Super Boiler: Packed Media/ Transport Membrane (PM/TM) Boiler Development and Demonstration - (CPS #1458)

Goals: (1) Develop and demonstrate an advanced gas-fired package boiler with ultra-high efficiency, ultra-low emissions, and reduced footprint; (2) Formulate a long-range RD&D approach for advanced boiler technology.

Challenge: U.S. industry needs more efficient, cleaner, and more cost-effective steam generation technology.

Benefits: Reduced fuel use in gas-fired industrial package boilers; potential energy savings of 630 trillion Btu/year; NOx reduction of 142,000 tons/year; space savings of 6 million sq ft.

FY05 Activities: Complete optimization of lab boiler and heat recovery system; design, build, install, and test a 10-MMBtu/h prototype; conduct field demonstration in southern California.

Participants: Gas Technology Institute, Cleaver-Brooks Div of Aqua-Chem, Pacific Northwest National Lab, Media and Process Technology.

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Barrier-Pathway Approach

Barriers

- Inability to recover latent heat from boiler stack gases
- Inefficient NOx reduction methods for boilers
- Compact boiler design not compatible with NOx reduction *or* higher efficiency

Pathways

- Development of novel heat recovery system with transport membrane condenser
- Two-stage combustion system with interstage cooling and premixing
- Implementation of convective sections with extended surfaces

Critical Metrics

- Fuel-to-steam efficiency
- NOx, CO, VOC emissions
- Boiler footprint

Benefits (est)	**2020**
Energy saved	630 TBtu/y
NOx reduction	142,000 t/y
CO_2 reduction	23 million t/y
Footprint reduction	6 million sq ft
Cost savings	$4.0 billion/y

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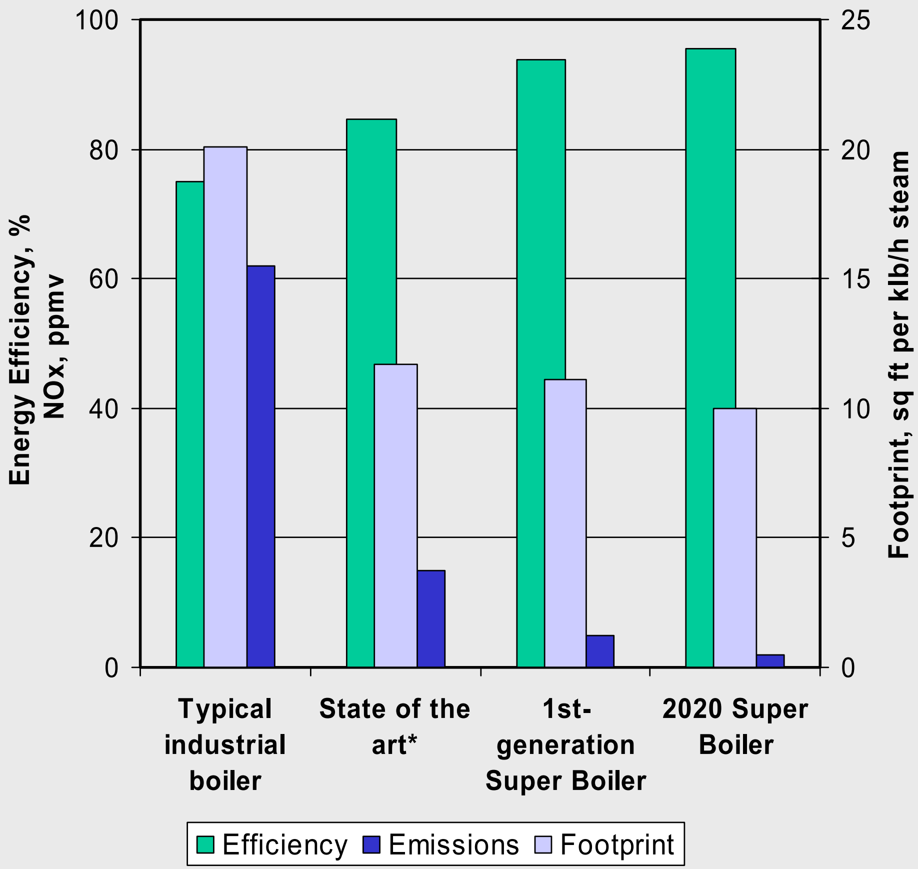
Boiler performance



* Not all in the same boiler

> Other key performance parameters
  – Safety
  – Turndown
  – Responsiveness
  – Ease of operation
  – Time between outages
  – Availability
  – Capital cost
  – Maintenance cost
  – Life-cycle cost
  – Market acceptability

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Project team

- Performing organizations
  - Gas Technology Institute
  - Cleaver-Brooks
- Sponsors
  - U.S. Dept of Energy - Industrial Technologies Program
  - Southern California Gas Company
  - GTI Sustaining Membership Program
  - Gas Research Institute
  - Cleaver-Brooks
- Other participants
  - Pacific Northwest National Lab
  - Media & Process Technologies
  - Dr. Jacob Korenberg

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State of boiler R&D

- Identified 14 active R&D paths with potential application to steam generation
- Formed Industrial Advisory Group
- Drafted Super Boiler 2020 RD&D Plan

Active R&D paths with Super Boiler potential	
catalytic combustion	regenerative oxide-based combustion
direct steam generation	surface combustion
turbocharged boiler	improved boiler tube corrosion protection
water vapor pump	advanced heat exchangers
forced internal recirculation burner	ceramic burner components
high-swirl burners	electric field flame stabilization
oxygen enriched combustion	corrosion-resistant materials

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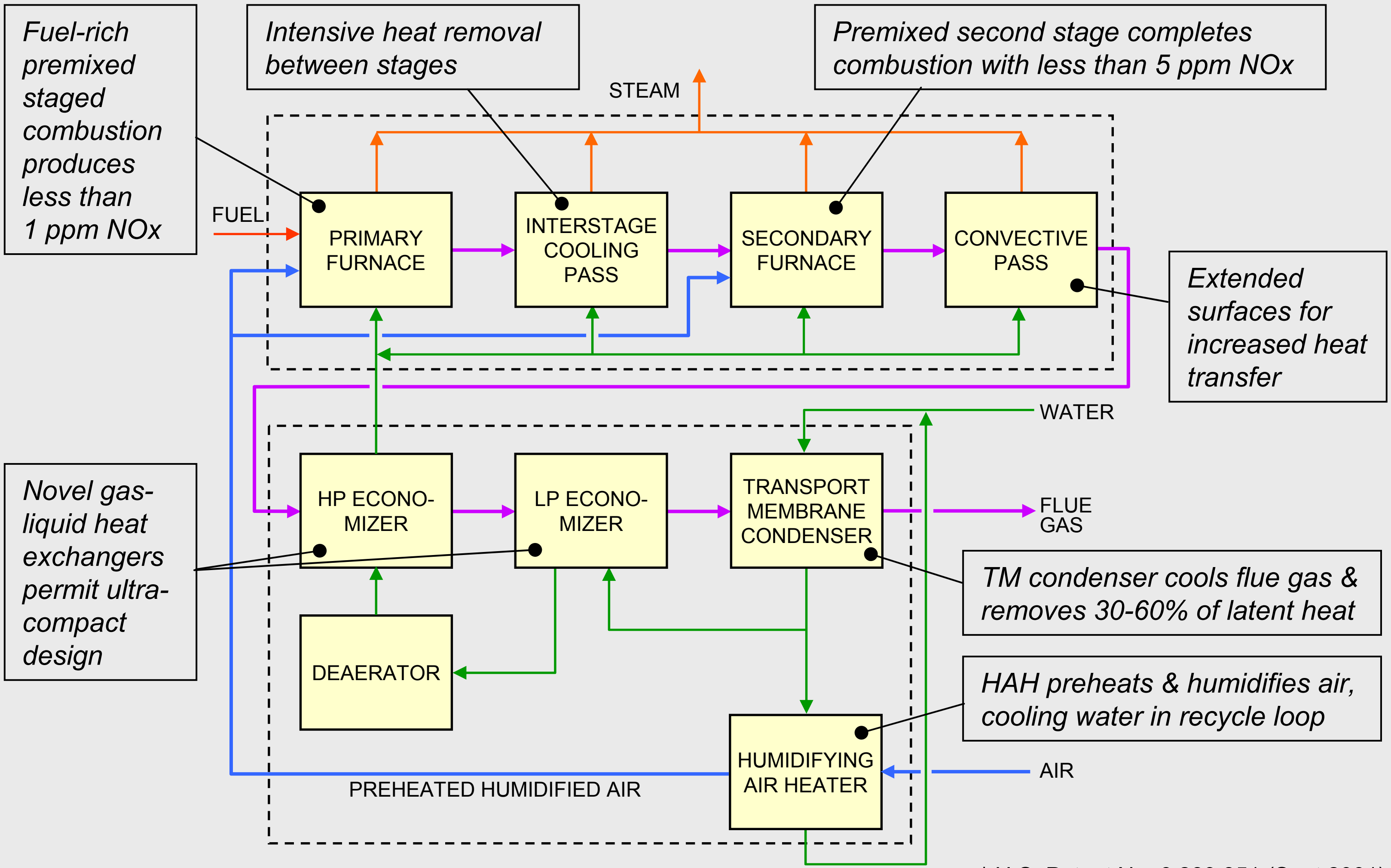
1st Generation Super Boiler

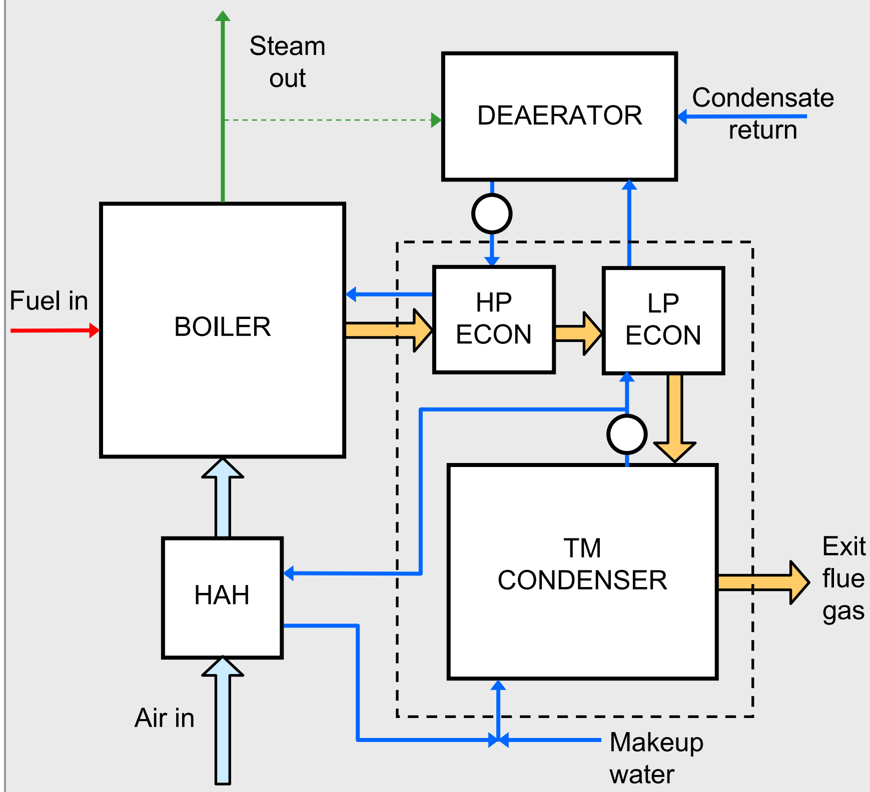
- Design approach selected
  - Latent heat recovery from stack gases
  - Staged combustion with better temperature & combustion chemistry control in second stage
  - Advanced heat exchanger technology for compact design
  - Smart controls

1st-Generation Super Boiler:
How it works*



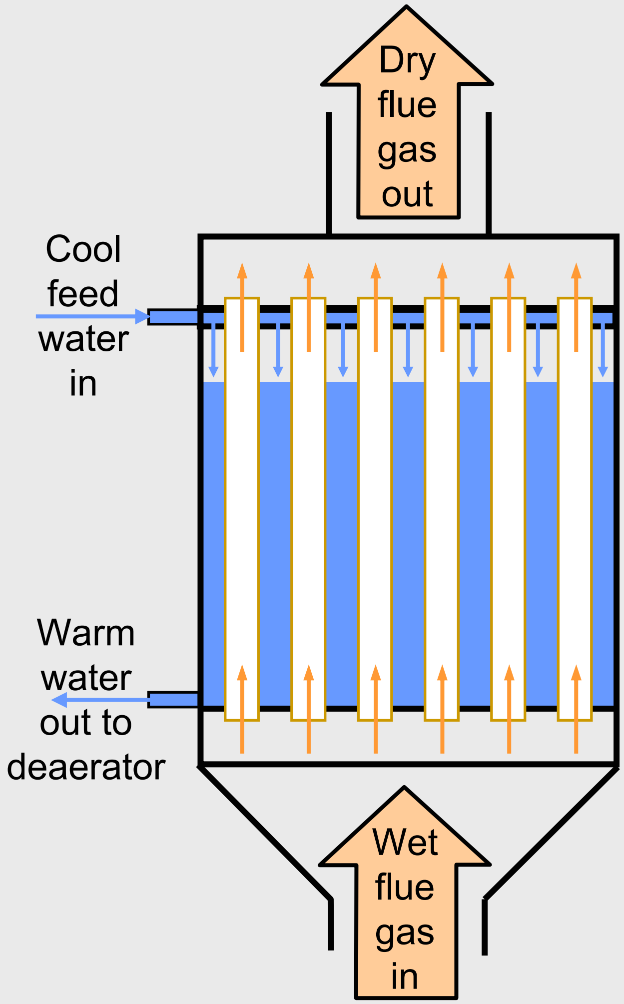
* U.S. Patent No. 6,289,851 (Sept 2001)

Item 1: Heat Recovery



- Compact staged economizers to remove sensible heat
- TM condenser module using membrane technology to cool & dehumidify flue gas
- Humidifying air heater (HAH) to cool and recycle TM condensate
- Advanced controls to maintain optimal conditions

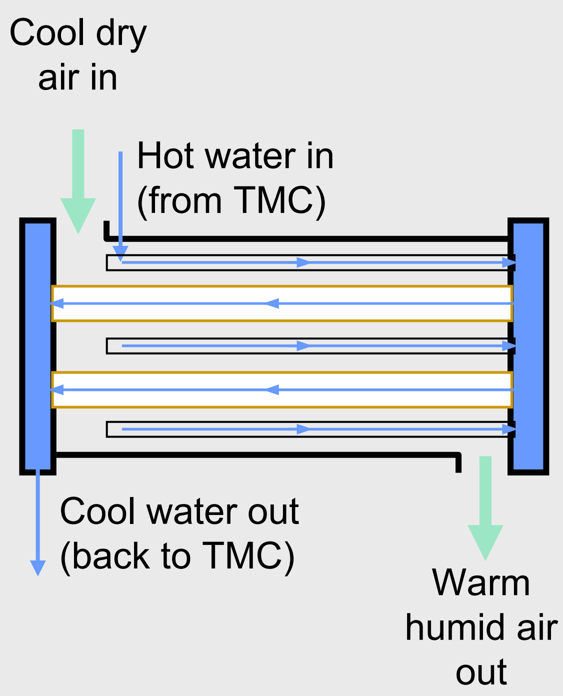
Heat Recovery:
TM Condenser*



- Selective transport of water vapor from flue gas to boiler feed water
- Cools *and* dries flue gas
- Transfers latent and sensible heat directly back to boiler energy loop
- Flue gas exits below 130°F with no condensation
- Feed water remains uncontaminated

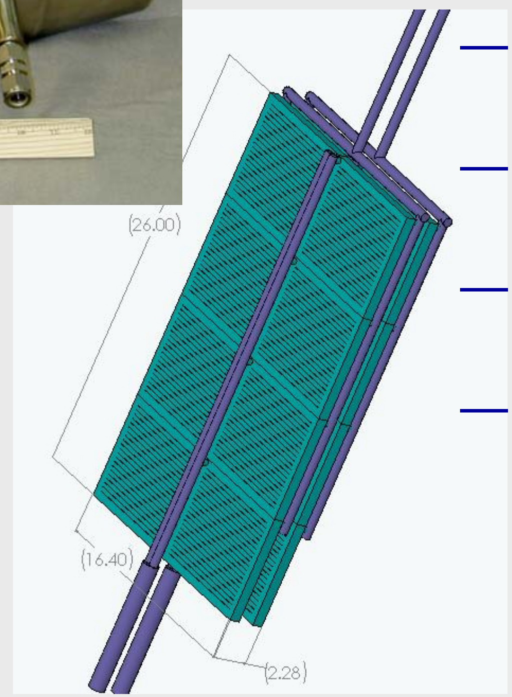
* U.S. Patent No. 6,517,607 (Feb 2003)

Heat Recovery :
Humidifying Air Heater



- Microporous ceramic membrane tubes
- Hot water first transfers heat to combustion air
- Partly cooled water passes through membrane to humidify combustion air
- HAH cools water for TM condenser and improves performance

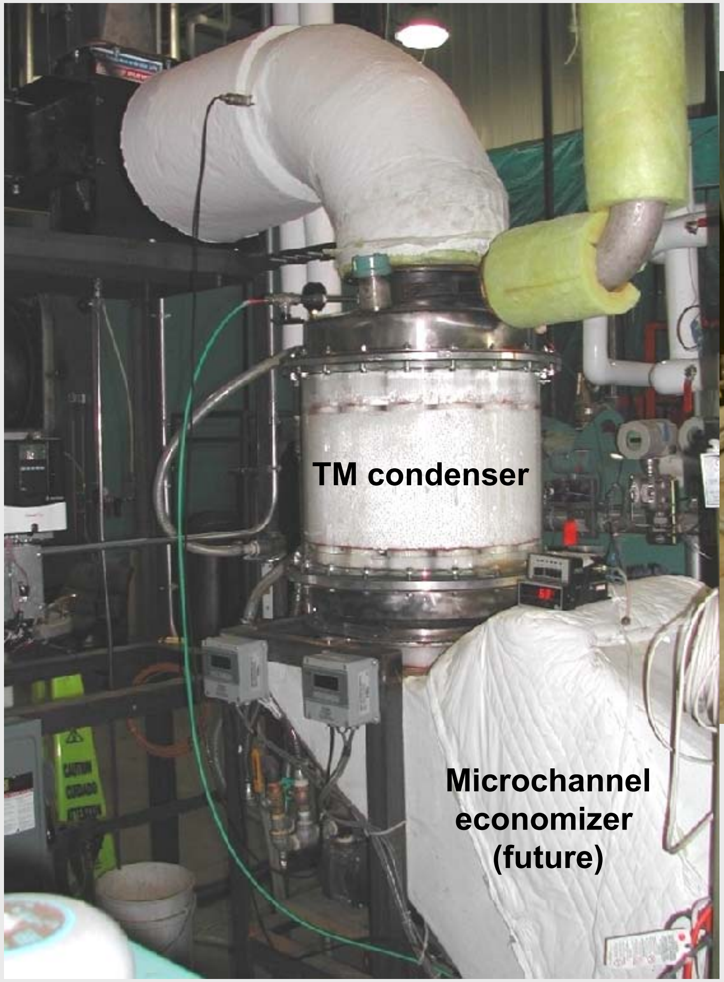
Heat Recovery:
Microchannel Economizer

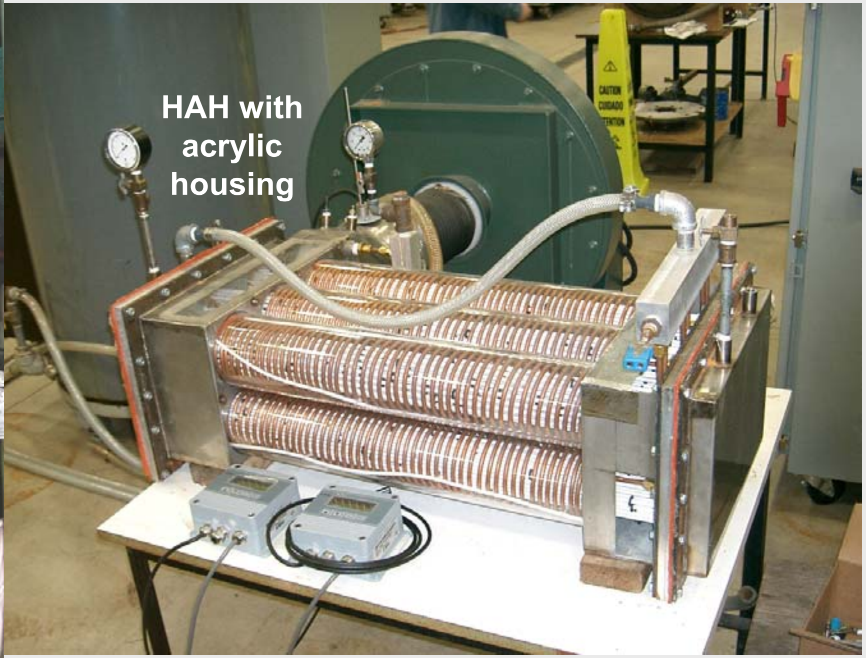


- PNNL microchannel heat exchanger
  - Tested on 60,000 Btu/h combustor
  - Tested as steam generator or economizer
  - Can be made from variety of materials
  - Volumetric heat transfer increased up to 65-fold*
  - Full-scale (3-MMBtu/h) prototype under construction

* 912,000 Btu/h/ft^3 *versus* 14,000 Btu/h/ft^3 for conventional economizer

Heat Recovery:
TM condenser & HAH



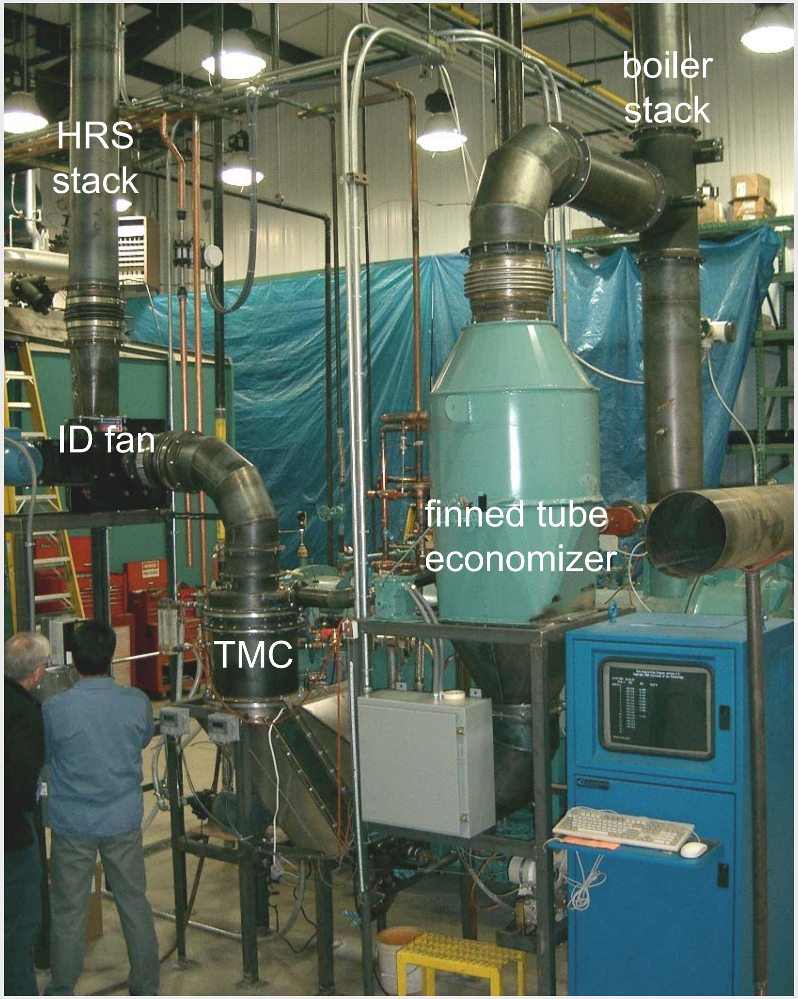


Heat Recovery:
Predicted Energy Efficiency

Case	Cond return (%)	Comb air temp (°F)	Stack temp (°F)	Stack dew pt (°F)	Efficiency (%)
1	None	134	120	102	95.2
2	25	132	132	114	93.5
3	50	120	141	123	91.8
4	75	95	149	131	90.0

- Natural gas: 93.7%CH_4, 2.8%C_2H_6, 0.6%C_3H_8, 2%N_2, 0.9%CO_2
- ISO combustion air (60%RH at 59°F)
- 10% excess air combustion
- 60°F makeup water
- 180°F condensate return

Heat Recovery:
Lab testing system



Heat Recovery Data:
Single economizer + TM condenser

Firing rate	1.75 MMBtu/h	3.00 MMBtu/h
Stack O_2, vol%	4.6%	2.8%
Gas temp, economizer inlet	325°F	317°F
" " economizer outlet	178°F	169°F
" " TM condenser outlet	122°F	125°F
Gas dew point, TM condenser inlet	131°F	131°F
" " " TM condenser outlet	117°F	119°F
Water temp, TM condenser inlet	57°F	72°F
" " TM condenser outlet	125°F	115°F
Water removed from flue gas	39.1% of total	36.3% of total
Calculated boiler efficiency	92.1%	92.3%

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Item 2: Heat Transfer

- Shorten convective passes
  - Firetubes with internal extended surfaces
  - Heat transfer up to 18 times more intensive than rifled tubes
  - 2-pass boiler can deliver efficiency of 4-pass design with smaller size and lower cost

Heat Transfer:
Estimated Size Reductions

	Design case		
% relative to base case	#1	#2	#3
Footprint	61	75	70
Cross-section	71	56	50
Volume	51	56	49
Weight	51	59	51

- Conventional boiler base case:
  - 10-MMBtu/h (250 hp) 3-pass firetube boiler w/450°F flue gas
  - 88" shell ID, 127-ft^2 footprint, 728-ft^3 volume, 11.2-ton dry weight
- Equivalent capacity and heat removal
- Compliant with NO_x emissions target

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Laboratory Boiler:
Single-stage boiler

- > Extended-surface firetube heat transfer testing
- > Pressure vessel design evaluation
- > Flue gas for heat recovery testing
- > Installation/shakedown completed Dec 2003
- > Testing
  - ✓ Heat transfer & pressure drops
  - ✓ General mechanical performance
  - ✓ Heat recovery system

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Heat Transfer Data:
1-stage 2-pass lab boiler

Firing rate, MMBtu/h	Firetube version	Conv pass ΔP, inwc	Sat steam temp, °F	Stack temp, °F	DT, °F
2.1	A	1.6	342	431	89
3.0	A	3.5	343	489	146
2.1	B	3.3	343	357	14
3.0	B	5.4	342	377	35

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Laboratory Boiler:
Two-stage boiler

- Combustion & integrated system testing
- Heat transfer optimization
- Installation/shakedown completed Feb 2004
- Started testing March 2004
  - ✓ Combustion performance
  - ✓ Heat transfer & pressure drops
  - ✓ Controls

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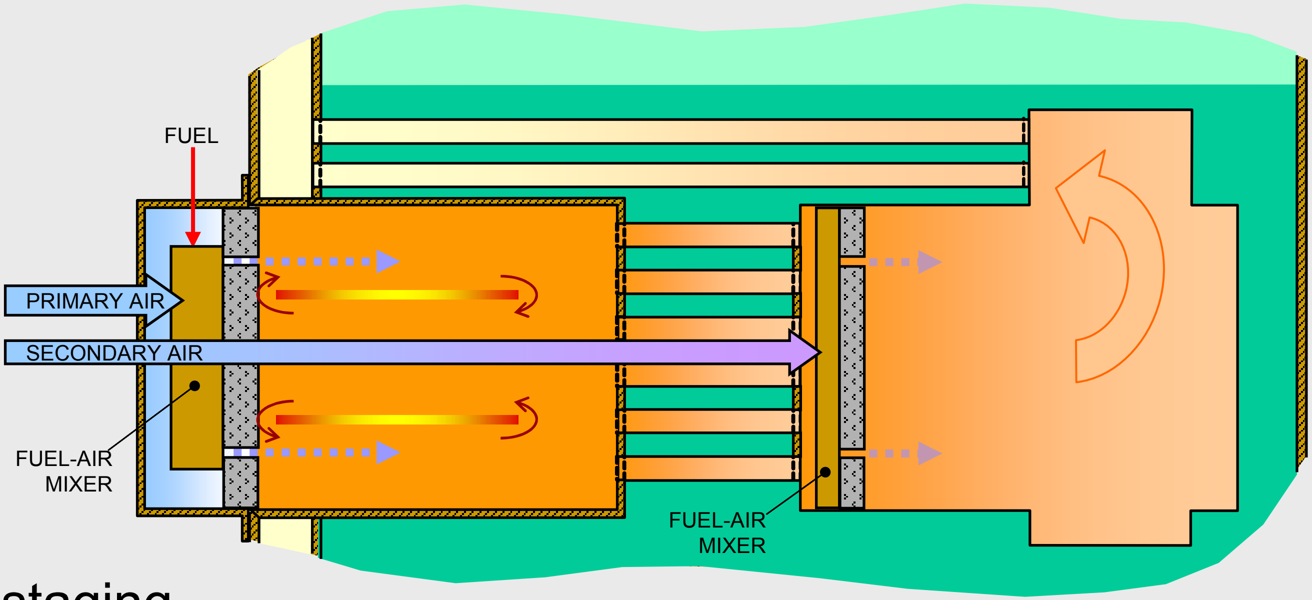
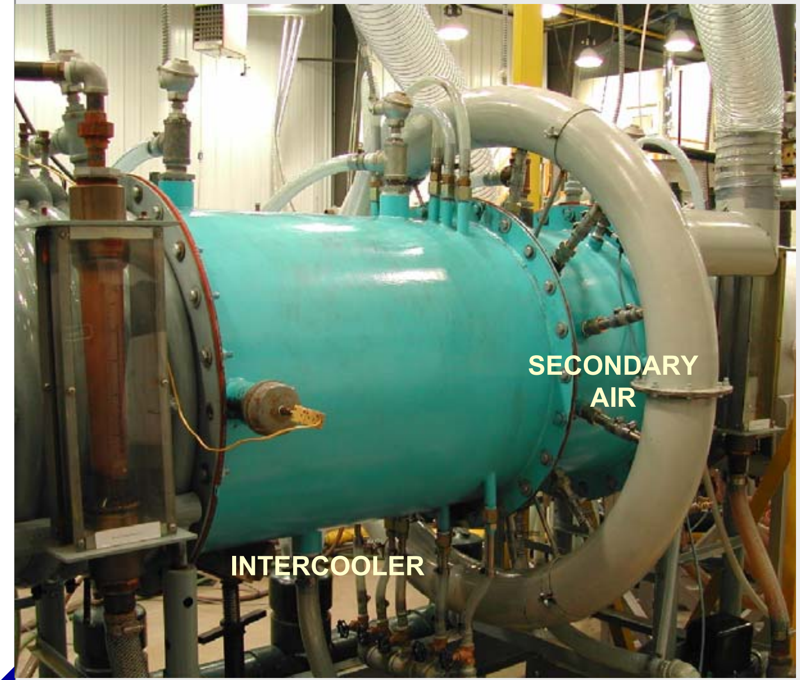
Item 3: Combustion

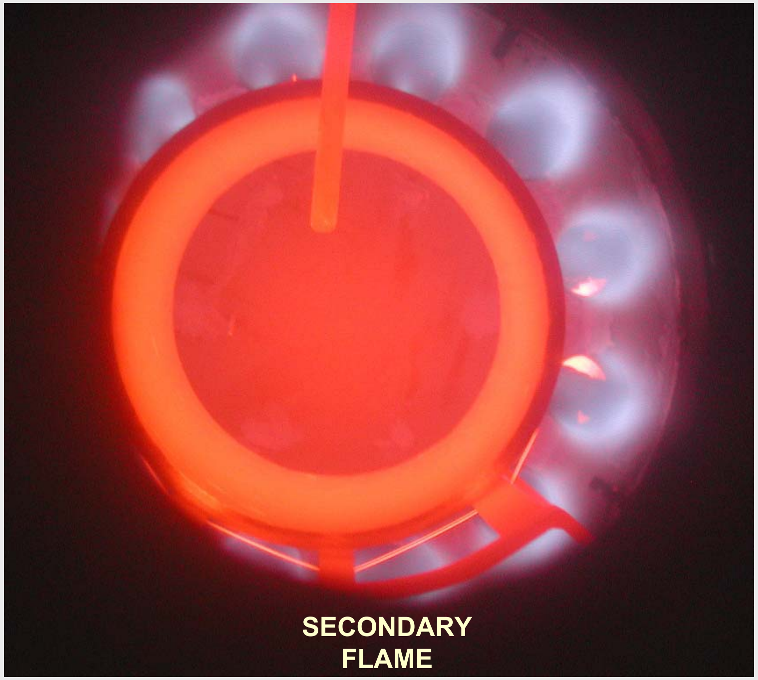


- Air staging
- Forced internal recirculation insert
  - Increases heat flux to water walls
  - Anchors and stabilizes flame
- Premixed fuel/air in both stages
- Interstage heat removal
  - Reduces 2nd-stage flame temperature

Combustion:
2-Stage design development

- Boiler simulator tests
  - Fired at 2 to 10 MMBtu/h (5:1 turndown)
  - NO_x below 5 vppm with good burnout at low excess air
  - High combustion intensity w/short secondary flame





Combustion Data:
2-stage lab boiler emissions

Firing rate, MMBtu/h	O_2, vol%	NO_x, vppm*	CO, vppm*	HC, vppm*
0.85**	7.2**	8.2**	14**	2**
1.70	2.0	2.2	6	0
2.52	3.4	3.3	5	7
3.00	3.0	2.6	7	0
3.65	2.1	3.0	7	0

* corrected to 3% exit O_2

** light-off: single-stage (fuel-lean) firing

3.0-MMBtu/h secondary flame

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Heat Transfer Data:
2-stage 2-pass lab boiler

Firing rate, MMBtu/h	Furnace 1 temp, °F	Furnace 2 temp, °F	Conv pass ΔP, inwc	Steam temp, °F	Stack temp,* °F
0.85*	1385	702	0.5	220	200
1.70	1222	1912	1.0	339	314
2.52	N/A	N/A	2.5	348	346
3.00	1853	2049	2.7	349	354
3.65	1941	2146	3.3	349	367

* Light-off - single-stage (fuel-lean) firing
** Does not account for heat loss from uninsulated stack nozzle

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Design issues:
Combustion

- Fan requirement
- Safety
  - Flame sensing
  - Air-fuel ratio control
- Turndown
  - 4:1 minimum, 6:1 desirable
- Responsiveness
  - Ramp rate & hysteresis
  - Maintain compliance during transitions
- Operability
  - Fully automatic unattended operation
- Backup fuel
  - No. 2 oil

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Design issues:
Heat transfer

- Code compliance
- Pressure drop
- Long-term durability
  - Corrosion
- Maintenance & cleaning
- Backup fuel
  - Compatibility
  - Cleanability

Design issues:
Heat recovery

- Code compliance
- Control strategy
  - Simplicity
  - Load-following capability
- Long-term durability
  - Membranes
  - Corrosion avoidance
  - Pumps, valves, and sensors
- Maintenance
  - Cleanability
  - Backup fuel

Progress and outlook

> Complete lab testing
  – Optimize combustion performance
  – Validate computer models for scale-up
  – Optimize heat recovery system performance
  – Optimize control strategy

> Field demonstration
  – Select best design features from lab testing
  – Select a Southern California host site
  – Design and build commercial prototype boiler
  – Conduct field demonstration

> Commercialization
  – Additional field demonstrations
  – Introduce into commercial and light industrial market

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