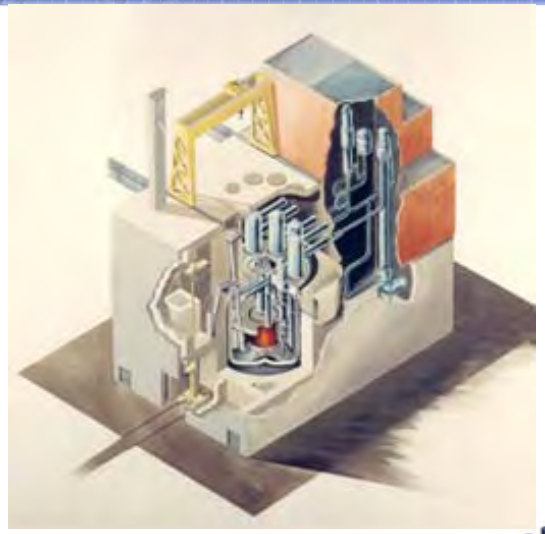
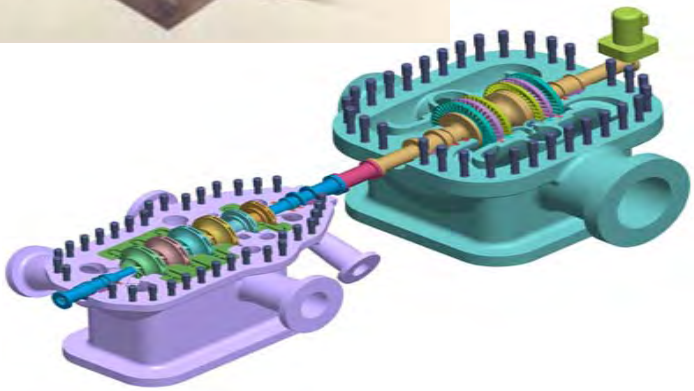
Rocketdyne Development of the Supercritical CO_2 Power Conversion System





Michael McDowell
Program Manager
Reactor & Liquid Metal Systems
Hamilton Sundstrand, Space Land & Sea-Rocketdyne

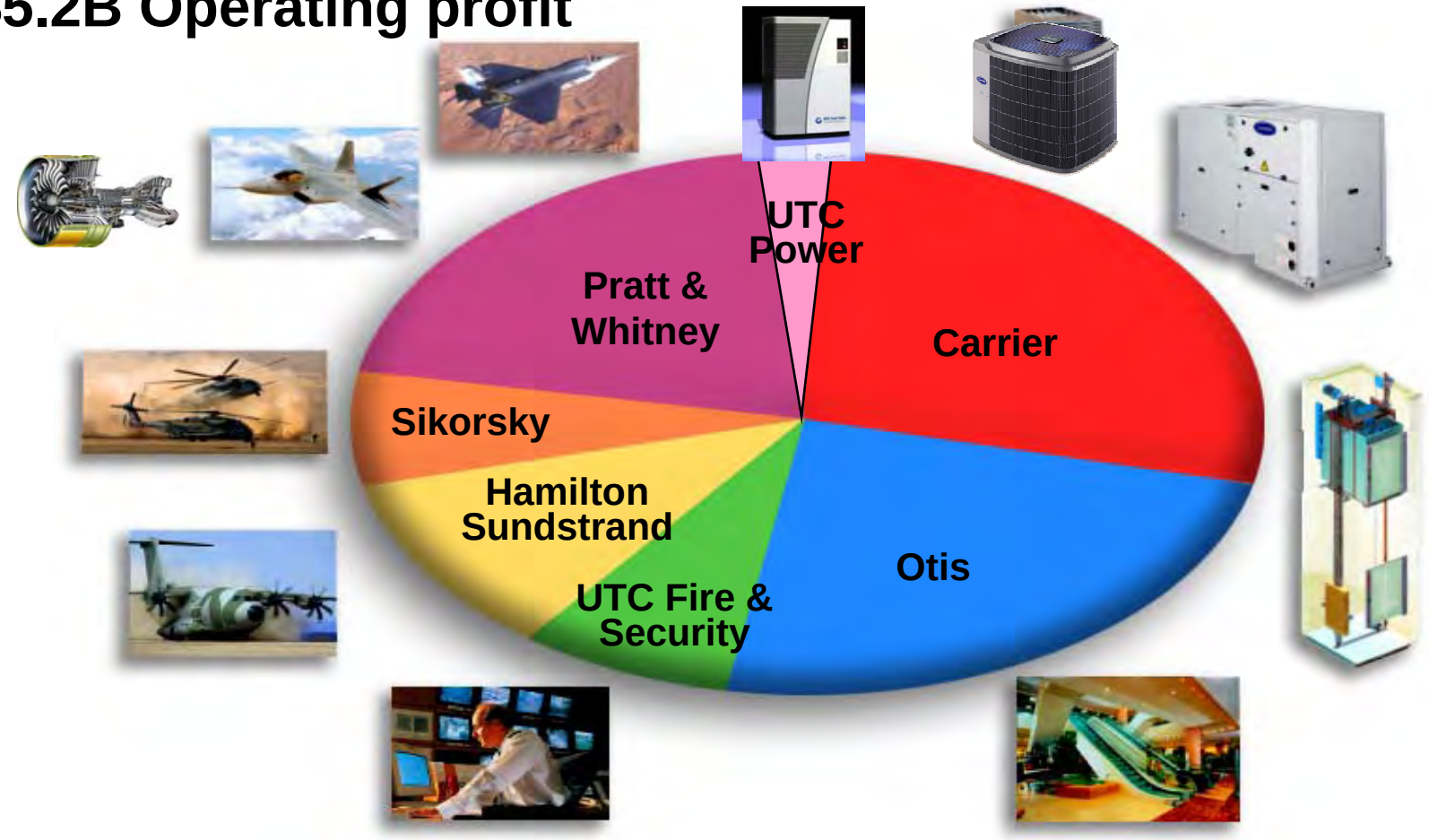
Hamilton Sundstrand
A United Technologies Company

Rocketdyne Development of the Supercritical CO_2 Power Conversion System

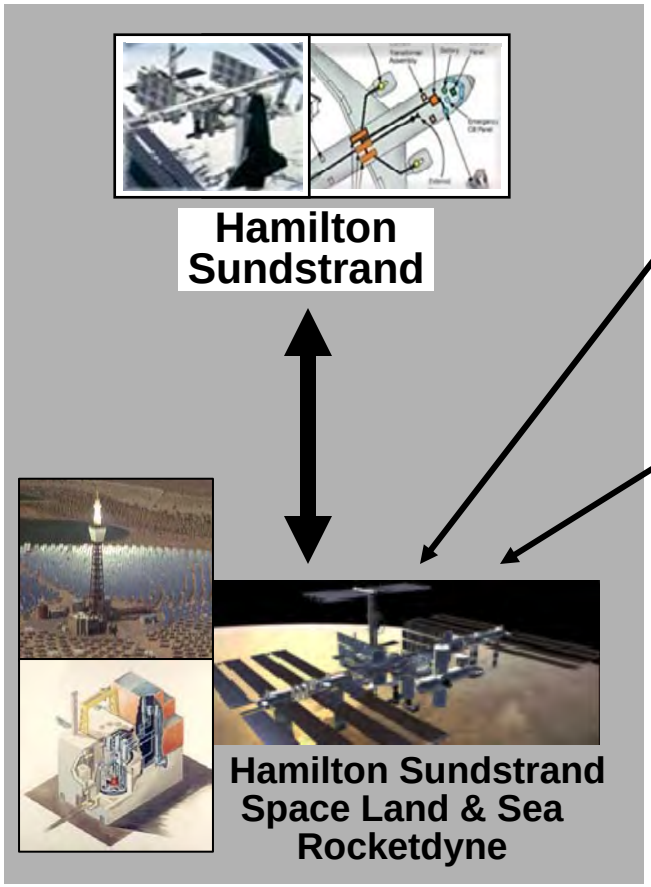
- **Rocketdyne – Organization, Heritage & Capabilities**
- **Supercritical CO_2 System & Equipment**
  - **System modeling / evaluation**
  - **Turbomachinery design**
  - **Heat exchanger evaluation**
- **Future Plans**

United Technologies Corporation (UTC)

- $42.7B Sales (2005)
- $5.2B Operating profit
- >200,000 employees
- Operating in 180 countries



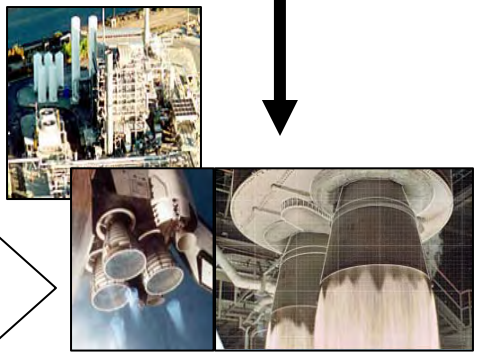
Rocketdyne Alignment after UTC Purchase of Rocketdyne from Boeing (August 3, 2005)




Research Center


UTC Power


Pratt & Whitney


Pratt & Whitney Rocketdyne

Share Campus, Processes & Resources

Advanced Power Systems Aligned with Hamilton Sundstrand

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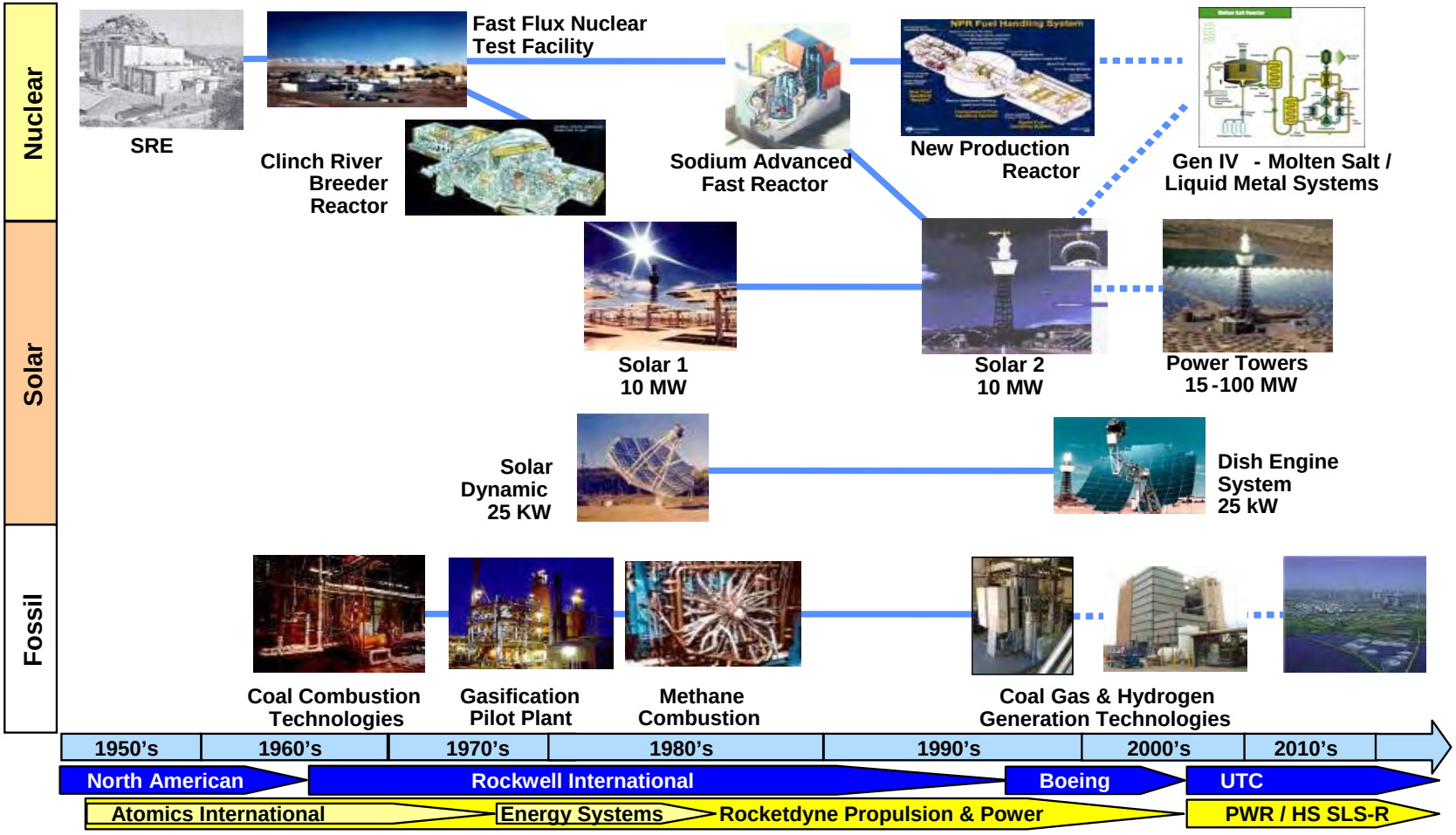
Rocketdyne Energy Heritage



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PWR Rocket / Space Program Heritage

1958

Navajo engine developed

1958

Redstone engine launches Explorer 1

1963

RL10 First Flight Atlas

1965

Snap 10A - First nuclear reactor launched

1969

F-1 and J-2 engines launch Apollo to Moon

1971

Space Shuttle Main Engine contract Starts

1980

Peacekeeper Stage IV developed

1985

International Space Station contract start

1988

RS-27A launches first commercial Delta rocket

1992

Terminal High Altitude Area Defense development begins

2000

1st RD-180 Launch Atlas III

Aerospike flight engine tests

2002

XSS-10 Micro Satellite launched

2002

RS-68 launches Delta IV

2003

Radioisotope Thermoelectric Generator initiated

1950's **1960's** **1970's** **1980's** **1990's** **Today**

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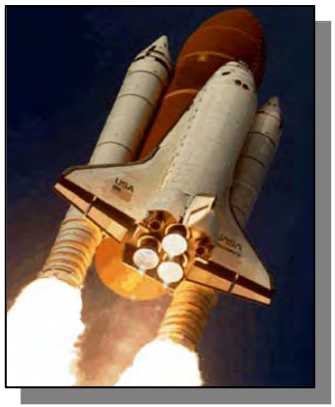
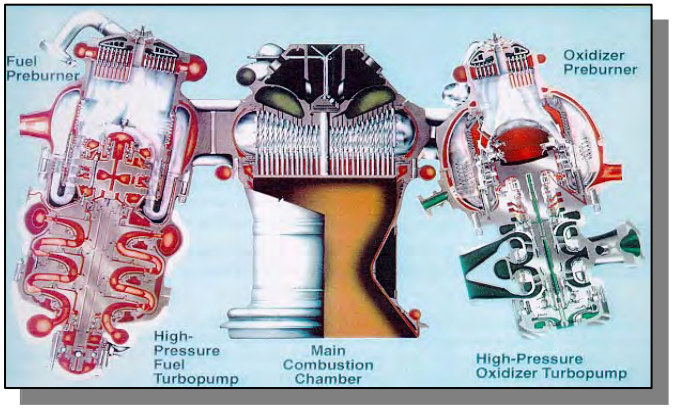
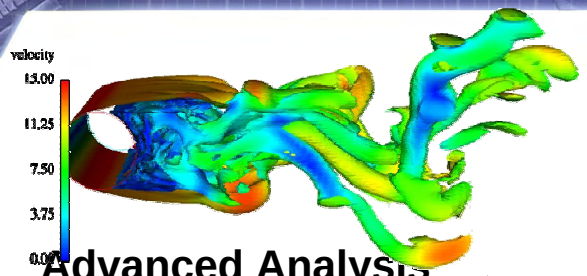
Rocket Engine Competencies Applicable to Energy Markets





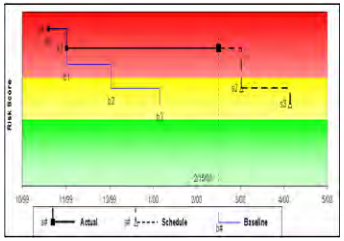
- **High energy density combustion**
  - **6000º F**
  - **5000 psia**
- **Regenerative cooling**
  - **Low metal temperatures**
  - **High system efficiency**
- **High speed rotating equipment**
  - **36,000 rpm**
- **Hydrogen technology**
- **Low cost < $10 per kW thermal**
  - **Unique design capabilities**
  - **Advanced manufacturing processes**
- **Manufacturing and test**
  - **Capacity > 200 GW thermal per year**
  - **Rapid prototyping**
  - **Extensive test capability**

Key Rocketdyne Processes



Advanced Analysis

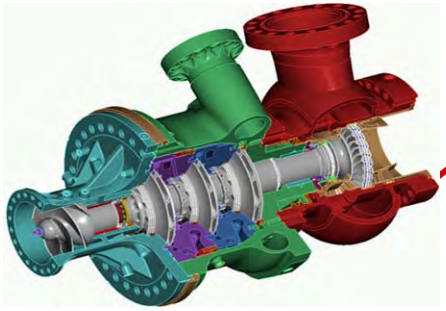
Test



System Engineering

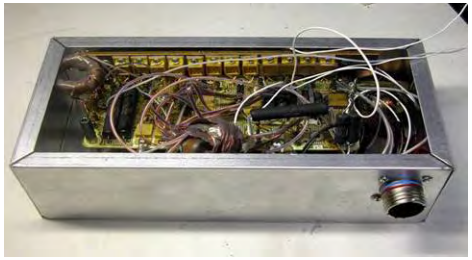
Tools and processes linked electronically

Materials Engineering



Mechanical Design

Manufacturing



Electronics Design

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Rocketdyne Development of the Supercritical CO_2 Power Conversion System

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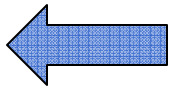
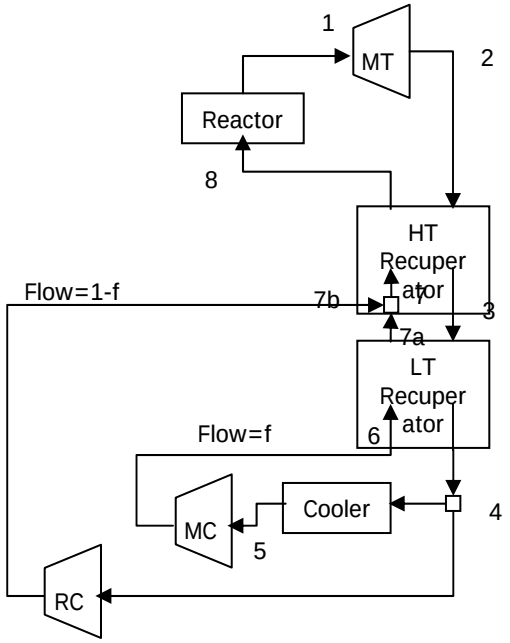
- Supercritical CO_2 System & Equipment 
  - System modeling / evaluation
  - Turbomachinery design
  - Heat exchanger evaluation
- Future Plans

Approach to Supercritical CO_2 System & Equipment Design

- Initiated technical evaluation in 2006 with internal funds
  - System modeling / evaluation
  - Turbomachinery conceptual design
  - Heat exchanger evaluation
  - Tools refinement – CFD
- Small contract for Sandia Laboratory on turbomachinery & test concepts
- Using supercritical CO_2 system knowledge on advanced reactor concepts in 2007

System Modeling / Evaluation

- Verified preceding wisdom on CO_2 cycle
  - Literature review: MIT reports
  - Select 300 Mwe LMR as baseline
  - Power system modeling for efficiency
  - Evaluated alternate configurations
  - Defined parameters for turbomachinery & heat exchangers
- Extended power system modeling other power systems
  - VHTGR
  - Solar thermal power



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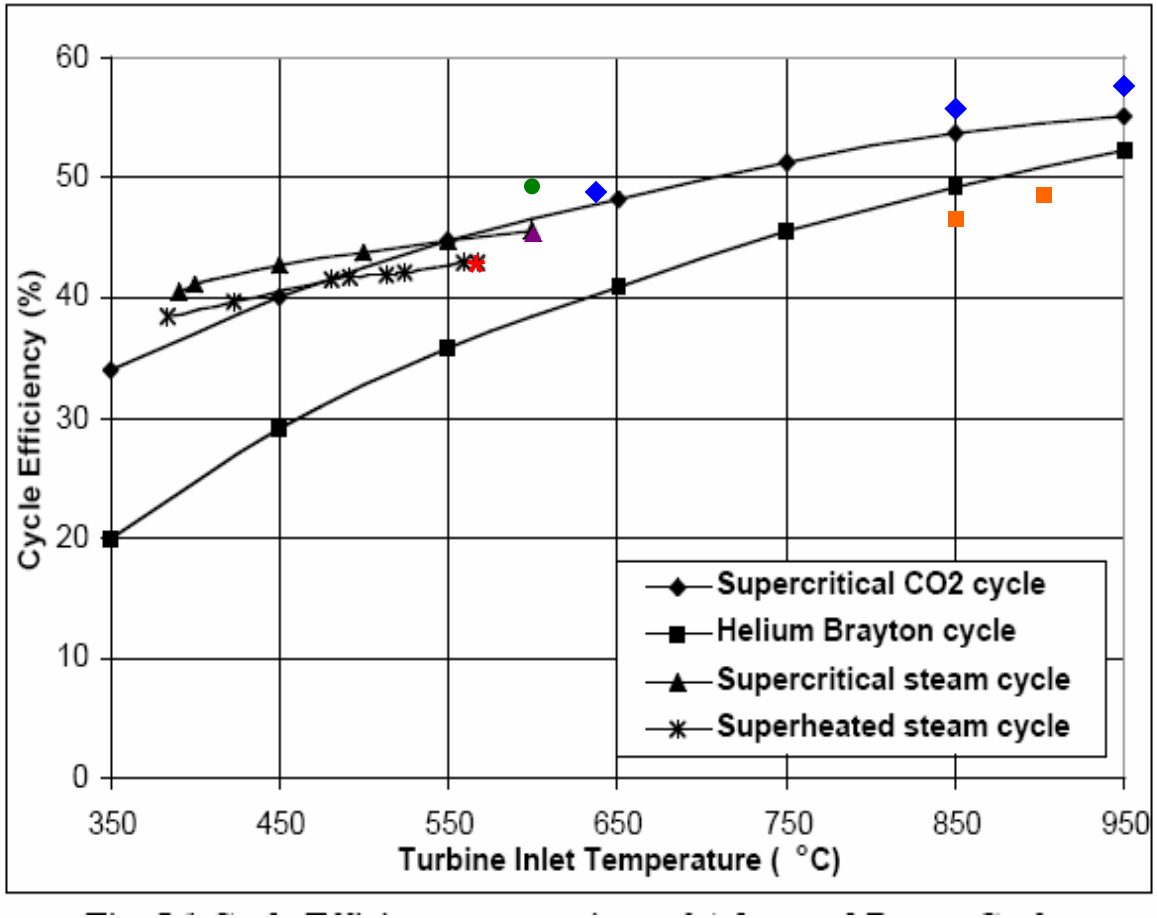
Modeling Results: VHTGR Power System Study



- **Supercritical CO_2**
- **Helium Brayton**
- **Supercritical Steam Single Reheat**
- **Supercritical Steam Double Reheat**
- **Subcritical Steam**

ChemCad used to model supercritical CO_2 and helium Brayton cycles

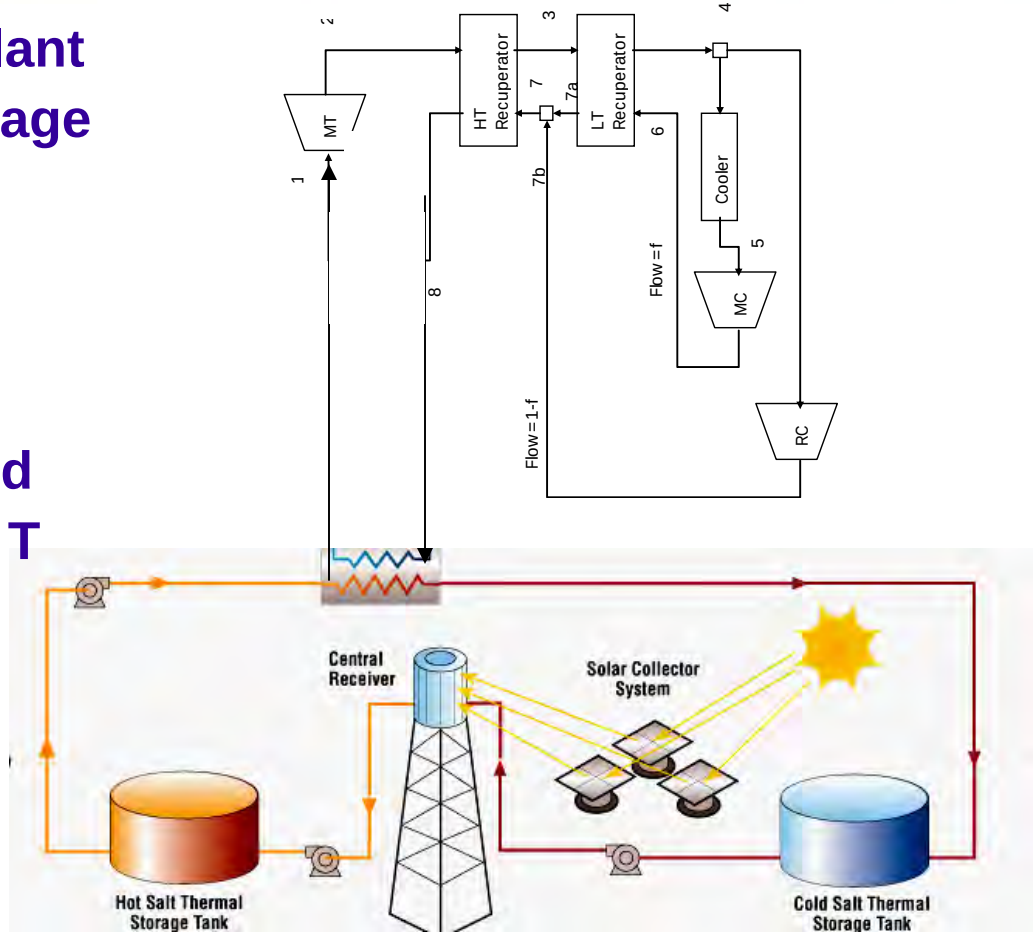
GateCycle used to model steam cycles

Plot from: Driscoll, M.J., Report No: MIT-GFR-019, "Interim Topical Report Supercritical CO2 Plant Cost Assessment", September 2004, Center for Advanced Nuclear Energy Systems, MIT Nuclear Engineering Department

Not every power system benefits from supercritical CO_2

- Rocketdyne solar power plant
  - Molten salt thermal storage
  - 550 to 300C across HX
  - Normally Rankine cycle

- CO_2 cycle performs poorly
  - Cycle highly recuperated
    - Wants reduced delta T
  - Reduced delta T lowers storage & circulation effectiveness
  - Added cost overcomes cycle efficiency



Solar Power Tower with Supercritical CO_2 Cycle

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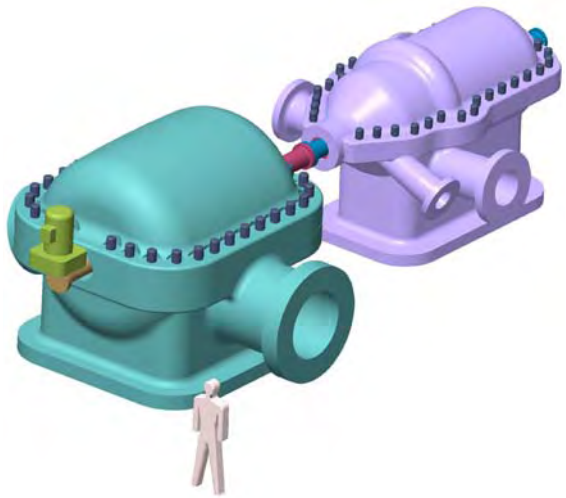
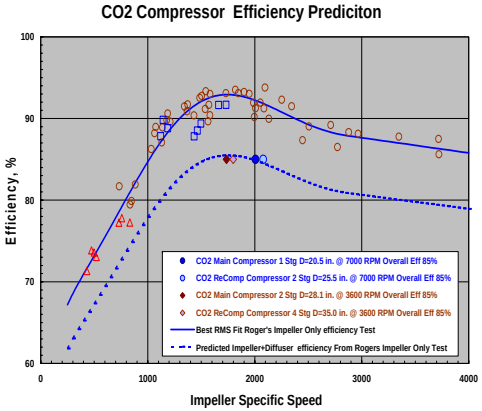
Turbomachinery Design: Summary of Results

- Baselined 300 Mwe LMR
- Established turbomachinery configuration and layout
  - Common shaft for all machines driven by power turbine
  - Shaft rotation speed (3600 rpm) compatible with industrial size electrical generators
  - Separate shaft seals on each machine
  - Balanced axial thrust
  - 3-D equipment drawings completed

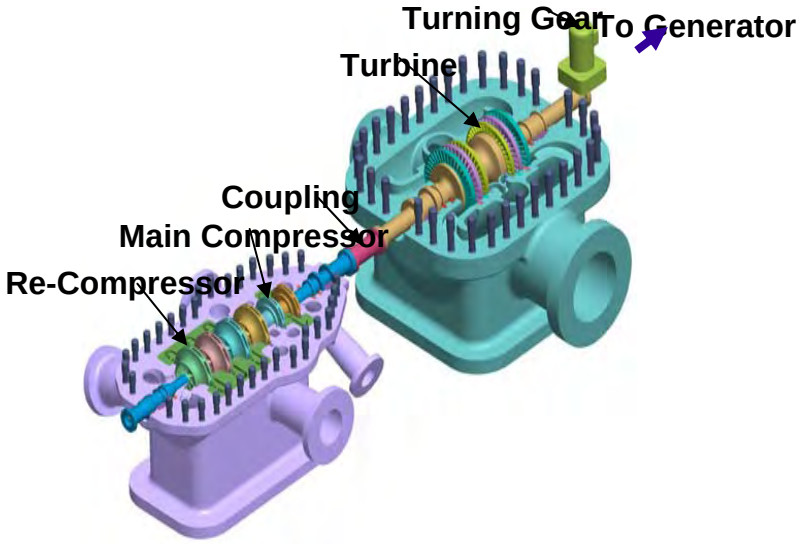


Turbomachinery Design: Summary of Results

- Identified preferred design approach for compressors
  - Two stage centrifugal path selected for main compressor
  - Four stage centrifugal path selected for recompressor



- Identified preferred design approach for turbine
  - Three stage axial path
  - Reaction blading
  - Fir tree and shrouded blades with dampers



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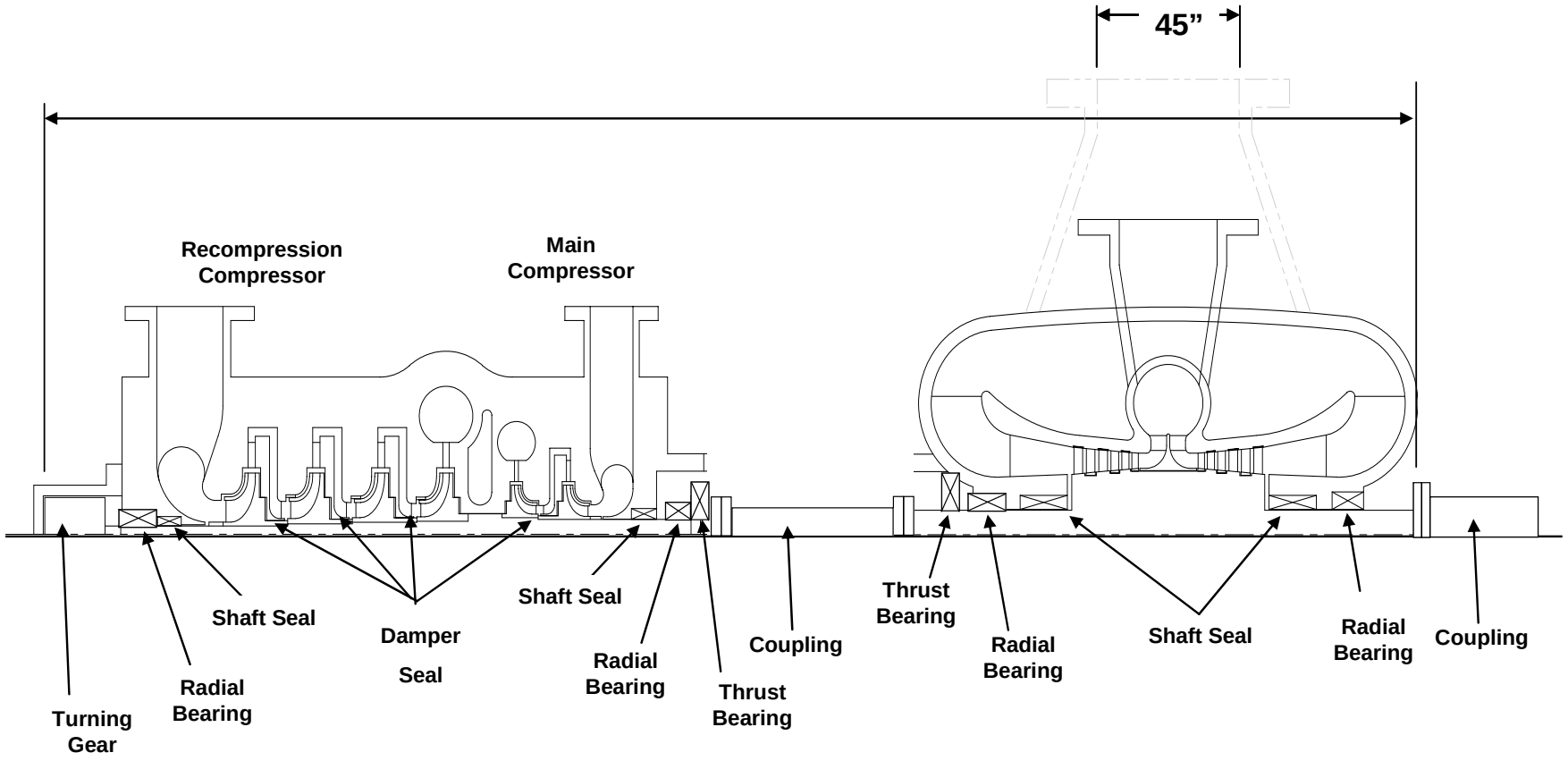
Turbomachinery Shaft Layout



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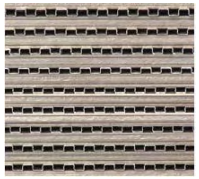
Heat Exchanger Evaluation

- **Basis: 300 Mwe LMR**
- **Evaluated heat exchanger for type (CHE or STHE)**
  - Sodium to supercritical CO2 IHX
  - High temperature SCO2 recuperator
  - Low temperature SCO2 recuperator
  - Pre-cooler SCO2 to water heat exchanger
- **Developed 3 designs/concepts for IHX**
  - Compact heat exchangers (CHE)
  - Shell and tube heat exchanger (STHE)
    - Straight tube
    - Coiled tube

Heat Exchanger Evaluation Results

- **CO_2 recuperators & pre-cooler**
  - Costs & configuration analyzed
  - CHE preferred for CO_2 recuperators
  - CHE pre-cooler very expensive
    - **Further evaluation needed**
- **IHX Comparison**
  - **CHE**
    - **Most compact**
    - **Most expensive**
    - **Thermal transient concern**
    - **Sodium side plugging**
  - **STHE**
    - **Lower cost by factor of almost 5**
    - **Building cost higher**
    - **Robust design**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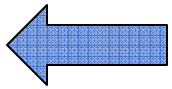

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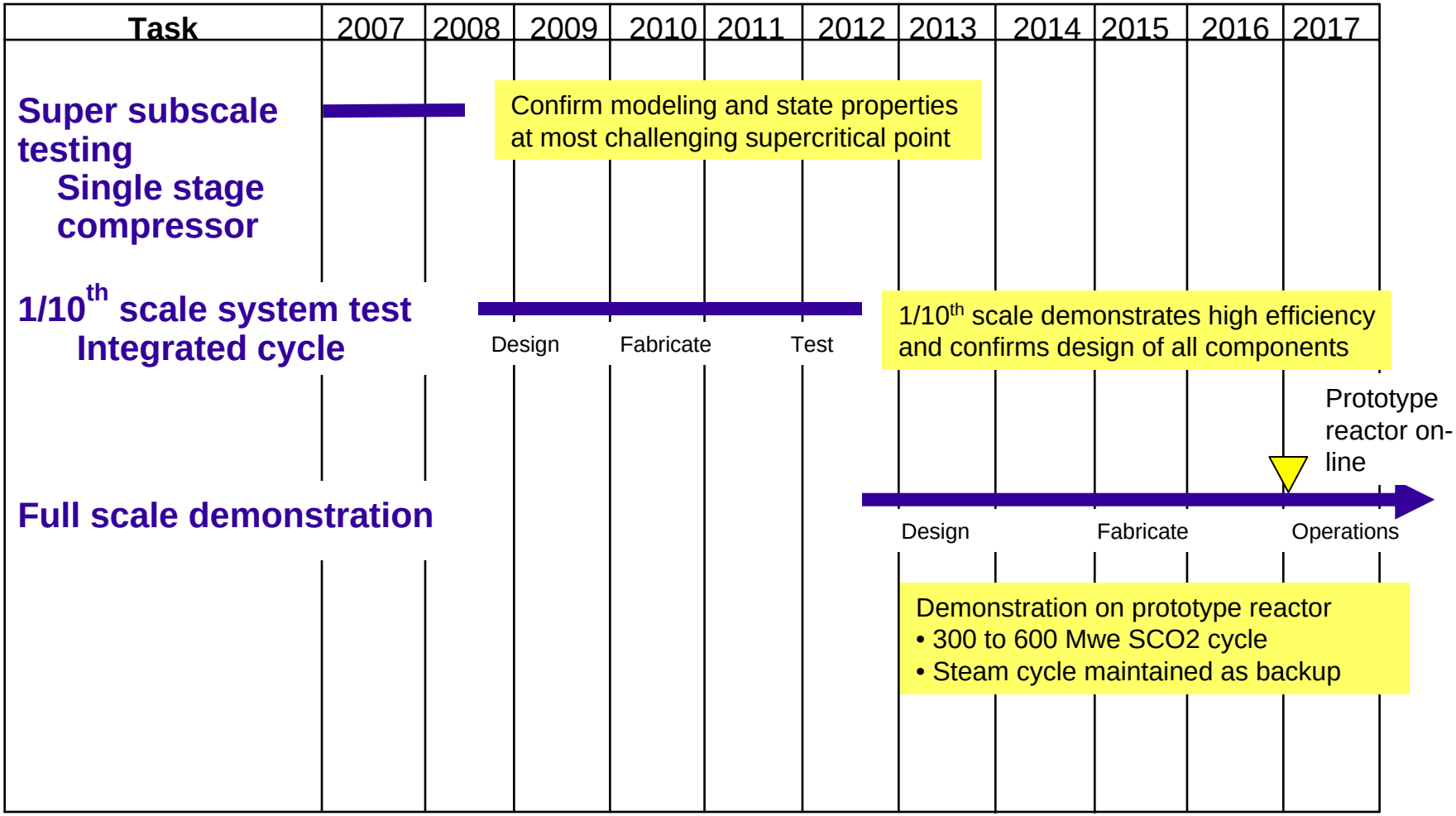
Supercritical CO_2 Turbomachinery Development Scenario/Schedule



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The Rocketdyne Path Forward
Demonstrate the promise of supercritical CO_2

- More detailed design & trade studies
  - Bearings
  - Disk / blade / crossover designs
  - CFD analysis
  - Re-look at multi-shaft configurations
- Dynamic system simulation analysis
- O&M and operability evaluations
- Implementation of development schedule
- Improve customer interest – Funding for path forward