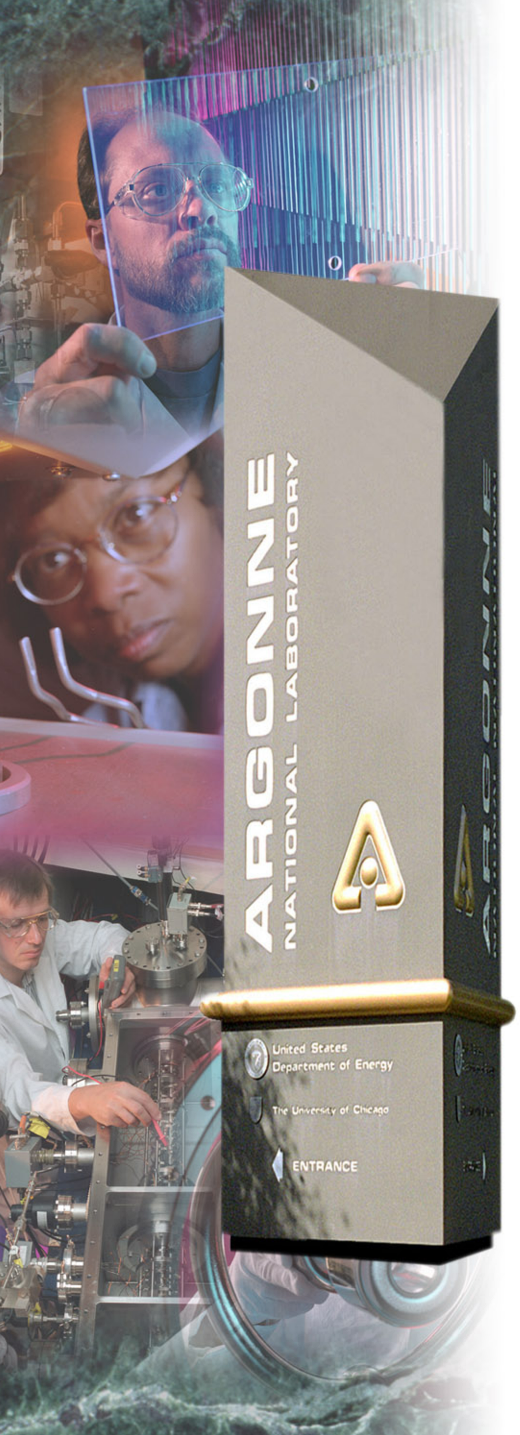

Supercritical CO_2 Brayton Cycle Control Strategy for Autonomous Liquid Metal-Cooled Reactors

by

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Outline

- Introduction
- STAR-LM reactor
- S-CO_2 Brayton cycle
- Autonomous load following
- Control mechanisms
- Control strategy

Introduction

- Why S-CO_2 Brayton cycle?
  - Higher efficiency than Rankine steam cycle
  - Simple BOP layout
    - Fewer components
    - Smaller components

- Better economics
  - Lower capital cost
  - Lower electricity generation cost

Introduction (Cont.)

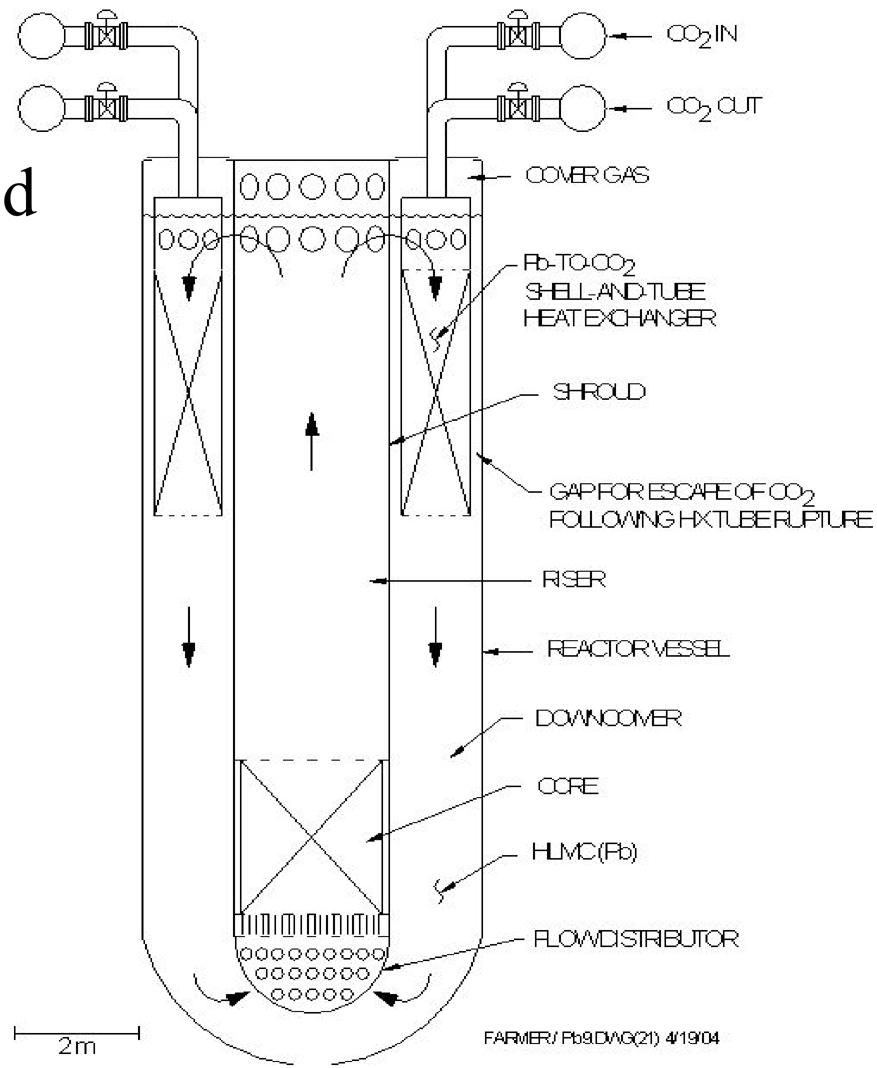
- S-CO_2 Brayton cycle applicable to
  - Na-cooled fast reactors
  - Pb or PbBi-cooled fast reactors
  - Gas reactors

- Control aspects of the S-CO_2 Brayton cycle coupled to a Pb-cooled fast reactor were investigated in this work

STAR-LM Reactor

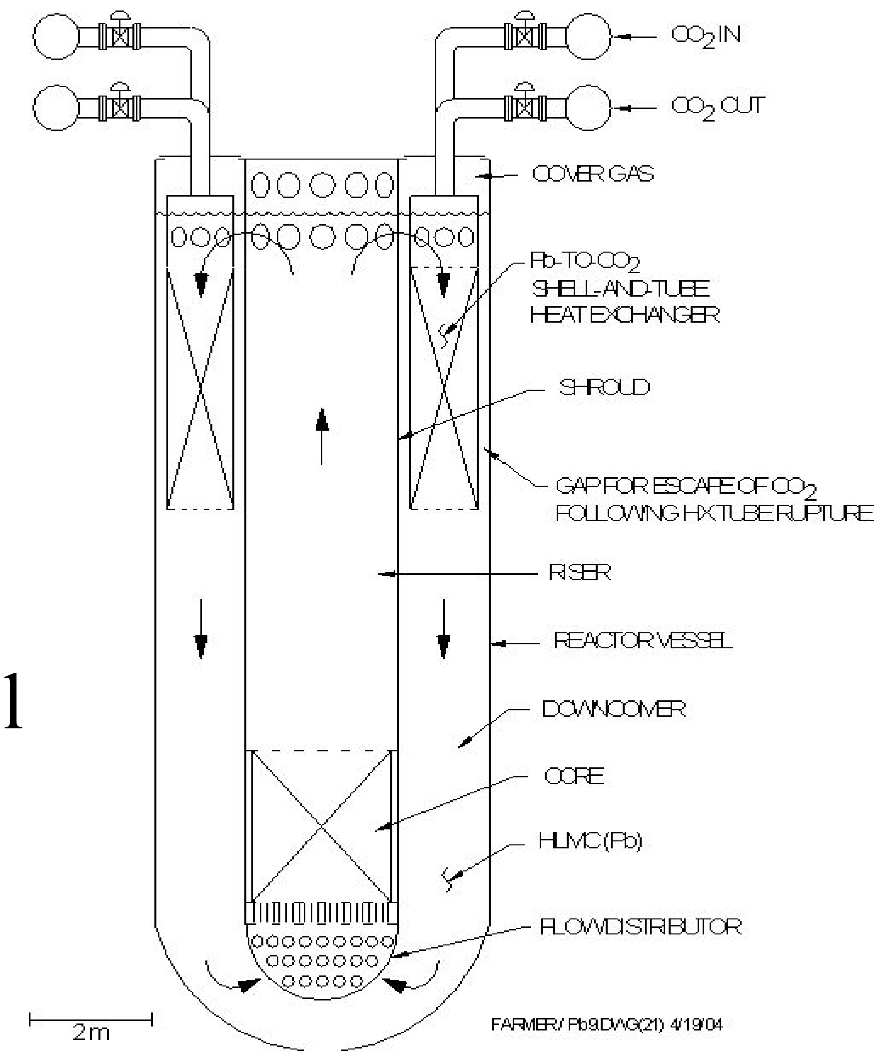
Secure Transportable Autonomous Reactor - Liquid Metal

- 400 MWt
  - Small modular plant intended for developing countries
- Lead-cooled fast reactor
  - Closed fuel cycle for sustainability
  - Passive safety of Pb coolant
    - Pb does not react with CO_2
    - High boiling temperature
- $\geq$ 15 yr core lifetime
  - Proliferation resistance

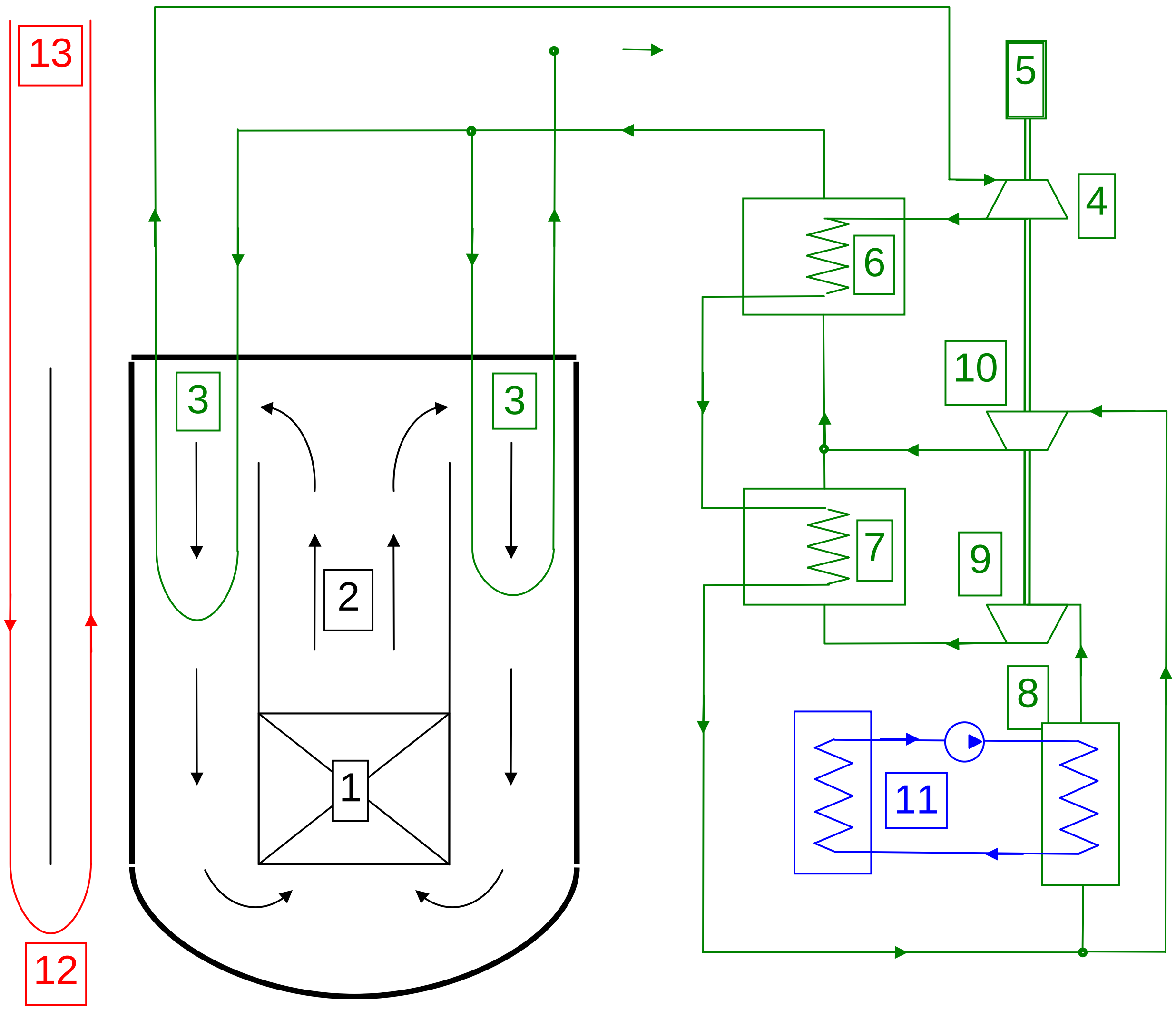


STAR-LM Reactor (Cont.)

- Natural circulation
- Nitride fuel
  - High melting temperature
  - Compatible with Pb
- Converter (CR~1)
  - LWR spent fuel (initially)
- No "active" power control by control rods
  - Shutdown and burnup compensation rods only



STAR-LM Coupled to the Brayton Cycle



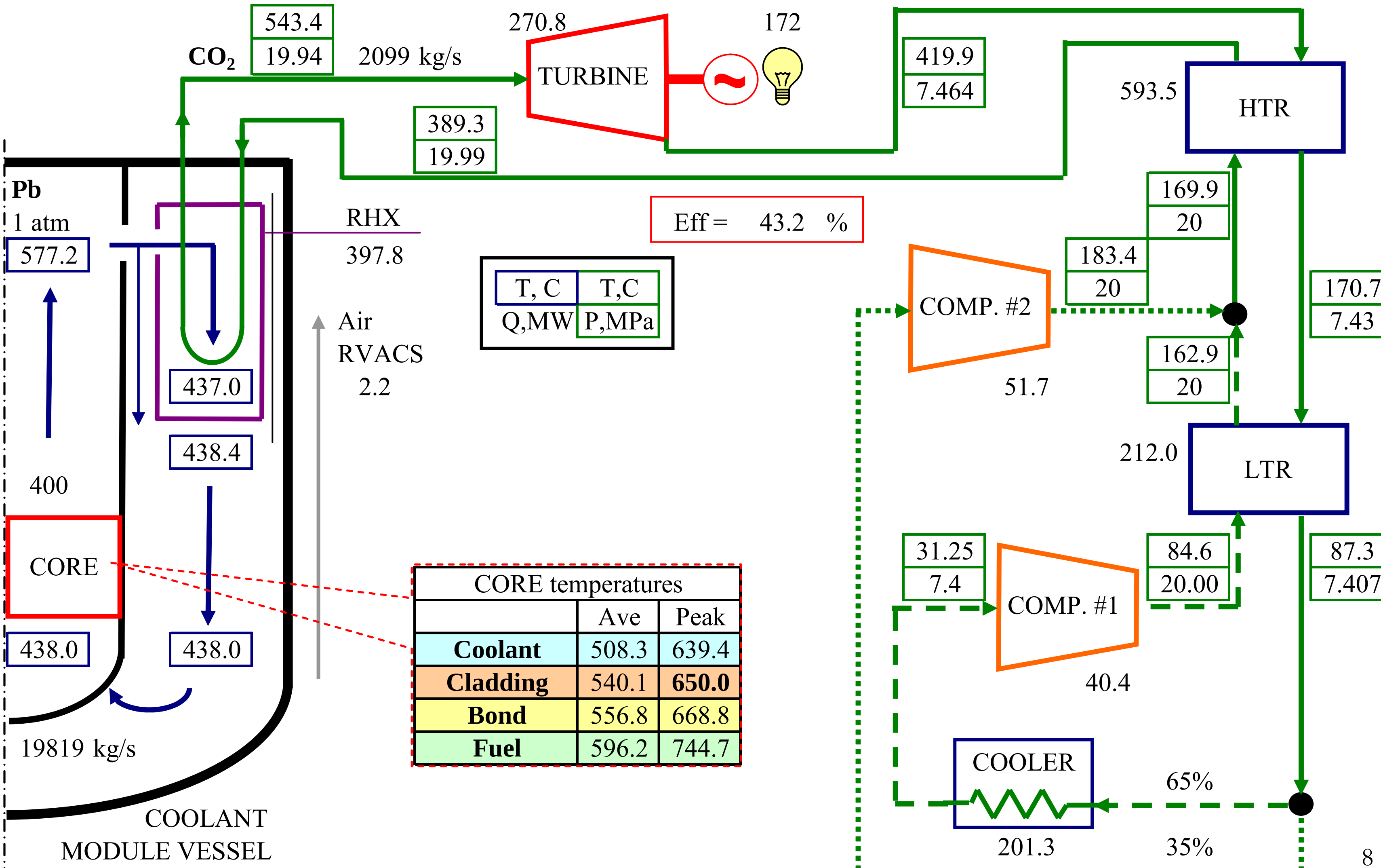
1 – Reactor core
2 – Pb primary coolant (natural circulation)

3 – Pb-to-CO_2 in-reactor heat exchanger
4 – CO_2 turbine
5 – Generator
6,7 – High and low temperature recuperators
8 – Cooler
9,10 – Compressors

11 – Cooling circuit to ultimate heat sink or desalination plant

12 – Guard vessel natural circulation air cooling system
13 – Atmosphere heat sink

STAR-LM Steady-State Performance



CORE temperatures		
	Ave	Peak
Coolant	508.3	639.4
Cladding	540.1	**650.0**
Bond	556.8	668.8
Fuel	596.2	744.7

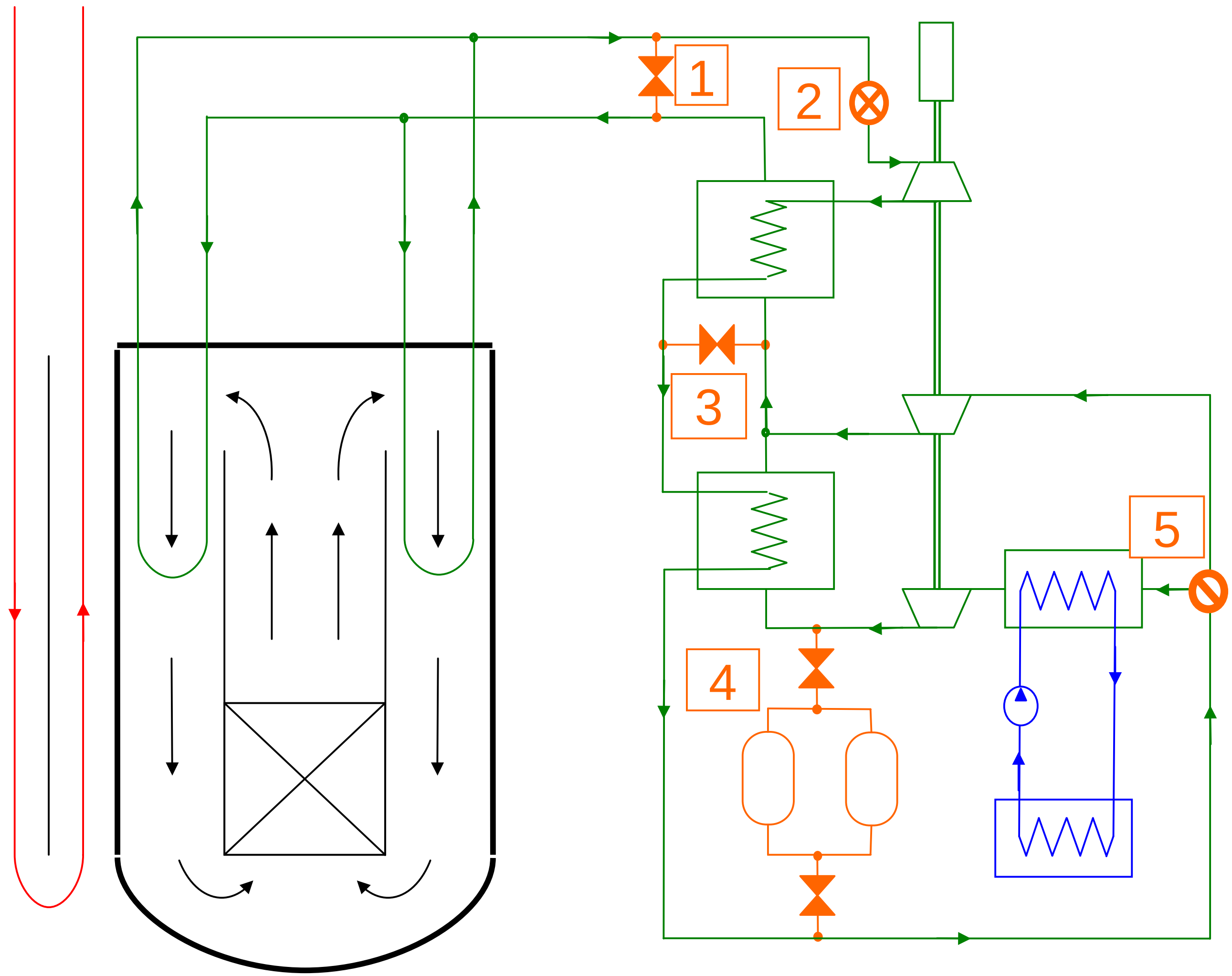
Brayton Cycle Control

- Adjust Brayton cycle to match the grid demand
  - 0% -100% load
- Autonomous (passive) approach
  - No direct control of the reactor power through control rods
  - Temperature reactivity feedbacks
    - Cause power to change to match the heat removal from the in-reactor heat exchangers

Brayton Cycle Control

- Possible means to control S-CO_2 Brayton Cycle
  - Reduce reactor power (Flow rate through IRHX)
  - Reduce turbine output
    - Flow rate through turbine
    - Pressure drop across turbine
  - Increase compressor power demand
    - Flow rate through compressors
    - Work away from optimal conditions (flow split, min. temperature)

Brayton Cycle Control



1 – In-reactor heat exchanger bypass valve

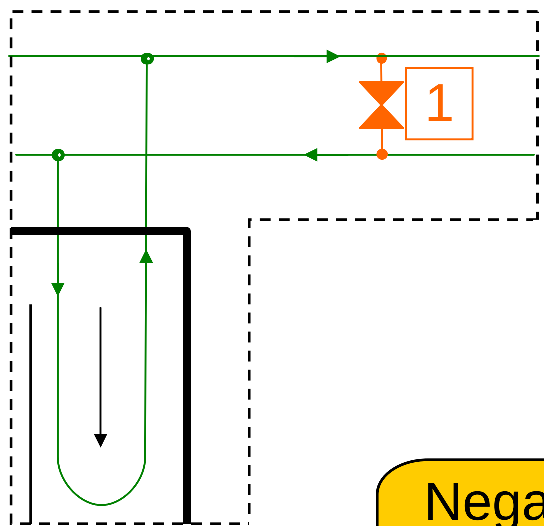
2 – Turbine inlet valve

3 – Turbine bypass valve

4 – Inventory control

5 – Flow split valve

In-Reactor HX Bypass Control



Only part of the CO_2 flow goes though the IRHX

↓

Decreased Pb cooling in IRHX

↓

Increase of the core-inlet temperature

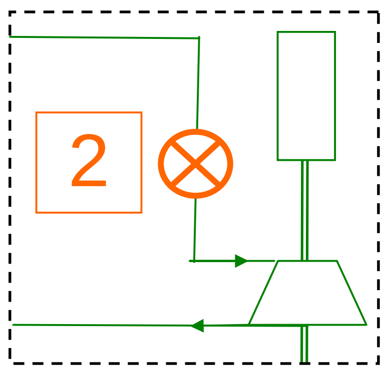
↓ (Negative reactivity feedback)

Decrease of the reactor power

↓

Decrease of the generator output

Turbine Inlet Valve Control



Introduce pressure drop before turbine

↓

Available expansion in turbine is reduced

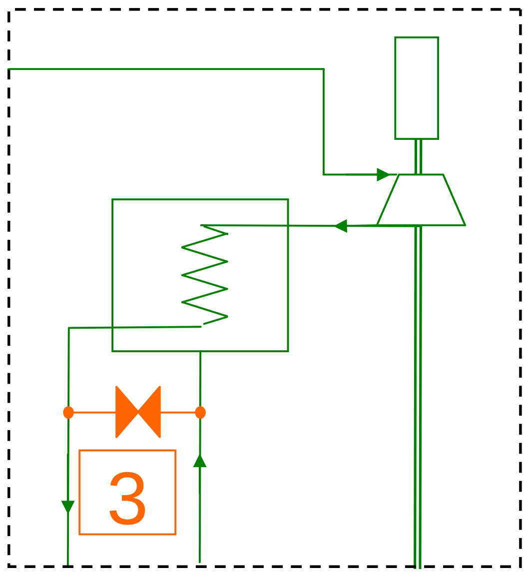
↓

Turbine output is reduced

↓

Decrease of the generator output

Turbine Bypass Control



Only part of the CO_2 flow goes through the HTR, IRHX, and turbine

↓

Flow rate through the turbine is less than that through compressors

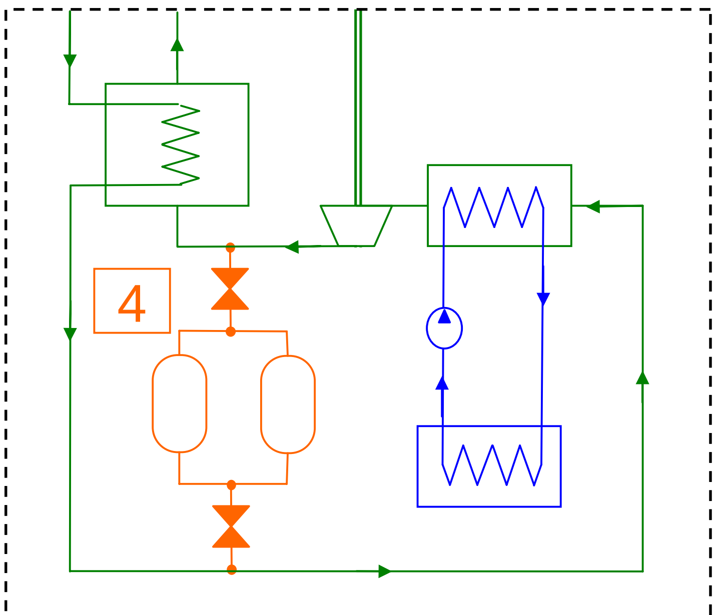
↓

Turbine work is reduced

↓

Decrease of the generator output

Inventory Control



Some CO_2 inventory is removed from the cycle

↓

System pressures are reduced

↓

CO_2 flow rate is reduced

↓

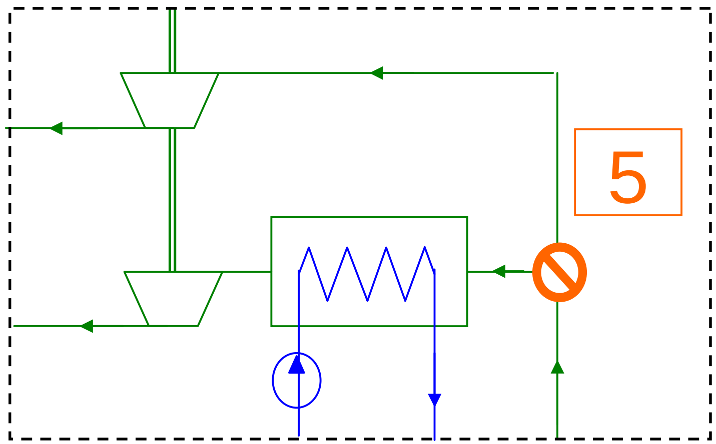
Turbine work is reduced

↓

Decrease of the generator output

Cycle temperatures are maintained

Flow Split Control



Changes CO_2 flow split between compressors

↓

Departure from the optimal conditions

↓

Compression work is increased

↓

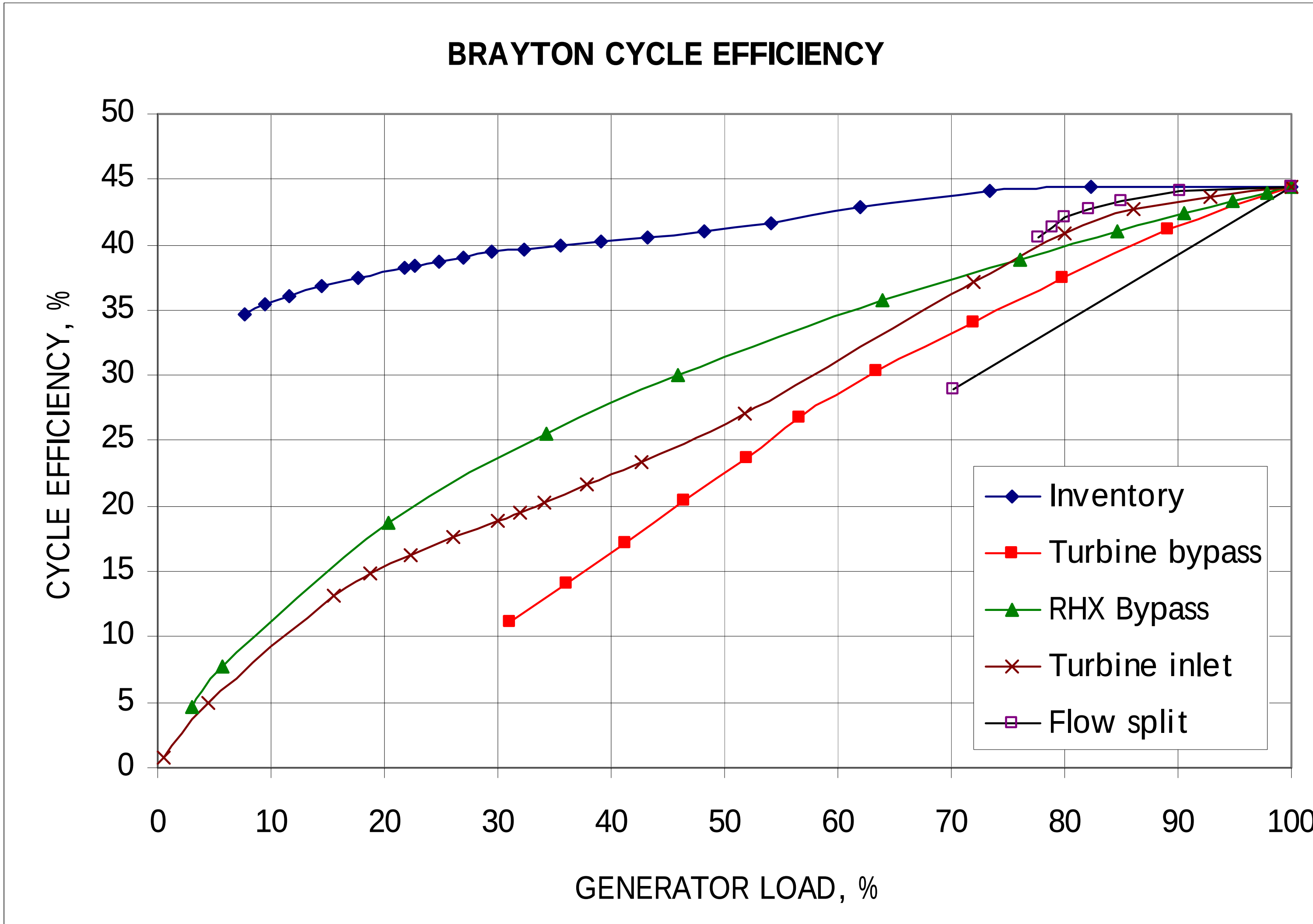
Decrease of the generator output

- Cooler (minimal temperature) control works on the same principle

Methodology

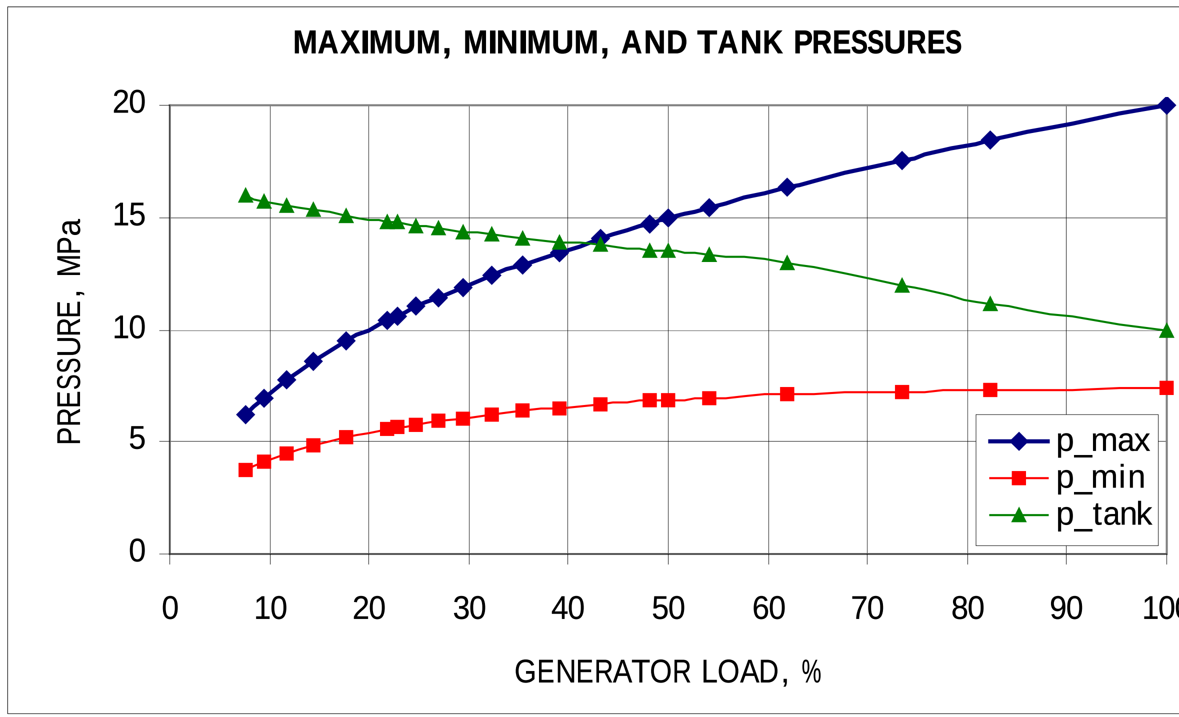
- Steady-state model is used in analysis
  - Quasi-static approach
- Off-design turbine/compressor performance subroutines are utilized

Control Mechanisms - Comparison



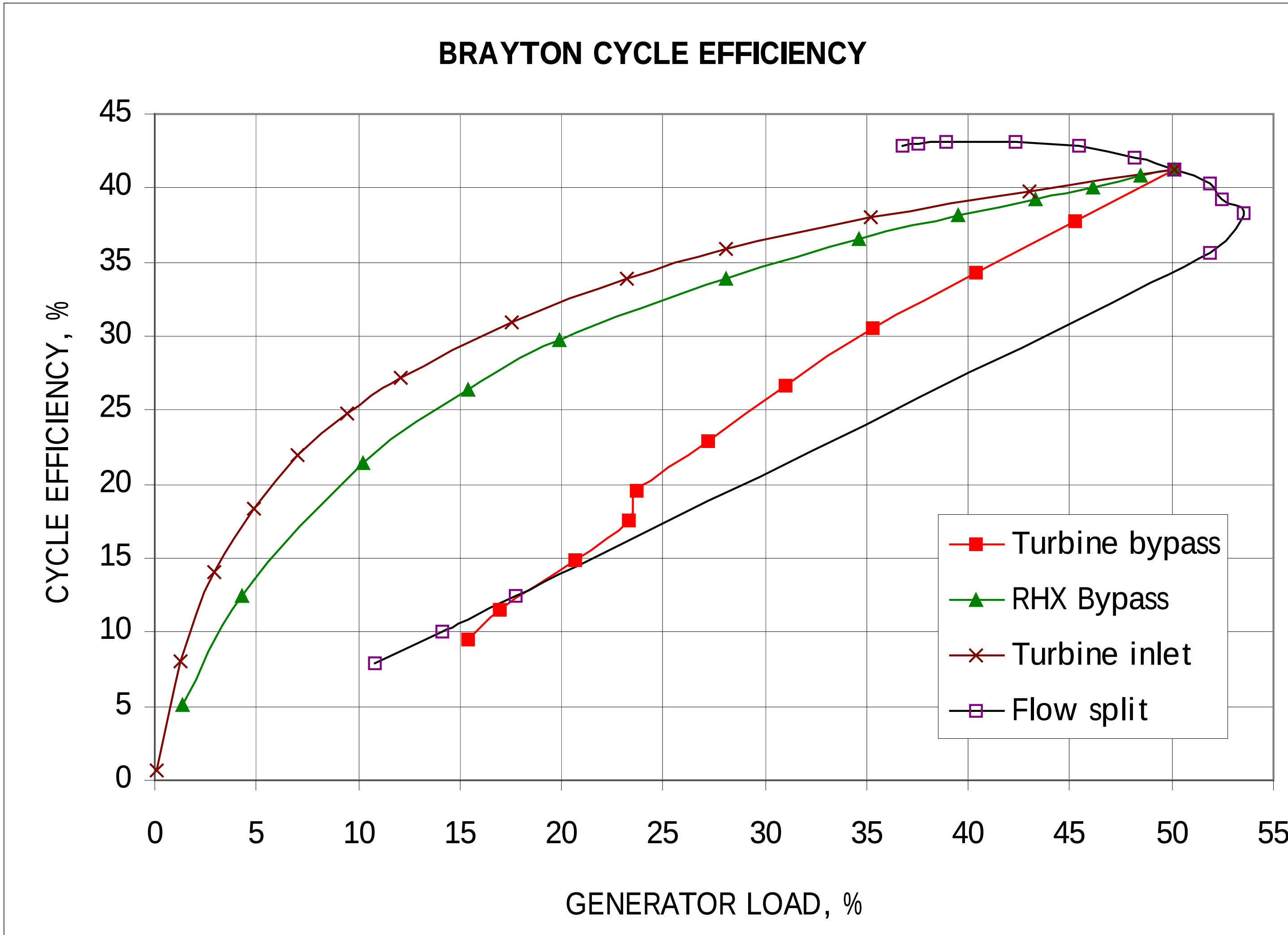
Control Mechanisms – Inventory Control

- Inventory control gives higher efficiency
- Inventory tank size and pressures limit the load range



➢ Used from 100% to 50% load

Control Mechanisms - Comparison (50%-0% Load)



Brayton Cycle Control Strategy

- 50% - 100%
  - Inventory control
- 0 % - 50%
  - Turbine inlet valve control
  - RHX bypass control
  - Or combination of both
- All loads
  - Use flow split and cooler controls to maintain optimal cycle efficiency

Conclusions

- S-CO_2 Brayton cycle control options were investigated
- Inventory control gives the best performance
  - Range is limited by the control tank volume
- Optimal control strategy is developed
  - 50% - 100% load – Inventory control
  - 0% - 50% load – Turbine inlet/RHX bypass controls
- Quasi-static approach was utilized
  - Steady-state code was used
  - Dynamic code is under development

- Questions?

- Backup slides

Turbomachinery Design

- Off-design performance
  - Same equations, fixed geometry, varying inlet conditions
- Calculate:
  - Outlet conditions
  - Power output/input

Turbine Performance Map