Nonlinear Incremental Thermal Stress Strain Analysis Portugues Dam

Thermal Analysis Project Team

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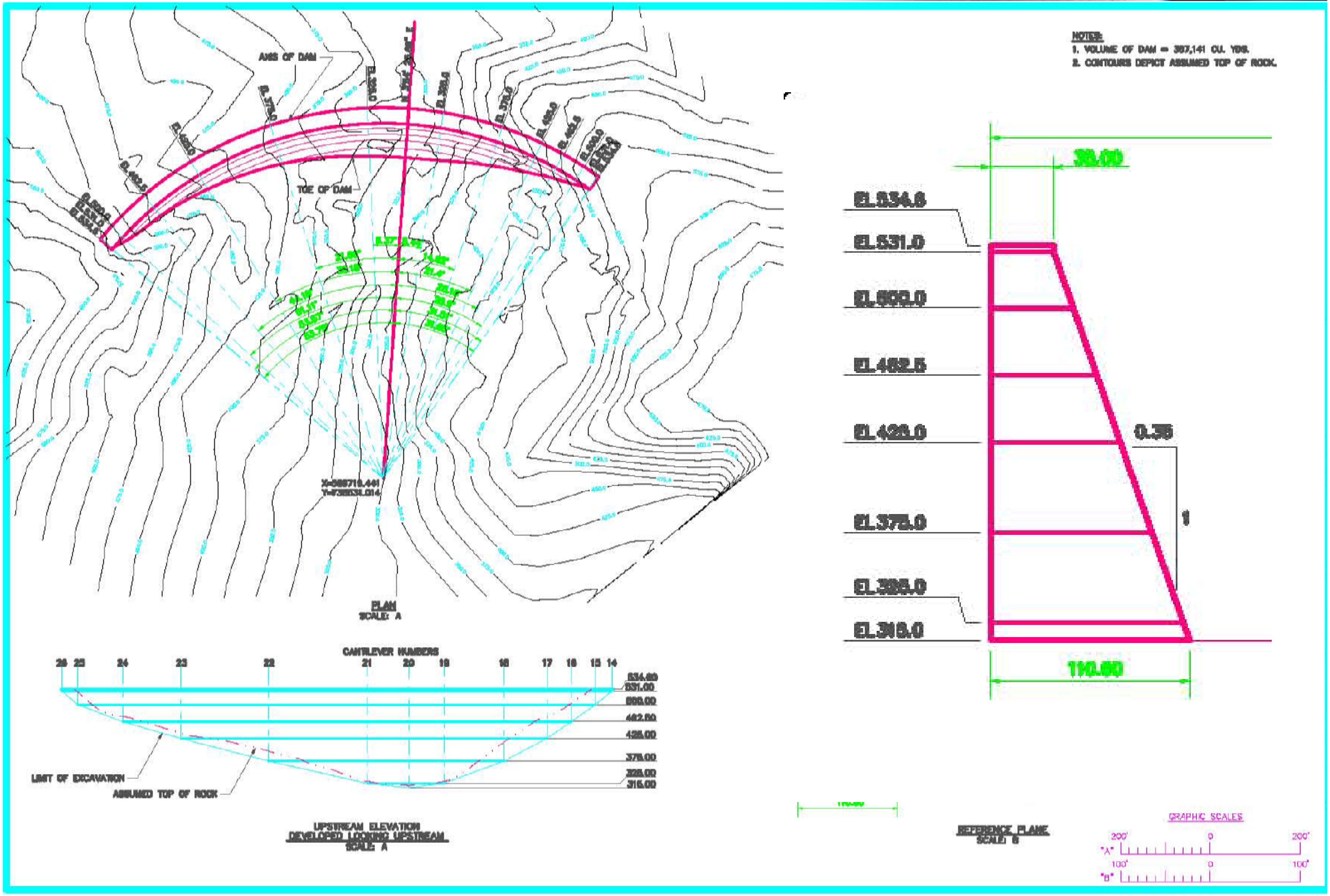
US Army Corps of Engineers® Jacksonville District

Objectives of Study

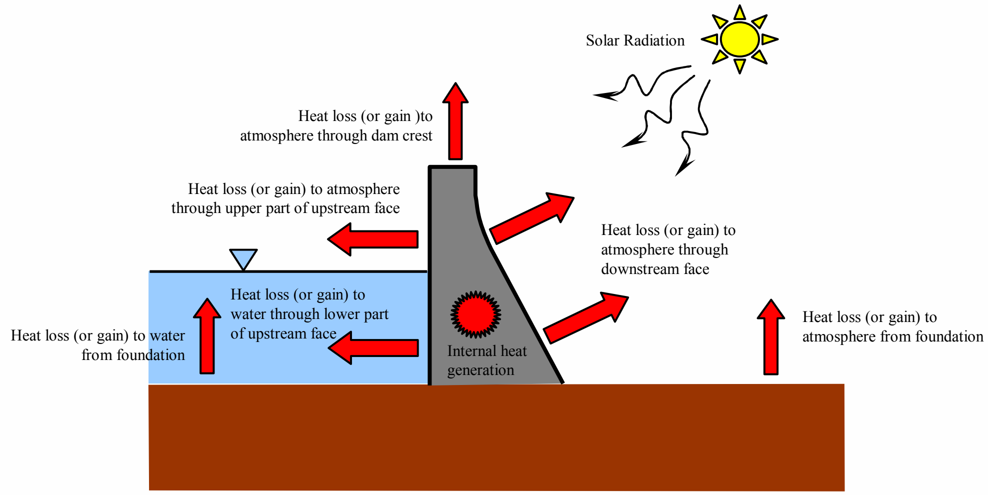
- Long term stable temperature response
- Location and behavior of contraction joints
- Potential for cracking
- Significance of material properties

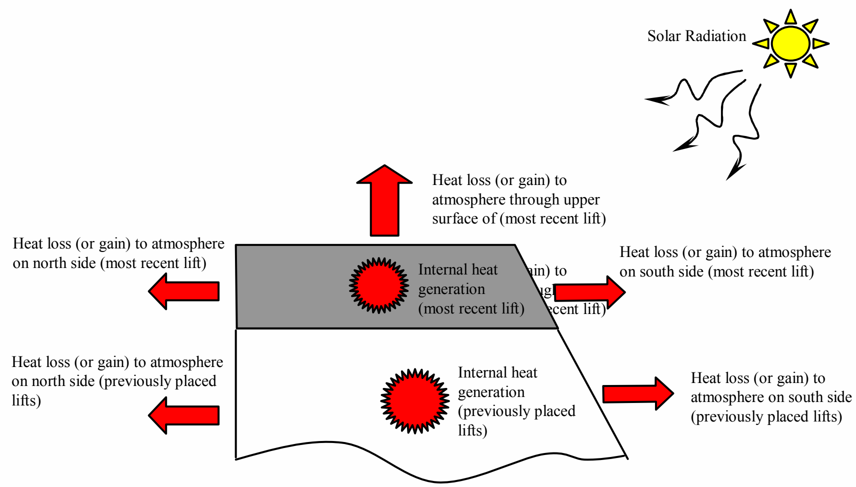

NOTES:
1. VOLUME OF DAM = 397,141 CU. YDS.
2. CONTOURS DEPICT ASSUMED TOP OF ROCK.
AXIS OF DAM
TOE OF DAM
PLAN
SCALE: A
CANTILEVER NUMBERS
26 25 24 23 22 21 20 19 18 17 16 15 14
534.00
531.00
500.00
462.50
425.00
375.00
325.00
315.00
LIMIT OF EXCAVATION
ASSUMED TOP OF ROCK
UPSTREAM ELEVATION
DEVELOPED LOOKING UPSTREAM
SCALE: A
EL.531.0
EL.500.0
EL.462.5
EL.425.0
EL.375.0
0.35
1
110.60
REFERENCE PLANE
SCALE: B
GRAPHIC SCALES
200' 0 200'
"A"
100' 0 100'
"B"

Project Approach

- Phase I - Preliminary Analysis
  - Model testing (concurrent with dam design)
  - Parametric study to determine significant parameters
- Phase II – Final Analysis
  - Final dam geometry
  - Final material properties

Analysis Procedure





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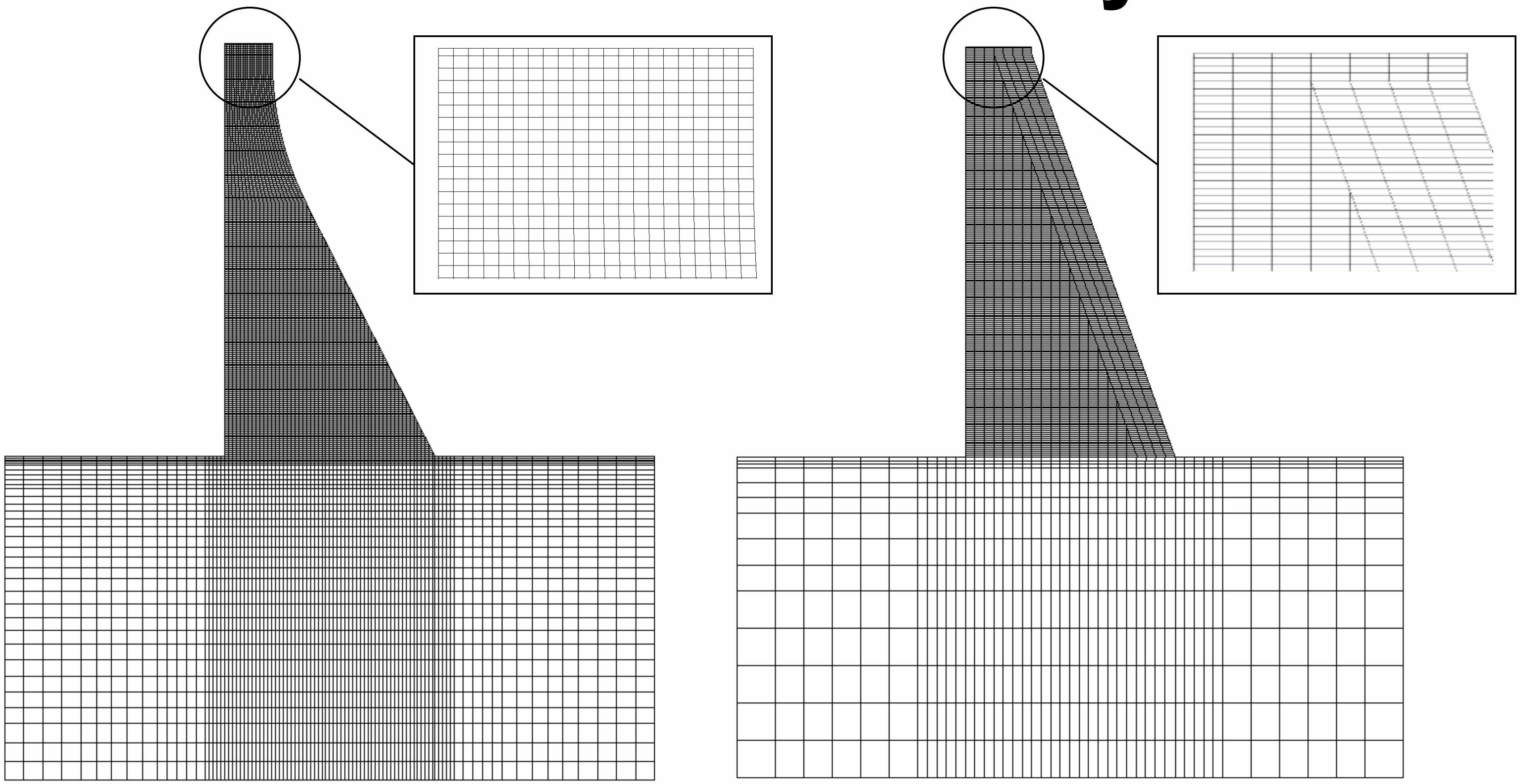
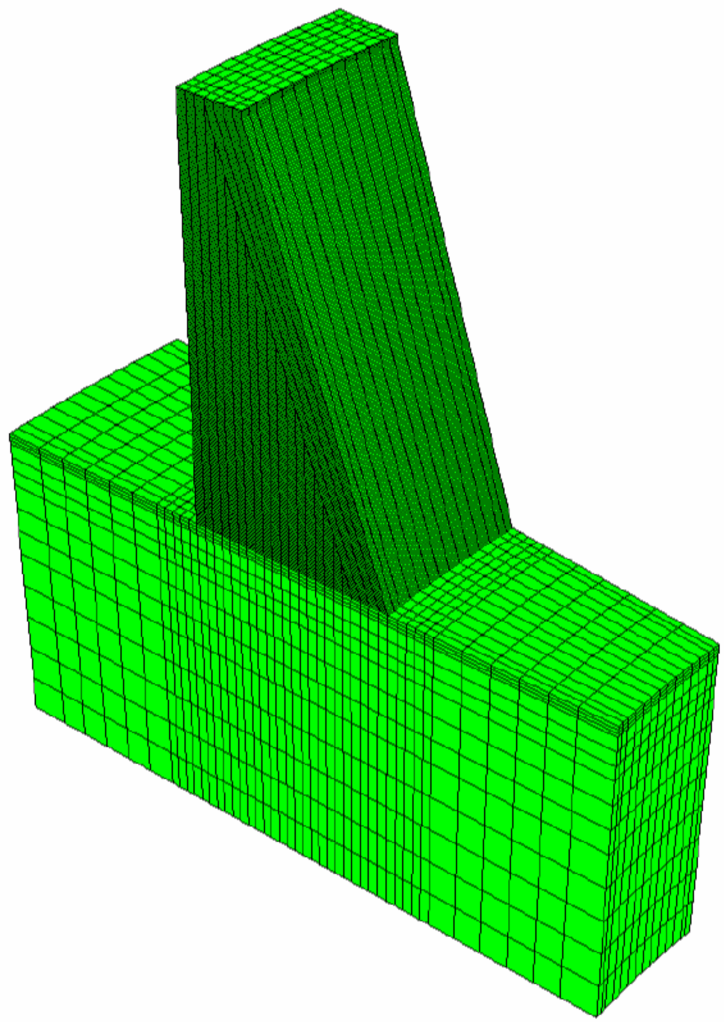
Analysis Approach
(ETL 1110-2-365)

- De-coupled thermal/stress analysis using ABAQUS/Standard
- Combination 2D and 3D analysis
- Incremental placement of lifts
- Material nonlinearity
- Boundary conditions

2D Dam Geometry

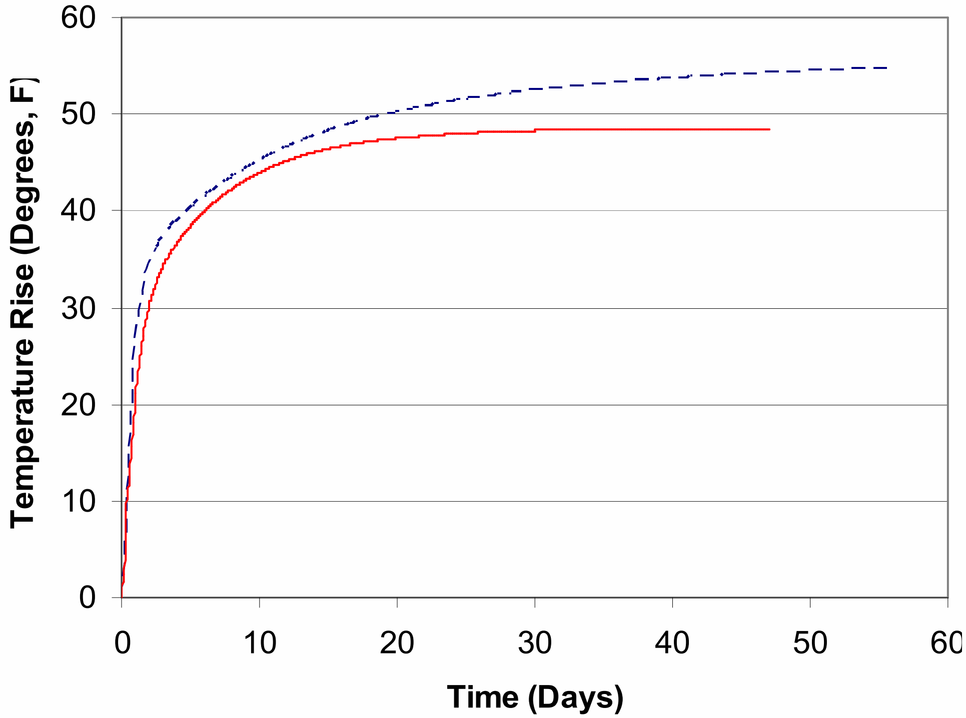


3D Dam Geometry



Thermal Material Properties

- Roller compacted concrete
  - Non linear internal heat generation (heat of hydration from adiabatic temperature rise)
  - All other properties linear (Cp, k, γ)
- Linear (uniform) foundation material



$$\dot{H} = \gamma \cdot C_p \cdot \frac{\Delta\theta}{\Delta t} \qquad (\text{BTU/in}^3/\text{day})$$

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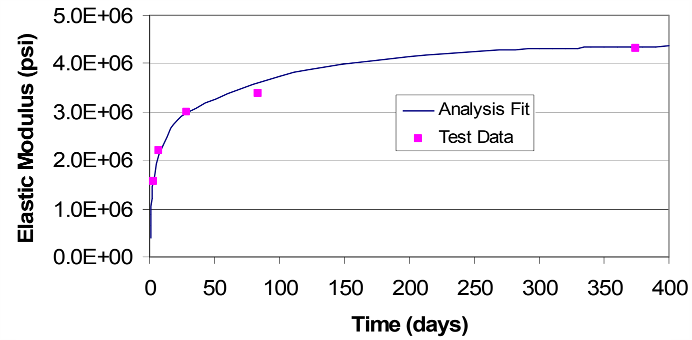
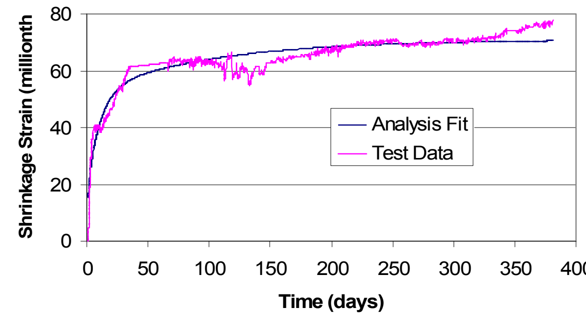
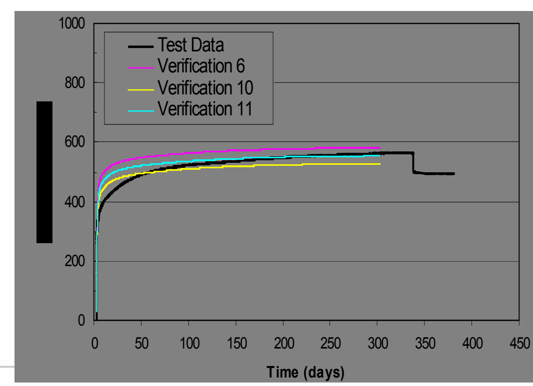
Structural Material Properties

- General nonlinear properties for RCC
  - Modulus
  - Shrinkage
  - Creep/Aging
- Linear foundation material







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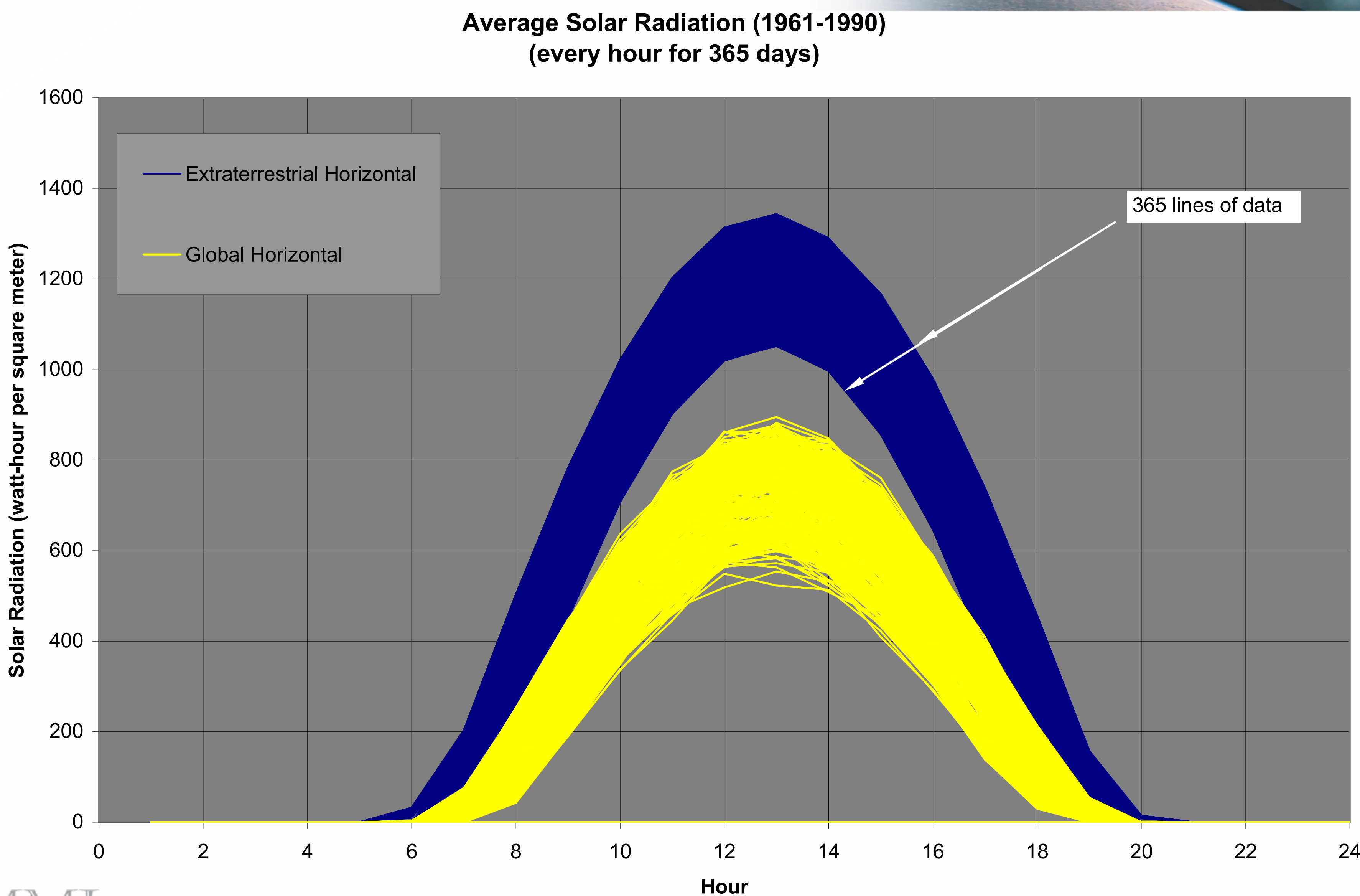
Boundary Conditions

- Thermal analysis
  - Time/temperature dependent transfer films
  - Solar radiation flux
  - Heat loss to foundation
- Structural analysis
  - Foundation constraint
  - 3D Model - contact at construction joints



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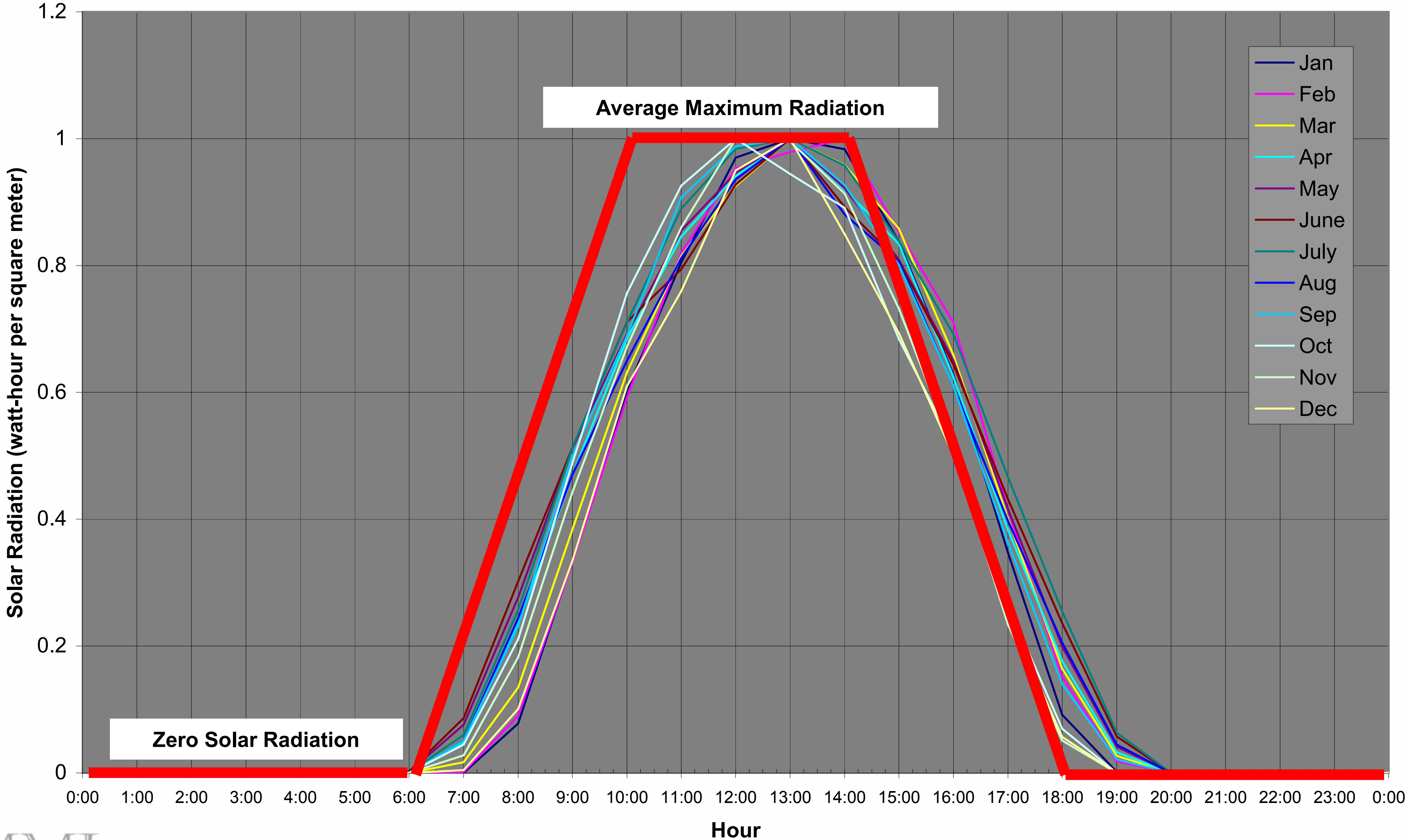
Average Data (1961 - 1990) 15th Day of Each Month
Global Horizontal (Normalized to Max)



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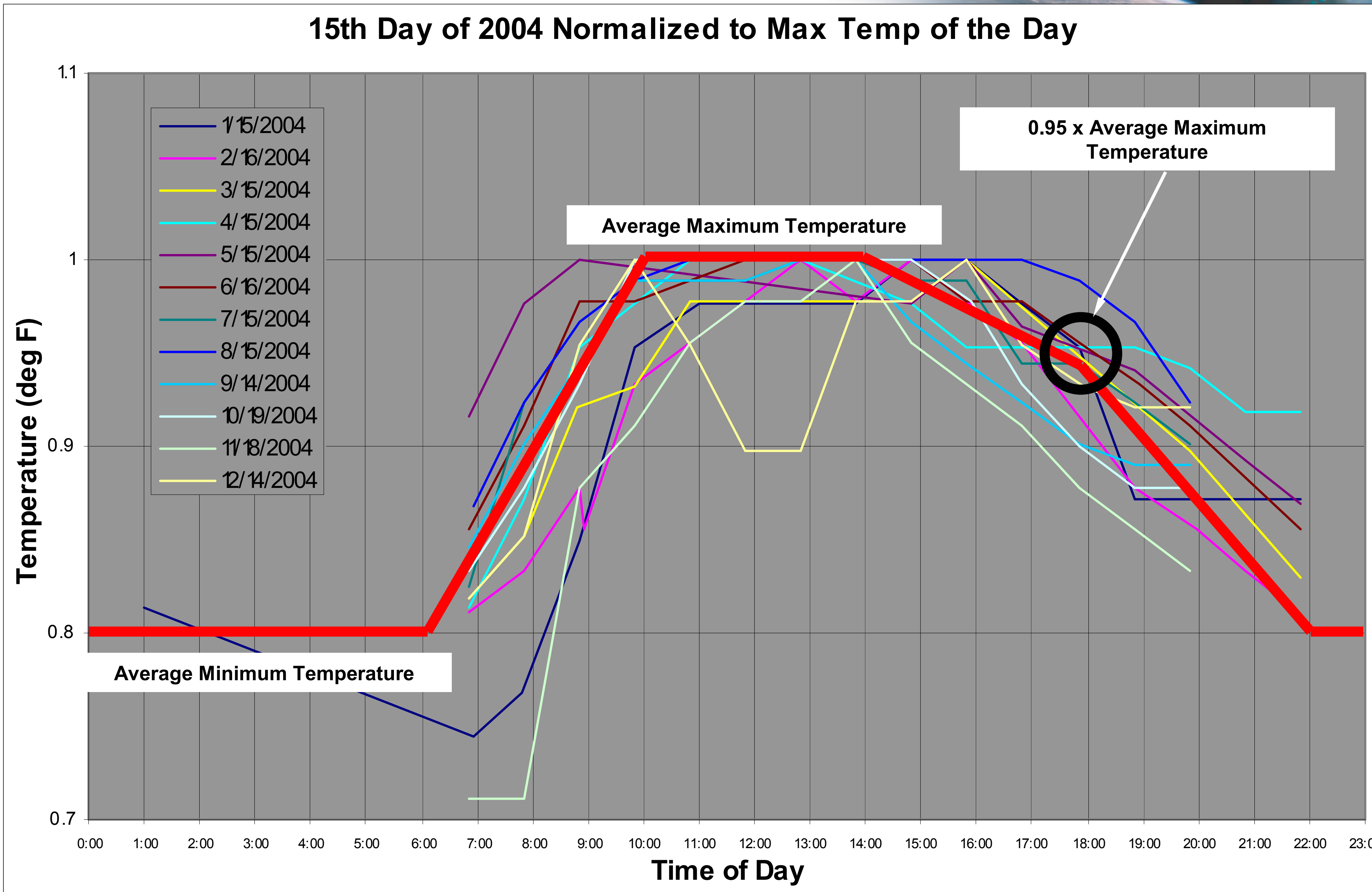
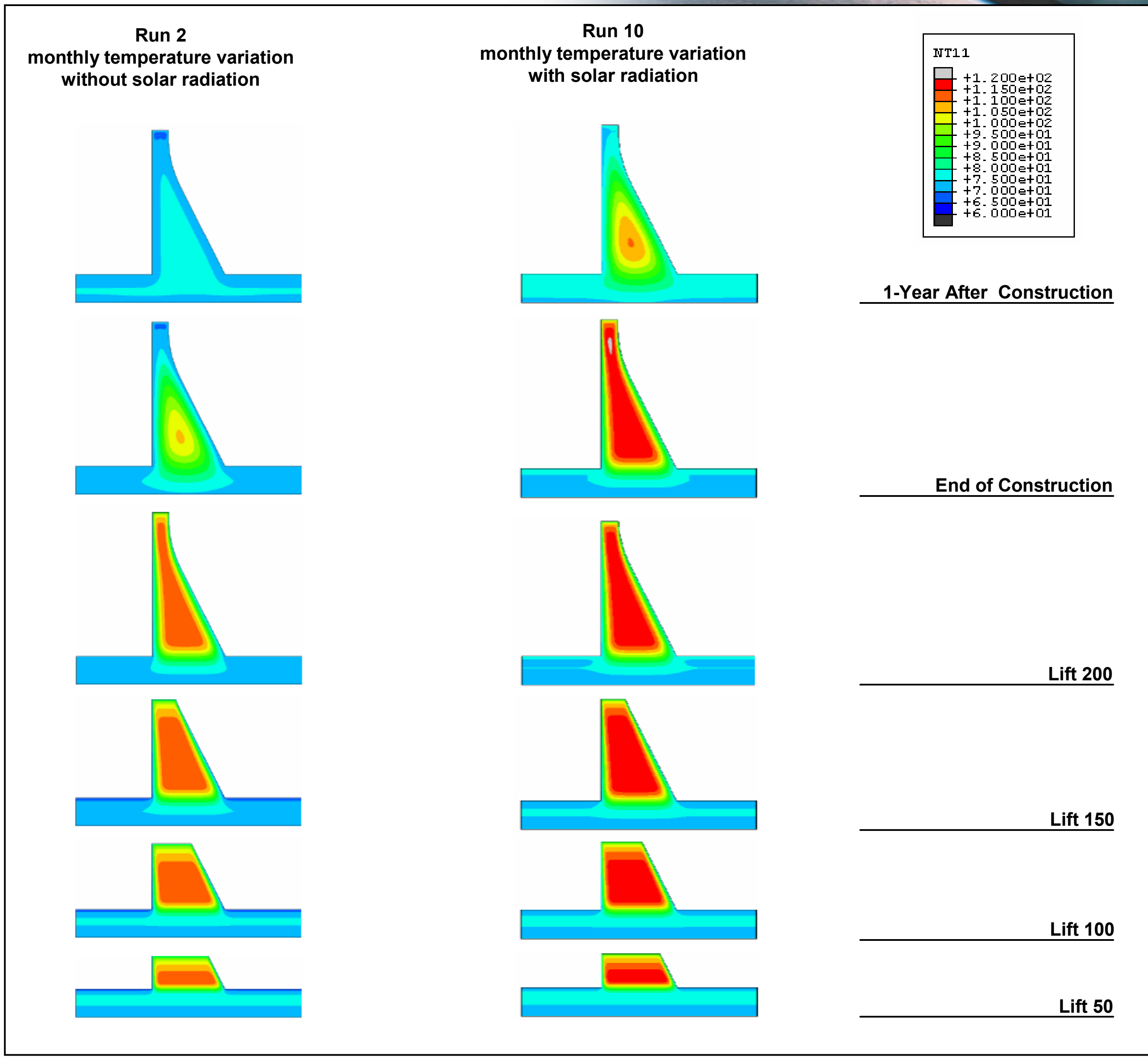
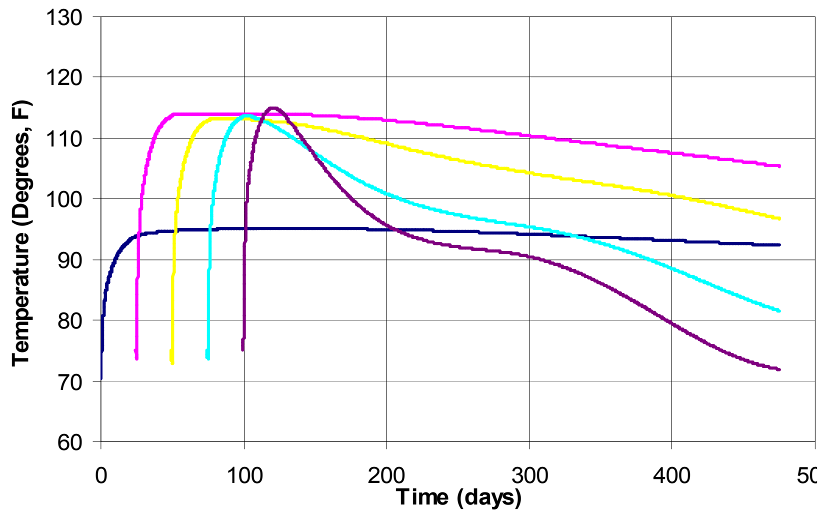


15th Day of 2004 Normalized to Max Temp of the Day
Temperature (deg F)
Time of Day
1.1
1
0.9
0.8
0.7
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
1/15/2004
2/16/2004
3/15/2004
4/15/2004
5/15/2004
6/16/2004
7/15/2004
8/15/2004
9/14/2004
10/19/2004
11/18/2004
12/14/2004
Average Maximum Temperature
0.95 x Average Maximum Temperature
Average Minimum Temperature

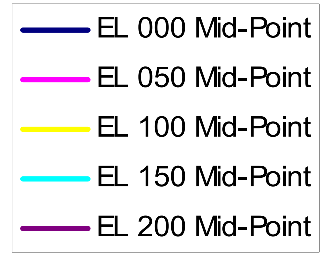
Phase I Example Results

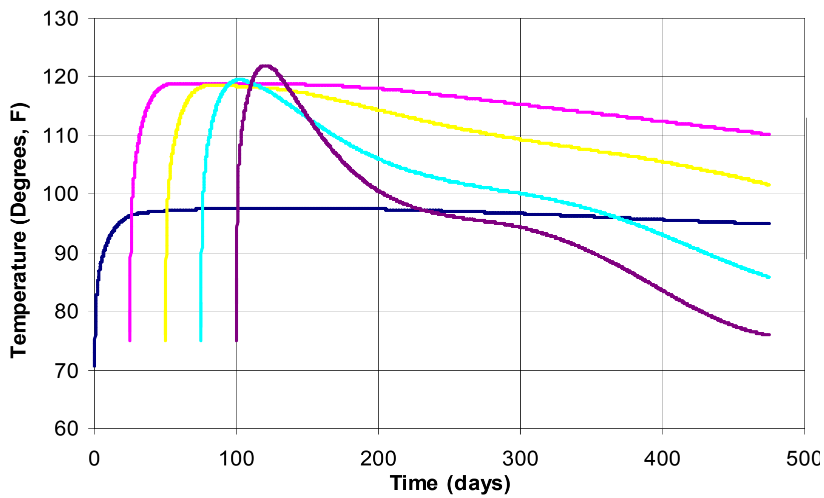


Phase I Example Results

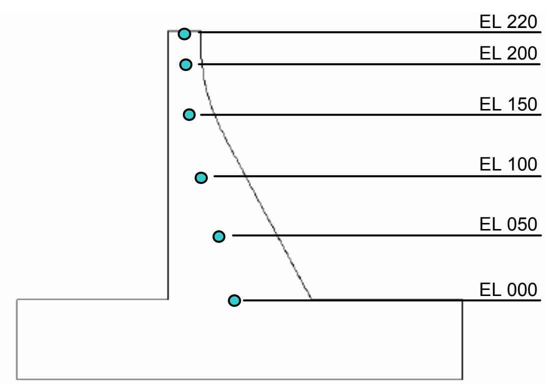


(a) Solar Radiation not Included (Run 2)

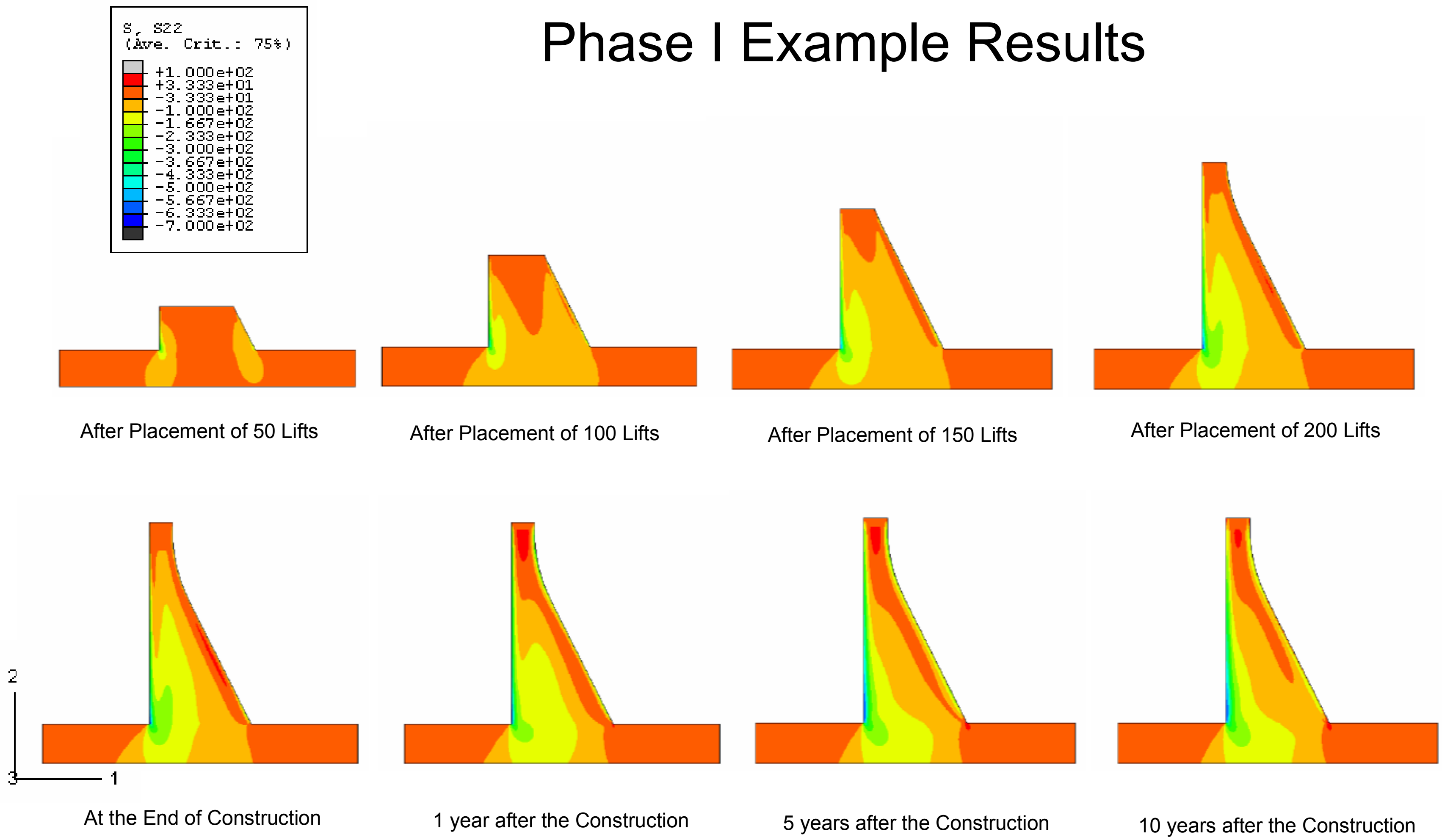




(b) Solar Radiation Included (Run 10)



Phase I Example Results



Simplified Analysis

- Tatro & Schrader
- ACI 207.2R-95
- ETL 1110-2-542

Simplified Thermal Analysis of Portugues Dam

Structural Properties

Crest length X	1,298.1 ft	15,577 in
Cross section length L	110 ft	
Cross section height H	220 ft	
L/H	0.5	
A_f/A_g	2.5	

Monthly Average Temperatures

January	75.0 °F
February	75.2 °F
March	75.7 °F
April	77.1 °F
May	78.9 °F
June	80.4 °F
July	80.9 °F
August	80.8 °F
September	80.2 °F
October	79.5 °F
November	77.9 °F
December	75.8 °F
Average	78.1 °F

RCC Thermal Properties

Adiabatic temperature rise T_{ad}	48 °F (25+ days)	
Specific heat C_h	0.234 BTU/lb-°F	
Conductivity K	1.835334 BTU/in-day-°F	
Diffusity h^2	3.5 in²/hr	0.024 ft²/hr

Thermal Data

RCC placement temperature T_i	78.1 °F
Final stable temperature T_f	78.1 °F

(Assume the internal mass will cool to the average annual temperature)

Induced strain

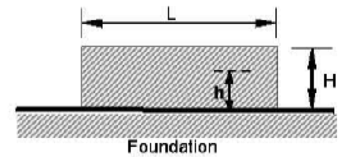
Long term temperature change $dT=T_i+T_{ad}-T_f$	48.0 °F
Induced strain $\varepsilon = C_T dT K_R K_f$	2.02E-04
Cracking strain $\varepsilon_{cr} = \varepsilon - \varepsilon_{sc}$	9.50E-05
Total crack width (shrinkage) $cw_{total} = \varepsilon_{cr} L$	1.48 in
Assumed crack width (cw)	0.125 in
No of cracks $N = cw_{total}/cw$	11.84
Average crack spacing $S = X/N$	109.6 ft

RCC Mechanical Properties

Coefficient of thermal expansion C_T	4.2E-06 /°F
Weight density w_c	0.09265046 lb/in³
Tensile strain capacity ε_{sc}	1.065E-04
Modulus of elasticity RCC E_c	4.30E+06
Modulus of elasticity foundation E_f	3.70E+06

Restraint Factors

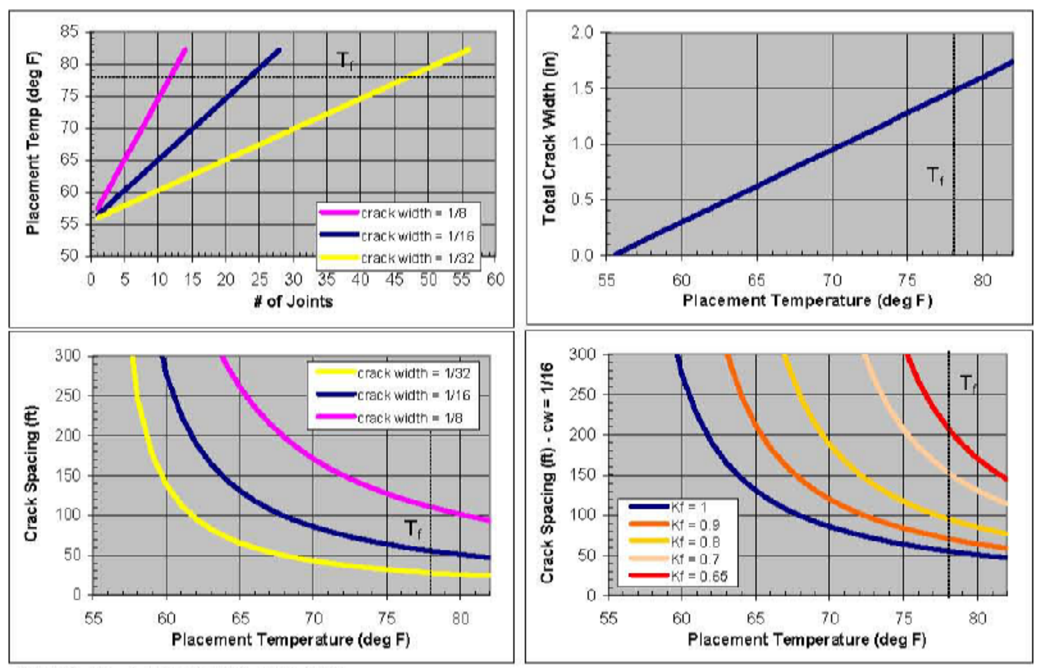
Compute restraint factors (Y or N)?	n
h/H	0
Structural restraint factor K_R	1.00
Foundation restraint factor K_f	1.00



$$K_R = \left(\frac{\frac{L}{H}-2}{\frac{L}{H}+1}\right)^{h/H} \quad for L/H \geq 2.5$$

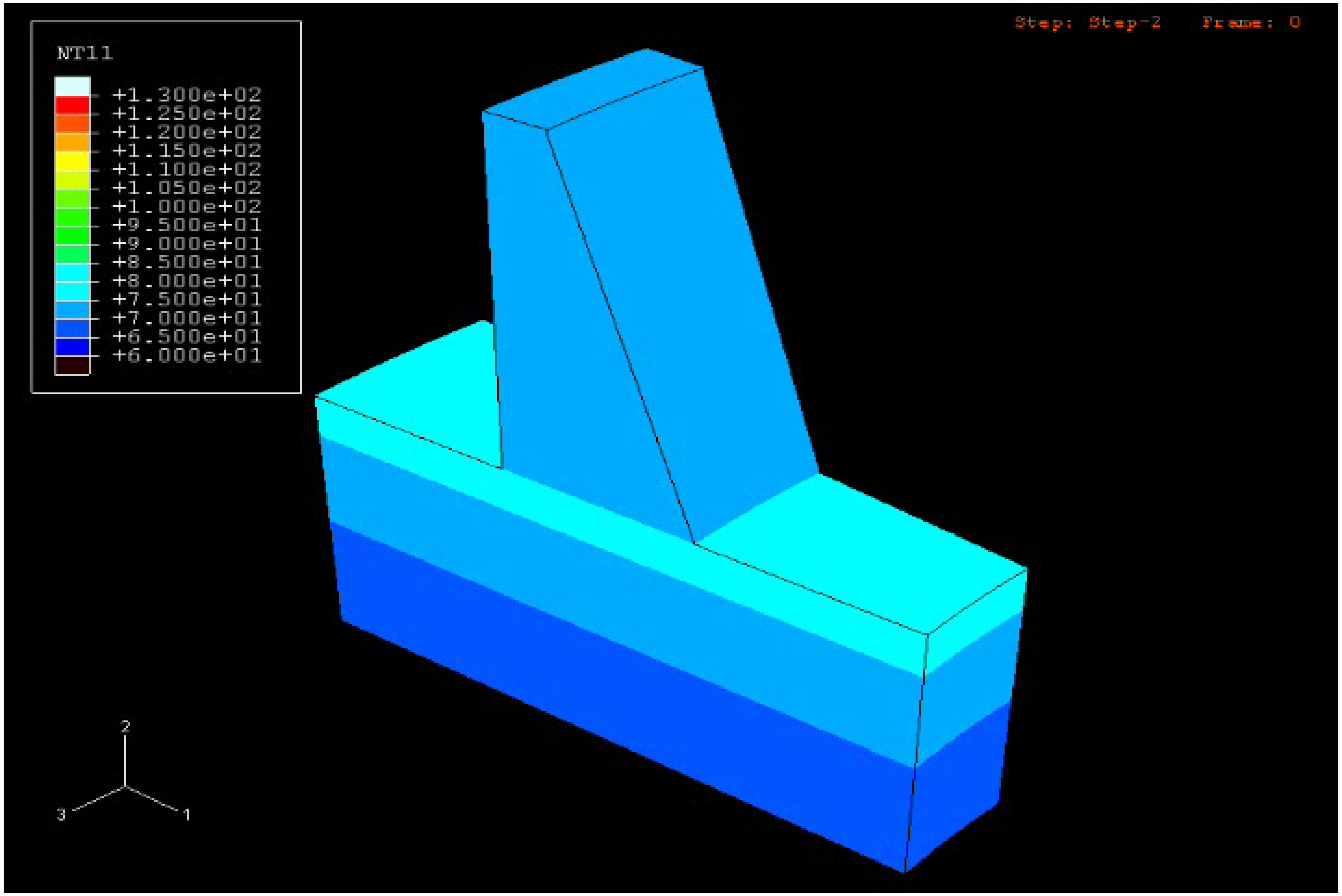
$$K_R = \left(\frac{\frac{L}{H}-1}{\frac{L}{H}+10}\right)^{h/H} \quad for L/H < 2.5$$

$$K_f = \frac{1}{1 + \frac{A_g E_c}{A_f E_f}}$$



Note: Kf = Kr = 1, if not specified on the graph

Results Status (Phase II) - Thermal



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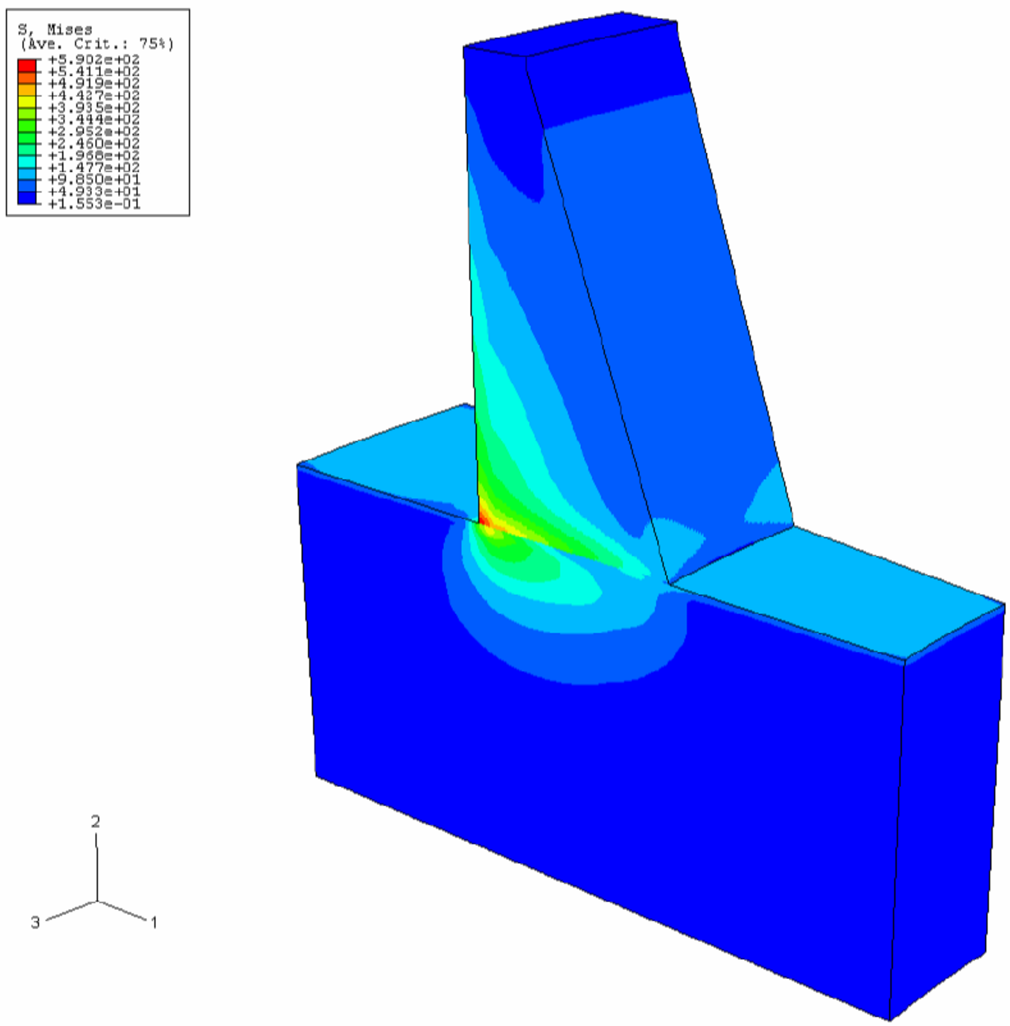
Results Status Phase II - Stress



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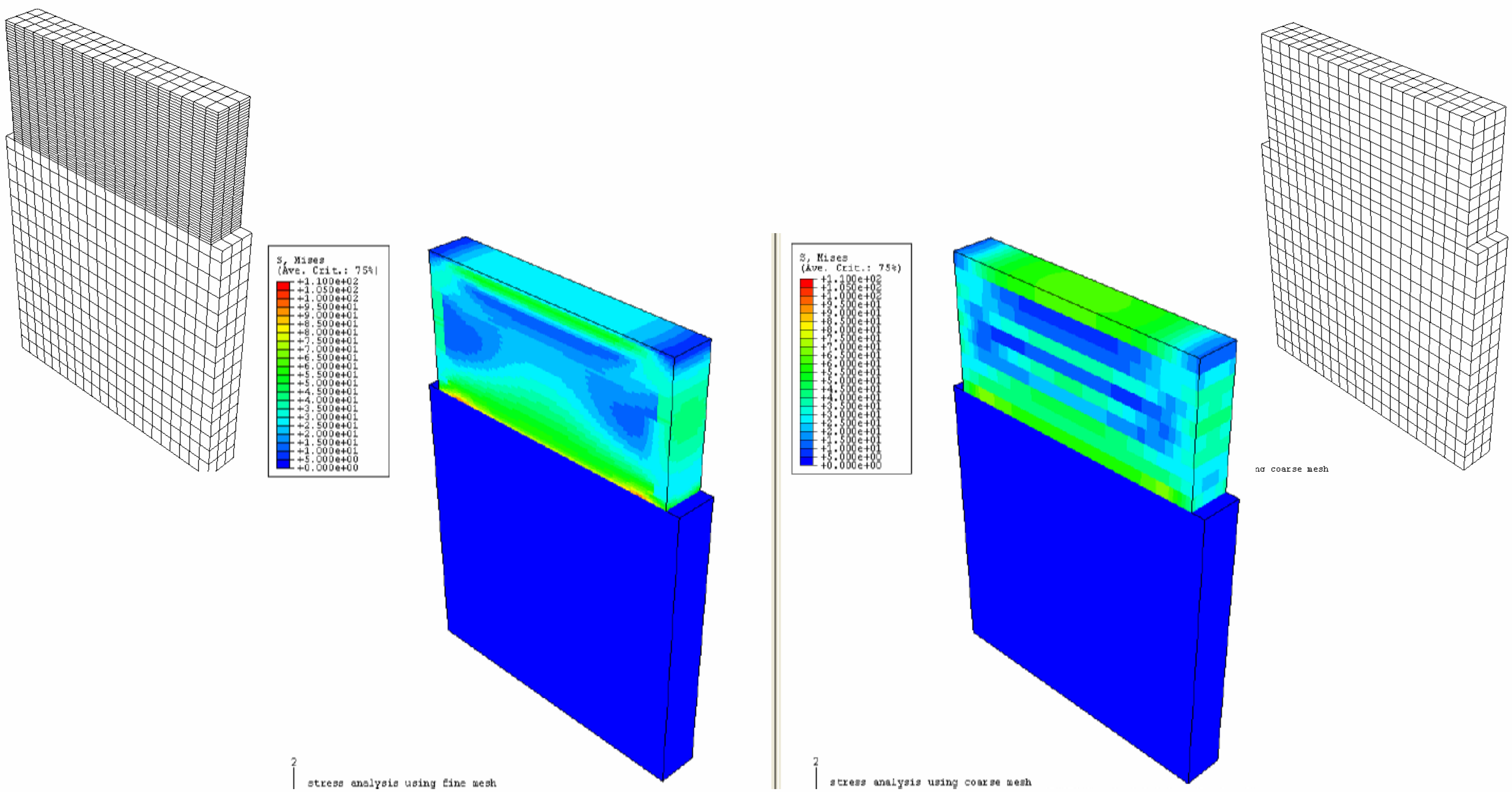
Remaining Steps

- Thermal component of analysis are nearing completion
- Stress analysis
  - Construction sequence completed
  - Long term cool down requires coarser mesh to achieve adequate computational performance
- Coarse mesh mapping of thermal results is underway – reasonable comparison is being obtained

Mesh Mapping Methods



Analytical Management

- Management of model size
  - Geometry (lift size)
  - Load time step resolution (solar radiation/daily temperature variation)
  - Long duration for dam cool down (years rather than months)
- 3rd party material model usage
  - It would be more convenient to use an internal material model in ABAQUS

Analytical Management

- Software bugs
  - Debugging vendor software
  - Memory management issues
    (porting of software to non native platforms)
- Software limitations (and workarounds)
  - Mesh mapping to reduce computational
    overheads of stress analysis phase of work
  - Selection of contact algorithms