TRANSIENT HEAT TRANSFER ANALYSIS AND TEMPERATURE MODELING FOR SOLUTION MINING CAVERNS

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- Introduction
- Mathematical Model
- Model Validation
- Discussions on Key Parameters
- Conclusions

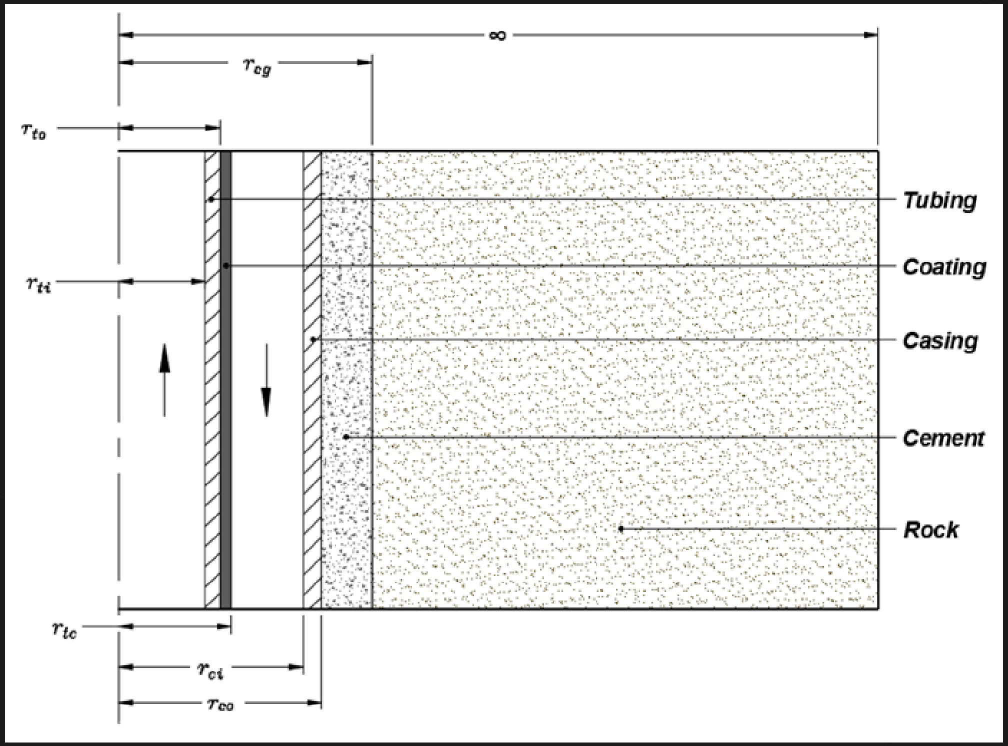
INTRODUCTION

- Solution Mining for Mineral Extraction
- Elevated Temperature Solvent
  - Higher Dissolution Rate
  - Higher Brine Grade
  - Higher Energy Consumption
  - Higher Creep Deformation
- Heat Transfer
  - Heat Transfer from Wells to Rock
  - Heat Transfer from Cavern to Rock
  - Heat Transfer between Solvent and Brine
  - Mineral Dissolution Heat

MATHEMATICAL MODEL

Heat Transfer between Brine and Surrounding Rock

- $$\frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{1}{x}\frac{\partial T}{\partial x}$$ (for wells)
- $$\frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t} = \frac{\partial^2 T}{\partial x^2}$$ (for caverns)



- α = the thermal diffusivity
- T = temperature (°C or °F)
- t = time
- x = distance from the well wall or distance from the cavern (m or ft)

MATHEMATICAL MODEL

Enthalpy Changes of Salt Minerals Dissolution

$$T_{drop} = \frac{2\sum_{i=1}^{n}(\Delta H_i \times m_i)}{m_{inj}C_{inj} + m_{pro}C_{pro}}$$

- T_{drop}=drop in temperature
- ΔH_i =enthalpy changes of one mole of salt mineral dissolving into water
- m_i = concentration of salt mineral in a unit volume
- m_{inj} = injection water mass in a unit volume
- C_{inj} = injection water specific heat
- m_{pro} = production brine mass in a unit volume
- C_{pro} = production brine specific heat

MATHEMATICAL MODEL

Temperature Drops at Wells and Caverns

- $$q" = -k\frac{\partial T}{\partial x}|x = r$$
- $$T_{drop} = \frac{q"A}{(mC)}$$

- *q*"= heat flux through well (or cavern) wall
- *k* = thermal conductivity of surrounding rock or salt
- *T*=temperature (°F or °C)
- *x*=distance to well or cavern
- *r* = casing inside radius
- *A*= well wall (or cavern wall) area
- *m*= water or brine flow rate
- *C* = specific heat of water or brine

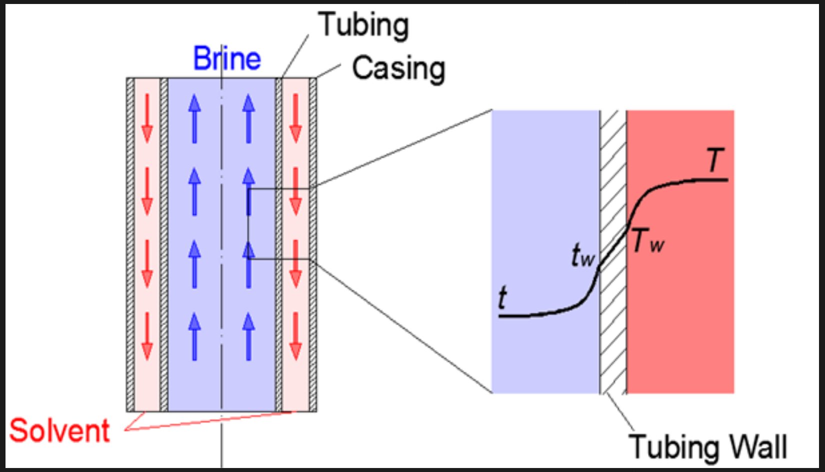
MATHEMATICAL MODEL

Heat Transfer between Solvent and Brine for Coaxial Well

- $\dot{Q} = UA\Delta T_m = \frac{\Delta T_m}{\sum_{i=1}^{n} R_i}$
- $\frac{1}{UA} = \sum_{i=1}^{5} R_i = \frac{1}{2\pi r_{ti} L h_i} + R_{f,i} + \frac{ln(r_{to}/r_{ti})}{2\pi k_p L} + R_{f,o} + \frac{1}{2\pi r_{to} L h_o}$

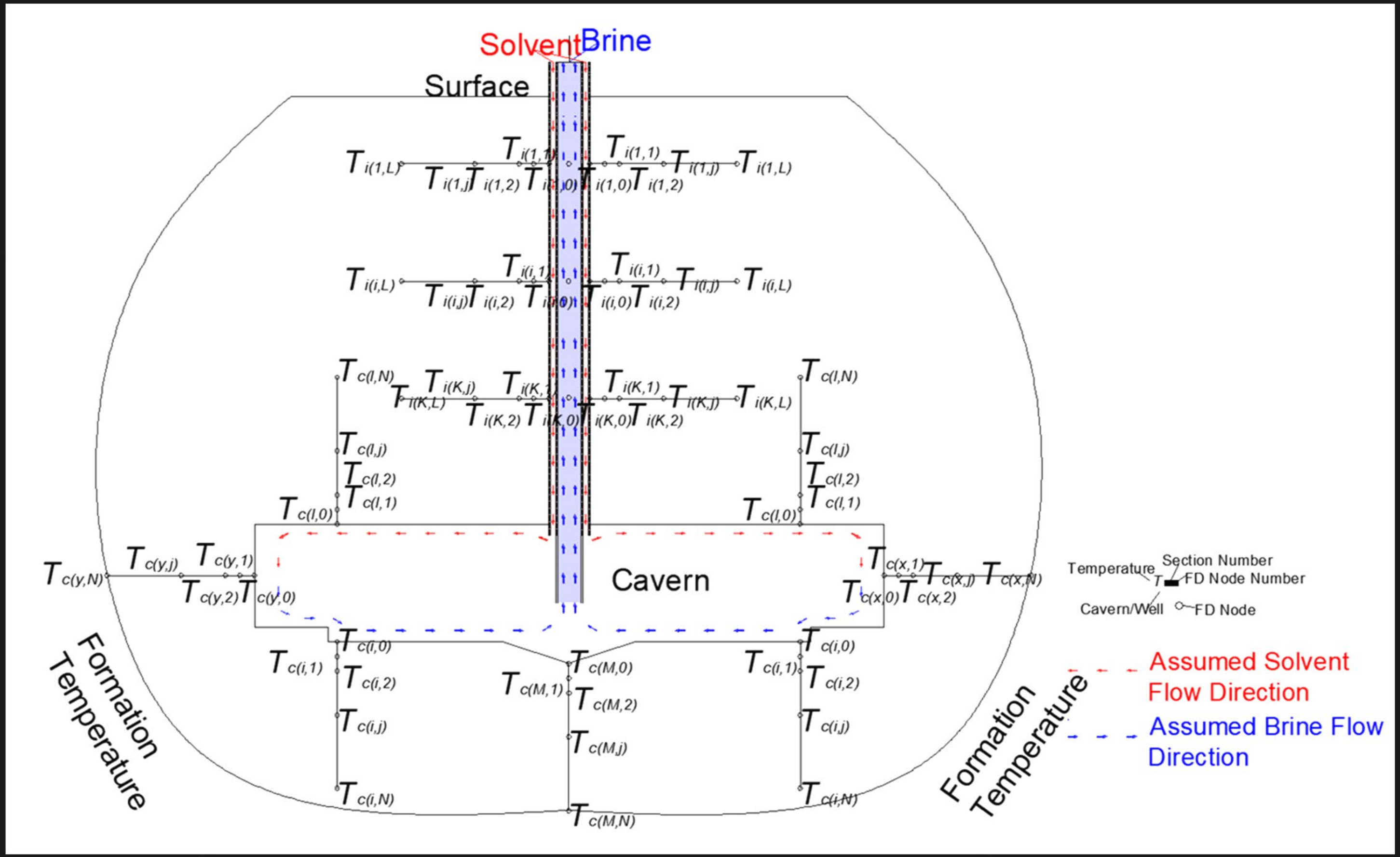
- U=the overall heat transfer coefficient (assumed to be constant over the surface area of the tubing)
- ΔT_m=the appropriate mean temperature difference
- $\sum R_i$ =the total thermal resistance to heat transfer between fluid streams in the casing

- L =the length of the tubing
- k_p =the thermal conductivity of steel
- h_i =the convection heat transfer coefficient of the brine side
- h_o =the convection heat transfer coefficients of solvent side



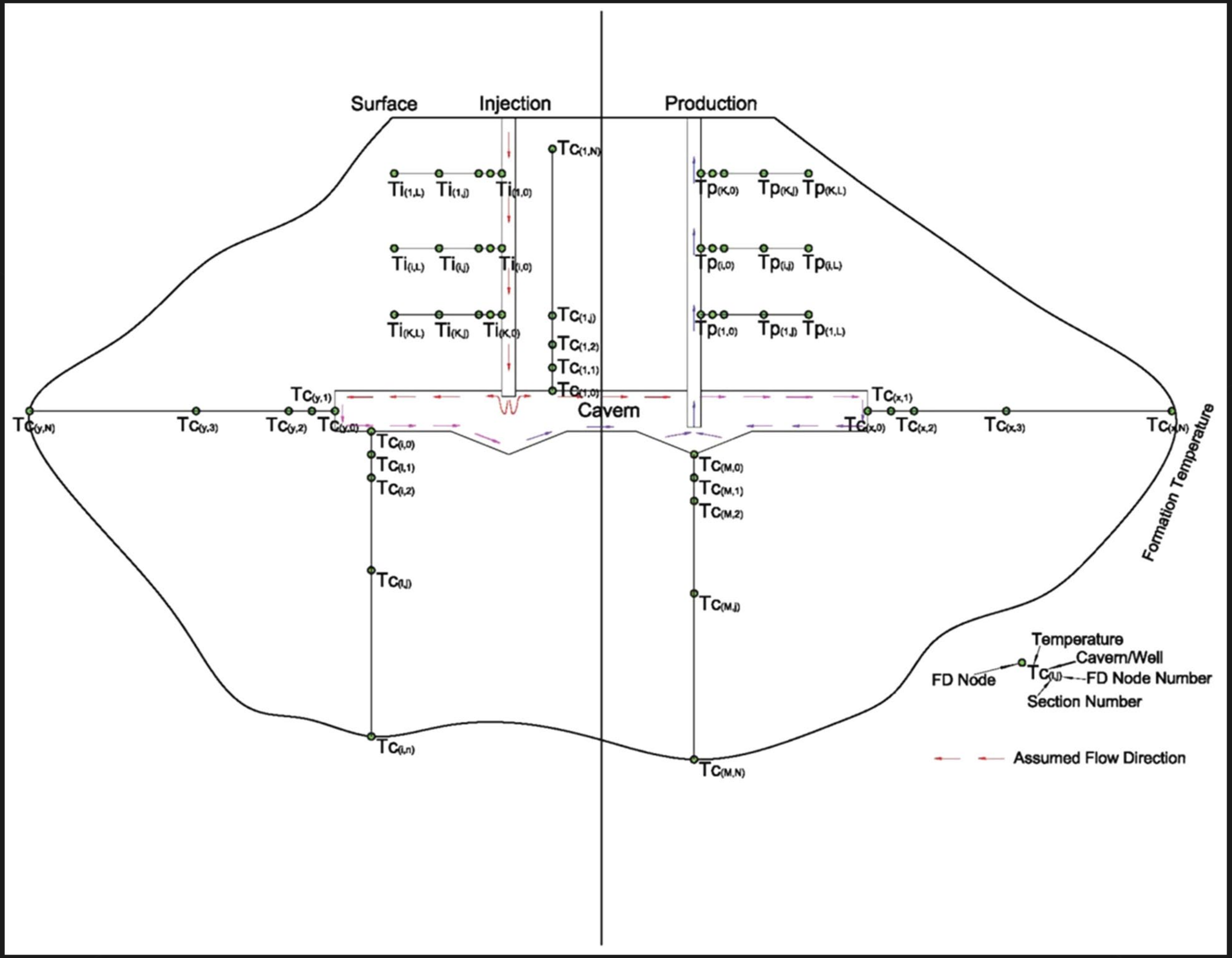
MODELING METHODOLOGY

- **Single Well Cavern Finite Difference Nodes**



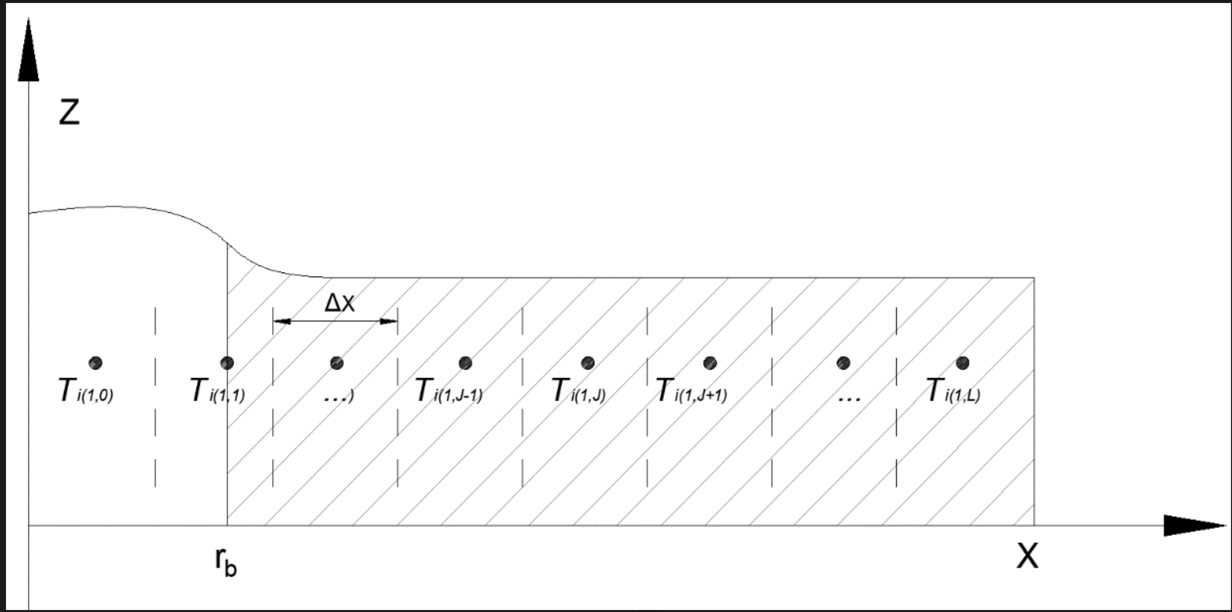
MODELING METHODOLOGY

Dual Well Cavern Finite Difference Nodes



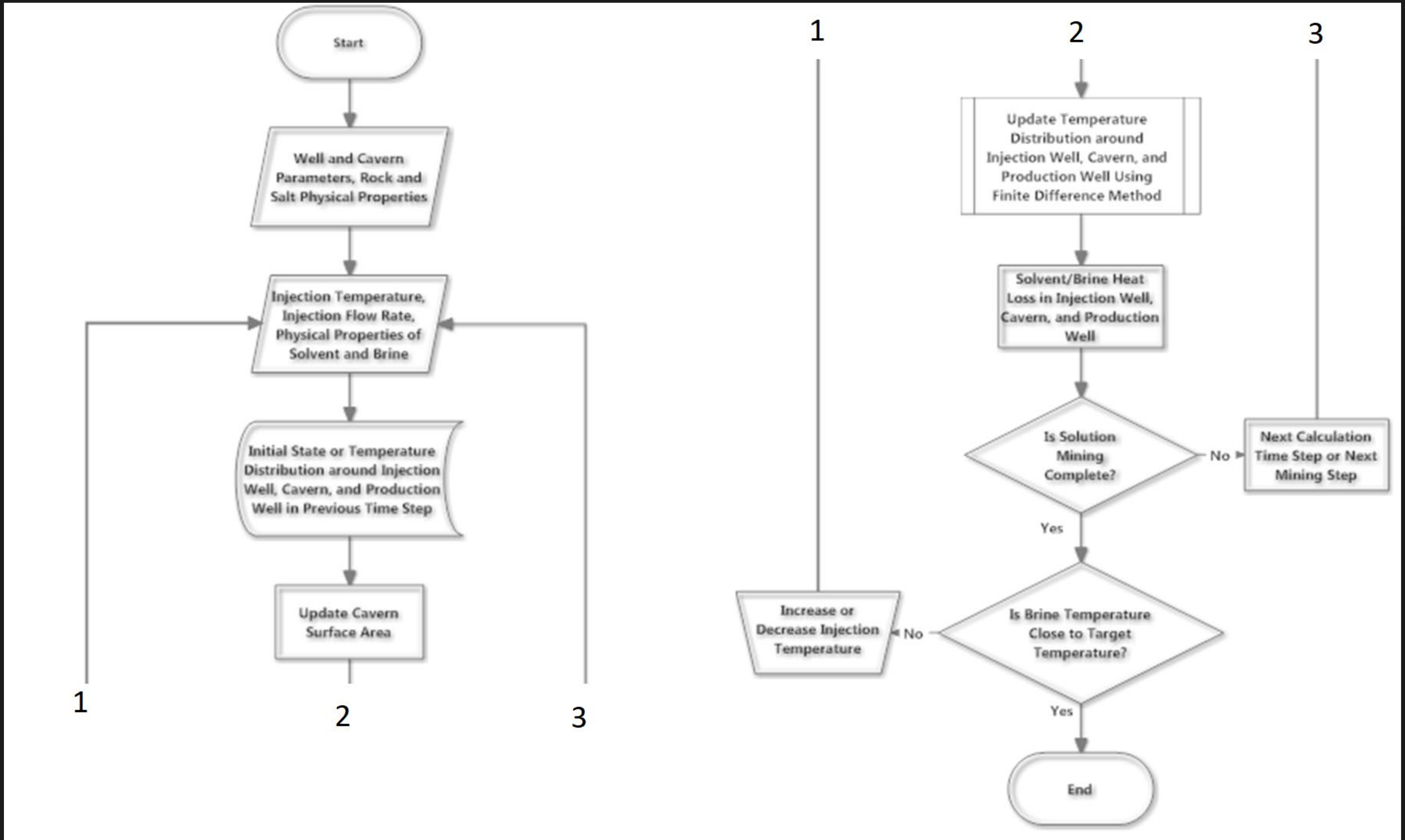
MODELING METHODOLOGY

- **Coupling of Conductive and Convective Model**



MODELING METHODOLOGY

- Cavern and Brine Temperature Prediction Flowchart

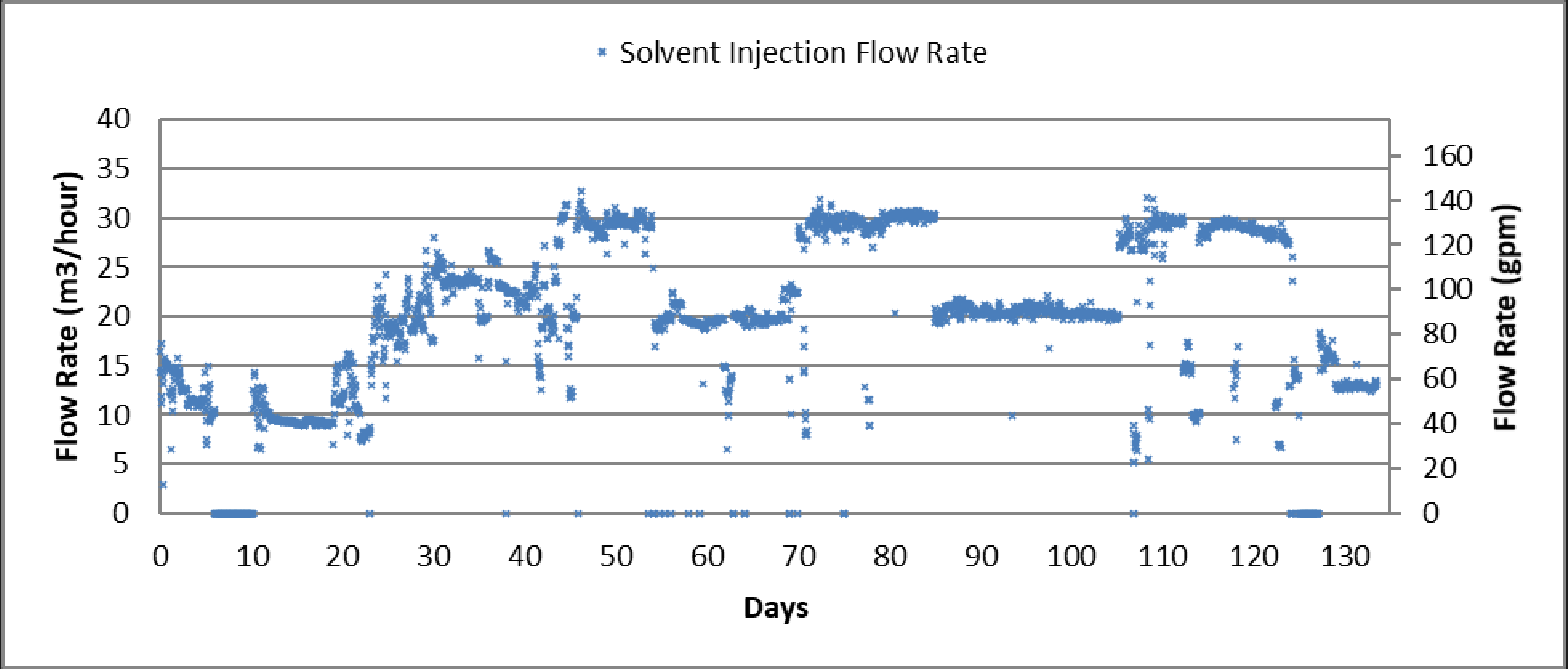


MODELING VALIDATION

- Validation Case
  - Depth: 500 m (1640.4 ft)
  - Cavern Length: 260 m (853 ft)
  - Estimated Cavern Width:13 m (42.7 ft)
  - Well Casing: 7 inches (178 mm)
  - Tubing: 4½ inches (114.3 mm)
  - Rock Heat Conductivity: 2.6 W/(m°C) (1.5 Btu/hr-ft-F)
  - Mineral Dissolution Heat: 107,926 J/kg (46.4 Btu/lb)
  - In-situ Rock Temperature: 23°C (75.5°F)
  - Geothermal Gradient: 0.04°C/m (0.022°F/ft)
  - Solvent Flow Rate: 10~15 m^3/h (44~66 gpm) for the first 20 days and increased to 20~30 m^3/h (88~132 gpm) after the first month
  - Injection Temperature: about 70°C (158°F) for the first 3 months and increased to about 90°C (194°F) thereafter

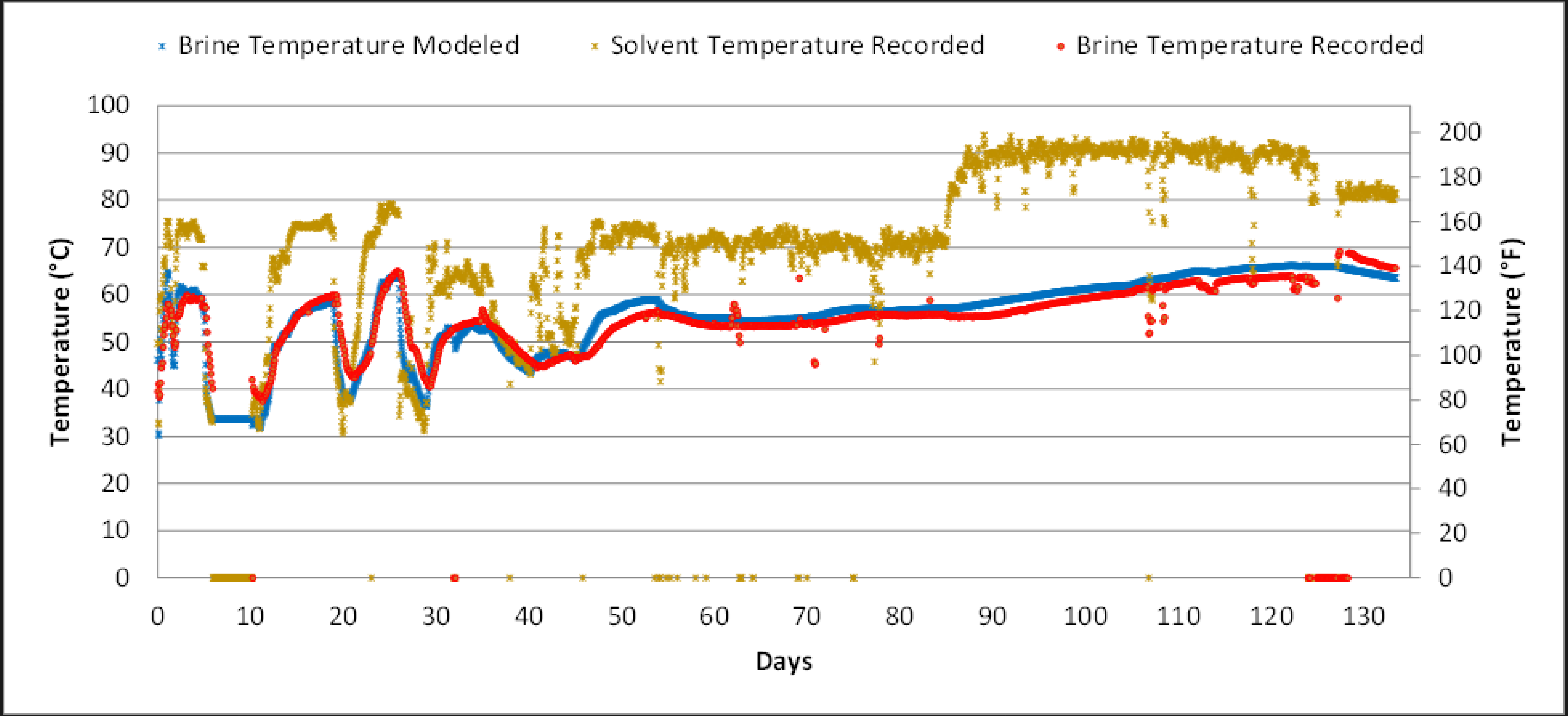
MODELING VALIDATION

- Solvent Injection Flow Rate



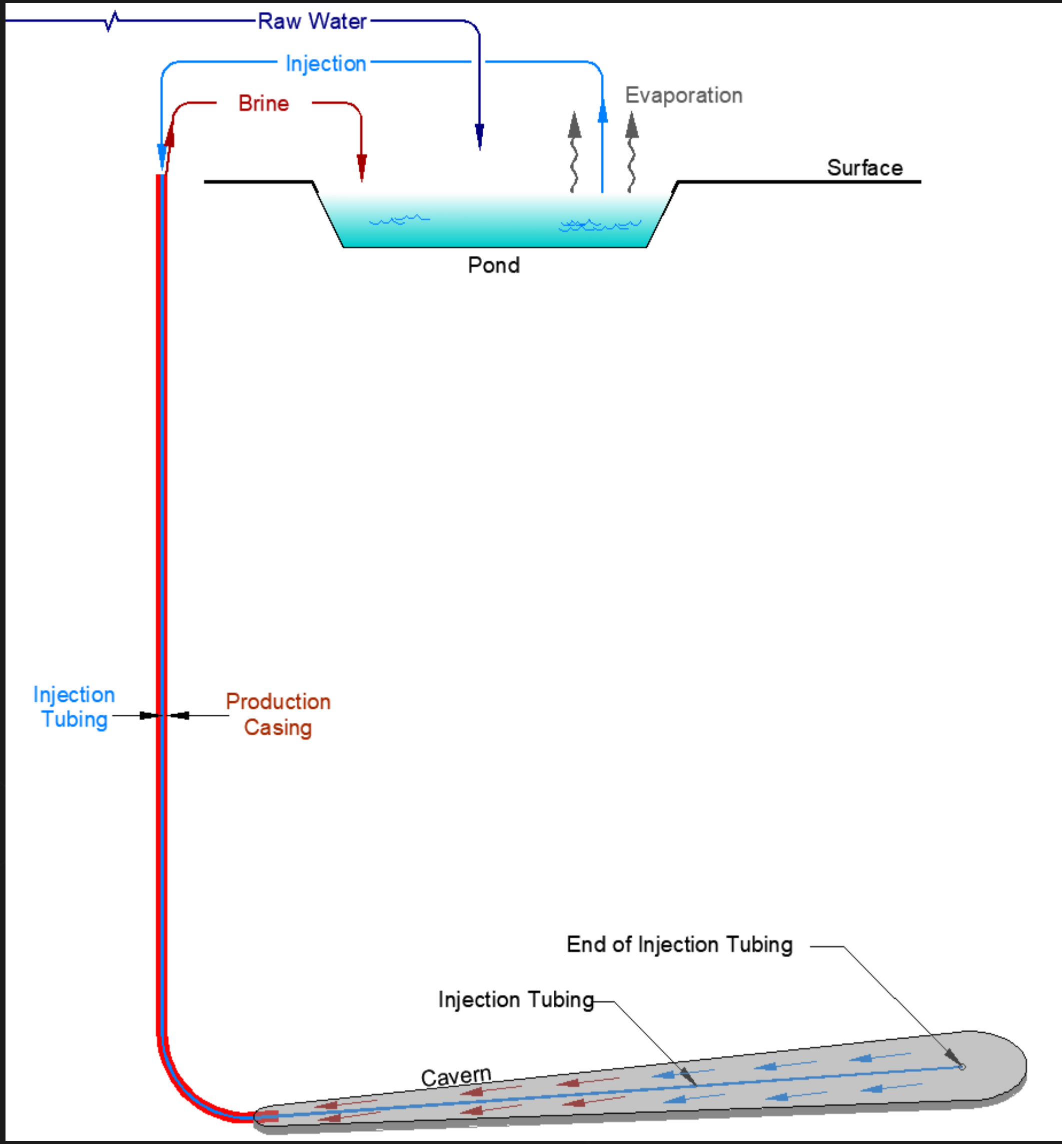
MODELING VALIDATION

- Recorded and Modeled Fluid Temperatures



DISCUSSIONS ON KEY PARAMETERS

- Fictitious Solution Mining Cavern
  - Single horizontal well
  - Production Casing
  - Injection Tubing
  - Injection Solvent
  - Production Brine
  - Crystallization Pond
  - Raw Water Supply

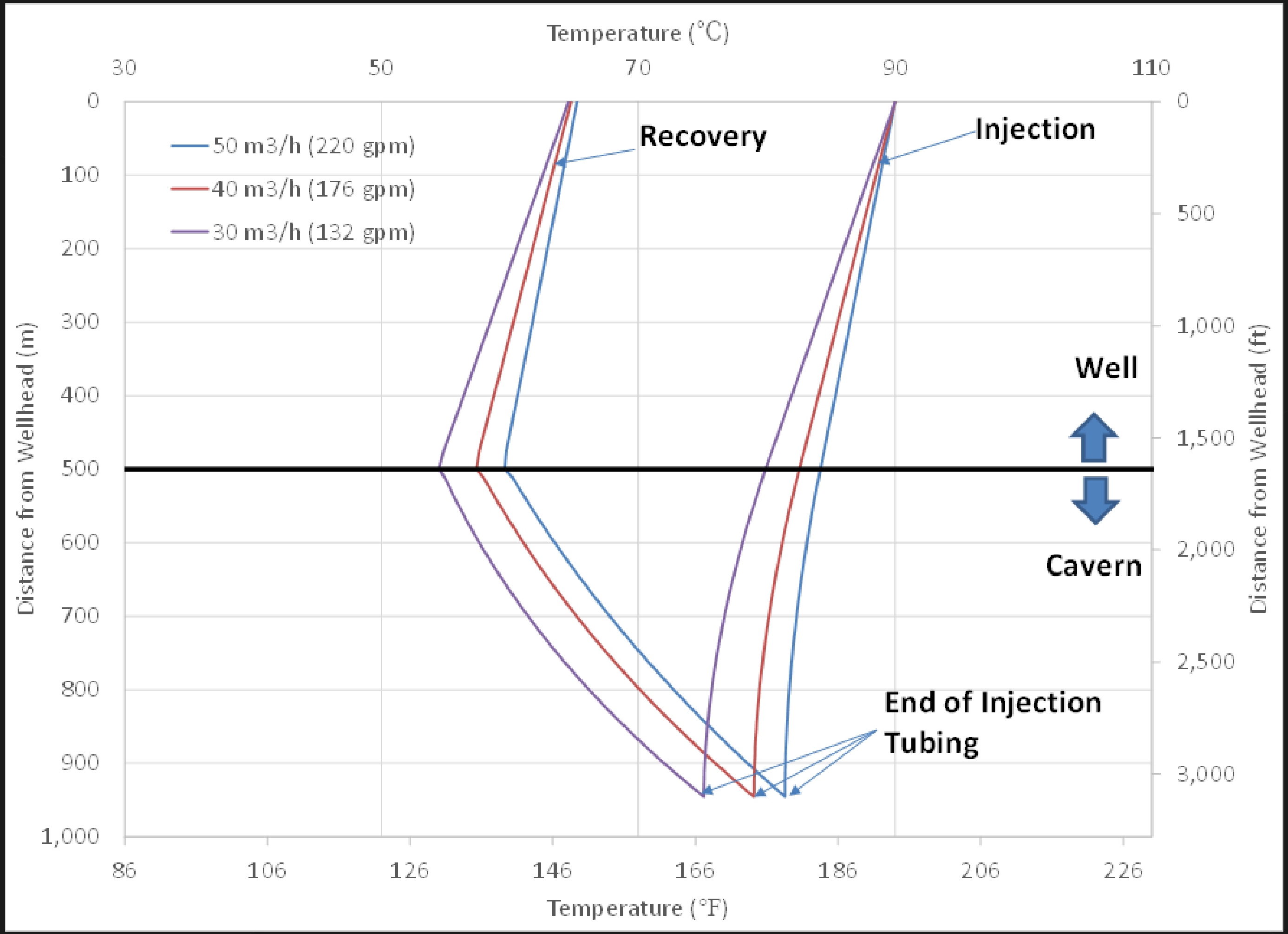


DISCUSSIONS ON KEY PARAMETERS

- Cavern Parameters
  - Well Length: 500 m (1640.4 ft)
  - Cavern Horizontal Length: 457 m (1,500 ft)
  - Well Casing: 7 inches (178 mm)
  - Tubing: 4½ inches (114.3 mm)
  - Rock Heat Conductivity: 2.6 W/(m°C) (1.5 Btu/hr-ft-F)
  - Rock Specific Heat: 850 J/(kg°C) (0.203 Btu/lb-F)
  - In-situ Rock Temperature: 26°C (79°F)
  - Geothermal Gradient: 0.05°C/m (0.027°F/ft)
  - Solvent Flow Rate: 30, 40, and 50 m3/h (132, 176, and 220 gpm)
  - Injection Temperature: 80, 90, and 100°C (176, 194, and 212°F)
  - Tubing Insulation: VIT Tubing, 5-mm [0.2 inch] lined tubing, and 1-mm [0.04 inch] lined tubing
  - Mineral Dissolution Heat: 50,000, 100,000, and 150,000 J/kg (21.5, 43.0, and 64.5 Btu/lb)

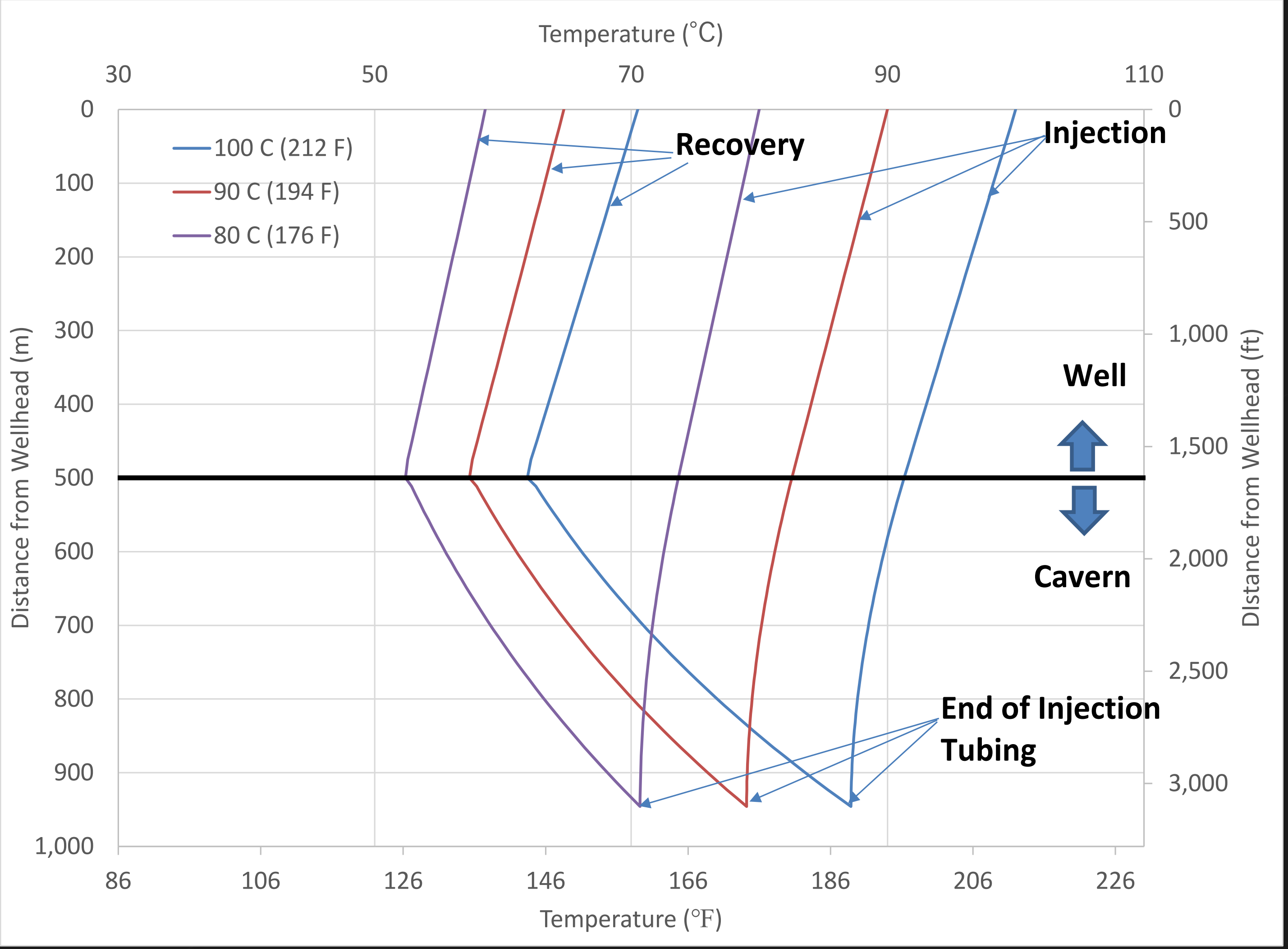
DISCUSSIONS ON KEY PARAMETERS

- Injection Flow Rate



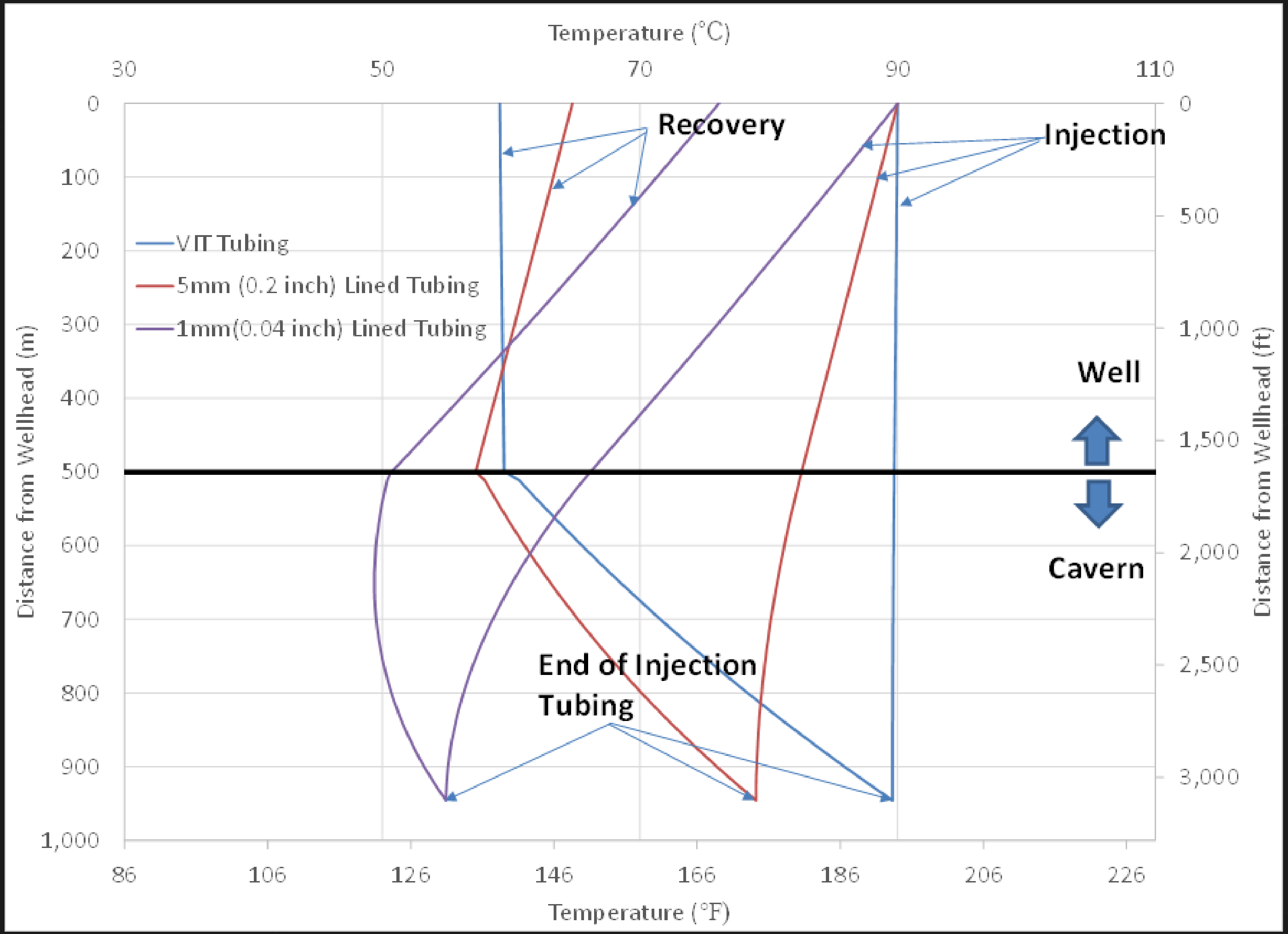
DISCUSSIONS ON KEY PARAMETERS

- Injection Temperature



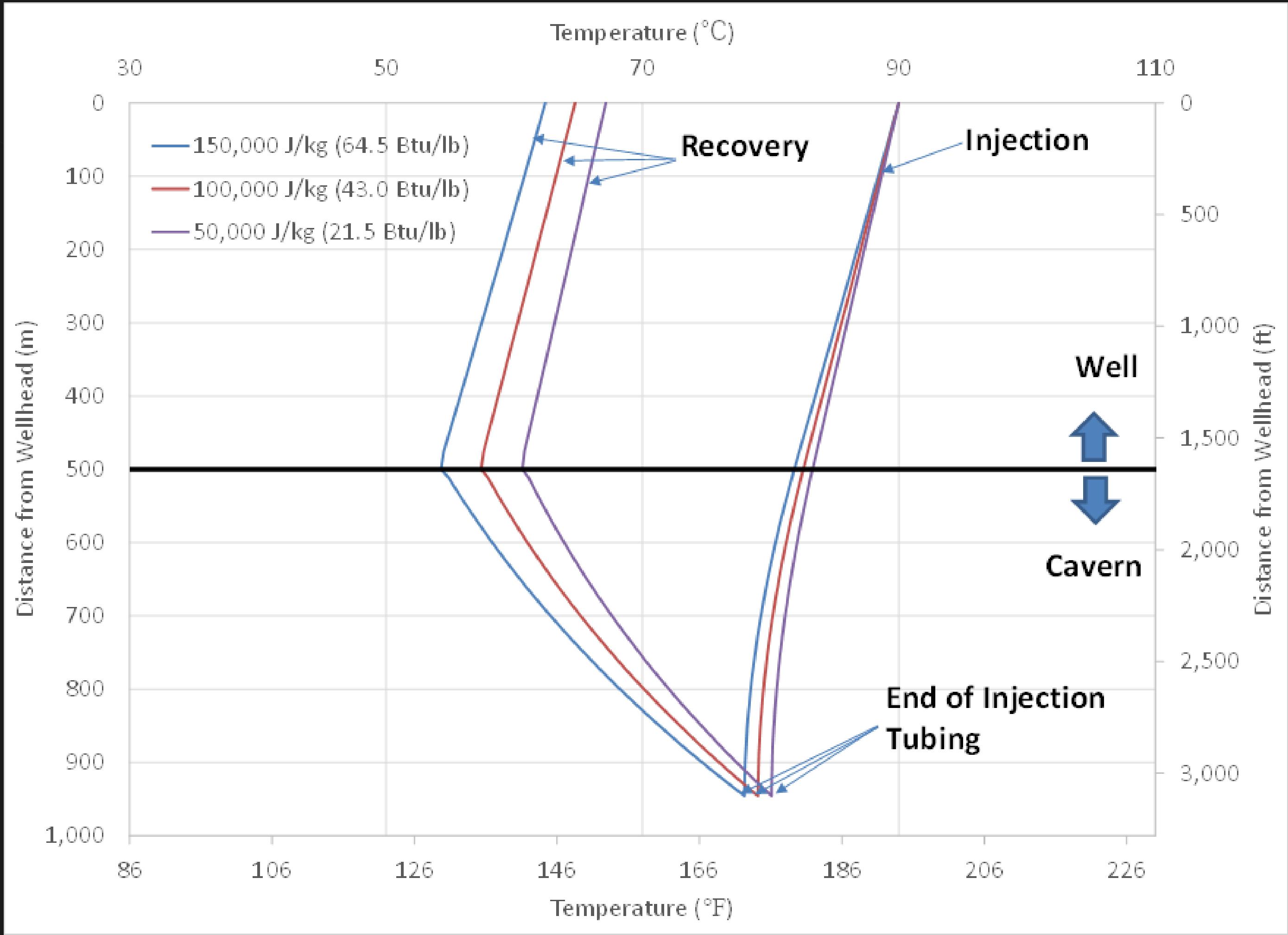
DISCUSSIONS ON KEY PARAMETERS

- Tubing Thermal Insulation



DISCUSSIONS ON KEY PARAMETERS

- Mineral Dissolution Heat



DISCUSSIONS ON KEY PARAMETERS

- Summary

Flow Rate (m^3/h)	Injection Temperature (℃)	Tubing Insulation	Dissolution Heat (J/kg)	Injection Temperature at Tubing End (℃)	Temperature at Recovery Bottom (℃)	Average Cavern Temperature (℃)	Cavern Temperature Drop (℃)	Total Temperature Drop (℃)	Temperature Utilization (%)
40	90	5 mm lined	100,000	79.00	57.40	66.96	21.60	25.25	85.6%
30	90	5 mm lined	100,000	75.11	54.47	63.26	20.64	25.43	81.1%
50	90	5 mm lined	100,000	81.42	59.60	69.46	21.82	24.76	88.1%
40	80	5 mm lined	100,000	70.70	52.40	60.52	18.30	21.37	85.6%
40	100	5 mm lined	100,000	87.15	61.90	73.04	25.25	29.48	85.7%
40	90	1 mm lined	100,000	54.94	50.64	50.75	4.30	13.86	31.1%
40	90	VIT	100,000	89.60	59.54	73.68	30.06	30.88	97.3%
40	90	5 mm lined	50,000	80.08	60.64	69.22	19.44	22.86	85.0%
40	90	5 mm lined	150,000	77.97	54.30	64.78	23.67	27.56	85.9%

Flow Rate (gpm)	Injection Temperature (℉)	Tubing Insulation	Dissolution Heat (Btu/hr-ft-F)	Injection Temperature at Tubing End (℃)	Temperature at Recovery Bottom (℃)	Average Cavern Temperature (℃)	Cavern Temperature Drop (℃)	Total Temperature Drop (℃)	Temperature Utilization (%)
176	194	0.2 inch lined	43.0	174.21	135.32	152.53	38.89	45.45	85.6%
132	194	0.2 inch lined	43.0	167.19	130.05	145.87	37.15	45.78	81.1%
220	194	0.2 inch lined	43.0	178.56	139.28	157.03	39.28	44.57	88.1%
176	176	0.2 inch lined	43.0	159.26	126.32	140.94	32.94	38.47	85.6%
176	212	0.2 inch lined	43.0	188.87	143.42	163.48	45.45	53.06	85.7%
176	194	0.04 inch lined	43.0	130.90	123.15	123.36	7.75	24.94	31.1%
176	194	VIT	43.0	193.28	139.17	164.62	54.11	55.59	97.3%
176	194	0.2 inch lined	21.5	176.14	141.15	156.60	34.99	41.14	85.0%
176	194	0.2 inch lined	64.5	172.34	129.74	148.60	42.60	49.61	85.9%

CONCLUSIONS

- semi-analytical approach for cavern temperature modeling
- finite-difference approach
- Measured temperature data from an actual solution mining cavern (Section 4) were compared with the modeling data (Section 5), which validated the model's accuracy
- the higher the flow rate and injection temperature, the higher the cavern temperature. The lower the tubing heat conductivity and the heat from mineral dissolution, the higher the cavern temperature. The temperature utilization percentage was very sensitive to the type of tubing insulation used, which suggests that a detailed trade-off study should be performed to select the optimal tubing insulation.

THANK YOU!

QUESTIONS?