CAVERN THERMODYNAMICS

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OUTLINE

- CAVERN THERMODYNAMICS
- NEW GAS CAVERN/FIELD DESIGN (CONVERSION OR NEW CAVERNS)
  - Cavern sizing
  - Well sizing
- EXISTING GAS CAVERN/FIELD
  - Model calibration
  - Inventory verification/Integrity monitoring
  - Gas nominations
- SUMMARY

CAVERN THERMODYNAMIC - VARIABLES

STATE VARIABLES

- Temperature T
- Pressure P
- Density $\rho = \dfrac{\text{mass}}{\text{volume}}$

VALUES EITHER KNOWN OR CALCULATED

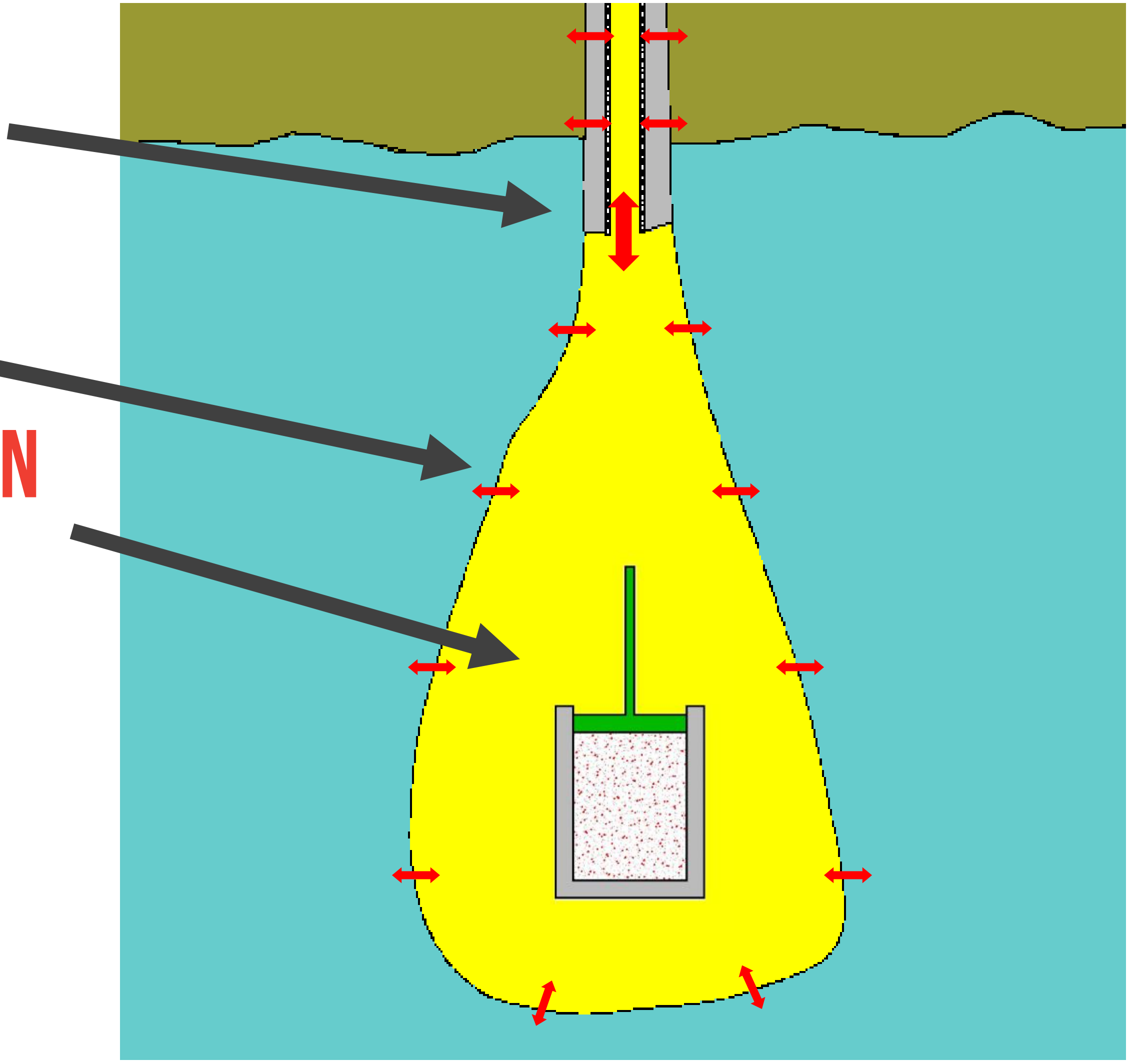
- Knowns: cavern gas density, injection/withdrawal rates, injection temperature
- Calculated: cavern gas temperature & pressure

THERMODYNAMIC EQUATIONS

- **CHANGES MUST SATISFY CONSERVATION EQUATIONS**
  - Mass (well and cavern)
  - Energy (well and cavern)
  - Momentum (well)
- **STATE VARIABLES RELATED BY EQUATIONS OF STATE**
  - Natural gas
  - Water-Brine
- **THERMODYNAMIC PROPERTIES DEPEND ON STATE VARIABLES**

CAVERN ENERGY BALANCE

- HEAT GAIN/LOSS DUE TO MASS FLOW IN AND OUT OF CAVERN
- HEAT TRANSFER WITH SURROUNDING SALT
- COMPRESSION/ DECOMPRESSION OF THE GAS



GAS EQUATION OF STATE

- THE MASS OF GAS, m, IN A CAVERN IS DEFINED BY THE EQUATION OF STATE FOR A REAL GAS

$$m = \frac{VPM}{zRT}$$

Where:

V = Cavern volume

P = Gas pressure

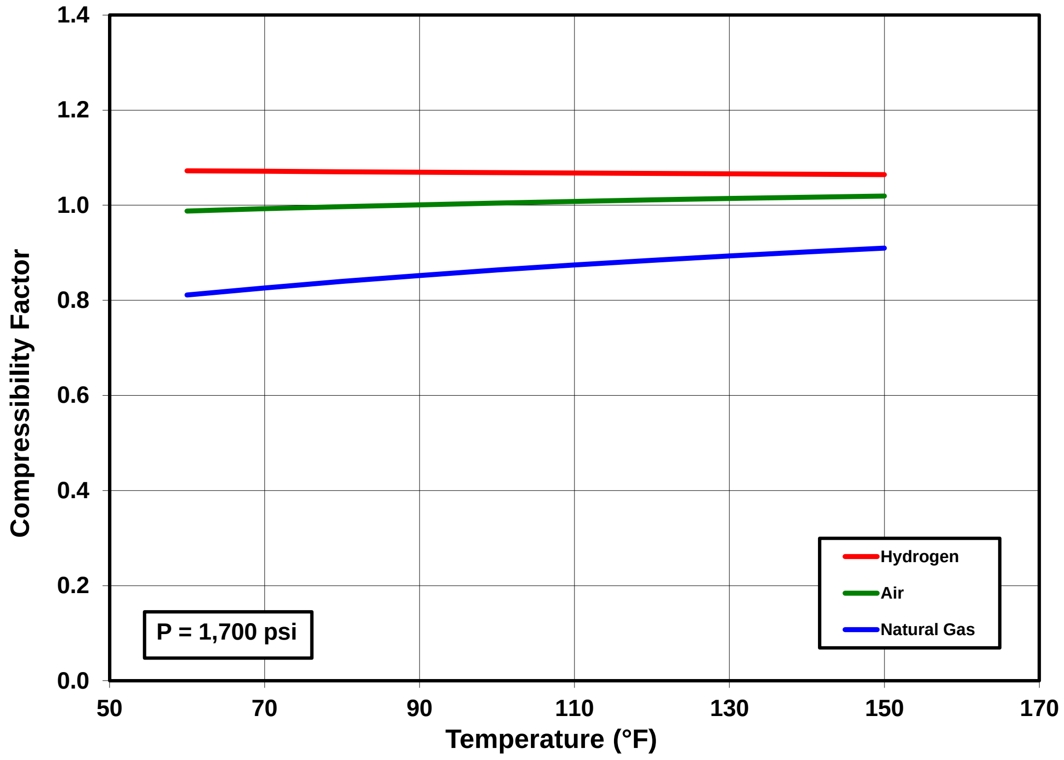
M = Molecular weight of gas mixture

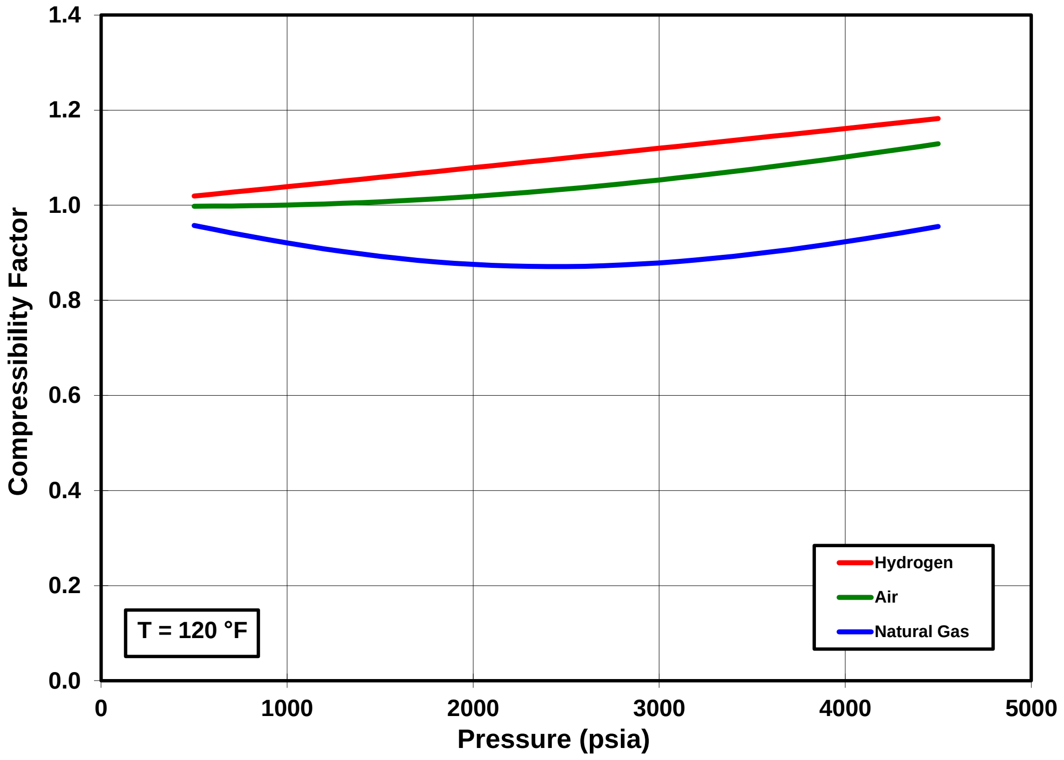
R = Universal gas constant

T = Absolute temperature of gas

z = Compressibility factor = *f(temperature, pressure)*

COMPRESSIBILITY FACTOR

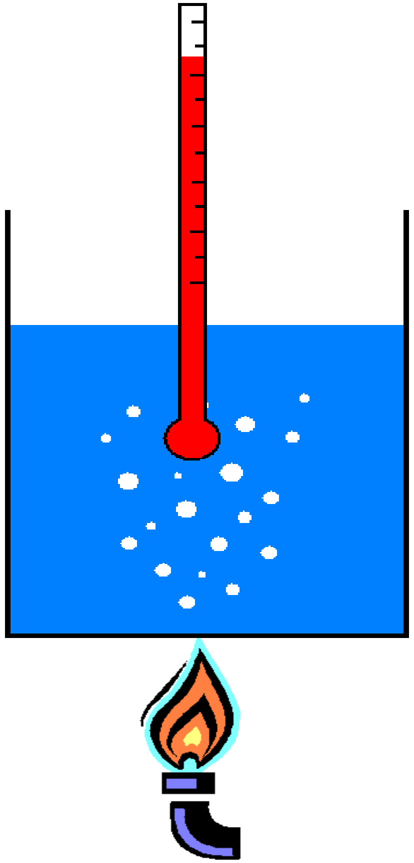




THERMODYNAMIC PROPERTIES

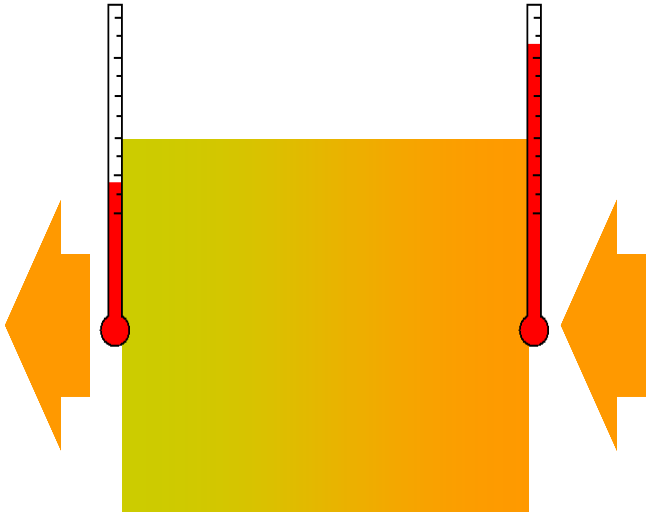
SPECIFIC HEAT

- Relates change in temperature to change in thermal energy (per unit mass)



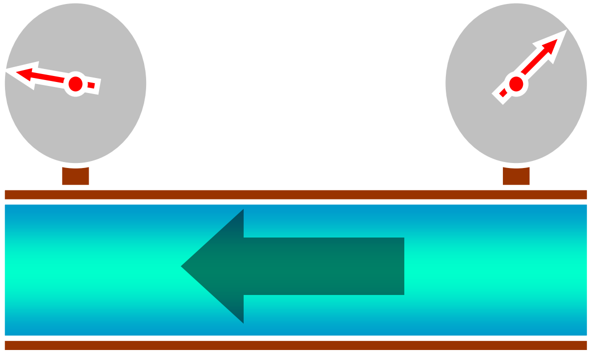
THERMODYNAMIC PROPERTIES

- **SPECIFIC HEAT**
  - Relates change in temperature to change in thermal energy (per unit mass)
- **THERMAL CONDUCTIVITY**
  - Relates conductive heat flux to temperature gradient



THERMODYNAMIC PROPERTIES

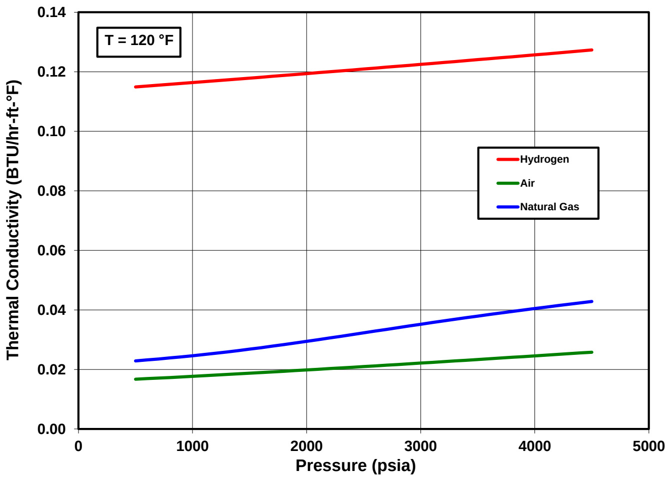
- **SPECIFIC HEAT**
  - Relates change in temperature to change in thermal energy (per unit mass)
- **THERMAL CONDUCTIVITY**
  - Relates conductive heat flux to temperature gradient
- **DYNAMIC VISCOSITY**
  - Relates shear stress to velocity gradient in fluids

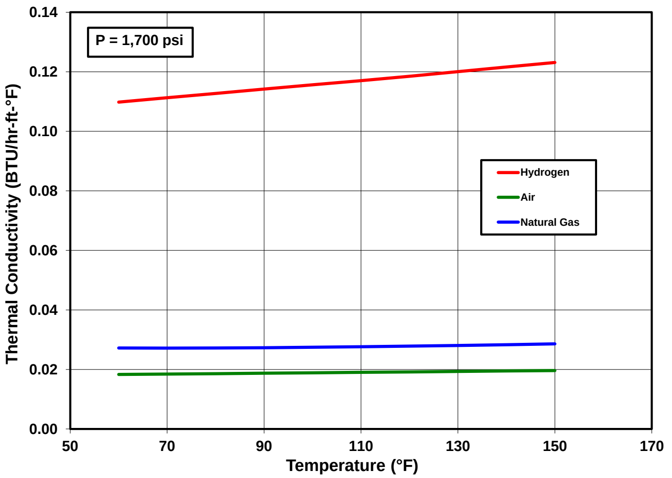


THERMODYNAMIC PROPERTIES

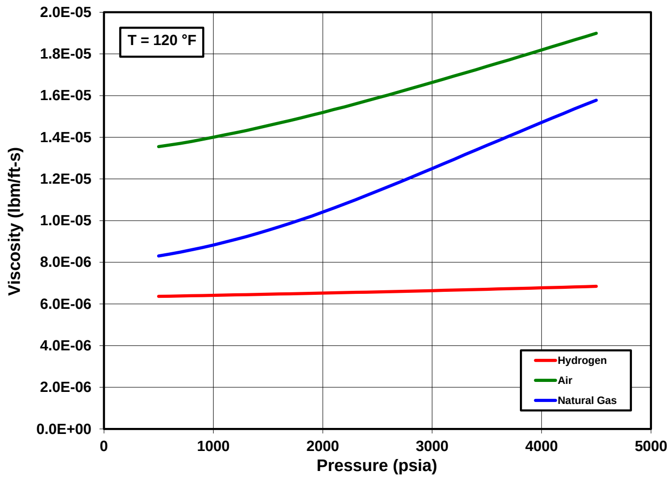
RESPEC

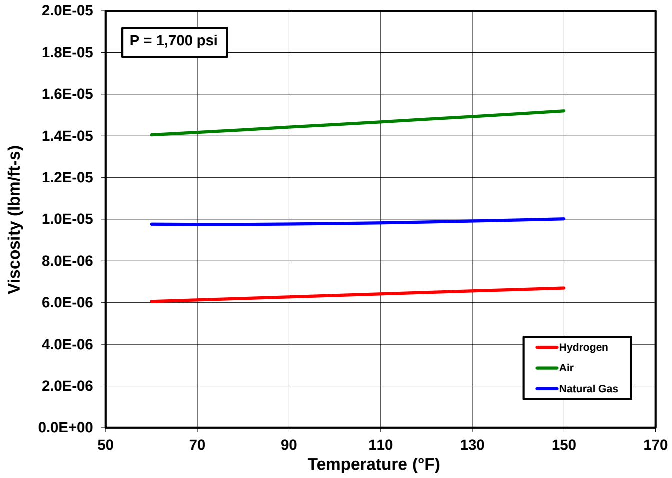
Thermal Conductivity



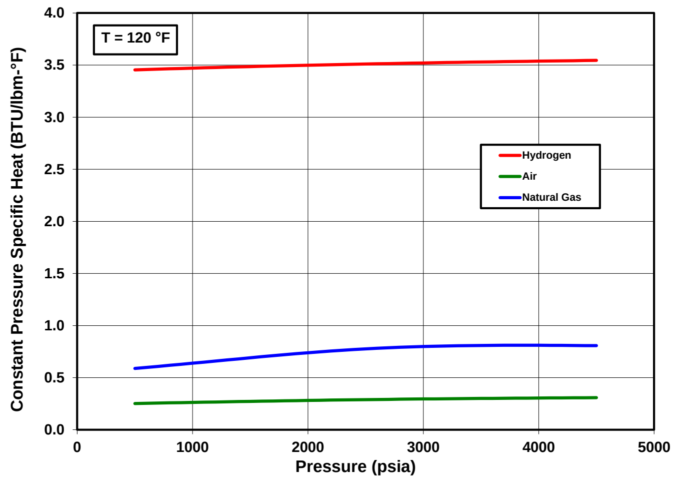


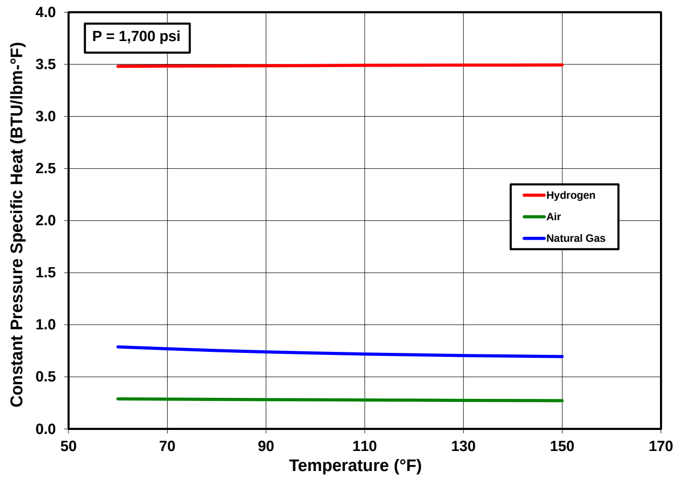
Viscosity



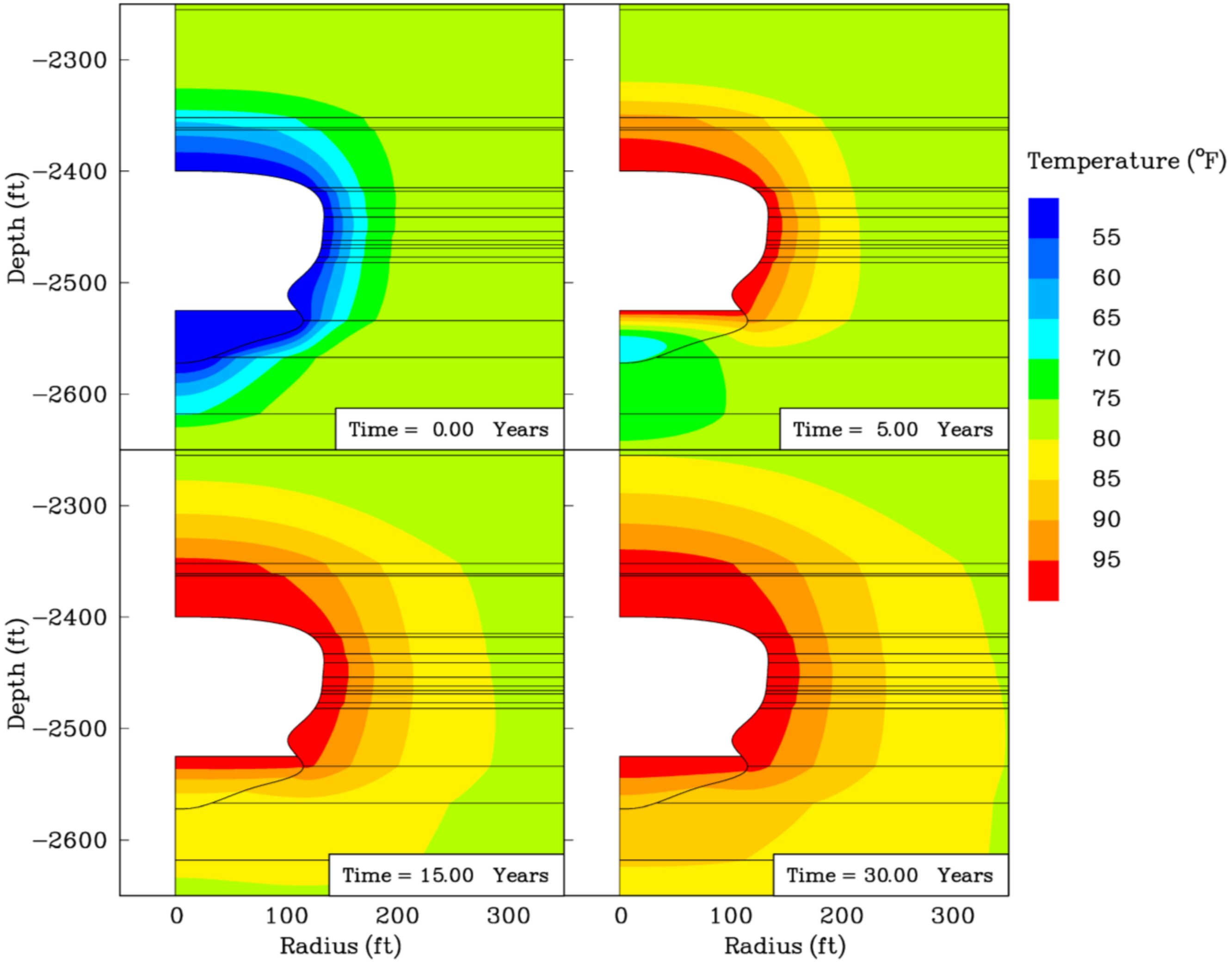


Specific Heat





TEMPERATURE CHANGES IN THE SURROUNDING ROCK

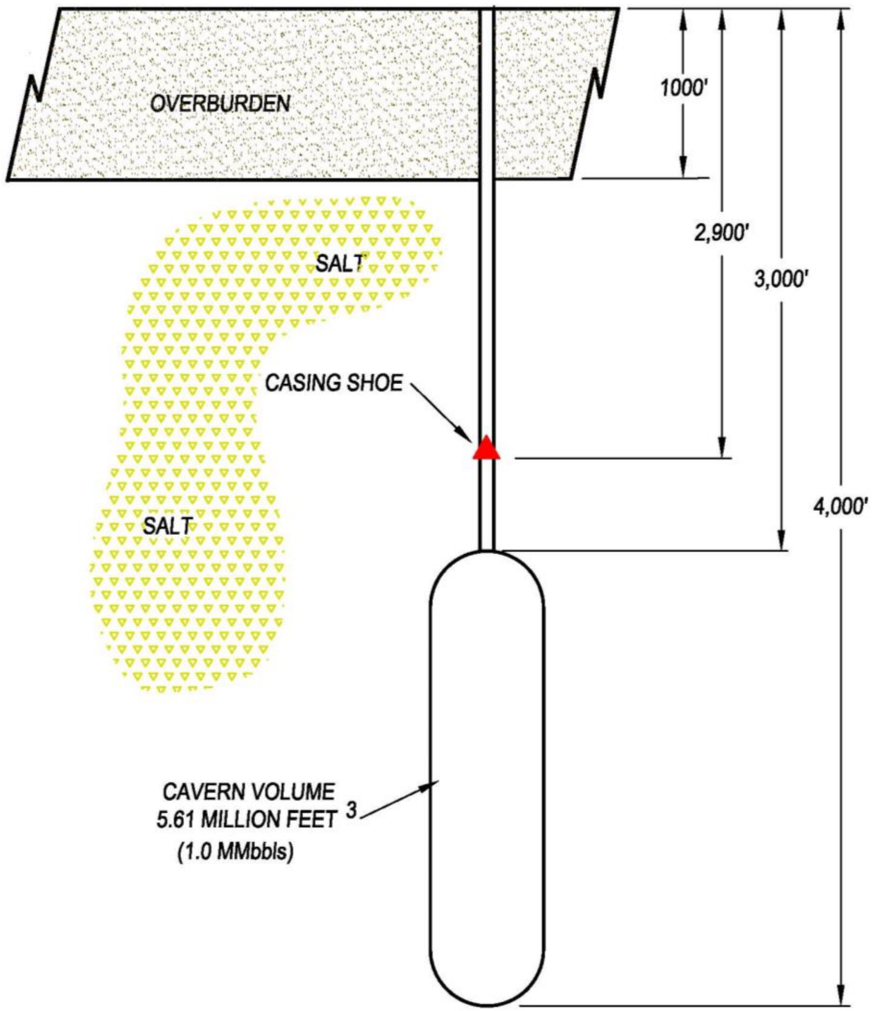


CAVERN DESIGN

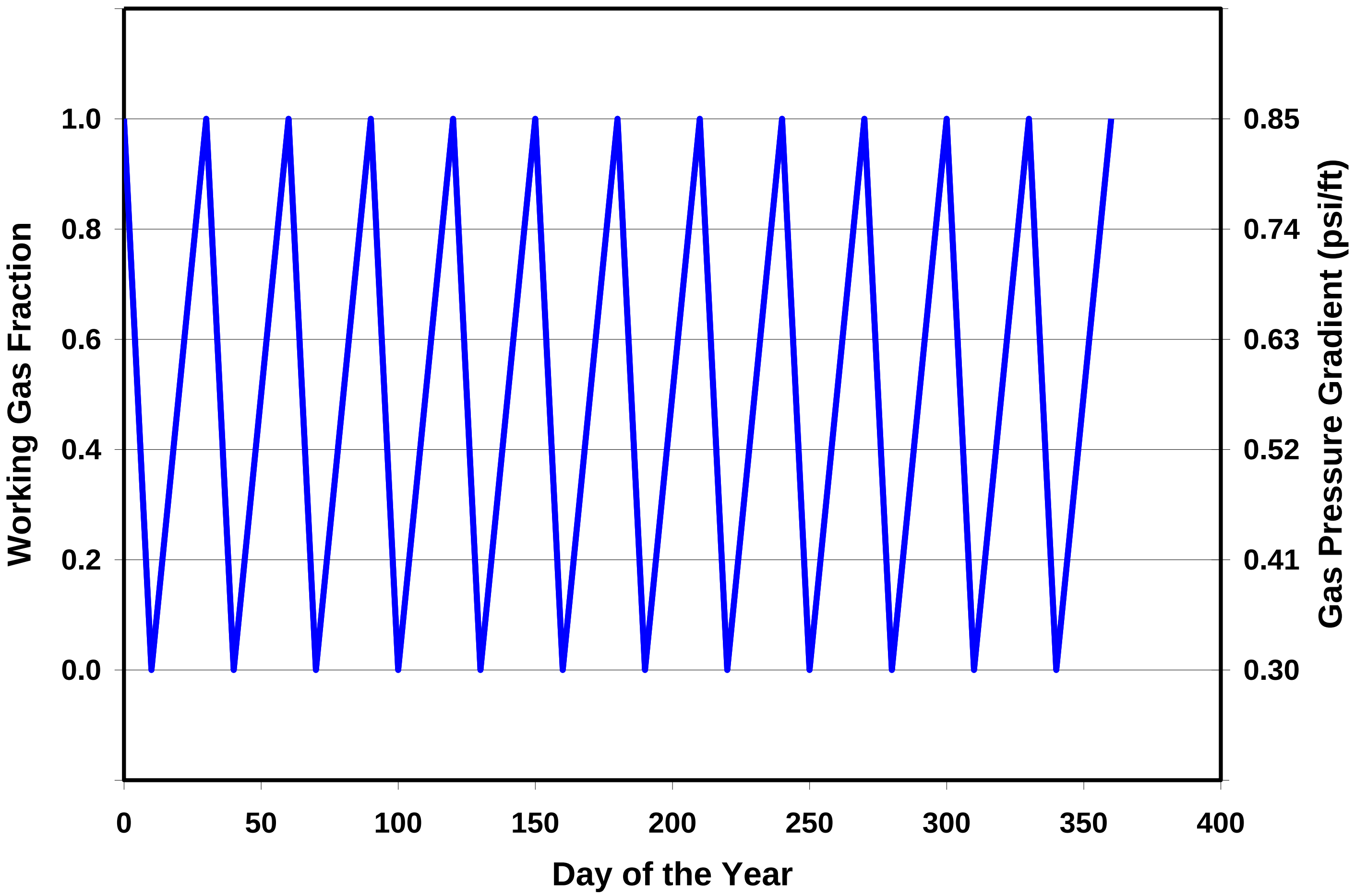
- NEW CAVERN STORAGE PROJECT
  - How much cavern volume is needed?
  - What well size is appropriate for desired flows?
  - How much compression is needed?
- CONVERSION OF EXISTING CAVERN TO GAS STORAGE
  - How much gas can be stored?
  - What flow rates can be achieved?
  - How much compression is needed?

EXAMPLE CAVERN CONVERSION

- **BASELINE PARAMETERS**
  - 12 Turns per Year
  - 100°F Gas Injection Temperature
  - Minimum Pressure of 0.30 psi/ft of Depth at Casing Seat
  - Maximum Pressure of 0.85 pis/ft of Depth at Casing Seat
  - Top of Cavern Depth at 3,000 feet



EXAMPLE CONVERSION PROJECT



EXAMPLE WORKING GAS CAPACITY

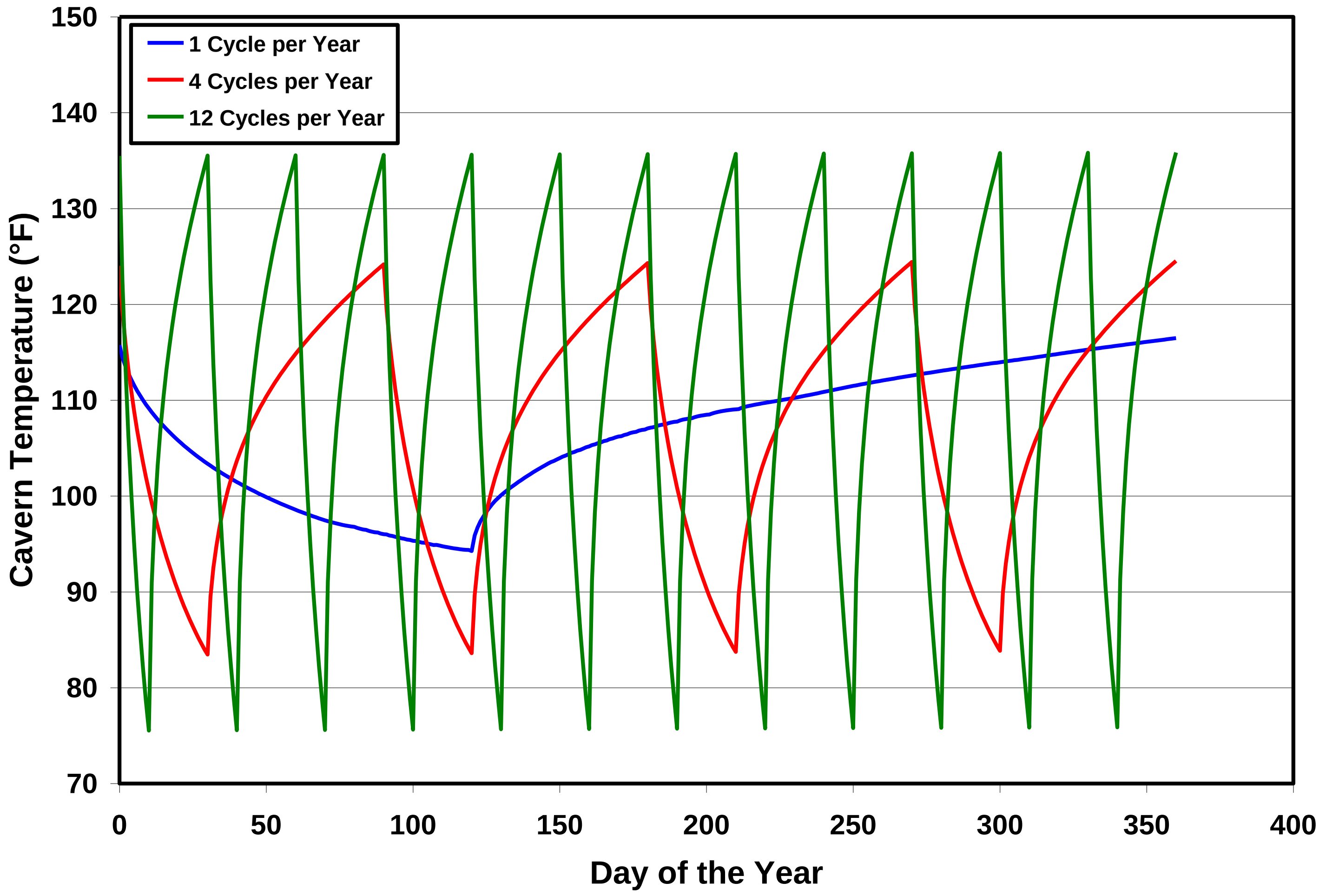
Gas	Working Gas (bcf)	Base Gas (bcf)	Working Thermal Energy (MDth)[a]
Natural Gas	0.57	0.37	581.4
Hydrogen	0.45	0.32	146.3
Air	0.48	0.33	n/a

a) Assumes 1020 Btu/scf for natural gas and 325 Btu/scf for hydrogen

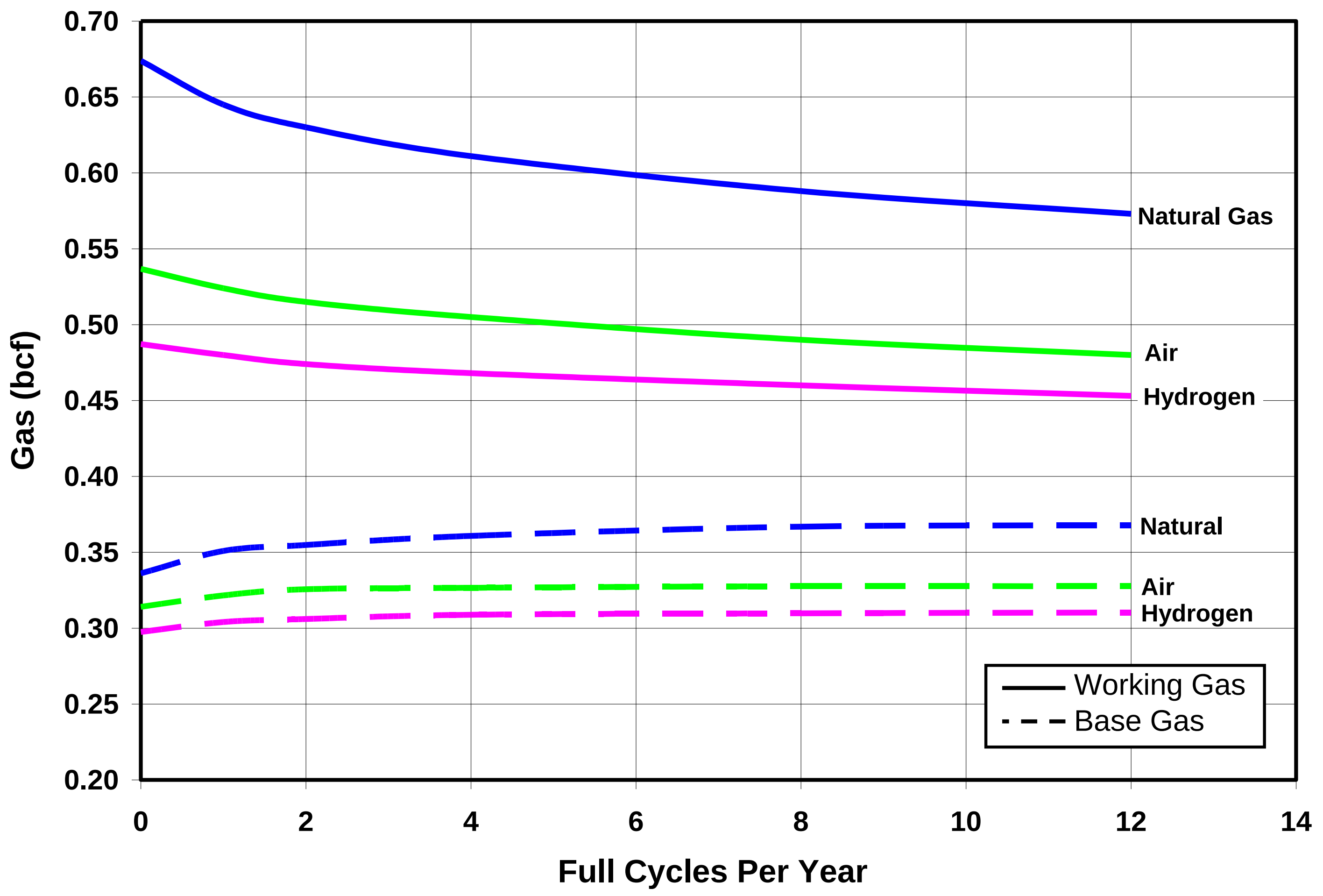
EFFECTS OF VARIOUS PARAMETERS

- TURNS PER YEAR
- MINIMUM GAS PRESSURE
- MAXIMUM GAS PRESSURE
- CAVERN DEPTH

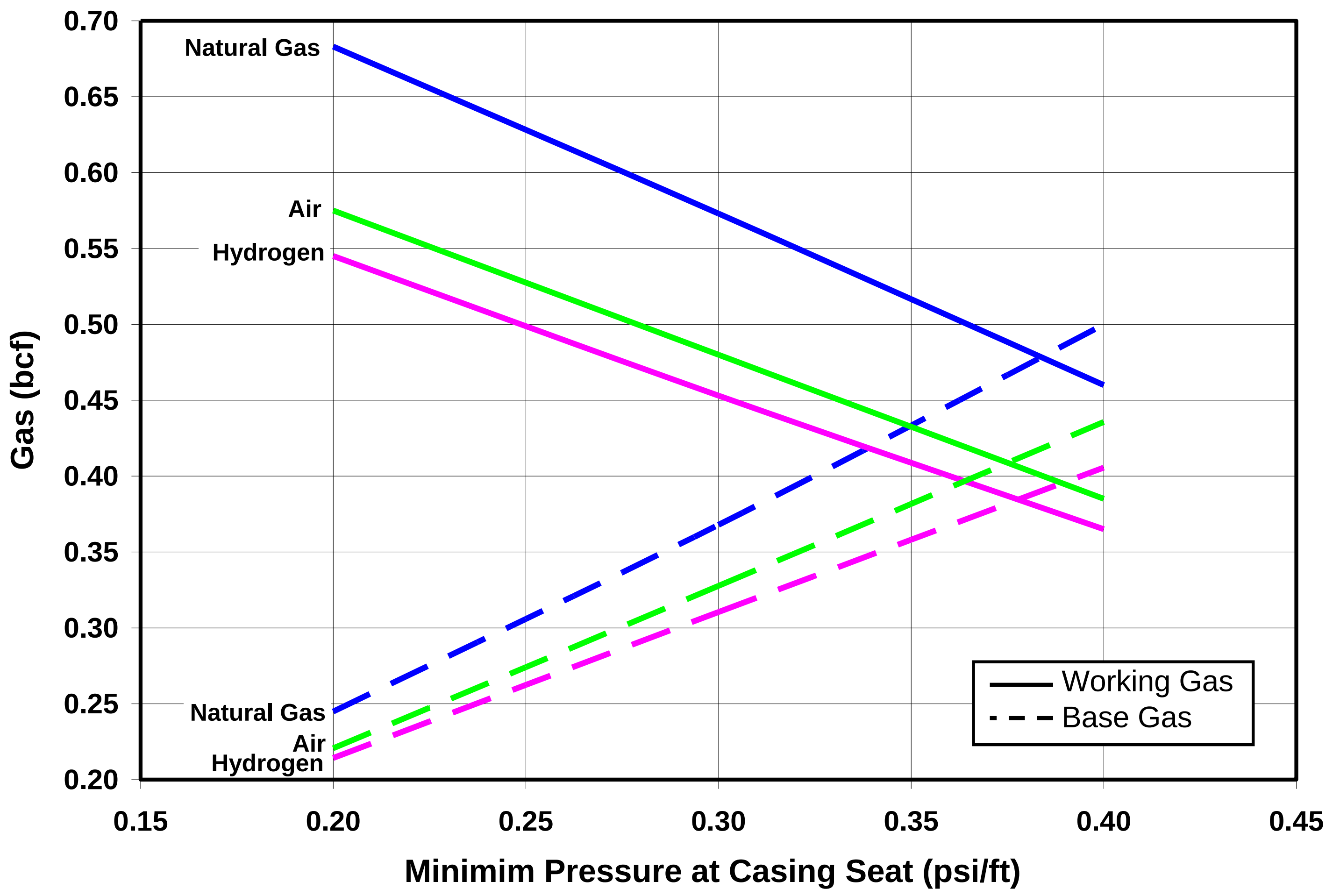
EFFECTS OF TURNS PER YEAR – NATURAL GAS



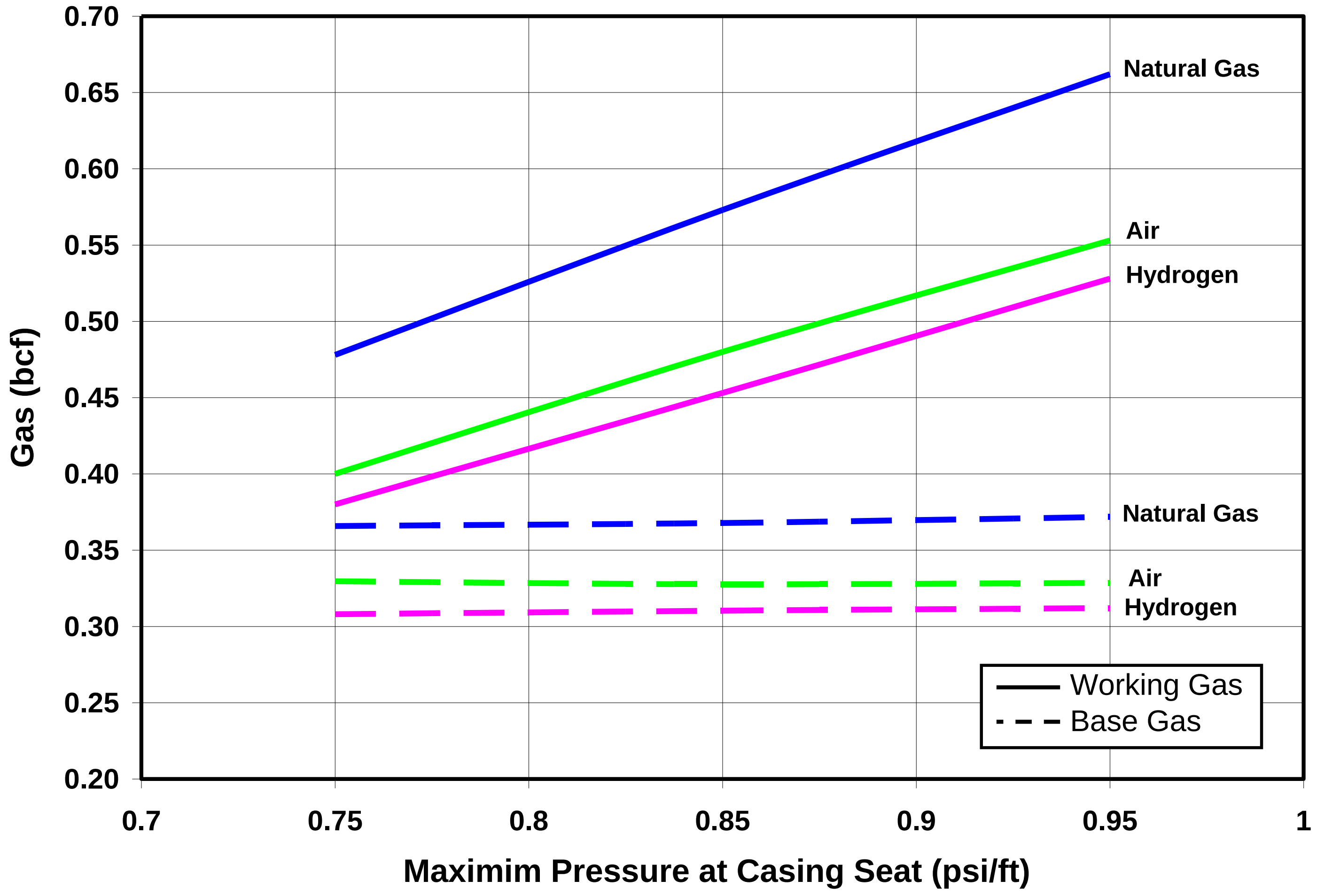
GAS CAPACITY VERSUS CYCLES PER YEAR



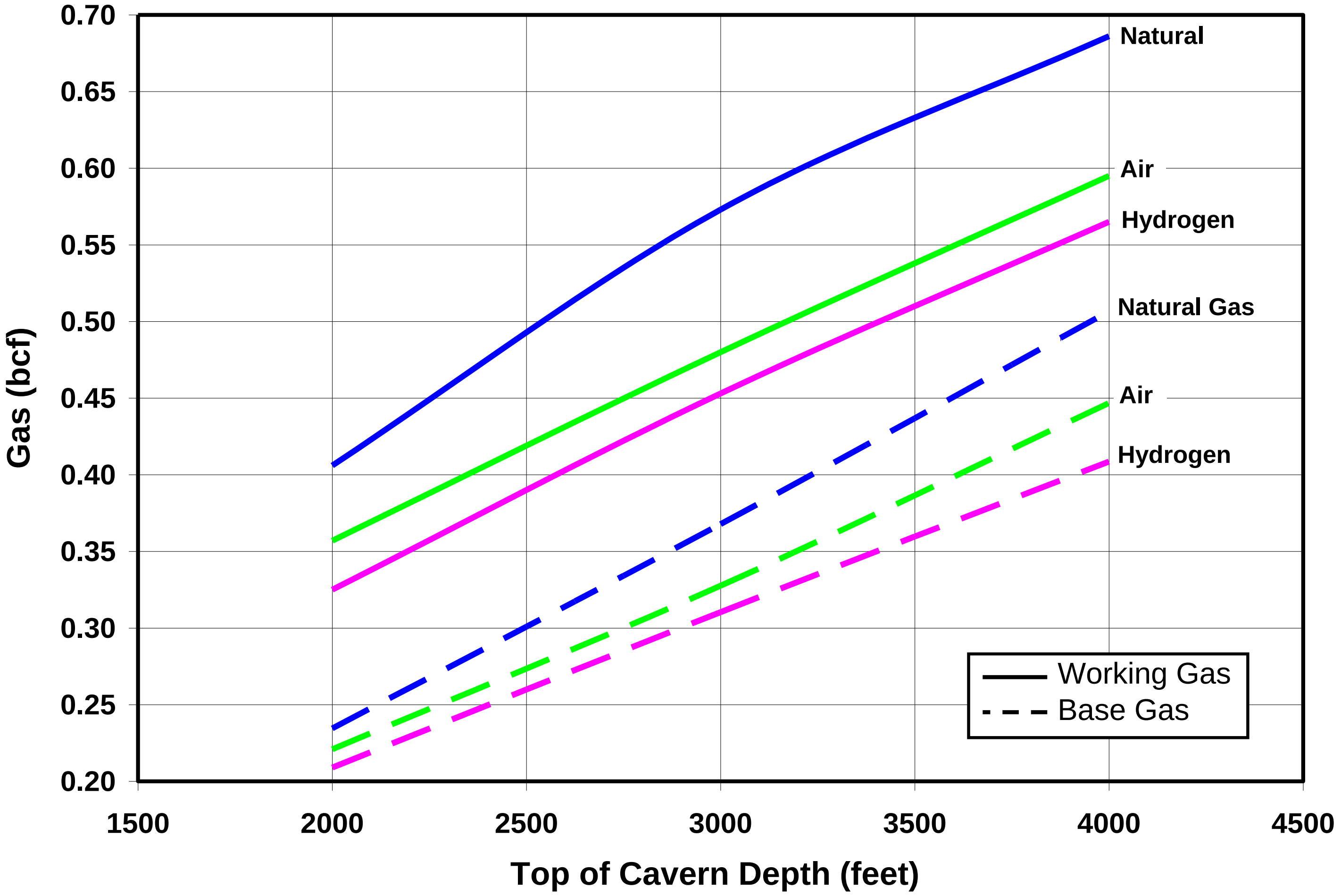
GAS CAPACITY VERSUS MINIMUM PRESSURE



GAS CAPACITY VERSUS MAXIMUM PRESSURE



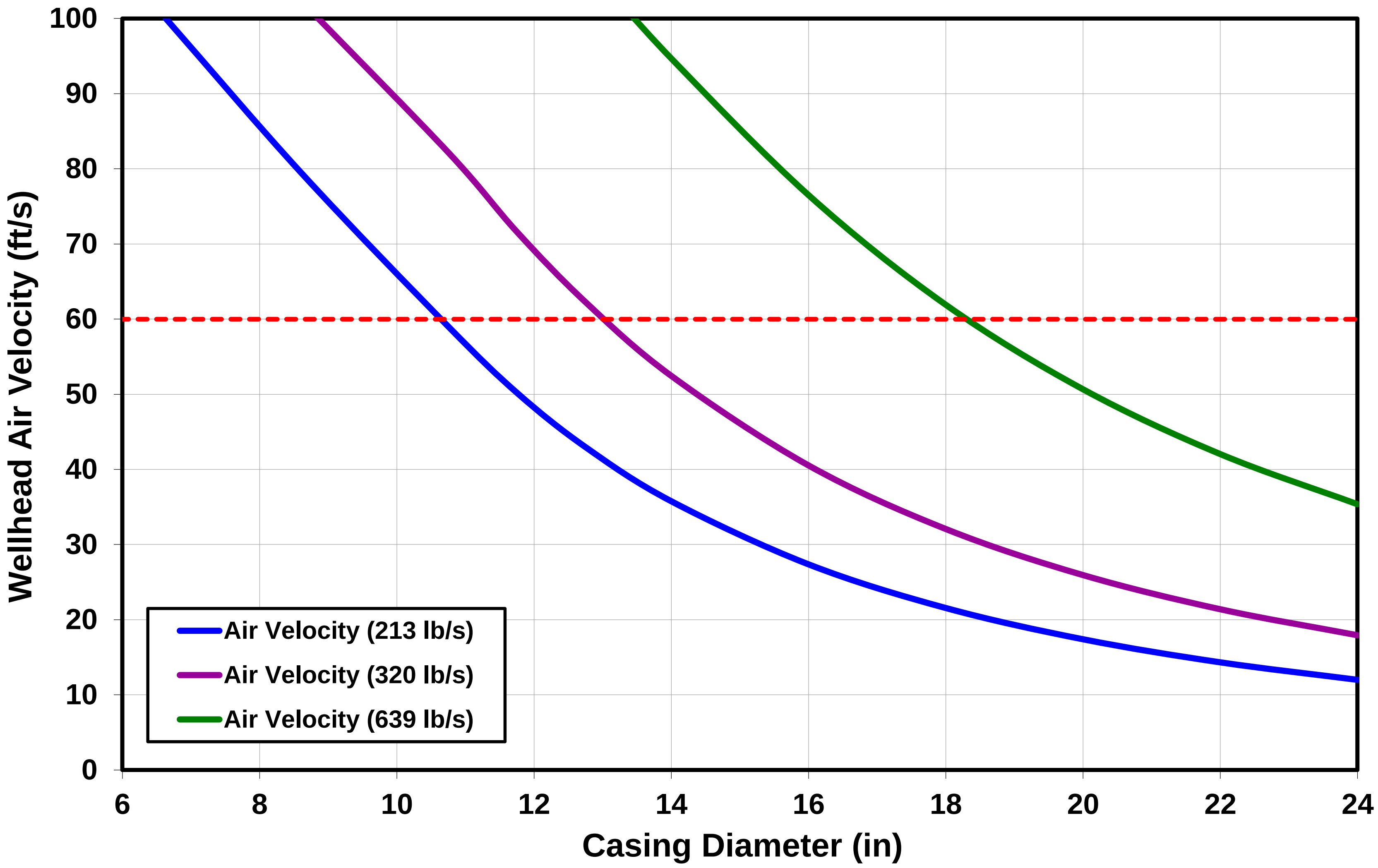
GAS CAPACITY VERSUS CAVERN DEPTH



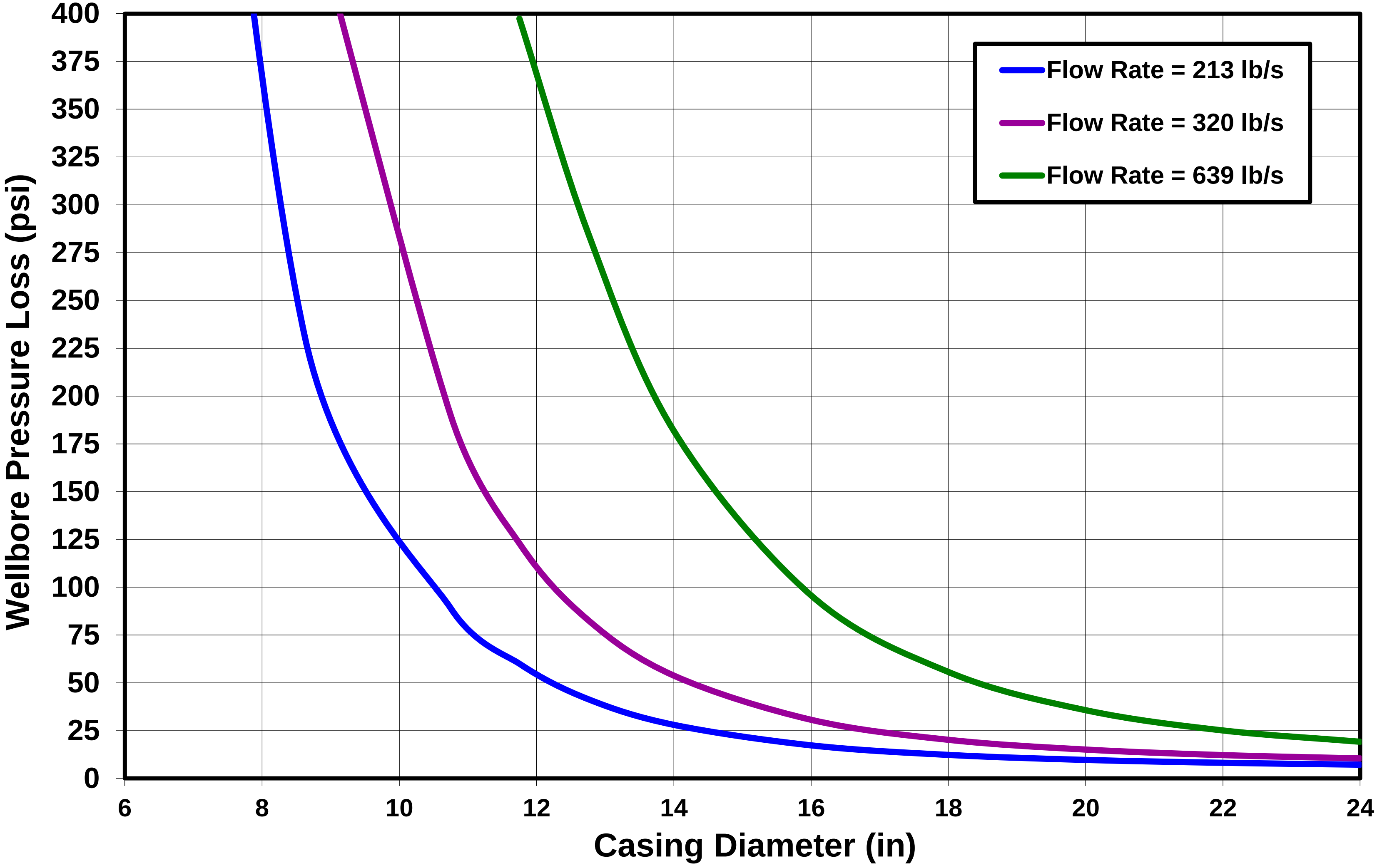
WELL DESIGN

- NEW CAVERN
  - How large should the casing be for desired flow rates?
- EXISTING CAVERN
  - How large can flow rates be in existing well?
- DESIGN CONSTRAINTS
  - Gas velocity (erosion, vibration, etc.)
  - Frictional pressure losses

CASING DESIGN – EROSION VELOCITY CONSTRAINTS



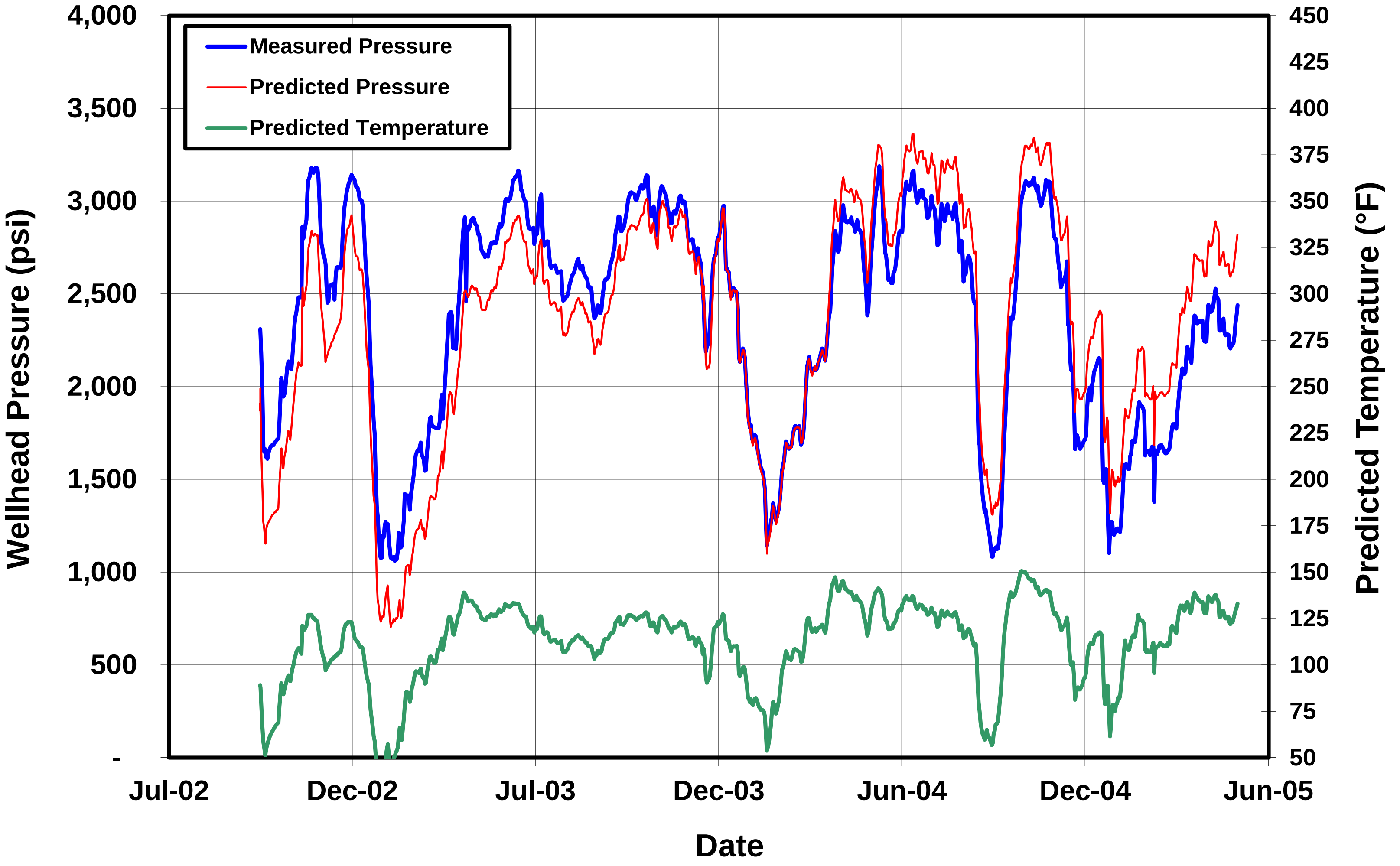
CASING DESIGN – FRICTIONAL PRESSURE LOSS



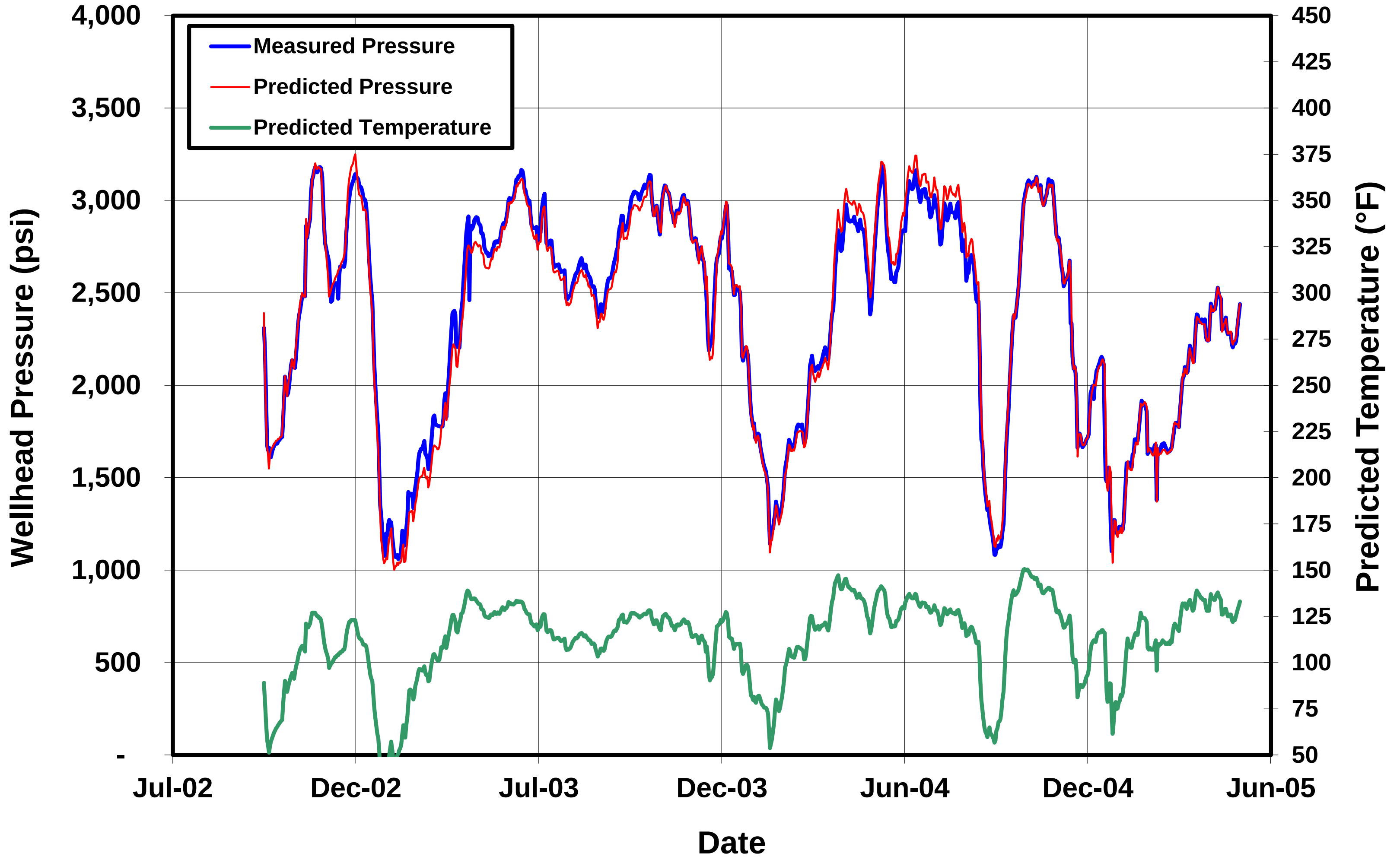
MODEL CALIBRATION

- **DETERMINING ONE OR MORE UNKNOWN MODEL PARAMETERS TO BEST FIT MEASURED DATA**
- **MEASURED DATA**
  - Wellhead gas pressure
  - Wellhead gas temperature
  - Cavern gas pressure
  - Cavern gas temperature
- **UNKNOWN FITTING PARAMETERS**
  - In situ salt temperature
  - Cavern volume
  - Cavern closure rate
  - Salt thermal properties (thermal conductivity & specific heat)
  - Heat transfer coefficient between cavern gas and salt

MODEL CALIBRATION – BEFORE CALIBRATION



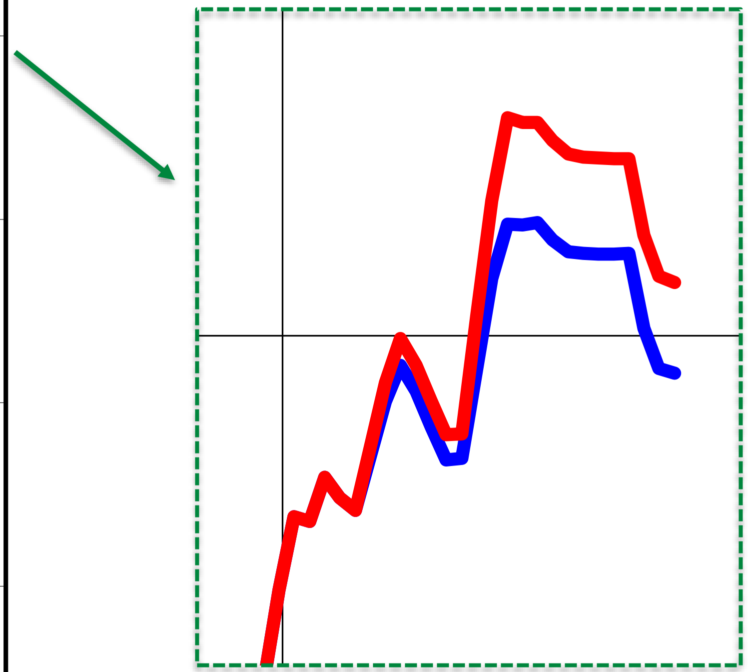
MODEL CALIBRATION – AFTER CALIBRATION



INVENTORY VERIFICATION/INTEGRITY MONITORING

- DOES THE CAVERN BEHAVE THE WAY IT SHOULD?
- DOES THE MODEL NEED RECALIBRATING

INVENTORY VERIFICATION/INTEGRITY MONITORING

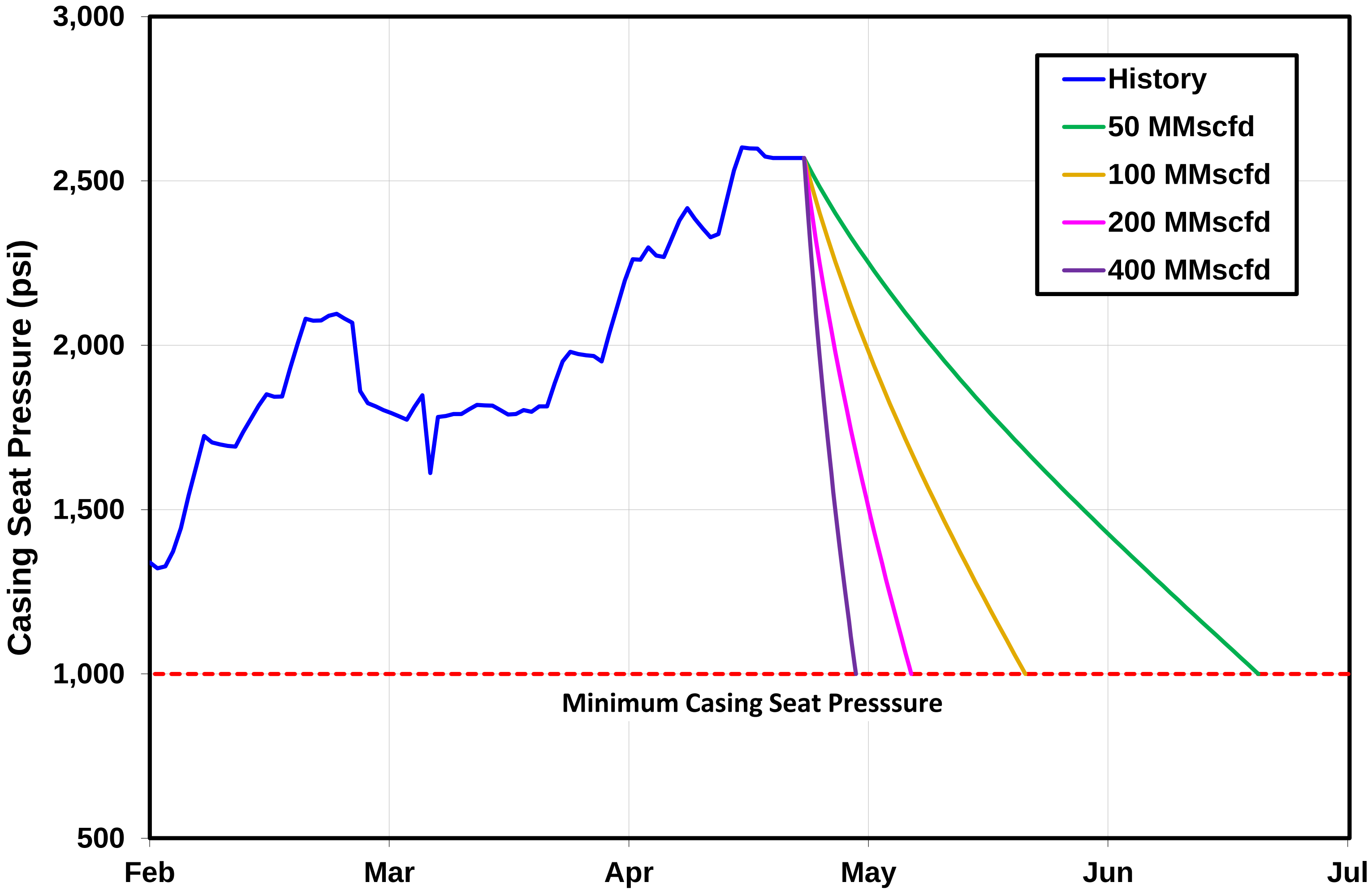


GAS NOMINATIONS

TYPICAL CONSTRAINTS

- Minimum pressure
- Depressurization rate
- Wellbore velocity
- Hydrate formation

GAS NOMINATIONS – MINIMUM PRESSURE CONSTRAINT



Gas Withdrawal Rate (MMscfd)	Gas That Can Be Withdrawn (bcf)
50	2.96
100	2.84
200	2.75
400	2.66

SUMMARY

- **THERMODYNAMICS IS IMPORTANT FOR BOTH:**
  - New Gas Cavern/field Design (conversion or new caverns)
    - Cavern sizing
    - Well sizing
  - Existing Gas cavern/field
    - Inventory verification/Integrity monitoring
    - Gas nominations