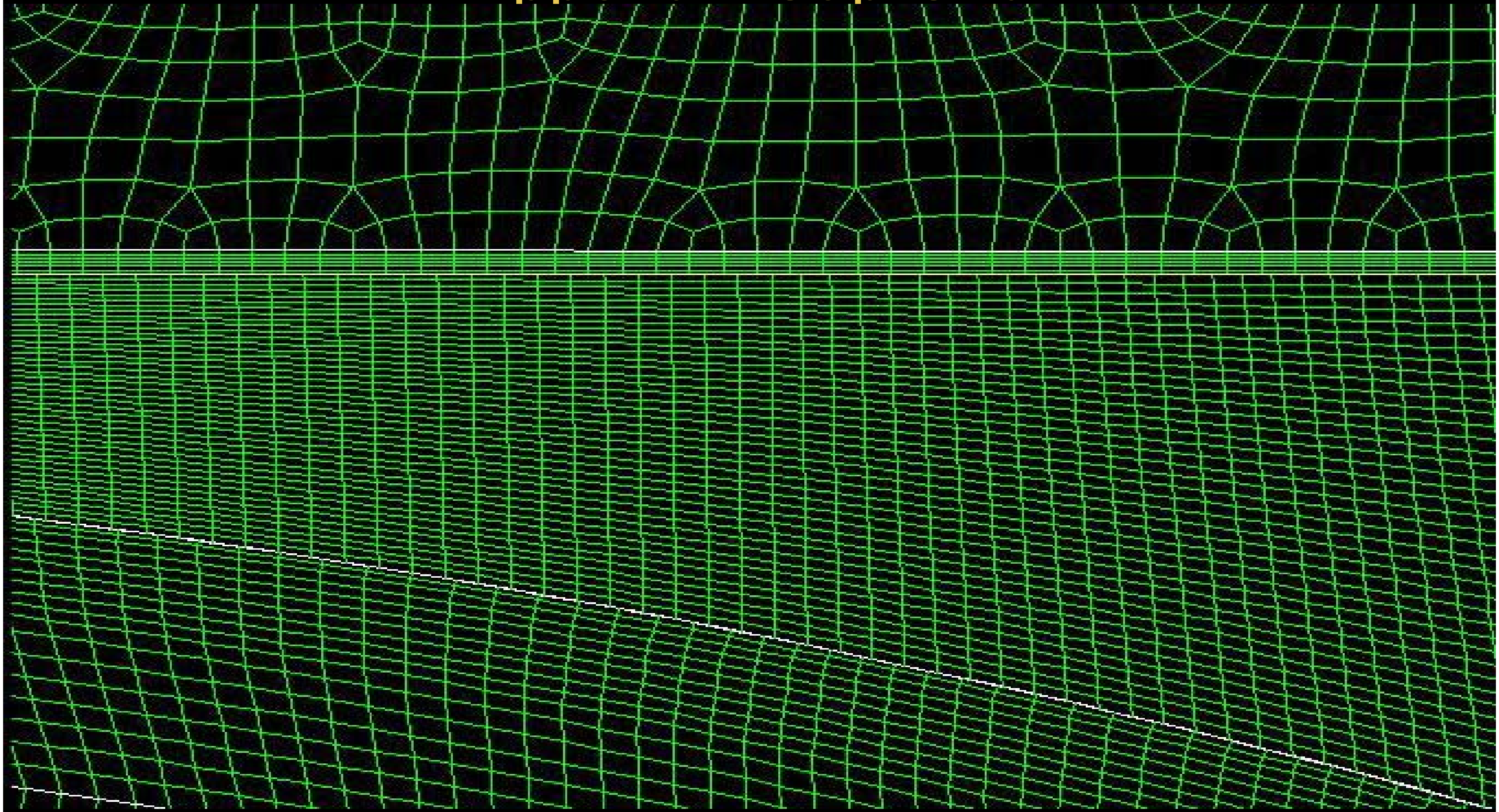
Displacer Seal and Compression Grid



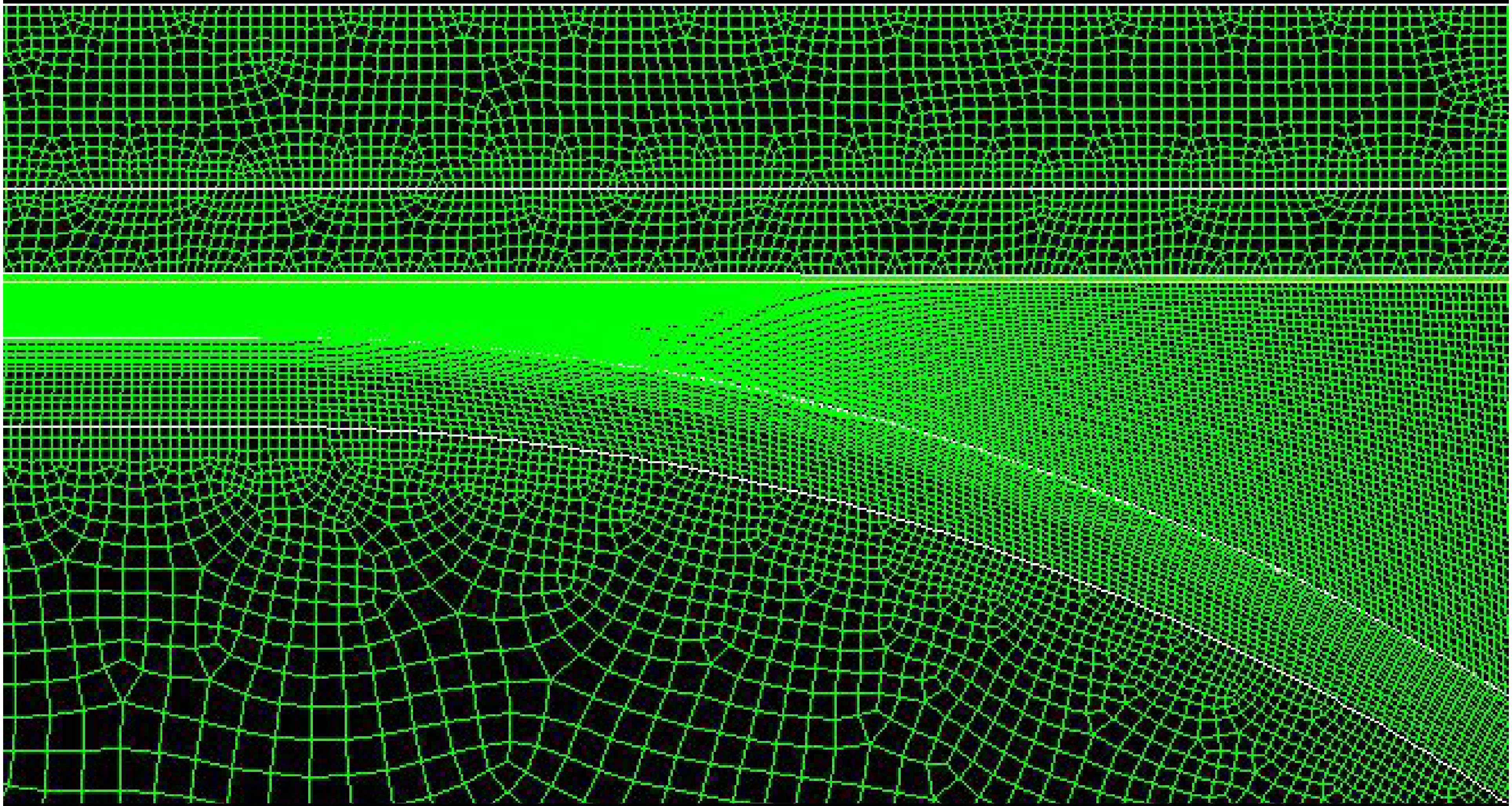
Both Seal Regions



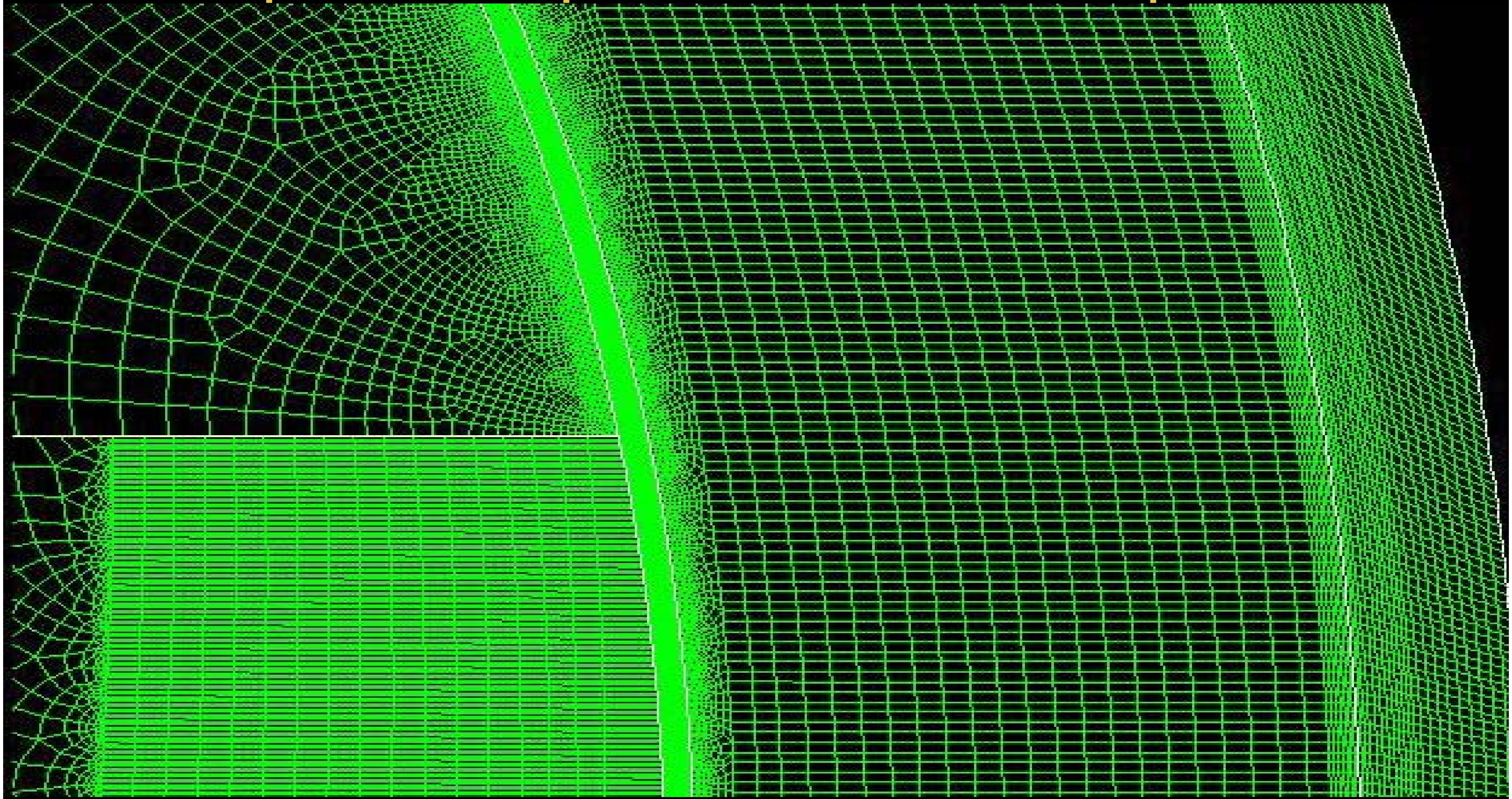
Appendix Gap Grid



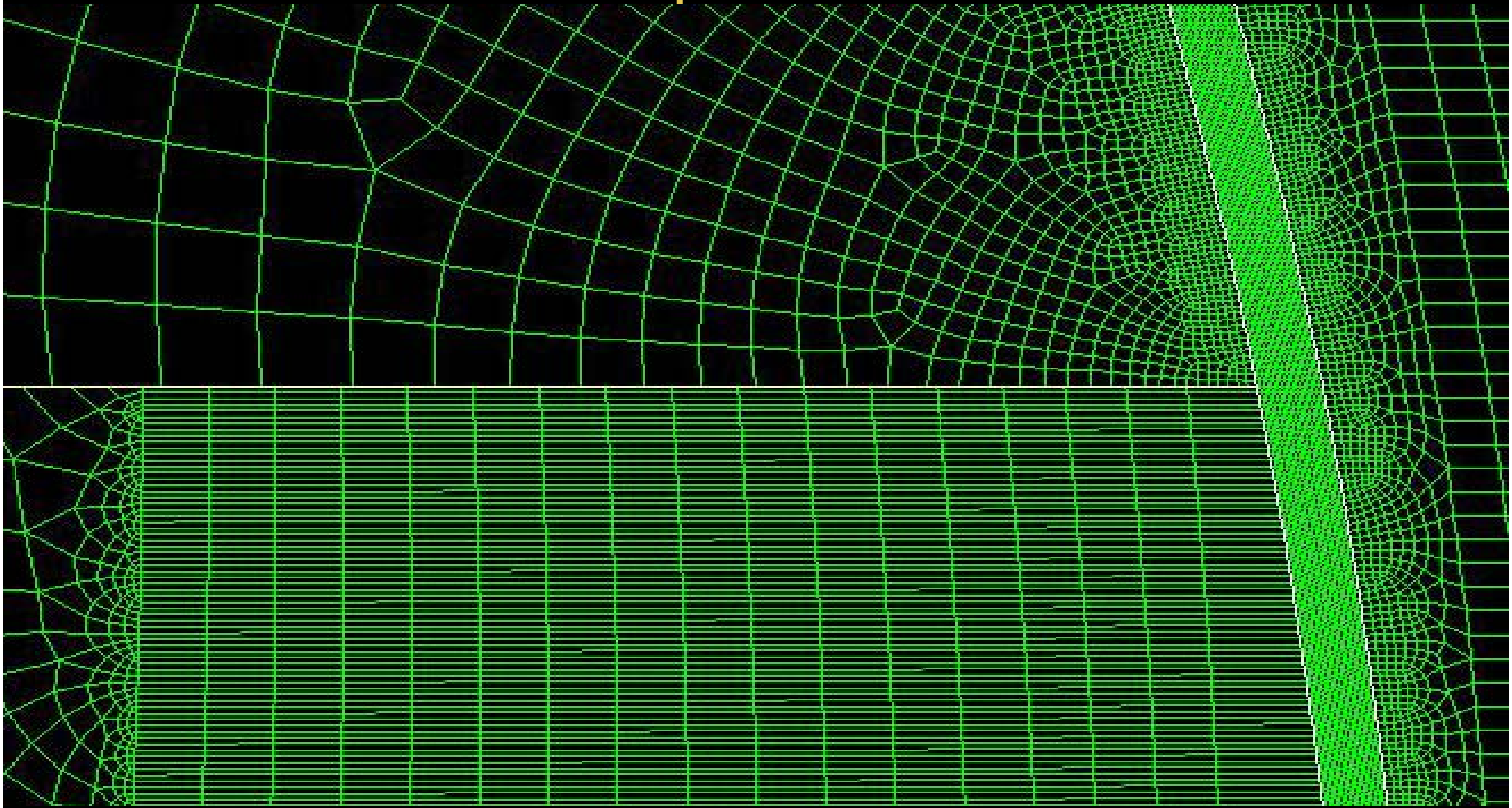
Appendix Gap Grid



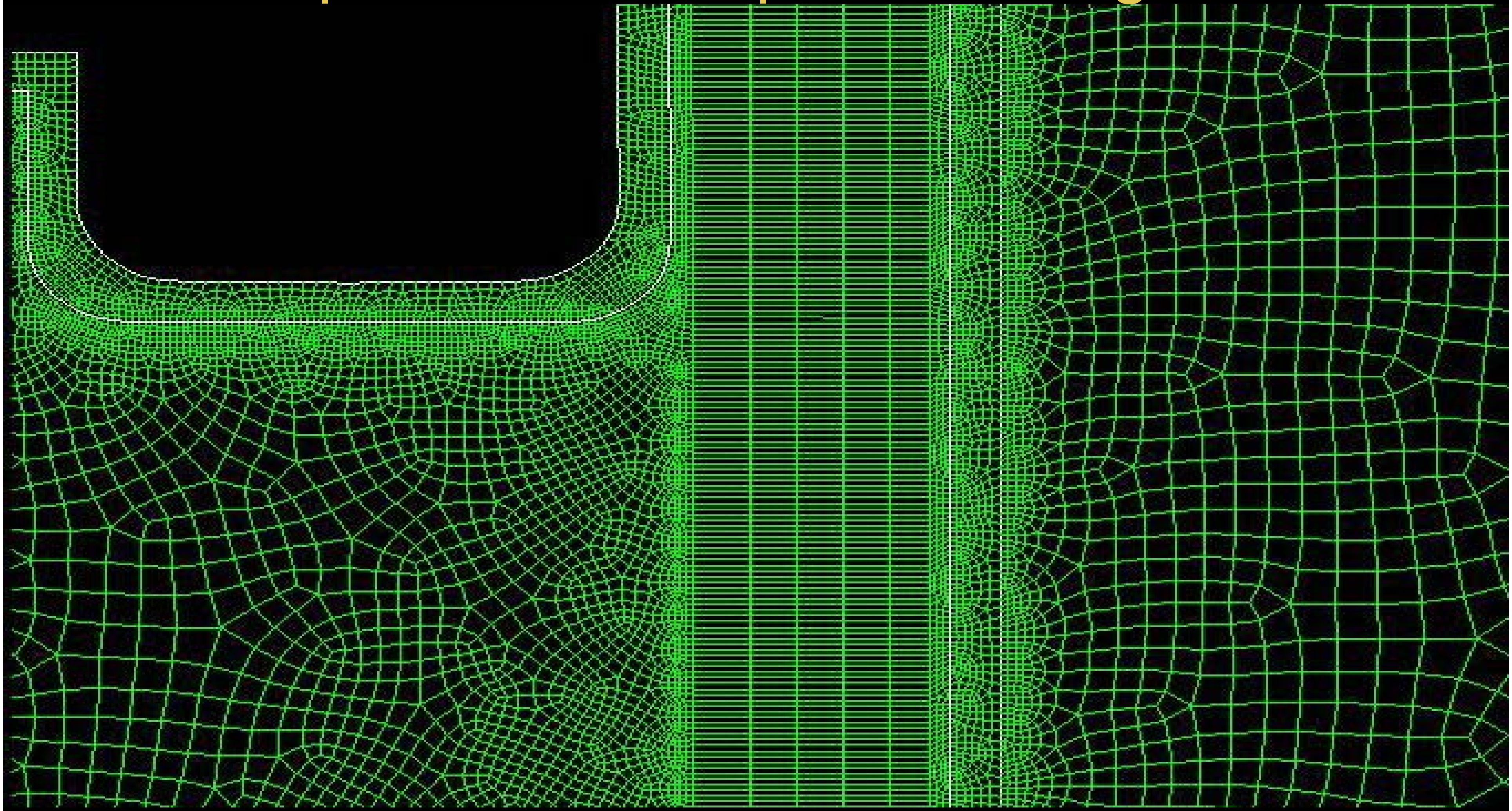
Expansion Space and Inside Displacer



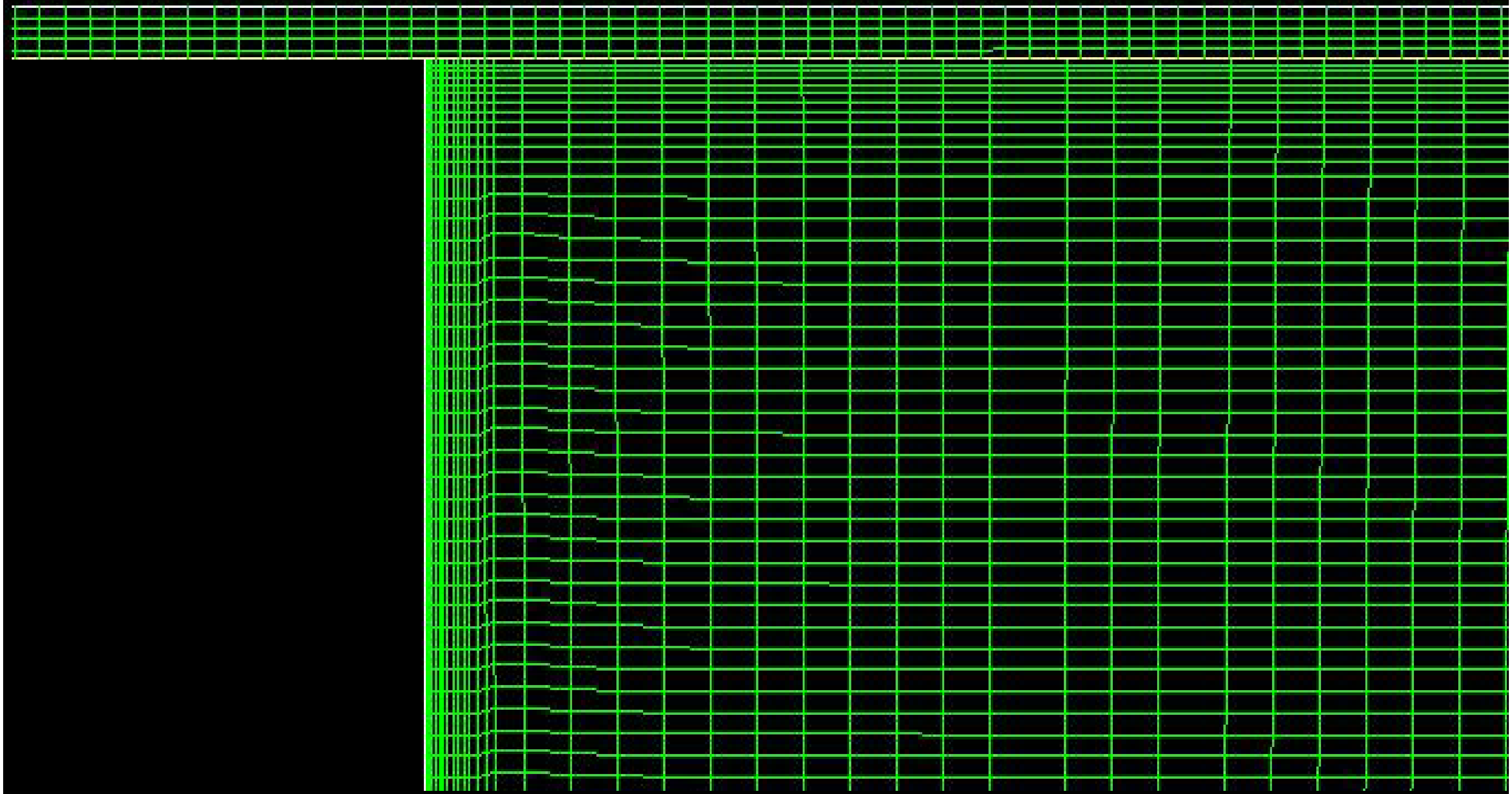
Inside Displacer and Wall



Spider and Compression Region

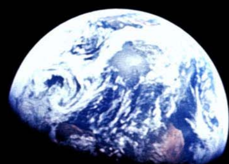


Piston Region



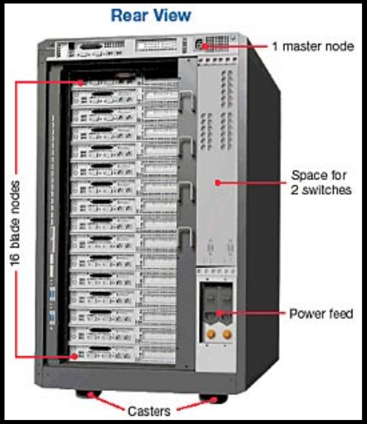
Conjugate Heat Transfer Strategy

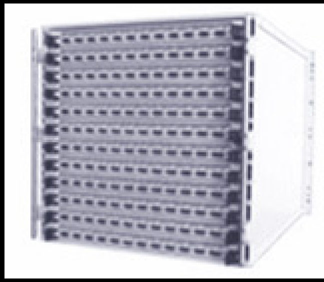
- Utilize coupled solver in double precision
- Maximize energy underrelaxation factor
- Double-sided boundary layers
- Turn off secondary temperature gradients
- Emphasize the coarse multigrid to avoid roundoff error
- Utilize explicit underrelaxation of temperature
- Maintain small time-steps (160/cycle)
- Go to higher space and time accuracy when possible



Higher Solution Speeds Achievable

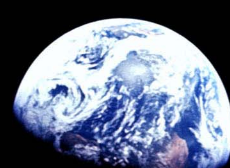
- Infiniband/High Capacity Switch
- 260 processors in a single 7 foot tower
- Higher-Order Techniques
- Quad/Octa Opteron Processors
- 256 bit computing



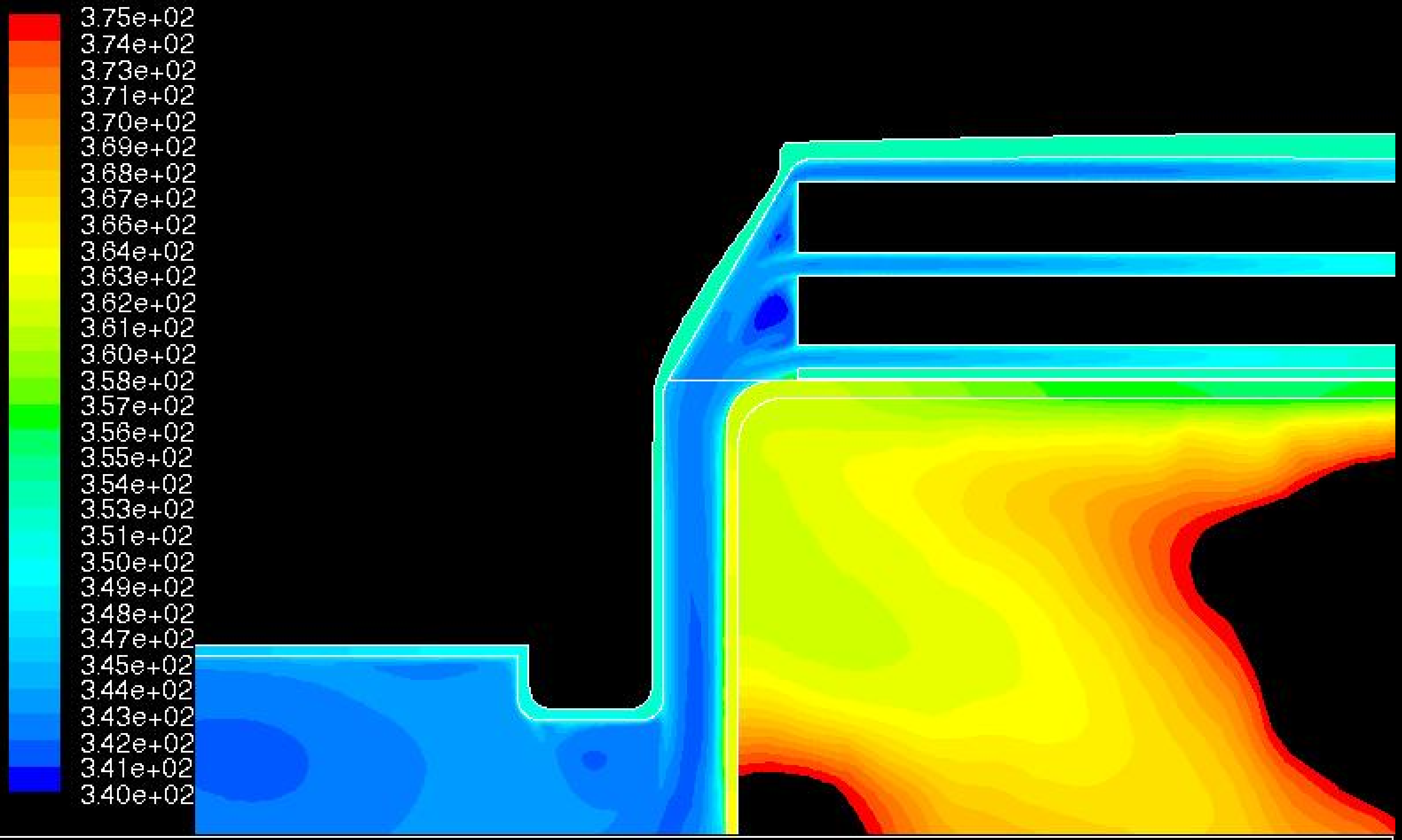


Conclusions

- First U.S. fully converged axisymmetric simulation of actual Stirling engine
- Comparison with experiment shows less than 1% error on power and efficiency
- More testing required to confirm
- Extending to three-dimensions for full part testing and integration

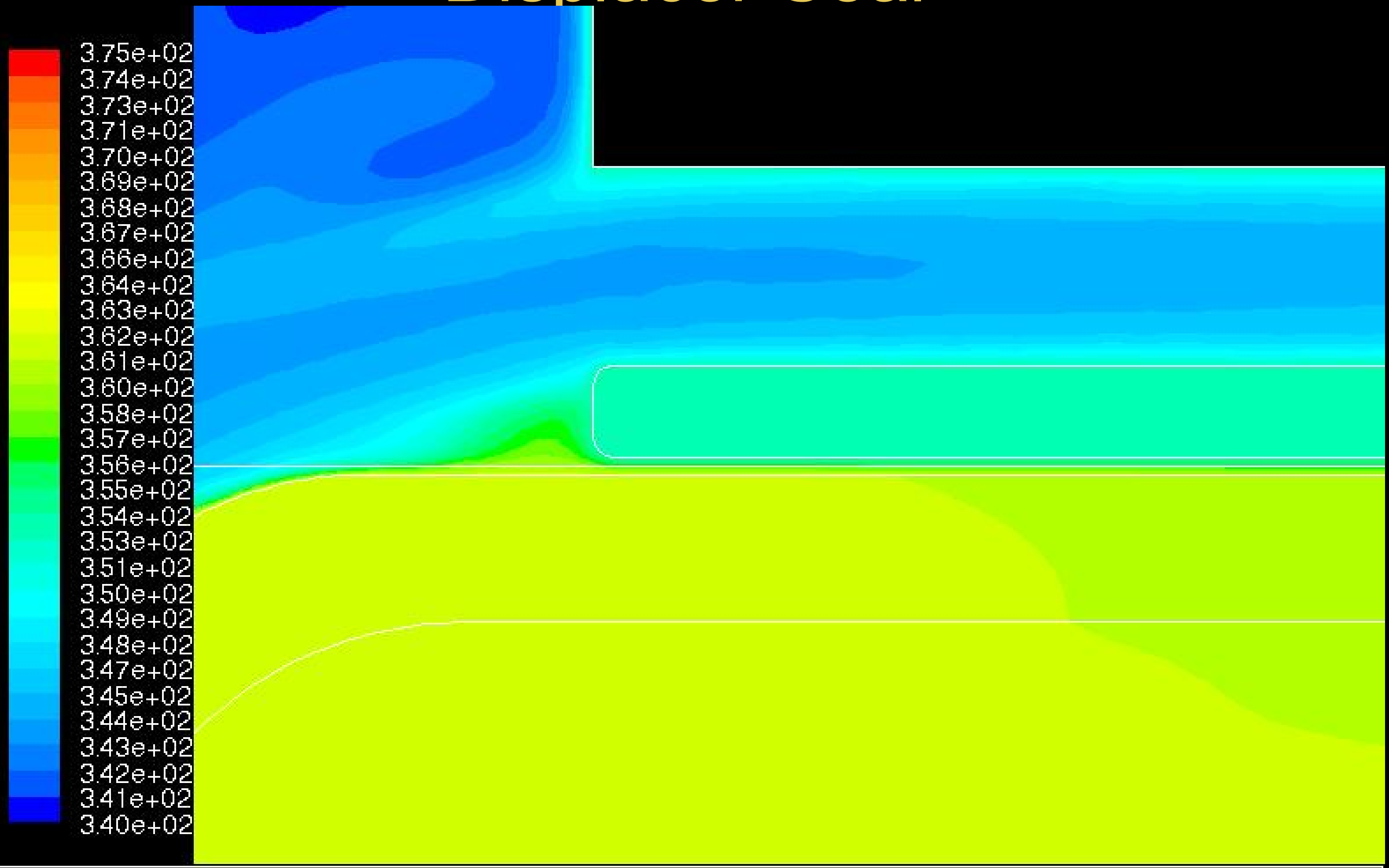


Cool End Heating



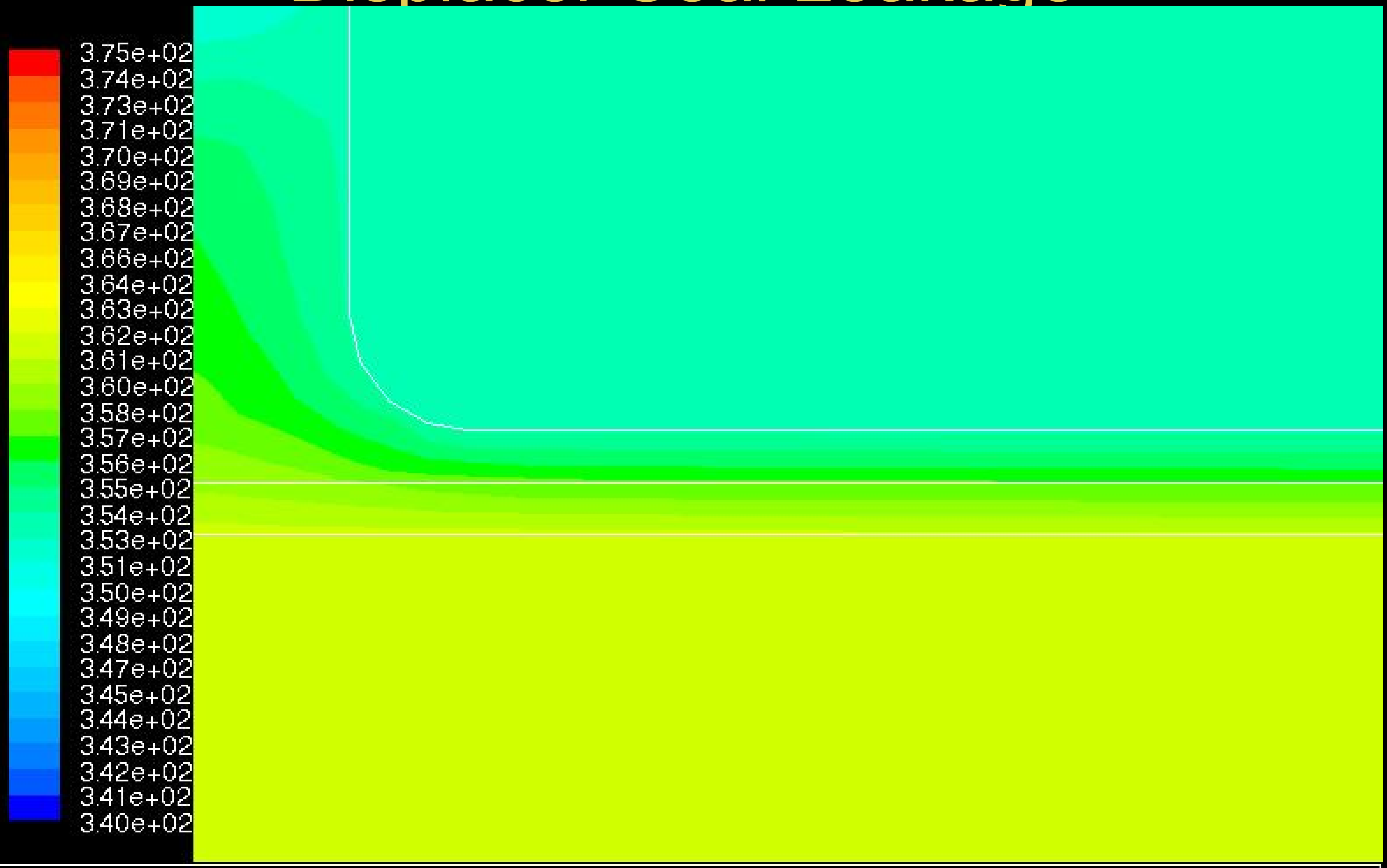
Contours of Static Temperature (k) (Time=5.1547e+00)

Displacer Seal



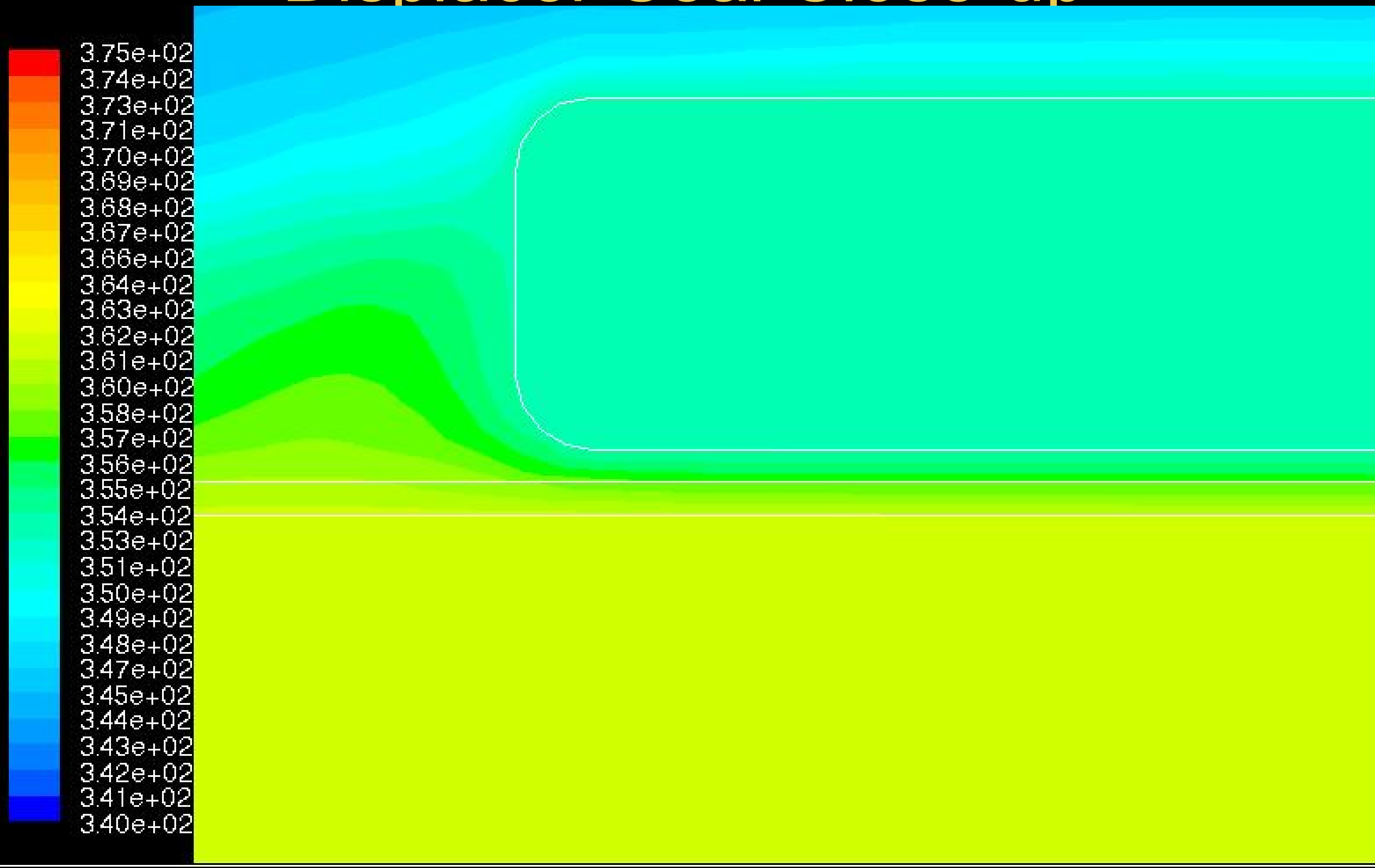
Contours of Static Temperature (k) (Time=5.1547e+00)

Displacer Seal Leakage



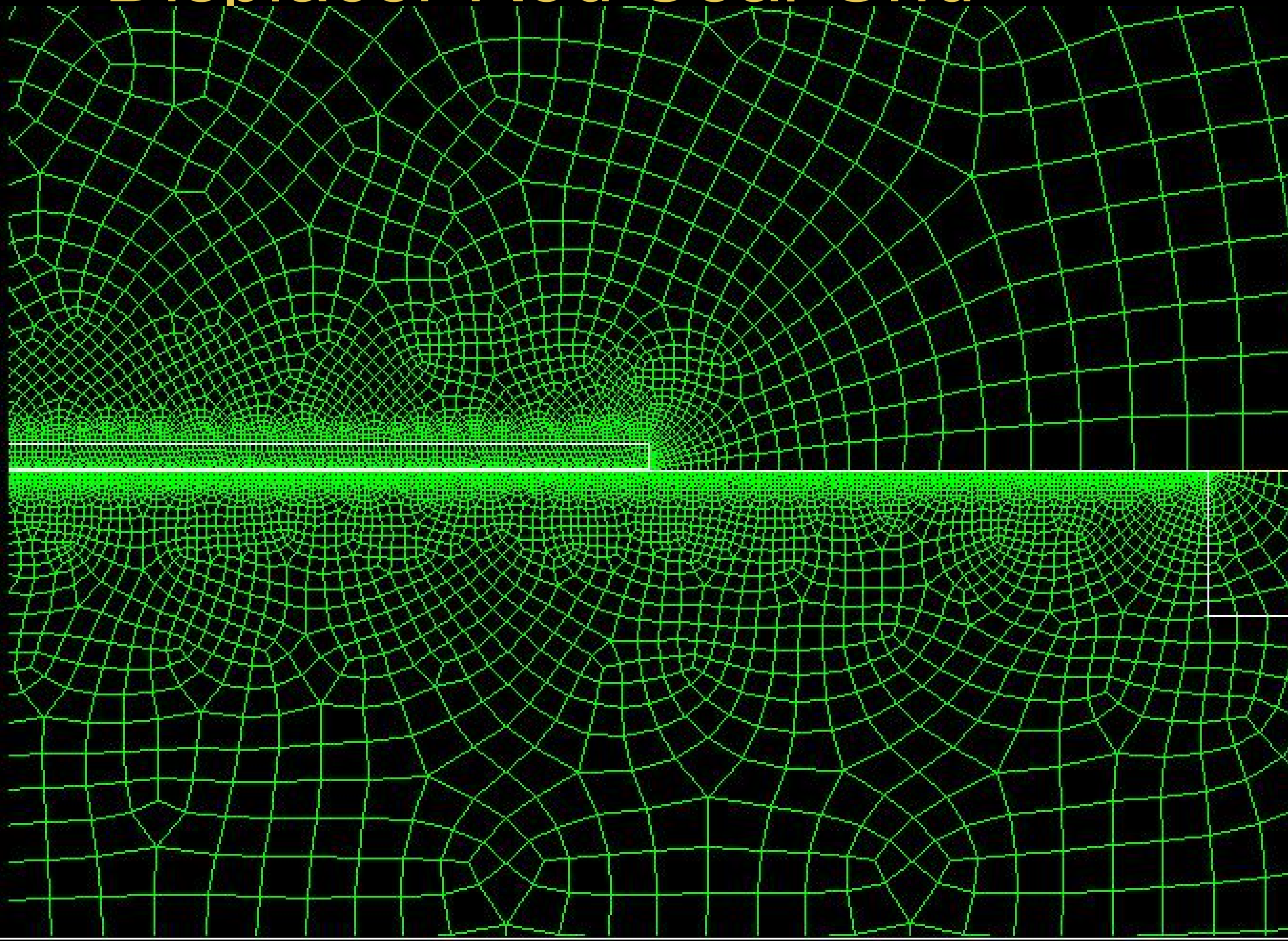
Contours of Static Temperature (k) (Time=5.1547e+00)

Displacer Seal Close-up



Contours of Static Temperature (k) (Time=5.1547e+00)

Displacer Rod Seal Grid



Grid (Time=5.1547e+00)