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CSP Training Module 5: Plant Startup and Shutdown

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Agenda

- 1. Basic Theory of Operation
- 2. Fuel
- 3. Modeling CSP plants
- 4. Basic construction and Design
- 5. Startup and Shutdown
- 6. Major System Operations
- 7. Plant Operation influences on the grid
- 8. Response to Weather Changes
- 9. Water Chemistry
- 10. Plant Performance Measurements
- 11. Safety Concerns

5. Startup and Shutdown

- Receiver startup and ramp rates
  - Building pressure and temperature
  - Superheat
  - Reheat
- Piping warmup
- Turbine warmup and ramp rates
    - Admissible steam conditions

Plant Startup

- Objective: Start up the receiver, admit steam to the turbine and bringing the plant on-line.
- Sunrise:
  - Sun must be above the horizon about 8 degrees before there is any appreciable DNI or reasonable optical efficiency.
  - Heliostat blocking is too high and the DNI is too low earlier in the morning to startup sooner.
- Prep for Receiver Startup
  - Heliostats need to be ready and in position to track the sun
  - Line-up valves associated with the receiver and piping:
    - Drum vent valve opened (if drum pressure < ~2 bar)
    - Superheater and reheater drain and vent valves opened
    - Continuous and intermitten blowdown valves closed
  - Drum level set to nominal

Receiver Startup

- Begin heating receiver
  - Heliostats commanded to point at the evaporator section of the receiver
  - As the sun rises, the power incident on the receiver will increase due to increasing DNI.
  - As the sun rises, the optical efficiency of the heliostat field increases.
- Receiver ramp rate limits
  - Receiver (boiler) has ramp rate limits based on the condition of the receiver
    - When the receiver panels have subcooled water, the flux is limited to prevent localized overheating
    - Once circulation is established the ramp rate is limited by the rate of pressure change of the drum and controllability of the drum level.
    - After the a certain threshold of drum pressure is reached, the allowable rate of pressure increase is much higher. Actual rates are a function of the design

Receiver Startup

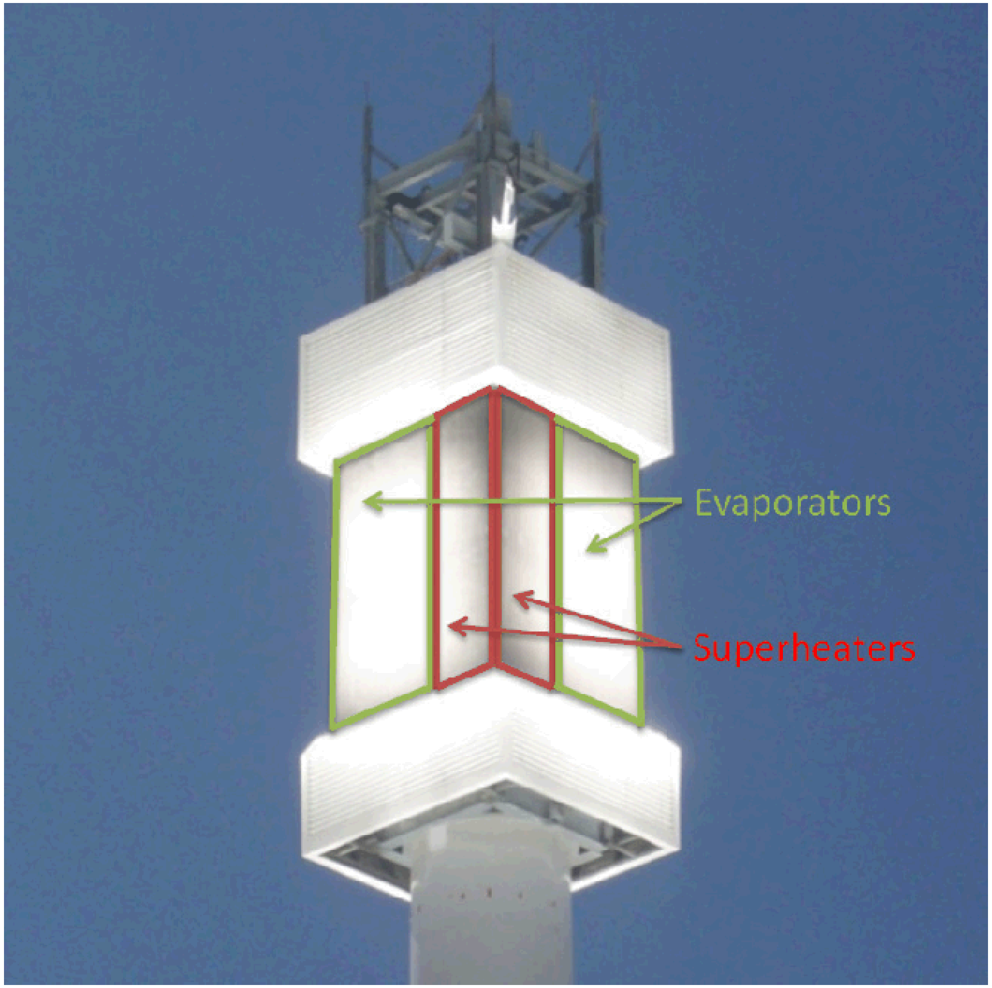
- Receiver builds pressure
  - Once the pressure exceeds about 2 bar, the drum vent valve is closed
  - Steam flows through the superheater, its vent and drain lines, the main steam stop valve, and through the piping
  - Condensate flows through the drain lines
- Drum level
  - As the water level in the drum drops, feedwater is introduced in the steam drum to make up the inventory lost
  - The drum level is maintained by modulating the feedwater FCV
- Once the superheater and reheater panels reach the steam temperature (typically the saturation temperature for the current pressure), then the drain and vent valves can be closed.

Receiver Startup

- Once pressure in the drum and steam flow rate reach acceptable levels
  - Heat can be added to the superheater and reheater sections of the receiver
- Balancing incident power between evaporator, superheater, and reheater
  - Creates a dynamic situation
  - External direct steam receivers actually have much more control of the heat flux on the various sections than fossil fire boilers
  - Power on the evaporator, P_{evap}, goes into evaporating water from the steam drum, establishing the flow rate of steam through the superheater and reheater.
  - Adding power to the superheater and reheater sections, P_{super} and $P_{reheater}$, increases the temperature of the steam. The target temperature is that which the turbine can admit and use.
    - $P_{total} = P_{evap} + P_{super} + P_{reheat}$

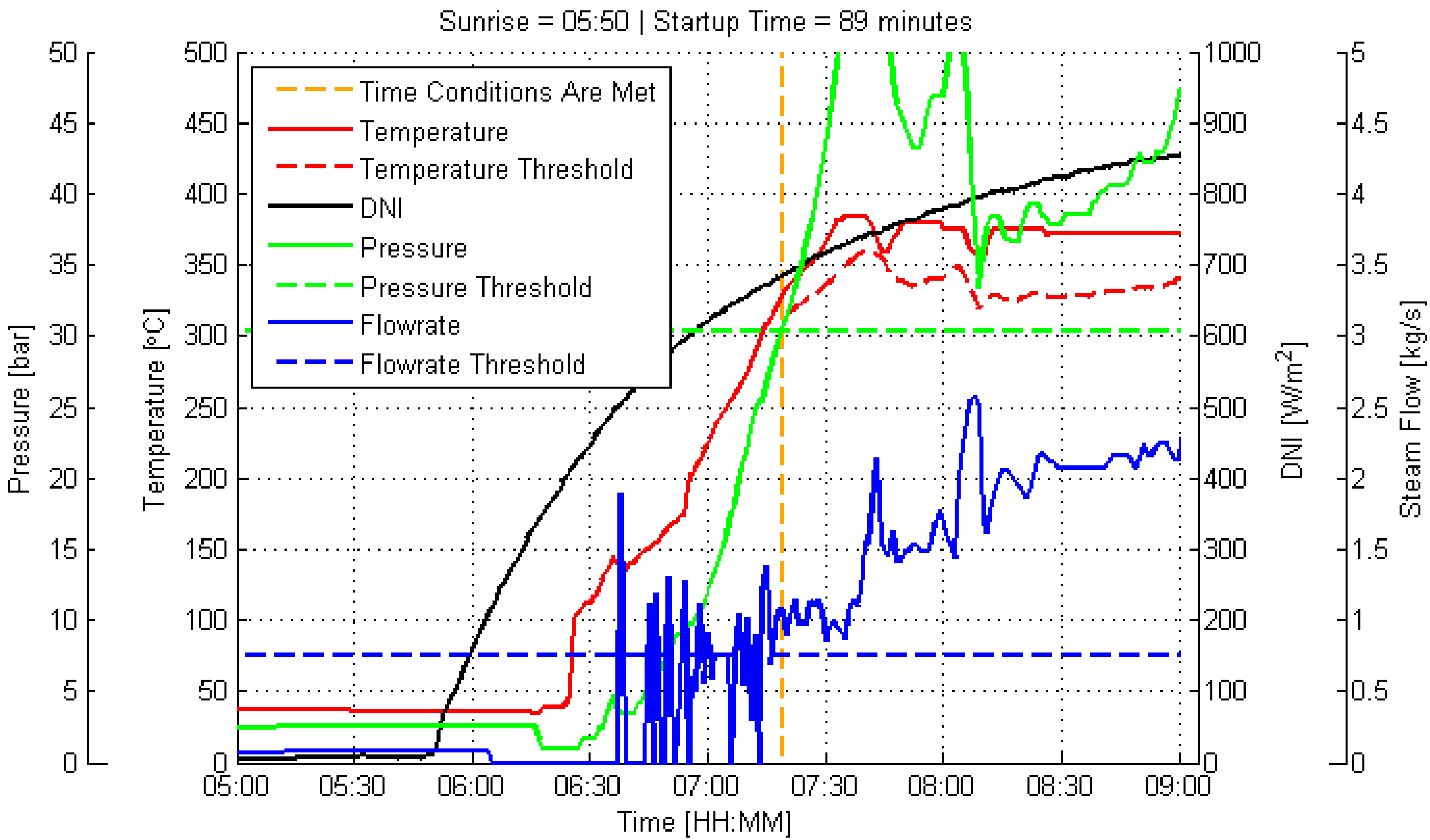
Example of Direct Steam Receive Startup

- eSolar receiver at Sierra Generating Station



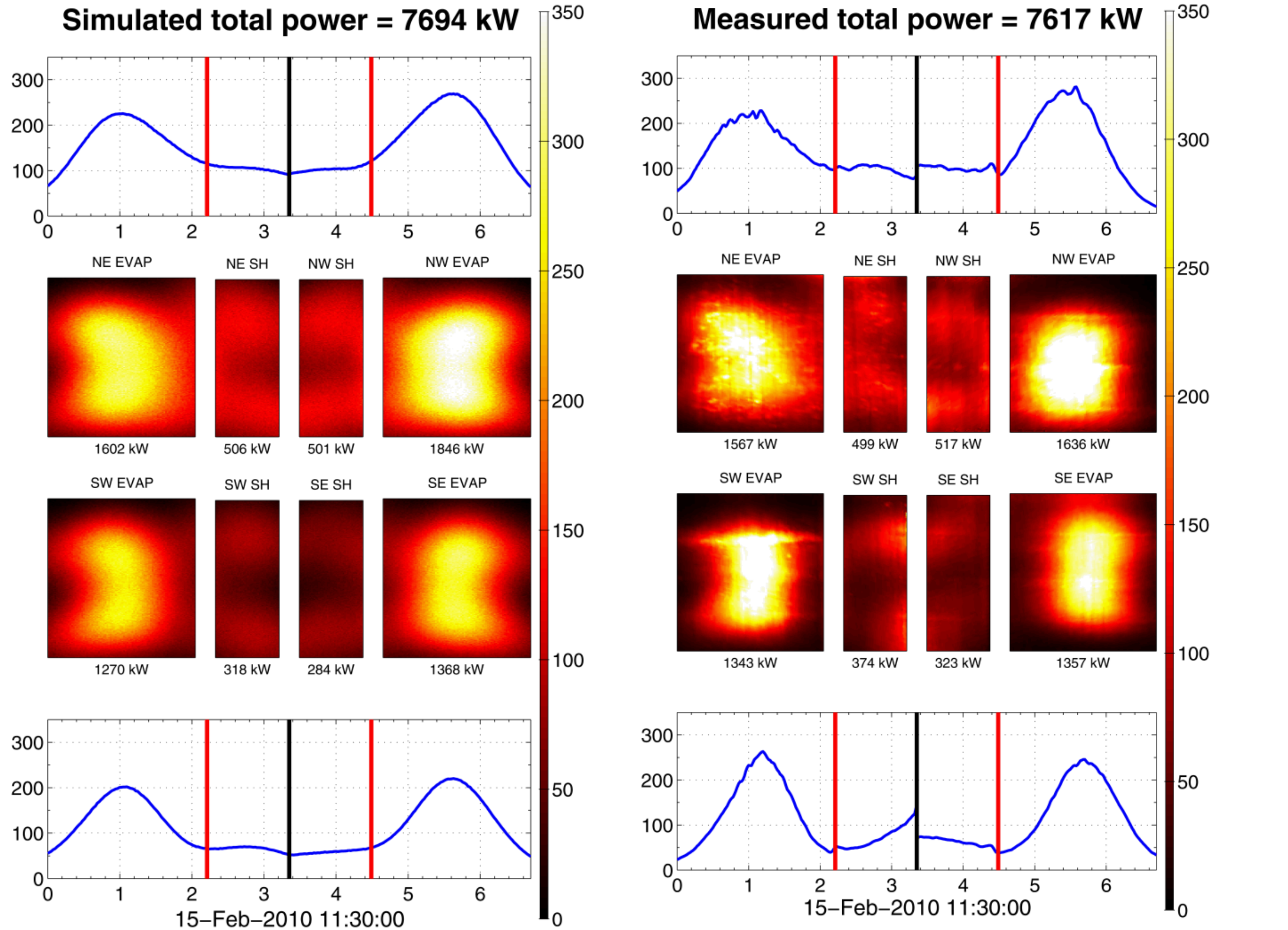
Source: M. Slack, P. Meduri, and A. Sonn, eSolar Power Tower Performance Modeling and Experimental Validation, SolarPACES 2011, Granada, Spain, Sept 2011.

Startup of Direct Steam Receiver



Source: P. Meduri, C. Hannemann, and J. E. Pacheco, Performance Characterization and Operation of eSolar's Sierra Suntower Power Tower Plant, SolarPACES 2011, Granada, Spain, Sept 2011.

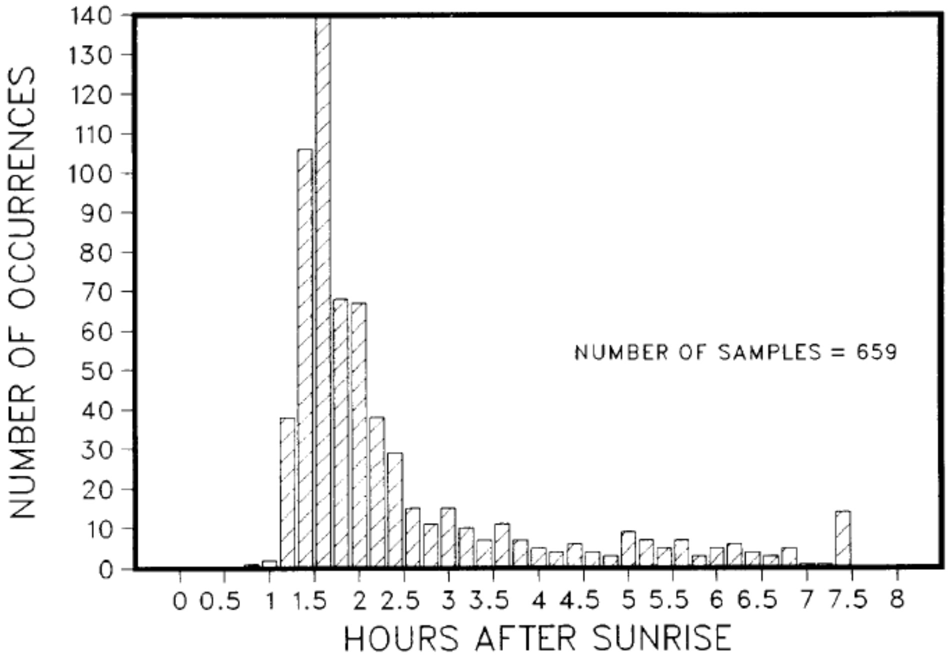
Balancing Evaporator and Superheater Flux



Source: M. Slack, P. Meduri, and A. Sonn, eSolar Power Tower Performance Modeling and Experimental Validation, SolarPACES 2011, Granada, Spain, Sept 2011.

How long should it take to startup the receiver in the morning?

- Depends on the design of the receiver and limits imposed by the receiver vendor
- Good goal is 1 to 1.5 hours after sunrise.
- Solar One experience: majority occur by 1.2 hours after sunrise



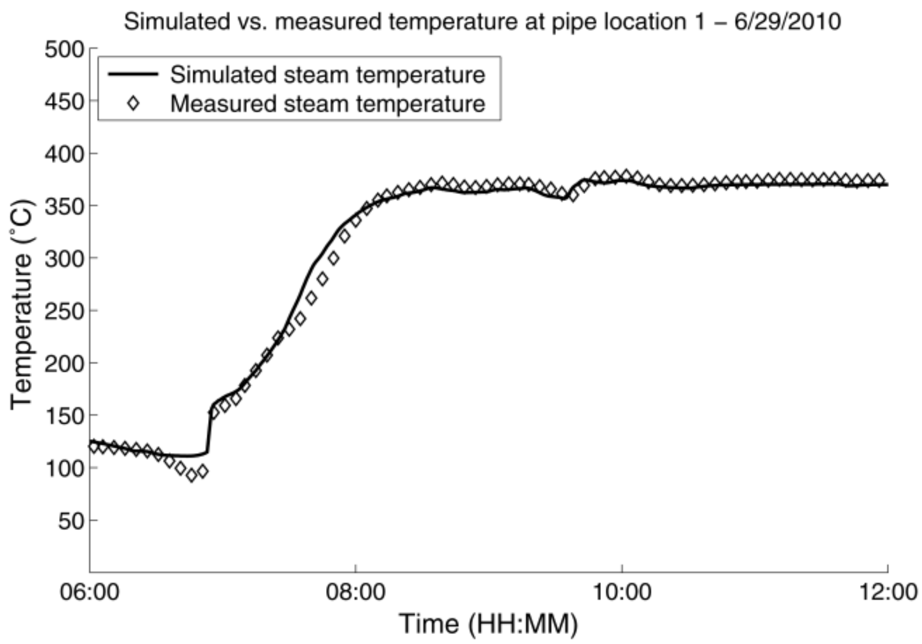
Source: L. G. Radosevich, Final Report on the Power Production Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant, SAND87-8022, March 1988

Piping Warm-up

- When flow is established in the receiver, steam flows through the main steam line
- Piping system warms up
- Steam will condense bringing the pipe to the saturation temperature
- When superheated steam flows through the piping system
  - The temperature ramp rate is slower than bringing it up to saturation temperature
  - Superheated steam has a lower heat transfer coefficient

Pipe Warm-up

- Compared piping modeled behavior to actual data
- Lumped capacitance model worked well
- Piping model computes the metal and fluid temperatures along the length of the pipe.
- Model validated with data from temperature sensors and thermocouples were installed along the length of the steam piping to measure the pipe metal temperature.



Source: M. Slack, P. Meduri, and A. Sonn, eSolar Power Tower Performance Modeling and Experimental Validation, SolarPACES 2011, Granada, Spain, Sept 2011.

Steam Turbine Warm-up and Ramp Rates

- Warming up the turbine consist of:
  - 1) first putting a vacuum on the condenser
  - 2) synchronizing to the grid
  - 3) then increasing output
- With the steam generator in the auxiliary steam state, establish a vacuum in the condenser by
  - 1) starting the gland steam exhaust pump,
  - 2) closing the vacuum breaker on the condenser,
  - 3) starting the vacuum pump, and
  - 4) establishing a flow of steam to the turbine shaft seals

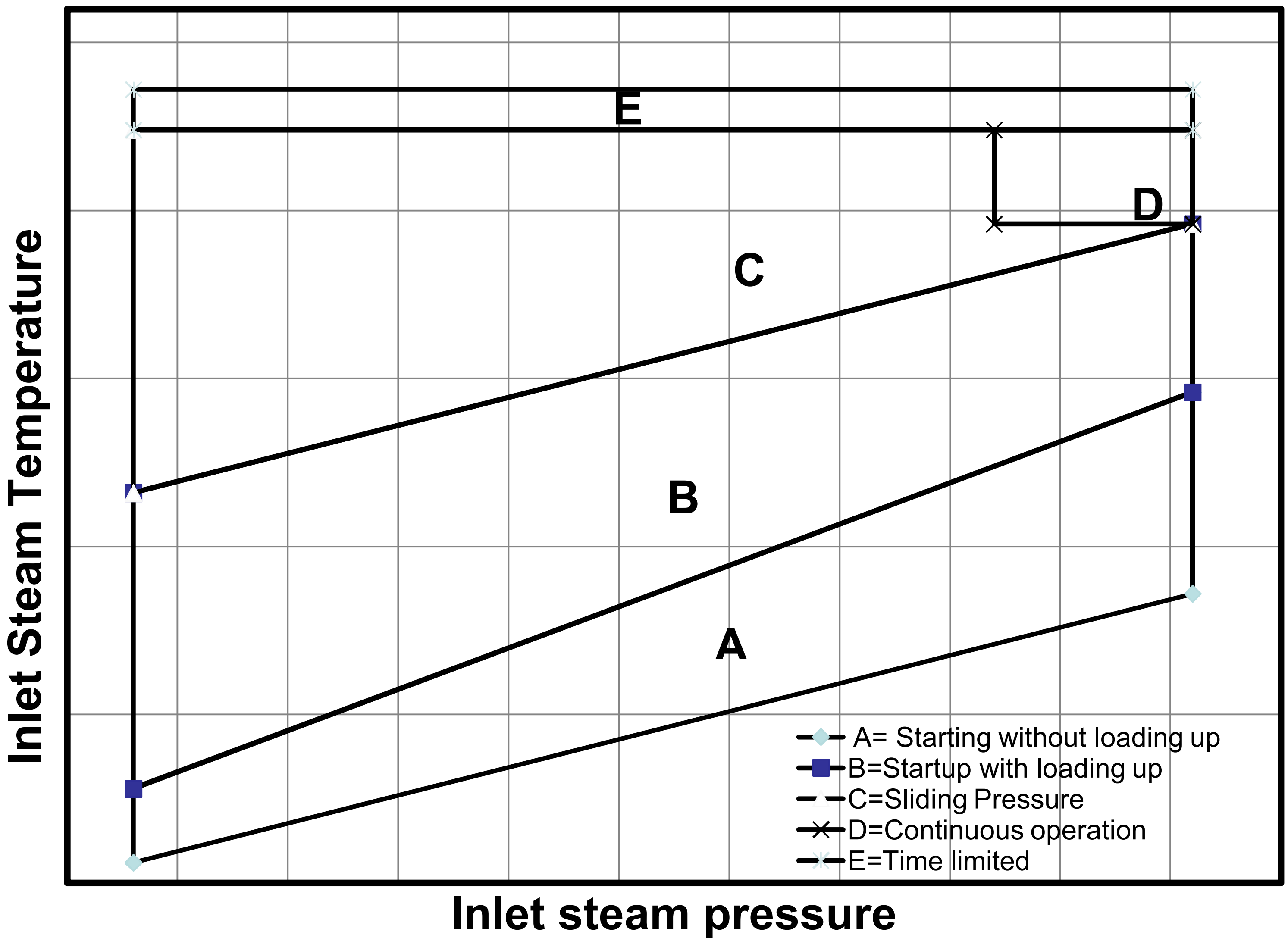
Steam Turbine Warm-up

- **Synchronize the generator** with the grid by:
  - 1) starting the main feedwater pump,
  - 2) establishing a nominal pressure of 1,200 lb/in2 on the upstream side of the main steam throttle valve to the condenser by opening the bypass valve around the main steam isolation valve,
  - 3) opening the main steam isolation valve,
  - 4) controlling the saturation pressure with the main steam throttle valve to the condenser,
  - 5) warming the main steam line to a temperature at least 100°F above the saturation temperature,
  - 6) opening the main steam stop valve,
  - 7) warming the turbine control valve steam chest to a temperature within 300°F of the temperature of the main steam line,

Steam Turbine Warm-up

- **Synchronize the generator** with the grid (continued)
  - 8) opening the turbine control valves and accelerating the turbine to a speed of 1,000 rev/min,
  - 9) holding the turbine speed at 1,000 rev/min to warm the rotor,
    10) accelerating the turbine speed to 3,600 rev/min,
  - 11) synchronizing the phases and voltage of the generator with the grid,
  - 12) closing the breaker between the generator and the grid,
  - 13) manually increasing the load on the generator until the main steam throttle valve to the condenser is almost in the closed position,
  - 14) placing the main steam throttle valve in manual and closing the valve,
  - 15) manually increasing the set point value for the turbine inlet pressure controller until the set point is slightly below the pressure in the main steam header,
  - 16) manually decreasing the load on the generator using the speed-load controller until the inlet pressure controller assumes command of the turbine control valves, and
  - 17) placing the extraction feedwater heaters in service in the following order: second, first, fourth, and third.

Admissible Steam Conditions (Example)



Steam Turbine Startup

- **<u>Increase output:</u>** With the steam generator in the normal operation state, increase the output of the turbine by:
  - 1) increase the steam flow rate,
  - 2) establishing a temperature set point for the receiver (e.g., 1050F),
  - 3) establishing a set point temperature (e.g., 950 F) for main steam attemperator, if necessary, and
  - 4) increasing the power on to the receiver (and corresponding steam flow rate) to the level desired by the operator.

Steam Turbine Ramp Rates

- The turbine ramp rates are determined by the casing temperature. It is usually correlated with the time since last operated.
- Example:
  - Hot start: shutdown time is <16 hours
    - Ramp up time: 10 minutes
  - Warm start: shutdown time is >16 hour, but < 40 hour
    - Ramp up time: 42 minutes
  - Cold start: shutdown time is >40 hours
    - Ramp up time: 60 minutes

Shutdown of the Plant

- Sunset
  - As the sun sinks into the sky, DNI will drop, field efficiency deminishes, flow rate, temperature, and pressure all drop.
  - Conditions fall below acceptable conditions for steam turbine
  - Turbine shuts down, goes on turning gear
  - Close main steam stop valve
  - Receiver surface temperature will cool down, as will piping system
  - Drain condensate
  - Close blowdown

Shutdown of the Plant

- Plant trip
  - Caused by an abnormal condition
  - Examples
    - Loss of off-site grid (power failure)
    - High temperature
    - High pressure
    - Pump trip
    - Low drum level
  - Heliostat may need to come off receiver quickly (scram) to prevent damage to the receiver
  - Force turbine to go off line quickly
  - Close main steam stop valve and blowdown
  - Receiver surface will cool and may depressurize
  - Condensate and drain valves may need to be opened

Steam Turbine Shutdown

- The basic procedures to shut down the turbine is:
  - Reduce the generator output to a nominal value (~25% name plate) by decreasing the steam flow rate.
  - Allow the power on the receiver to drop off. The turbine generator will trip when the operating conditions drop below acceptable limits .
  - Maintain a source of auxiliary steam for the turbine shaft seals until the speed of the turbine decays to 1,000 rev/min. The condenser vacuum can then be broken without generating an excessive flow of cold air past the seals and rapidly cooling the ends of the turbine shaft.