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Quick Starting Fuel Processors - A Feasibility Study

*2004 DOE Hydrogen, Fuel Cells &
Infrastructure Technologies Program Review*

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Objectives

- **Study feasibility of fast-starting a fuel processor (*FASTER*)**
 - To meet DOE targets for on-board fuel processing (FP)
- **Estimate energy consumed (by FP) during start-up**

Relevance : On-board fuel processing will ease the transition to the hydrogen economy

Technical Barrier :

I: FP Startup, Transient Operation

L: CO Clean-up

M: FP Efficiency

Budget : \$2.4M

Approach

- **Design, fabricate, and demonstrate the fast-starting capability of a laboratory-scale fuel processor**
 - ATR/WGS/PrOx based design
 - Experimental evaluation at ANL
 - Compare experimental data with model predictions
 - Identify barriers and improvement strategies
- **Collaborative effort with DOE labs and private industry**
 - Component and technical support
 - *LANL, ORNL, PNNL, PCI, AM, QG, university faculty*
- **Model fuel cell system designs to estimate the lifetime (start-up and drive cycle) fuel usage**

Project targets and specifications

- **Start-up Time** **60 seconds**
- **FP Rated Capacity** **10 kWe**
- **Start-up Capacity** **9 kWe (145 SLPM of H₂)**
- **Fuel** **Chevron-Philips Gasoline**
- **Reformate @ 60 sec.** **H₂ > 30%; CO < 50 ppm**

Reviewer Comments

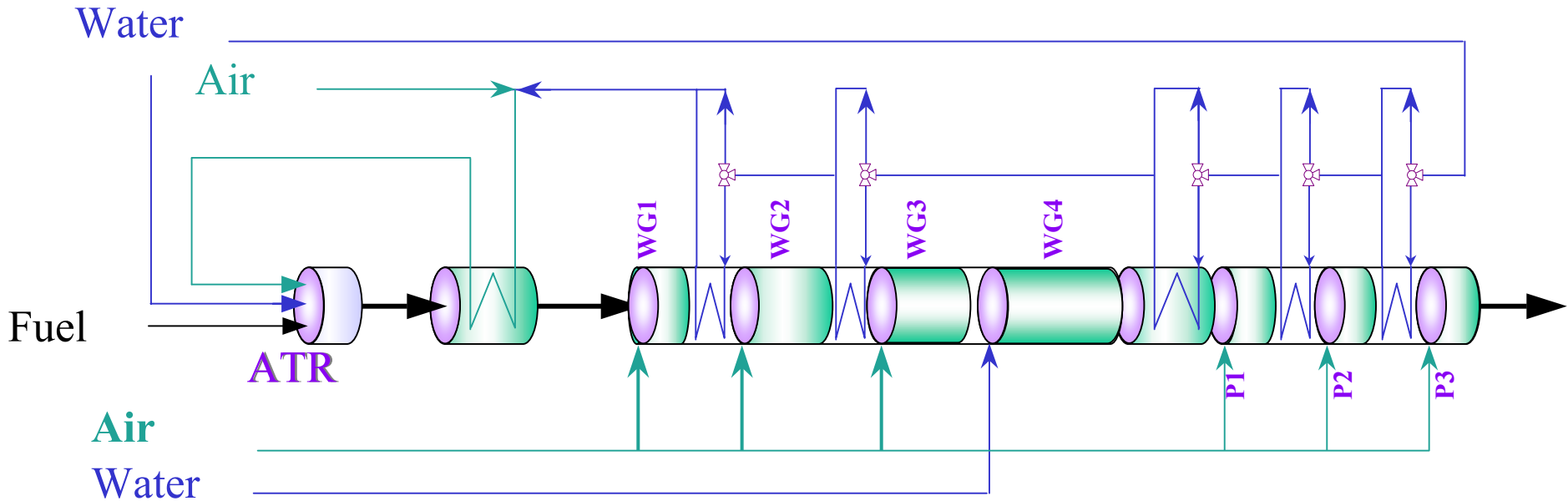
- **... means of ATR ignition have not been adequately considered**
 - Established ATR ignition after testing with liquid/vapor feeds and commercial heating elements
- **Add more schedule time for system optimization after controls testing and total system testing**
 - Capital investments are done, expect to obtain valuable data in the coming weeks and months
- **More detailed control strategies should be investigated**
 - Expect model to enable greater predictive control
- **System design is complicated, too many reactors and HXs**
 - Component and mass reduction opportunities are being explored

Project Safety

- Reviewed by committee of scientific, divisional safety, ANL staff (fire, ES&H)
 - Detailed document includes P&ID, electrical drawings, identification of hazards and mitigation, procedural checklists, and qualified operators
 - Set up in a canopy hood with H₂-sensor and dedicated exhaust
 - Continuously monitor each value (T, P, flow) with automated shutdown triggered at defined alarm condition
 - 3 automated shutdown sequences
 - *Emergency*
 - *Manual soft shutdown*
 - *PC-based normal shutdown*

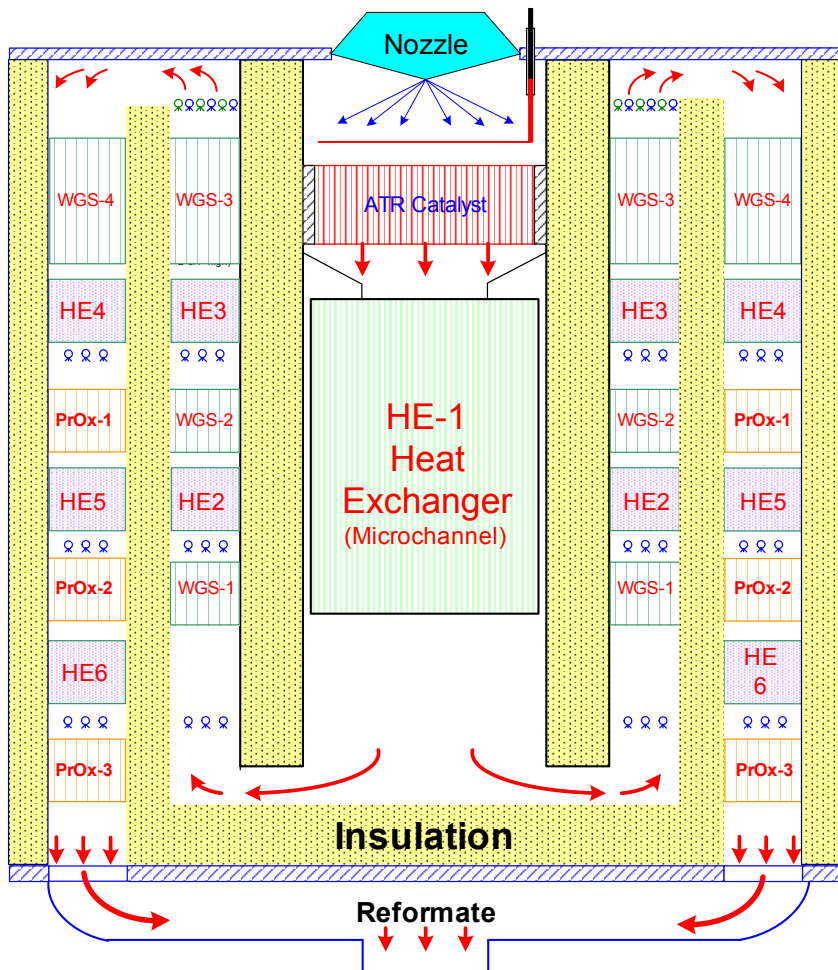


Start-up Strategy: Produce (H_2+CO) in ATR, oxidize downstream to generate heat



- **ATR is ignited to produce hydrogen**
- **Reformate oxidation in shift zones generate heat for shift reactors**
- **PrOx catalysts are active at room temperature**
 - Active at 25°C, get better as they warm up

Components received from partners were assembled at ArvinMeritor



Components

- HE1
Microchannel HEX- PNNL
- HE2-6
Foam HEX – ORNL
- ATR
Microlith™ support – PCI
- WGS
Microlith™ support – PCI
- PrOx
Foam support – LANL
- Assembly
ArvinMeritor

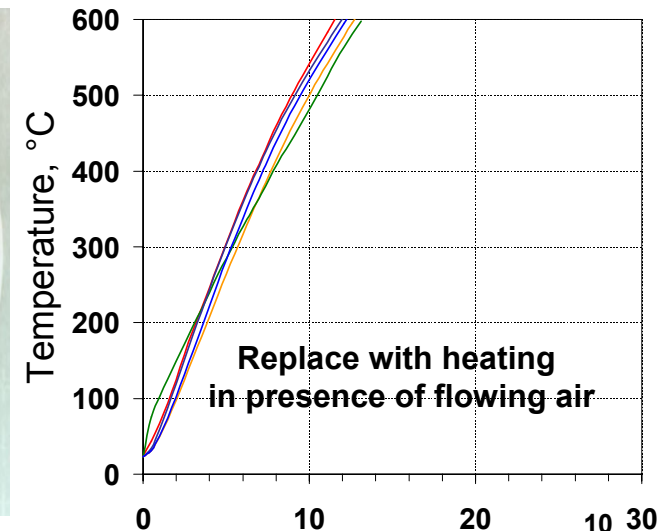
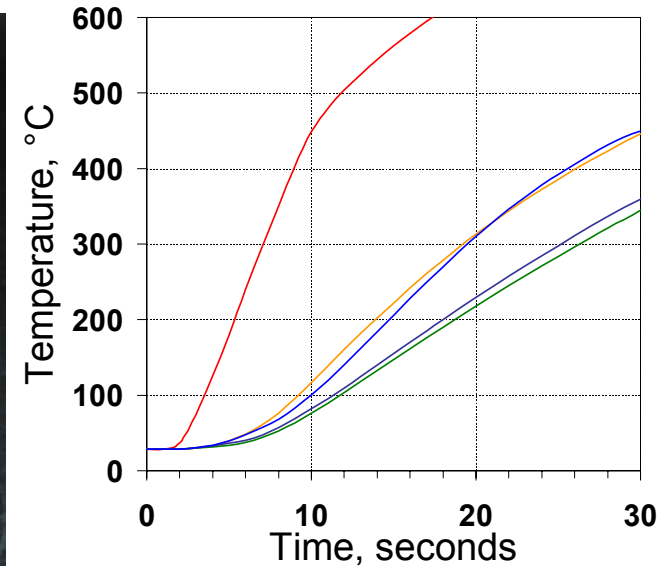


Ignition in the ATR requires appropriate feeds and catalyst temperature

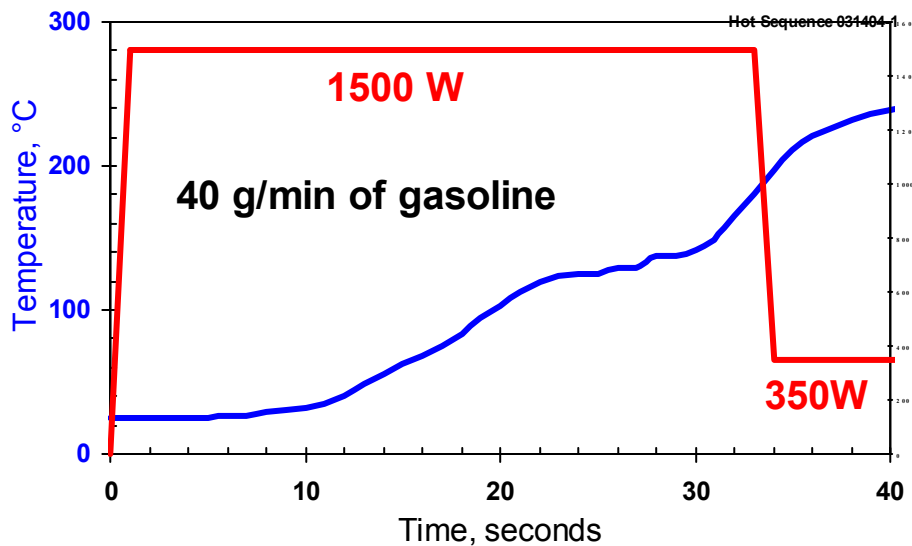
- **Catalyst heated above ignition temperature**
 - Direct heating
 - *catalyst loaded on an electrically-heated support*
 - Indirect heating
 - *by air flowing past a heating element*
- **Fuel injection for POX reaction**
 - Inject fine, uniformly distributed spray of liquid fuel
 - Inject vaporized fuel, premixed at the nozzle
- **Air injection**
- **Water injection for ATR reaction**
 - Inject fine, well-distributed spray of liquid water
 - Inject steam, premixed with air or vaporized fuel

A coiled heater rod was used to preheat the catalyst

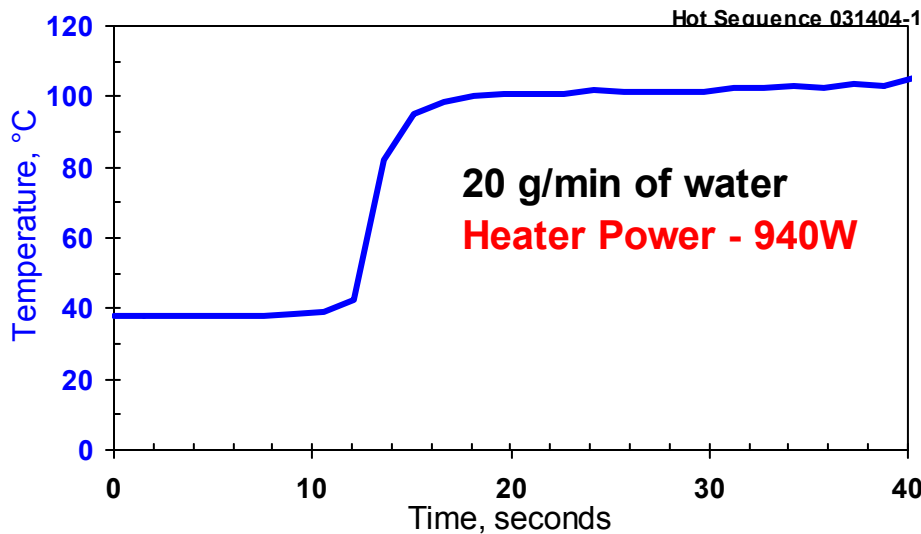
- **Coiled heater rod required 25 s to heat catalyst to 300°C**
 - 3 × 400 W
- **Commercial heated support reaches 500°C in 10 s**
 - 12 Volts, 130 Amps, ~1.6 kW
- **Coalesces liquid particles**
 - Should remain powered during liquid water spray
- **Catalyst/support combination needs development**



Fuel can be injected into ATR at 30 s



- At 30 s, the exit stream reaches 150°C
- More responsive fuel vaporizer can be designed



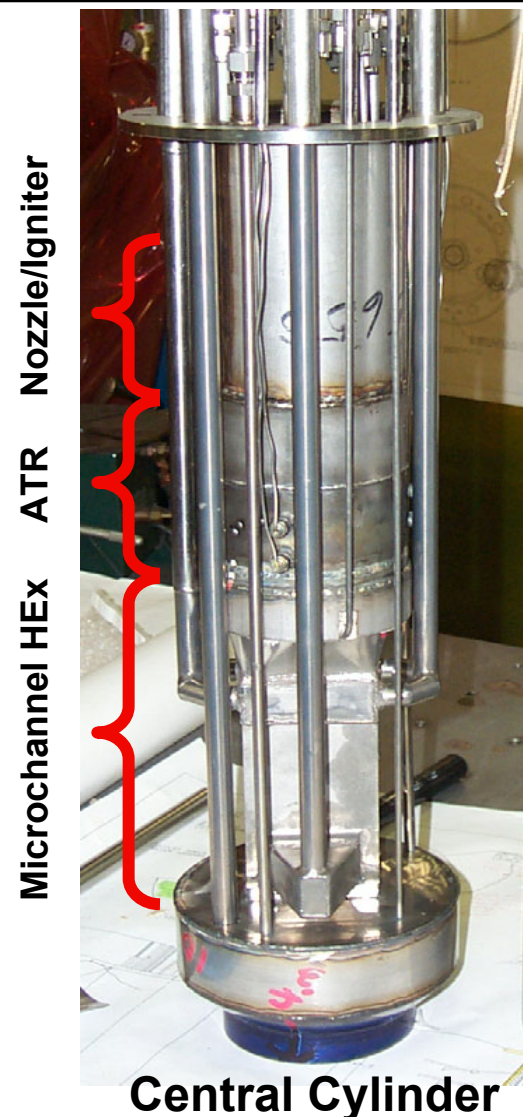
- 20 g/min of steam can be available in 20 s
- ATR conditions reduce coking potential, promote shift conversion

ATR start-up tests were done using the central assembly of the FASTER hardware

The central cylinder includes

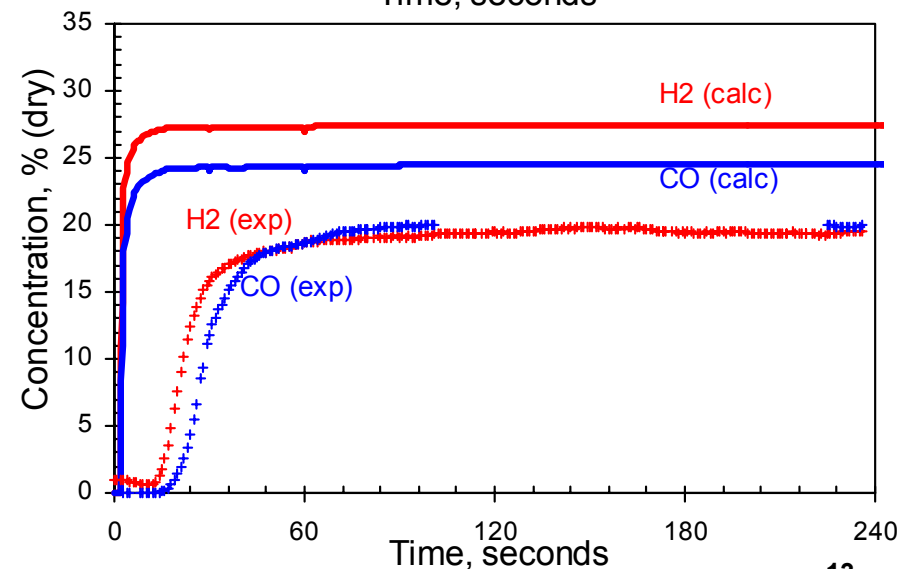
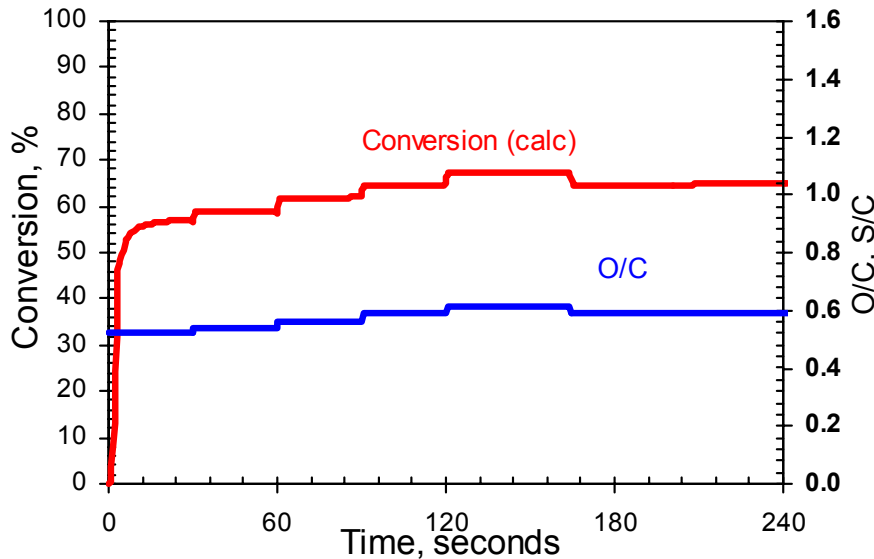
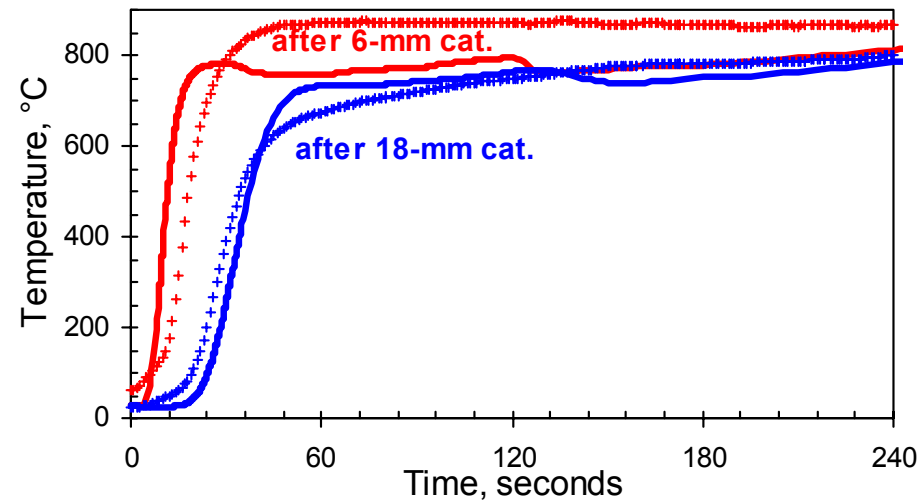
- Nozzle assembly
- Igniter heater coils
- Microlith-based ATR (3-layers)
- Microchannel HEX
- Nozzle assembly permits
 - Liquid spray injection (fuel and water)
 - Mixing of gaseous streams
 - *Air, vapor fuel, steam*
- Reformer was started in POX mode:
 1. (Liquid fuel^(a) + air) + liquid water
 2. Vapor fuel^(a) + air
 3. (Vapor fuel^(a) + air) + steam^(b)
 4. (Vapor fuel^(a) + air) + liquid water

(a) 40 g/min; (b) 20 g/min



CPOX Reforming : 10% H₂ available in 22 s

- Gasoline vapor at 40 g/min
- 65% fuel conversion at O/C=0.6
- 700°C in 75 s (at 18-mm depth)
- Peak temperature (900°C) limited O/C
- H₂ concentration exceeds 15% in 28 s
- Model under-predicts CH₄ yield
- CO concentration exceeds 20%
 - on-line CO analyzer max. is 20%.

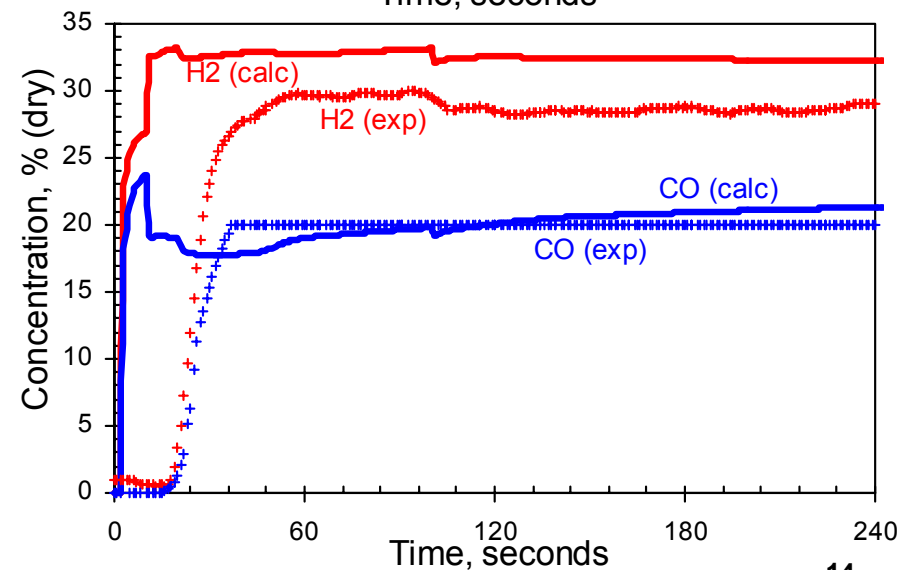
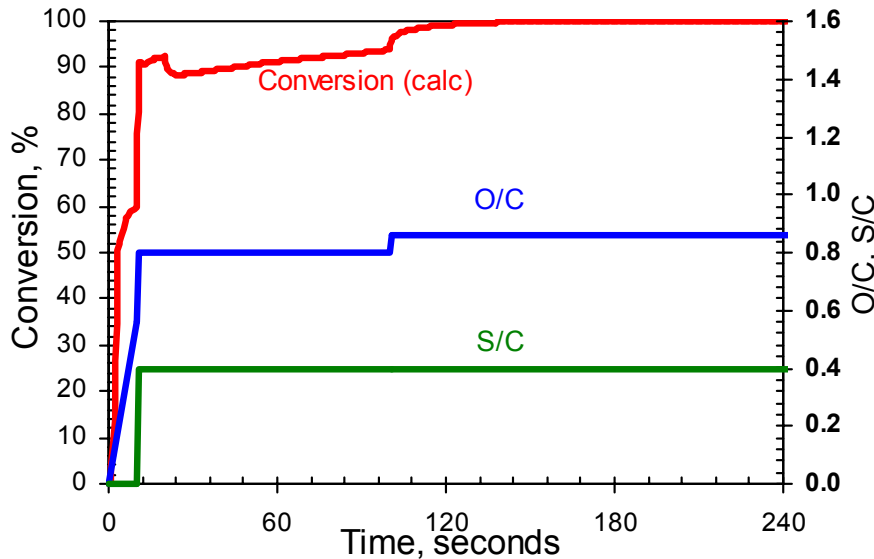
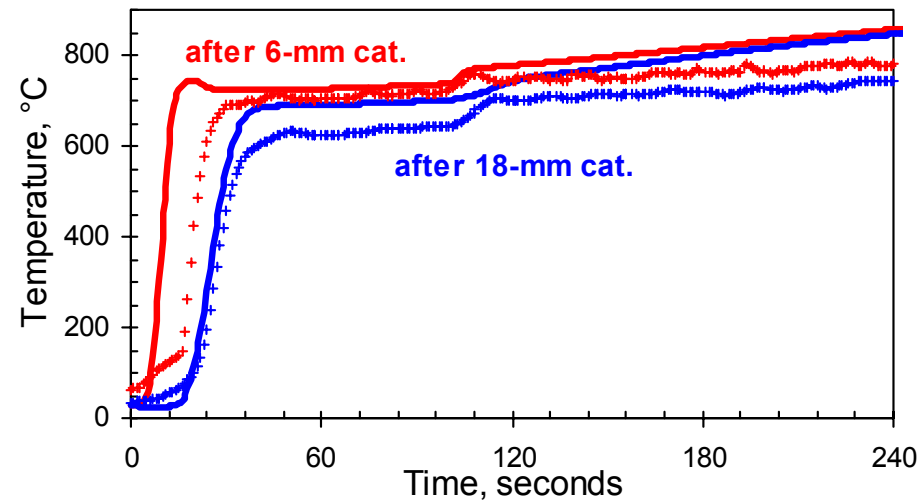


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Transition to ATR using steam assists a smooth start-up transition

- 100% fuel conversion at O/C=0.8, S/C=0.4
- Temperature variations between successive layers are smaller than with CPOX
- H₂ concentration is higher than with CPOX

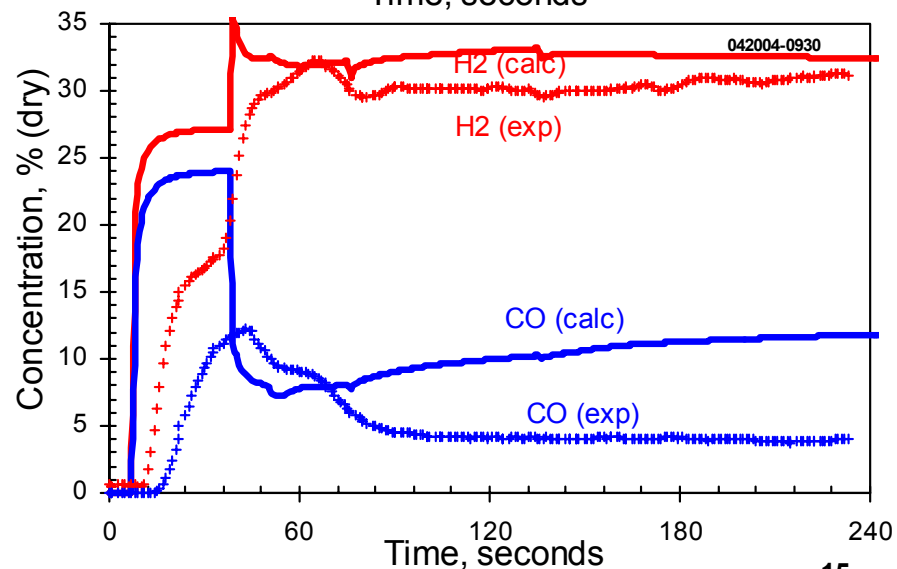
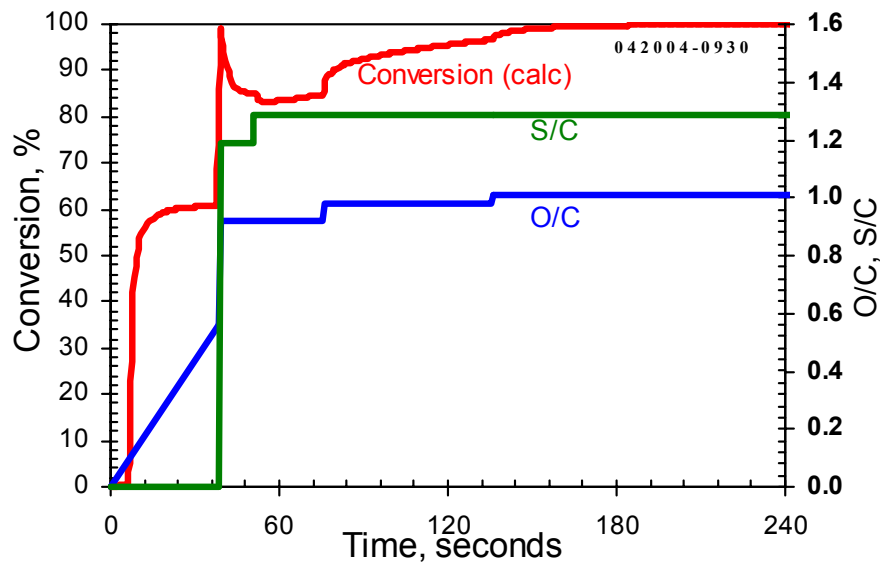
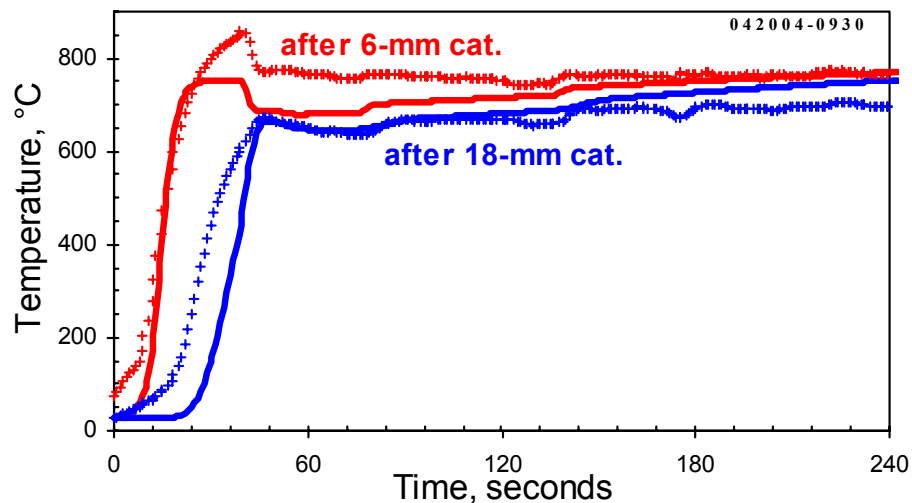


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Switching to ATR with liquid water is possible

- Stability depends on spray size, distribution, and catalyst temperature
- Temperature non-uniformities near catalyst inlet edge
 - General trends are reproducible
- H₂ and CO yields are suitable for oxidation in WGS
- Igniter heaters can be turned off

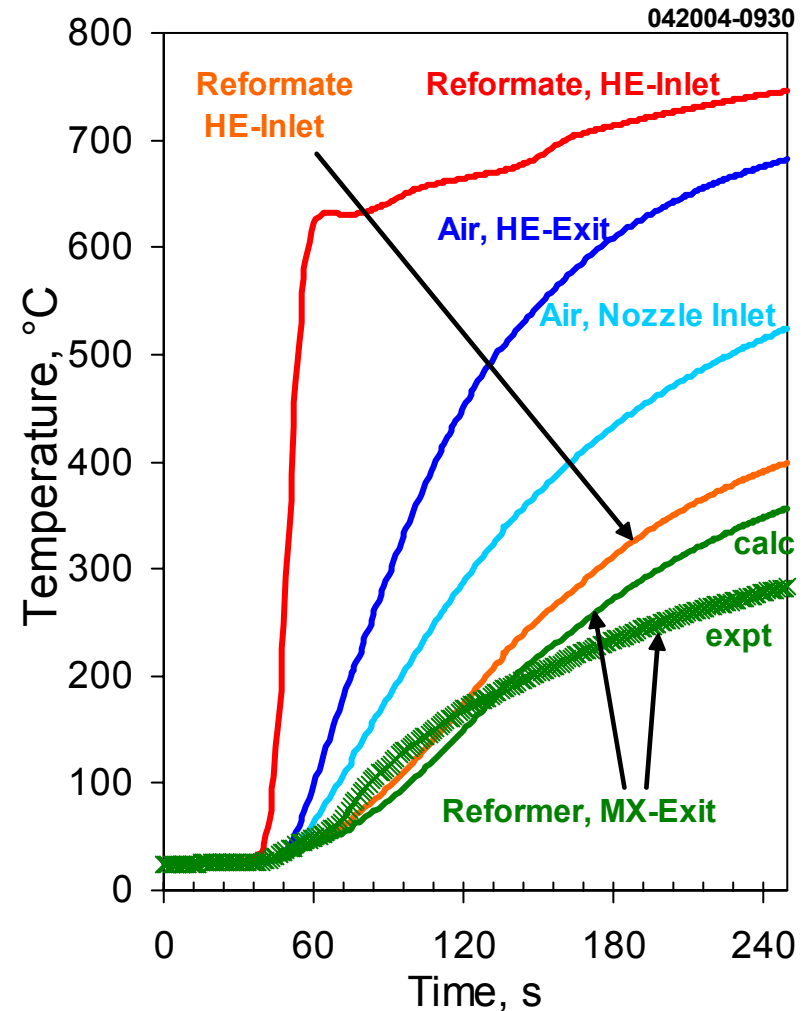


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Reformate from HE1 reaches 100°C in 200s

- At 100°C, the WGS catalyst is expected to support oxidation reactions
- Microchannel heat exchanger designed for a heat load of 3.6 kW
- Considerable mass contributions from supporting structures
 - 1988 g for heat exchanger block
 - 737 g for ancillary block
 - 388 g for inlet and outlet tubes



Components fabricated are heavier and will require more start-up fuel than estimates based on functional elements (e.g., catalyst) only

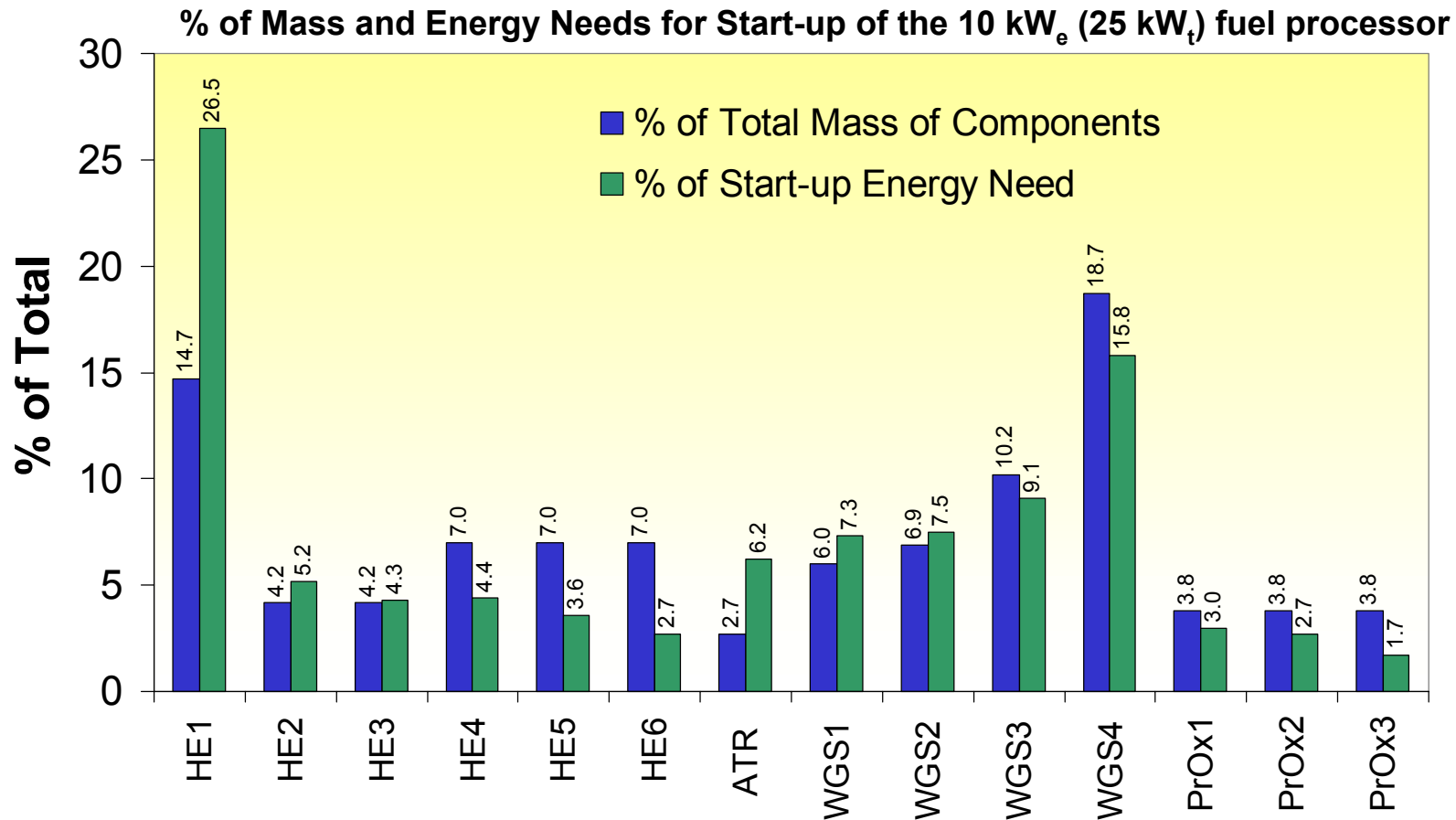
For the 10 kW_e (25 kW_t) fuel processor

<i>Catalysts</i>	ATR	WGS1	WGS2	WGS3	WGS4	PROX1	PROX2	PROX3
Functional Element Wt., g	150	235	375	690	1,150	290	290	290
Component Weight, g	578	1276	1460	2163	3978	800	800	800
Th. Energy Need, kJ	178	210	215	261	454	87	78	48
	Initial Estimate = 430 kJ; Revised = 1531 kJ							

<i>Heat Exchangers</i>	HE-1	HE-2	HE-3	HE-4	HE-5	HE-6
Functional Element Wt., g	1100	586	586	943	943	943
Component Weight, g	3140	898	898	1500	1500	1500
Th. Energy Need, kJ	760	150	124	125	102	78
	Initial Estimate = 654 kJ; Revised = 1339 kJ					

- Support structures and instrumentation access needs have added to the weights

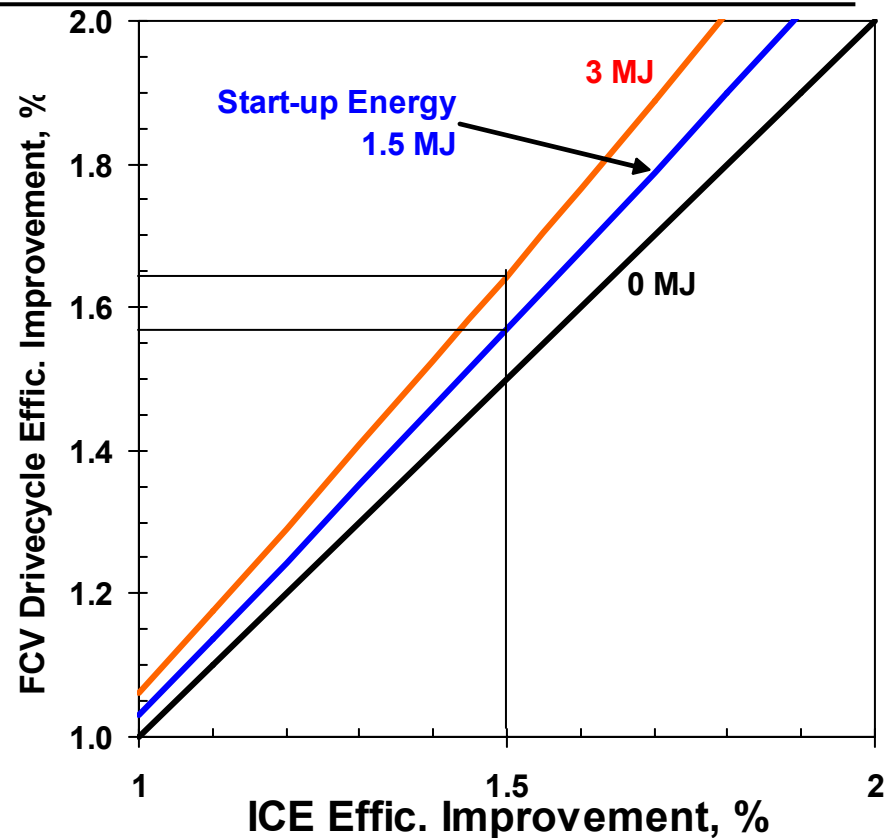
Start-up energy needs are dominated by HE1 and WGS4



- The mass of each component is expected to drop with further development
- Model indicates that the number of components can be reduced

Fuel cell vehicles can offer fuel economy better than today's cars

- Current (ICE) vehicles provide 23.7 mpg (including cold-start)
- Operates for 100,000 miles with 10,000 cold-starts
- If next generation cars should yield 50% higher mpg (35.6)
- A fuel cell vehicle with on-board reformer will have to be more than 50% more efficient than the ICE
- If FP consumes 3MJ per cold-start, the FCV will need a drive-cycle efficiency to be 65% higher than the ICE vehicle
- Draft DOE target for 50-kWe fuel cell system
 - 2 MJ per start: 1.5 MJ thermal, 0.5 MJ electrical accessories

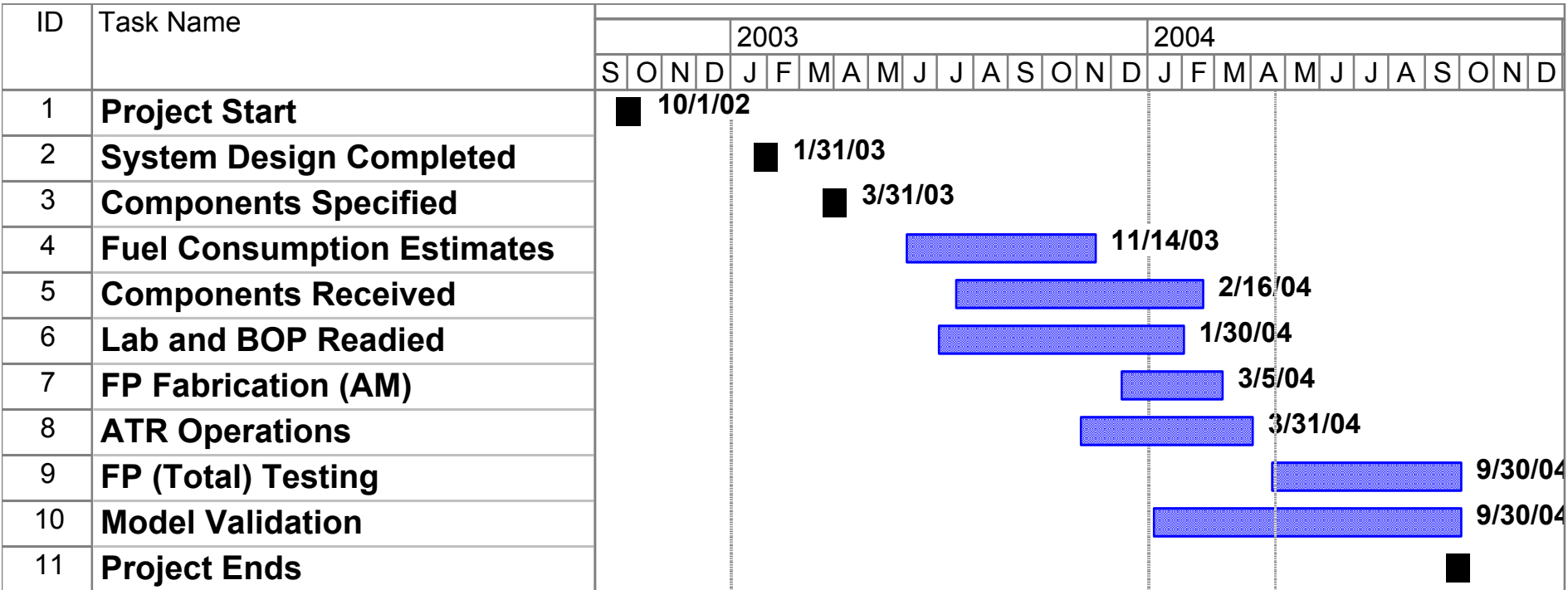


Three FP configurations were studied to improve the lifecycle efficiency

- **FP-1** : FASTER design
- **FP-2** : Compact FASTER design
- **FP-3** : Integrated with Anode Gas Burner

	FP-1 (FASTER)	FP-2	FP-3
Stages of WGS / PrOx / HEx	4 / 3 / 6	2 / 2 / 4	
WGS Exit CO, %	1	1.4	0.4
FP Drive-Cycle Efficiency, %	82	80	78
Lifecycle Efficiency, %		73	75
Start-up Energy Consumption, MJ	7 MJ	3.3 MJ	1.6 MJ

Project Timeline



Interactions and Collaborations

- **Close collaboration with consortium partners**
 - Components from LANL, ORNL, PNNL, PCI
 - Fabricated at ArvinMeritor
 - Technical support visits, model development support
 - FASTER update meeting, Dec. '03
 - University faculty participation
 - Private companies contributed significant resources
- **Update to FreedomCar Tech Team, Feb. '04**

Accomplishments

- **A collaborative effort has converted a FP concept into experimental hardware**
 - Components received from LANL, ORNL, PNNL, PCI
 - Assembled and fabricated at ArvinMeritor and ANL
 - Test apparatus built and safety approved
 - Set up a flexible data-acquisition and control system
 - *PLC, SCXI based signal processing unit, LabView*
 - *Start-up sequence established for ATR-readiness*
- **Models have supported process design, experiments have validated models**
 - Kinetics established from stand-alone experiments
 - CFD used for component design, data interpretation
 - FEMLAB model to predict steady-state performance and transient response (for control algorithm)
 - GCTool model to design FP system and component sizing
- **Estimated start-up fuel consumption of current FP design**
 - Investigated FP design options that promise improved fuel economy of the FCV

Future Work

- **Accelerate ATR readiness with**
 - Nozzle development
 - *deliver fine, distributed liquid spray*
 - *distribute air uniformly*
 - Catalyst loaded on electrically heated support
- **Revisit reactor configuration for easy access**
- **Further develop control algorithms (with safety interlocks)**
- **Develop catalyst to improve durability, use alternative supports**
- **Reduce thermal mass of fuel processors with focus on lifecycle efficiency**
 - Trade-off with drive-cycle efficiency
 - Significant mass reductions anticipated
 - *reduced number of components*
 - *heat exchanger redesign*

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