DOE sCO_2 Workshop 2019

Molten Nitrate Salt Thermal Energy Storage

National Renewable Energy Laboratory

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Nitrate Salt Thermal Storage

- Commercial projects
  - Solar parabolic trough and central receiver
  - Two-tank (hot tank and cold tank) designs
  - No thermocline systems have been built to date
- Nitrate salt
- Tank design basis
- Foundation design basis
- Experience from solar thermal projects

Commercial Solar Projects

Project		Capacity, MWe	Storage, hours
Andasol-1	Trough	50	7.5
Andasol-2	Trough	50	7.5
Andasol-3	Trough	50	7.5
Arcosol 50 - Valle 1	Trough	49.9	7.5
Arenales	Trough	50	7
Ashalim Trough	Trough	121	4.5
Aste 1A	Trough	50	8
Aste 1B	Trough	50	8
Astexol II	Trough	50	8
Bokpoort	Trough	55	9.3
Casablanca	Trough	50	7.5
Cerro Dominator	Tower	110	17.5
Crescent Dunes	Tower	110	10
DEWA Tower Project	Tower	100	10
DEWA Trough Unit 1	Trough	200	10
DEWA Trough Unit 2	Trough	200	10
DEWA Trough Unit 3	Trough	200	10
Extresol-1	Trough	49.9	7.5
Extresol-2	Trough	49.9	7.5
Extresol-3	Trough	50	7.5
Gemasolar Thermosolar Plant	Tower	19.9	15
Kathu Solar Park	Trough	100	4.5
KaXu Solar One	Trough	100	2.5

Project		Capacity, MWe	Storage, hours
Khi Solar One	Tower	50	2
La Africana	Trough	50	7.5
La Dehesa	Trough	49.9	7.5
La Florida	Trough	50	7.5
Manchasol-1	Trough	49.9	7.5
Manchasol-2	Trough	50	7.5
NOOR I	Trough	160	3
NOOR II	Trough	200	7
NOOR III	Tower	150	7
Planta Solar 10	Tower	11.02	1
Planta Solar 20	Tower	20	1
Solana Generating Station	Trough	280	6
SunCan Dunhuang 10 MW Phase I	Tower	10	15
Termesol 50 - Valle 2	Trough	49.9	7.5
Termosol 1	Trough	50	9
Termosol 2	Trough	50	9
Xina Solar One	Trough	100	5.5
Shagaya	Trough	50	10
Ilanga	Trough	100	5
Supcon Delingha	Tower	10	2
Supcon Delingha	Tower	50	7
CGN Delingha	Trough	50	9
Suncan Dunhuang	Tower	100	11

Commercial Solar Projects - Continued

- 250 MWe Solana project, with 6 storage units

Commercial Solar Projects - Continued

- Thermal storage tanks at the 110 MWe Crescent Dunes central receiver project

Nitrate Salt

- 60 weight percent $NaNO_3$ and 40 weight percent KNO_3
  - Not the eutectic (50 mole percent each), but less expensive
  - Freezing range of 220 to 240 °C
- Oxidizing material, but chemically stable
  - In air, as the ullage gas in the thermal storage tanks
  - In water, when exposed to leaks in the steam generator
- Very low vapor pressure; less than 20 Pa at 600 °C
- Upper temperature limit of ~ 600 °C
  - First equilibrium reaction: $NO_3 \leftrightarrow NO_2 + \frac{1}{2} O_2$
  - Second (quasi) equilibrium reaction: $NO_2 \leftrightarrow NO_{(g)} + O^-$
  - Oxide ions react to form nickel oxide, iron oxides, and soluble chromium oxides
  - At oxide concentrations above ~ 200 ppm, corrosion rates exceed commercially acceptable values

Tank Design Basis

- Large volumes (15,000 m^3) and low vapor pressures (10 Pa) lead to a flat bottom tank with a self-supporting dome roof as the lowest cost approach
- Necessarily requires the tank to be supported by, and to interact with, a foundation
- ‘Closest’ design code is American Petroleum Institute 650 - Welded Tanks for Oil Storage
- API 650 is limited to 260 °C
  - For higher temperatures, allowable material stresses are taken from ASME B&PV Code Section II - Materials
  - Combination of Codes must be approved by the local Authorized Inspector

Tank Design Basis - Continued

- Materials
  - Carbon steel for temperatures below 375 °C
    - Defined by corrosion rate and allowable long-term creep deformation
  - Type 304L stainless steel for temperatures between 375 °C and 538 °C
    - Ferritic materials (chrome-moly) offer acceptable corrosion resistance
    - However, the higher chrome alloys require post weld heat treatment
  - Type 347H stainless steel for temperatures above 538 °C
    - ‘H’ grade stainless steels (> 0.04 percent C) are required
    - However, the common types, such as 304H and 316H, can be permanently damaged by intergranular stress corrosion cracking
    - Stabilized stainless steels, including Type 321 and Type 347, are less susceptible to intergranular stress corrosion cracking

Tank Design Basis - Continued

- Requirements not specifically addressed in API 650 or ASME Section II
  - The tank must be preheated to 350 °C prior to filling with salt
  - The tank operates through daily pressure and temperature cycles
  - The low cycle fatigue life must be at least 10,000 cycles
  - The tank, when full, can either increase in temperature or decrease in temperature. Friction between the thin floor (6 to 8 mm) and the foundation places the floor into either tension or compression.
  - The EPC must specify weld filler materials, weld procedures, and post weld heat treatments
    - Post weld heat treatment of carbon steel is specified in Section VIII
    - Post weld heat treatment of stainless steel is optional in Section VIII; i.e., an EPC decision
    - Tricky decision for stabilized stainless steels

Tank Design Basis - Continued

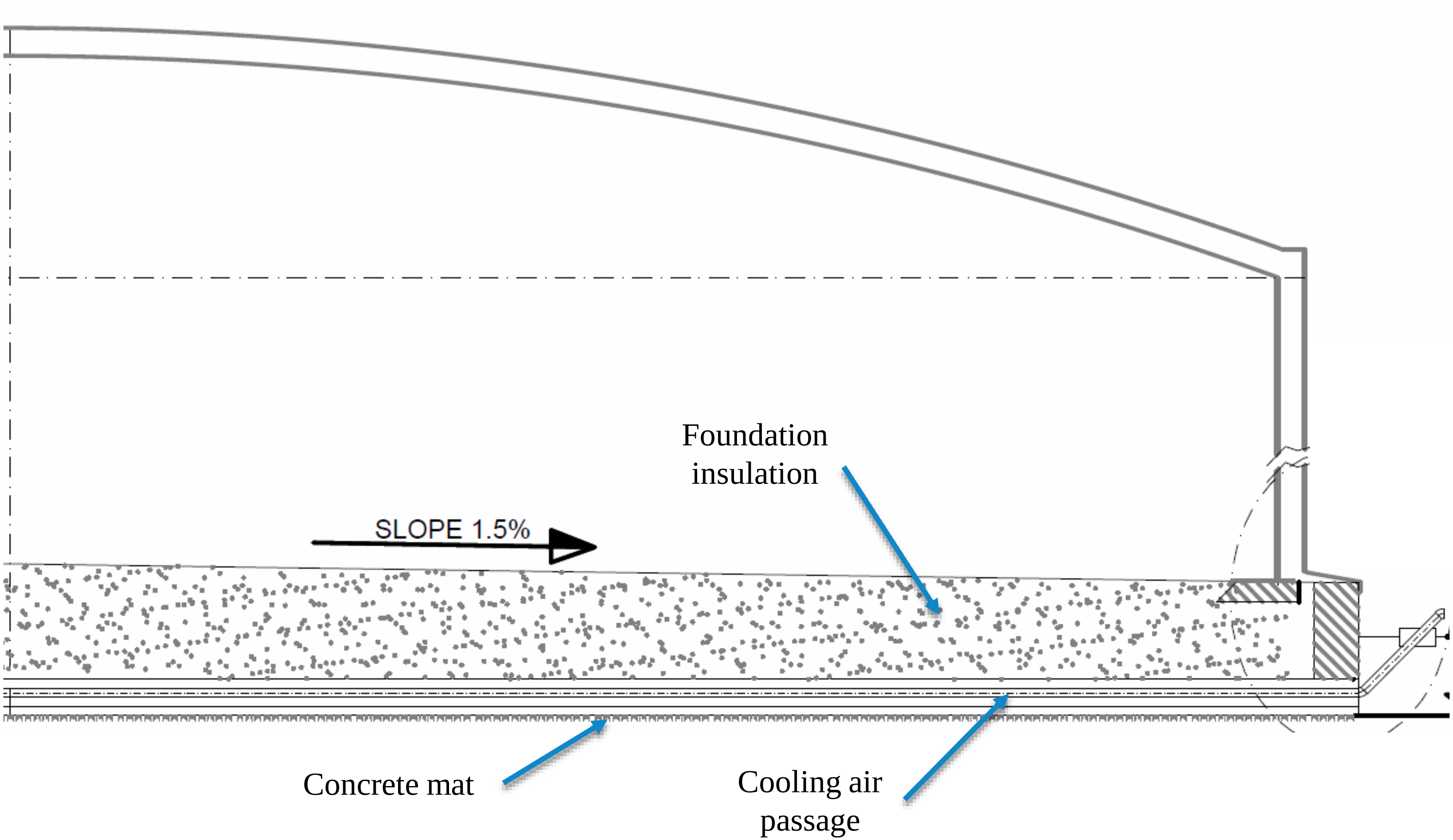
- Tank inlet piping and eductor arrangements may not provide perfect mixing, particularly during trip conditions
- Foundation temperatures are high enough to produce soil desiccation and oxidation of organic material. To prevent excessive foundation settlement, cooling must be provided to limit soil temperatures to 75 °C.
- The EPC must develop
  - Tank specifications based on API 650, ASME Section II, Section VIII Division 1 (infinite fatigue life), Section VIII Division 2 (low cycle fatigue life), and modifications to the rules in API 650
  - CFD analyses of flow distributions during transient conditions, and the associated FEA analyses of the floor and wall stresses
  - Operating procedures consistent with a 30-year fatigue life
- The storage system, particularly the hot tank, is neither isobaric nor isothermal

Foundation Design Basis

- Concrete base slab
- Forced convection air cooling of the concrete
- Rigid perimeter ring wall of a refractory material (cast or bricks) to accommodate the concentrated vertical loads from the wall and the roof. Expanded clay as the sole foundation material has repeatedly been shown not to work.
- Expanded glass as the primary insulation material
- Contiguous drip pan to isolate the foundation from a salt leak
  - Salt has a higher thermal conductivity than the insulation
  - Foundation thermal losses will markedly increase due to salt contamination
- Sand layer to reduce friction forces between bottom of the tank and the foundation
  - Reduce the potential for buckling of the thin floor plates

Foundation Design Basis - Continued

- Cooling air ducts in a (somewhat non-representative) tank foundation



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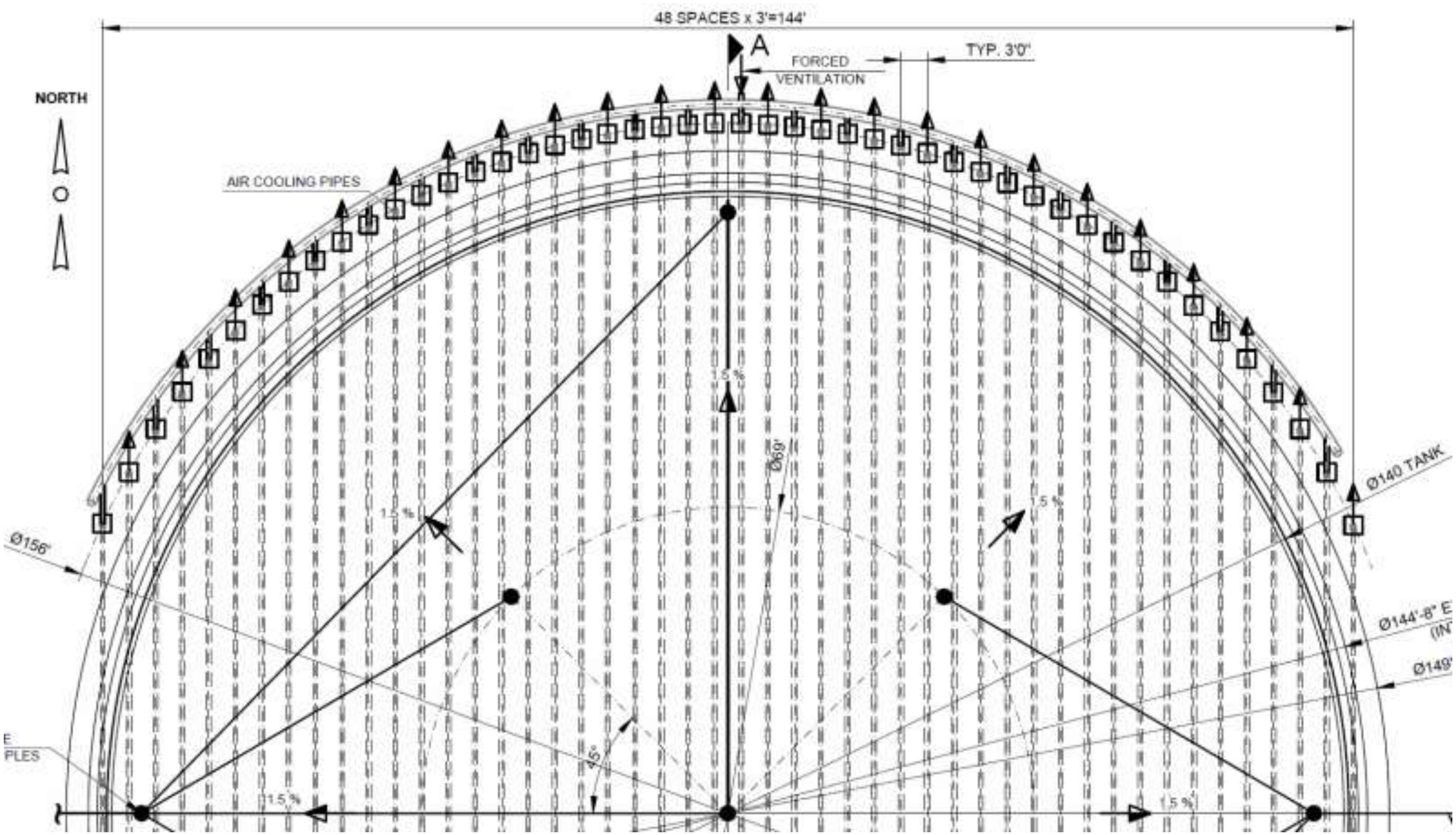
Foundation Design Basis - Continued

- Tank foundation cooling air passages



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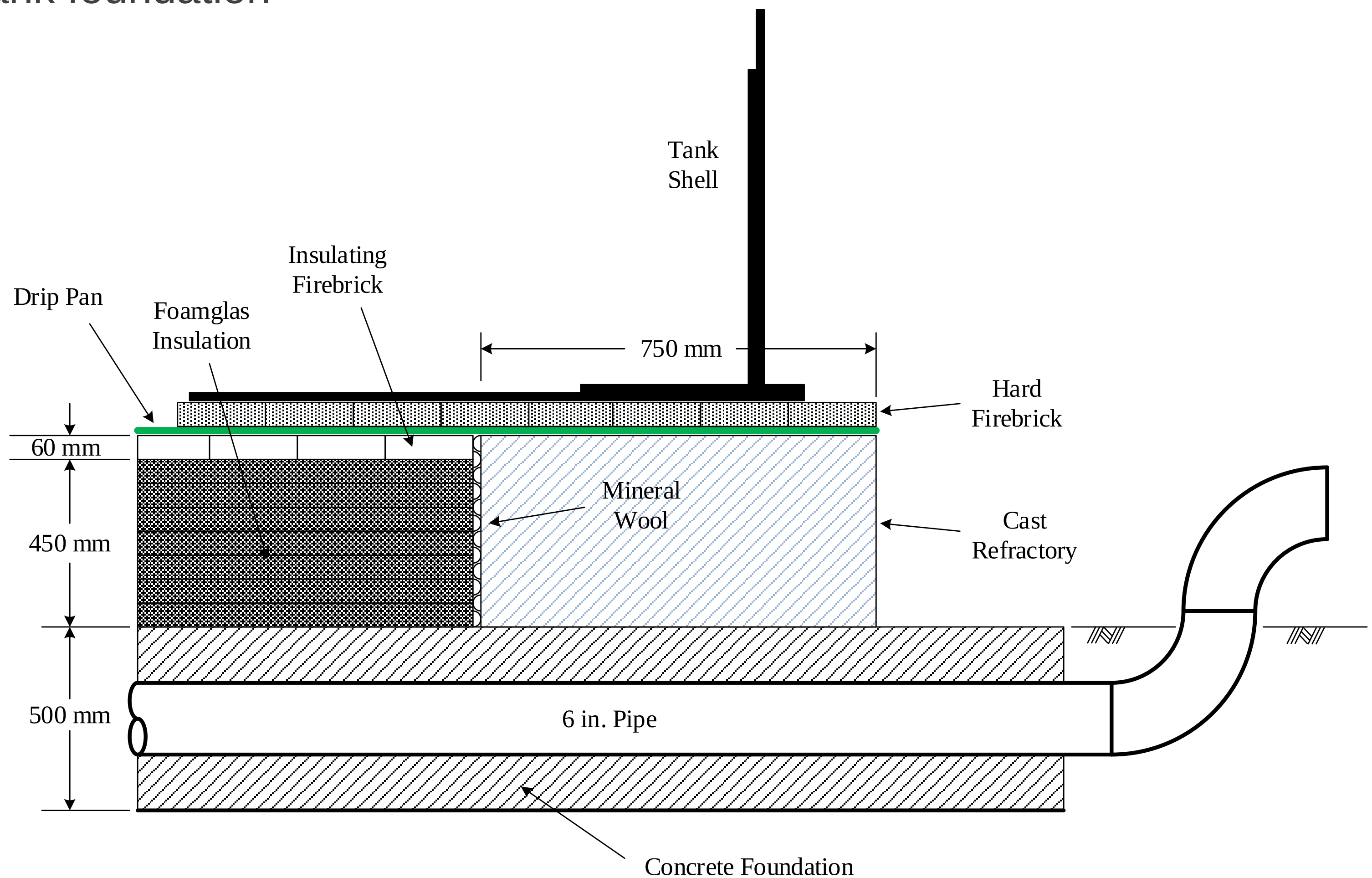
Foundation Design Basis - Continued

- Hot tank foundation



Nitrate Salt Pumps

- Pumps with extended shafts draw suction from bottom of storage tanks
- Turbine pumps, with bearings lubricated by the salt
- Avoids need for below-grade pump sumps, fed by gravity from storage tanks
- Reliability has been excellent

Parabolic Trough Thermal Storage

- Indirect thermal storage
  - Therminol heat transfer fluid in the collector field
  - Nitrate salt thermal storage fluid
  - Oil-to-salt heat exchange during charging; salt-to-oil heat exchanger during discharging
- 300 °C cold tank temperature, and 385 °C hot tank temperature
- All carbon steel construction
- Tank dimension limits
  - 12 m tall based on allowable soil bearing pressures
  - 40 m diameter to avoid ASME Section II requirements for post weld heat treatment of carbon steel with thicknesses greater than 38 mm
- 78 tanks built to date, with only 1 reported leak (perhaps due to a weld defect)

Central Receiver Thermal Storage

- Receiver supplies salt directly to the cold tank or to the hot tank based on diversion valve positions
- 295 °C cold tank temperature, and 565 °C hot tank temperature
- Carbon steel cold tank, and Type 347H stainless steel hot tank
- Tank dimensions are similar to parabolic trough projects
- 4 storage systems built to date: Solar Two; Gemasolar; Crescent Dunes; and Noor III
- No cold tank leaks
- 4 hot tank leaks to date: 2 at Gemasolar; and 2 at Crescent Dunes
  - Primarily due to problems with the foundation
  - No evidence of stress relaxation cracking, intergranular stress corrosion cracking, incorrect selection of weld filler materials, or unexpected corrosion processes

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Central Receiver Thermal Storage - Continued

- Revised hot tank design and operation
  - Tank specification addenda to API Standard 650 regarding friction forces between the foundation and the floor
  - For transient conditions, CFD/FEA analyses of salt flow distributions, metal temperature distributions, and floor and wall stress distributions
  - 30-year low cycle fatigue analyses
  - Foundation materials, particularly at the perimeter of the tank, that limit local settlement due to tank thermal expansion and contraction cycles
  - For a given inventory level and temperature, DCS permissives on inlet flow rate and temperature
- An increase in tank dimensions brought new failure modes, but the problems are generally understood and practical solutions are at hand