NUVERA
FUEL CELLS

Advanced High Efficiency, Quick Start Fuel Processors for Transportation Application

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Agenda

- STAR™ (1999-2003)
  - Substrate based Transportation application Autothermal Reformer
- HiQ (2001-2005)
  - High Efficiency Quick Start Transportation Fuel Processor

STAR Program Overview

Mission Statement

Building on Nuvera's past experience, develop an automotive multi-fuel processor which will meet or exceed FreedomCAR targets (efficiency, power density, durability, etc.)

Technical Approach

Replace conventional pelleted catalysts and heat exchangers with compact and low thermal mass substrate (monolith, foam, reticulate) based media

Program Overview

- Four year R&D program (1999-2003)
- Subcontractors: SudChemie, Inc.; Corning, Inc.; STC Catalysts, Inc.
- Deliverables: STAR automotive fuel processor to Argonne National Lab

STAR Program Activities

Period	Activities	Accomplishment
1999-2001	Component R&D -Substrates -Monolithic catalysts -Compact heat exchangers -Desulfurization technology	All substrate-based catalysts - ATR, HTS, LTS, PROX, TGC
2001-now	Integrated FP and FCPS -Design of STAR fuel processors -Fuel processor construction and gasoline testing -Integration of STAR FP and Nuvera's PEM FC -Controls development	Over 10X reduction over previous design fuel processor

STAR Fuel Processor

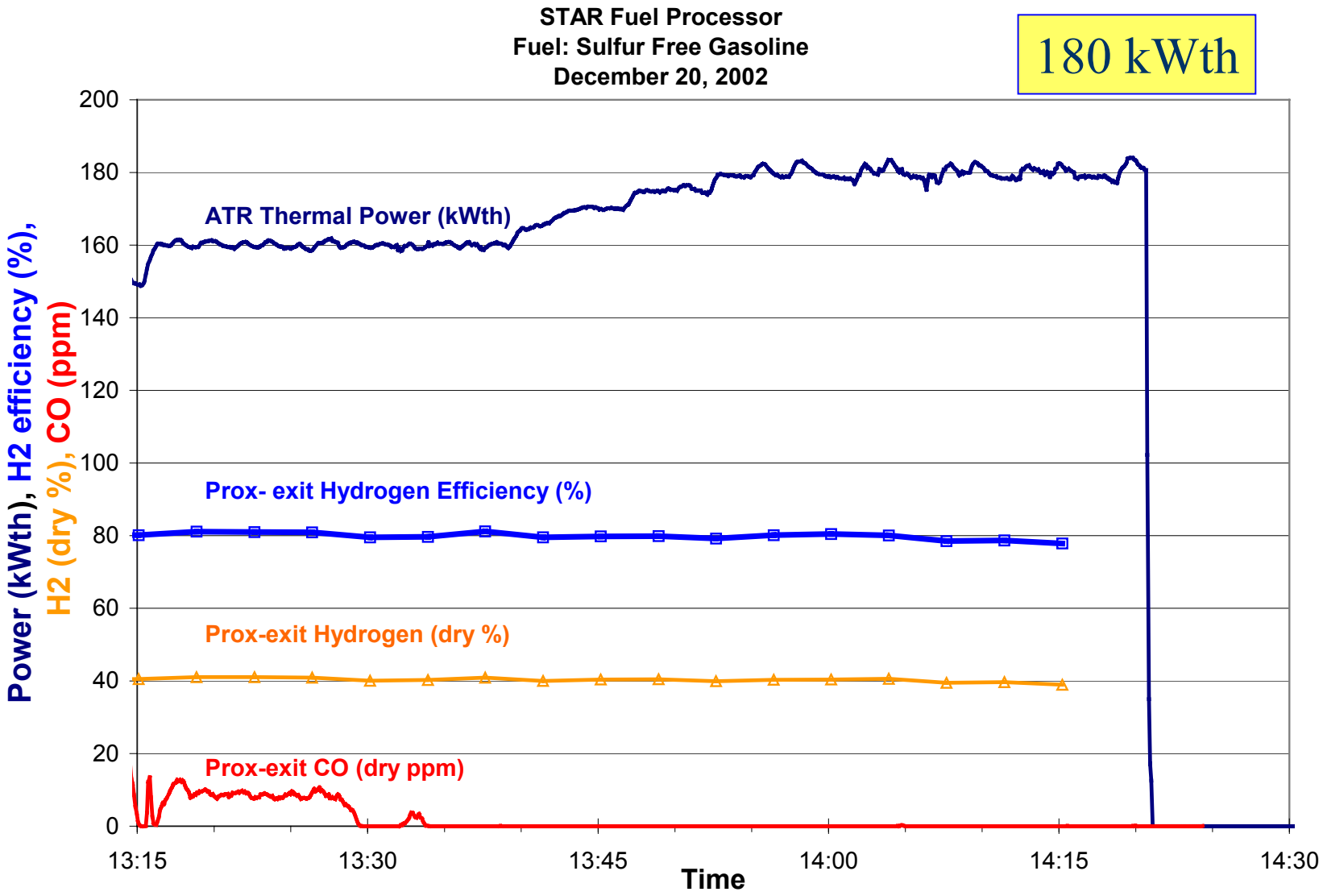
- Autothermal reformer
- Substrate-based catalysts (no pellets)
- 200 kWth input
- Automotive volume (~75 liters)
- Design focus on gasoline
- Under-vehicle “flat” aspect ratio
- Modular, serviceable design

STAR Program Highlights

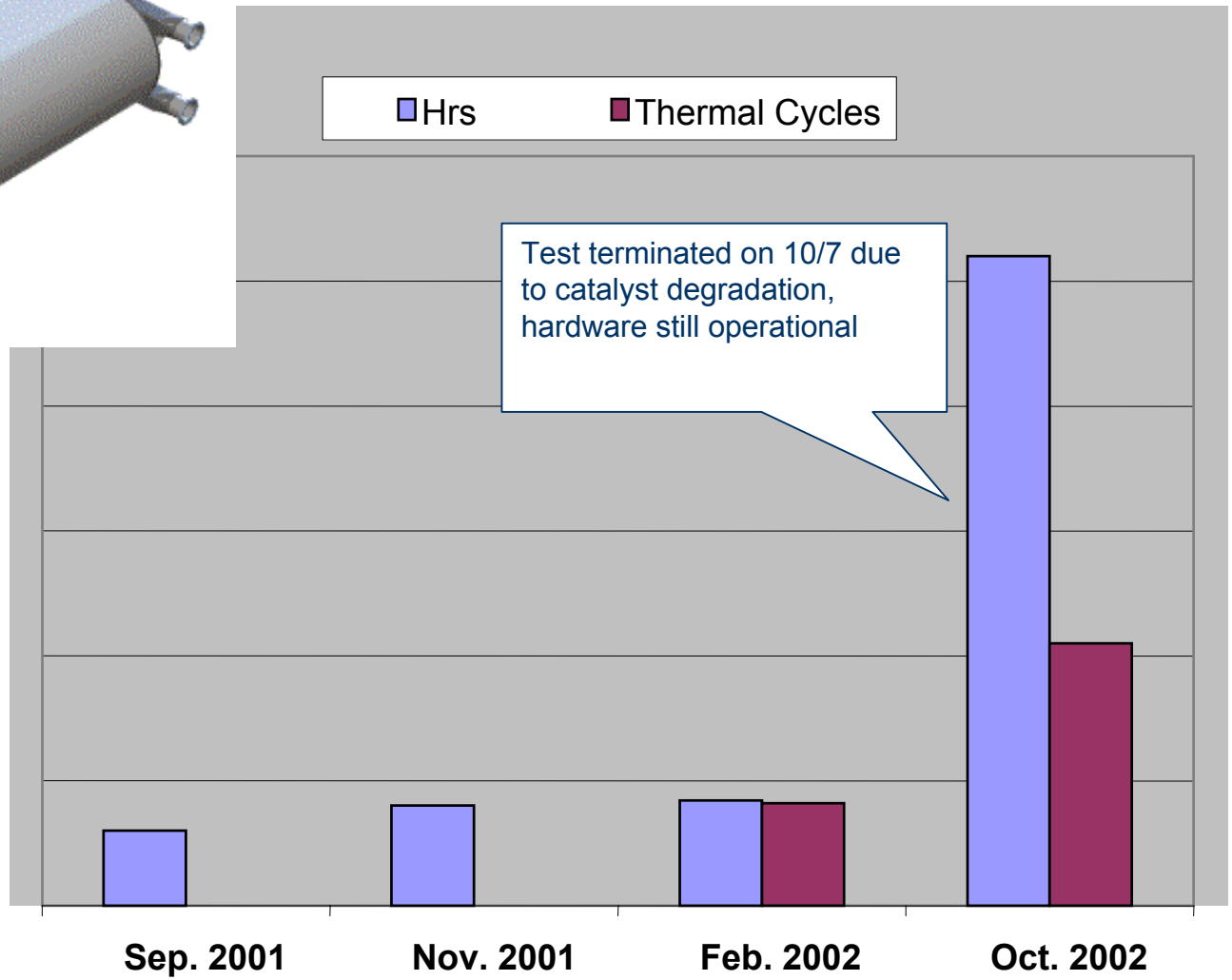
- **Meets or exceeds several fuel processor targets**
  - High power density -75 liters and 200 kWth gasoline feed rate
  - Efficiency - 80% hydrogen efficiency
  - Reformate quality - undetectable ammonia, CO < 10 ppm
  - Packaged for auto application

- **Successfully integrated with Nuvera's PEM fuel cell**

STAR Test Data (Gasoline)



Durability Improvement



Other STAR Highlights

- **Rapid development process**
  - Built and tested six design iterations
- **Design improvements in many areas**
  - Thermal Stress
  - Serviceability
  - Mixing
  - Heat Exchange
  - Thermal Integration
- **Controls Development**
  - Automated Startup
  - Custom Control System

STAR Status in 2003

Specification	2005 Target	STAR
Energy Efficiency	78%	80%
Power Density	700 W/L	➡
Specific Power	700 W/kg	640
Cost	25 $/kWe	TBD (➡)
Start-up Time	<1.0 min	➜
Transient Response	5 sec	TBD
Emissions	< Tier II	➡
Durability	4000 h	TBD
CO in Product	<10 ppm	➡
H2S in Product	<50 ppb	➡
NH3 in Product	<0.5 ppm	➡

2003 STAR Plans

- Continue characterization on gasoline - Q2
- Demonstrate multi fuel capability (ethanol and natural gas) – Q3
- Prepare system for Argonne National Laboratory delivery – Q3
- Support operation at ANL – Q4
- Submit Final Report – Q4

HiQ Program Overview

Mission Statement

- Design, develop and test a high power density, multi-fuel fuel processor system that enables high efficiency and quick start operation of an integrated fuel cell power system for automotive applications

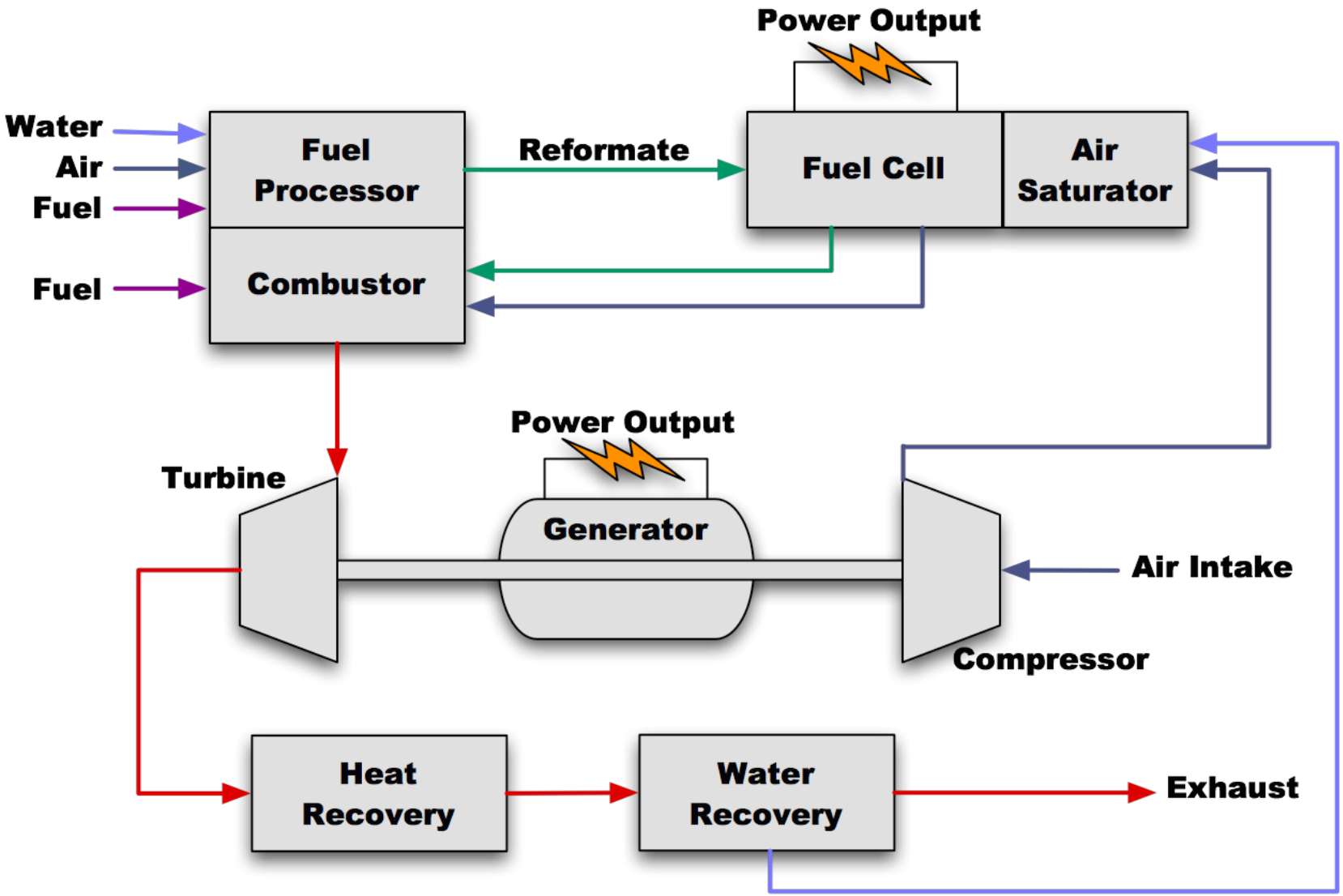
Technical Approach

- Integrate fuel processor with a turbo-generator system to recover waste energy from stack and provide capability for rapid start to low power levels

Program Overview

- Four year R&D program (Oct. 2001 - Oct. 2005)
- Subcontractors: Engelhard Corp. (catalyst and membrane development)
  Worcester Polytechnic Institute (catalyst kinetics)
- Deliverables: Complete automotive fuel processor to Argonne National Lab

HiQ System Concept



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Main Advantages of Hybrid Design

- **Significantly higher net system efficiencies**
  - Stack "waste heat" is converted into useful work
  - Rankine cycle adds sufficient power to turbine to create net power output from turbine - compressor system
  - Brayton cycle is also made more effective via turbine
  - Best performance with elevated stack temperatures (~90 °C)
- **Use of existing automotive-type compressor-expander**
  - Higher efficiency than reciprocating or low-T compressor-expanders
  - Low cost, proven durability
  - Limits system size to > 50 kW_e (smallest available turbines)
- **Reduced radiator size**
  - Lower heat duty due to efficiency improvement
  - Higher LMTD due to high exhaust dew point
- **"Instant" startup to low power output**
  - Turbo-generator / burner can produce power very quickly without stack

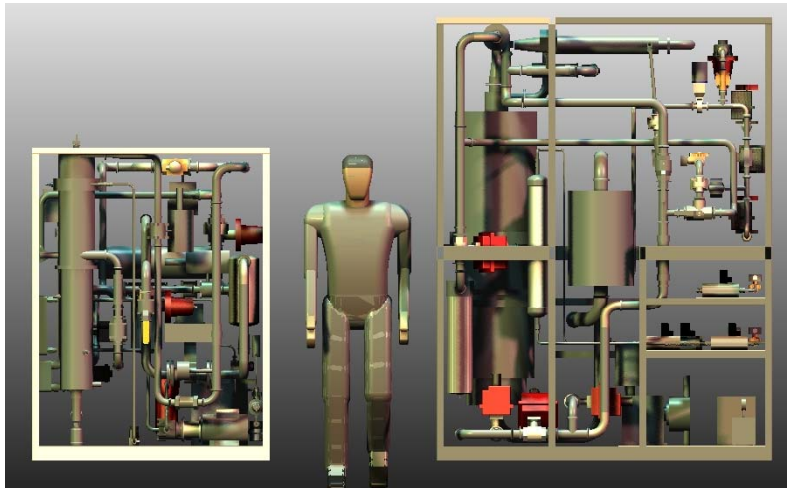
Major Milestone Demonstrations

Milestone	Date	Equipment	Purpose
Proof of Concept	1/31/2003	FP 1 Turbocharger Stack Simulator (80 - 90 °C)	▪ Support modeling results ▪ Startup demo (<60 s) ▪ Burner demo
Turbo - Generator Integration	12/31/2003	FP 1 Turbocompressor / Motor-Generator Stack Simulator (80 - 90 °C)	▪ Motor-driven startup (30 s) ▪ Show generator power output (= high efficiency)
Automotive FP Demo	3/31/2005	HiQ Automotive FP Turbocompressor / Motor-Generator Stack Simulator (90 - 110 °C)	▪ High power density FP ▪ 30 second startup ▪ High system efficiency
ANL Delivery	10/31/2005	HiQ Automotive FP Turbocompressor / Motor-Generator	▪ System automation ▪ Test unit at ANL

Proof of Concept System Testing

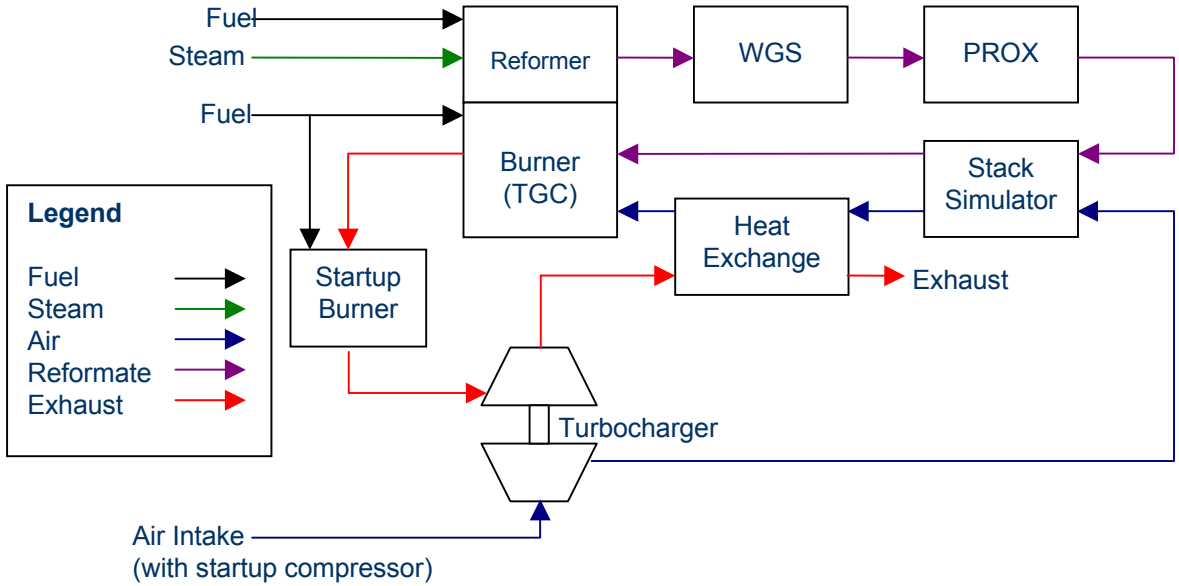
Stack simulator

- Accurate simulation of anode / cathode returns
- Low cost



Proof-of-concept fuel processor

- Low-cost, durable catalysts
- Focus is new cycle, not power density



Proof of Concept vs. HiQ Fuel Processor

Proof of Concept System

- **Low Power Density Fuel Processor**
  - Use proven, durable reforming technology
  - Keep focus on system concept
- **Turbocharger**
  - Avoid motor-generator complications and development times
  - Vent excess compressor air / bypass turbine flow to simulate generator load
- **Stack Simulator**
  - Provide realistic return streams for stack at elevated temperature
  - Important for developing burner that runs on cathode return air

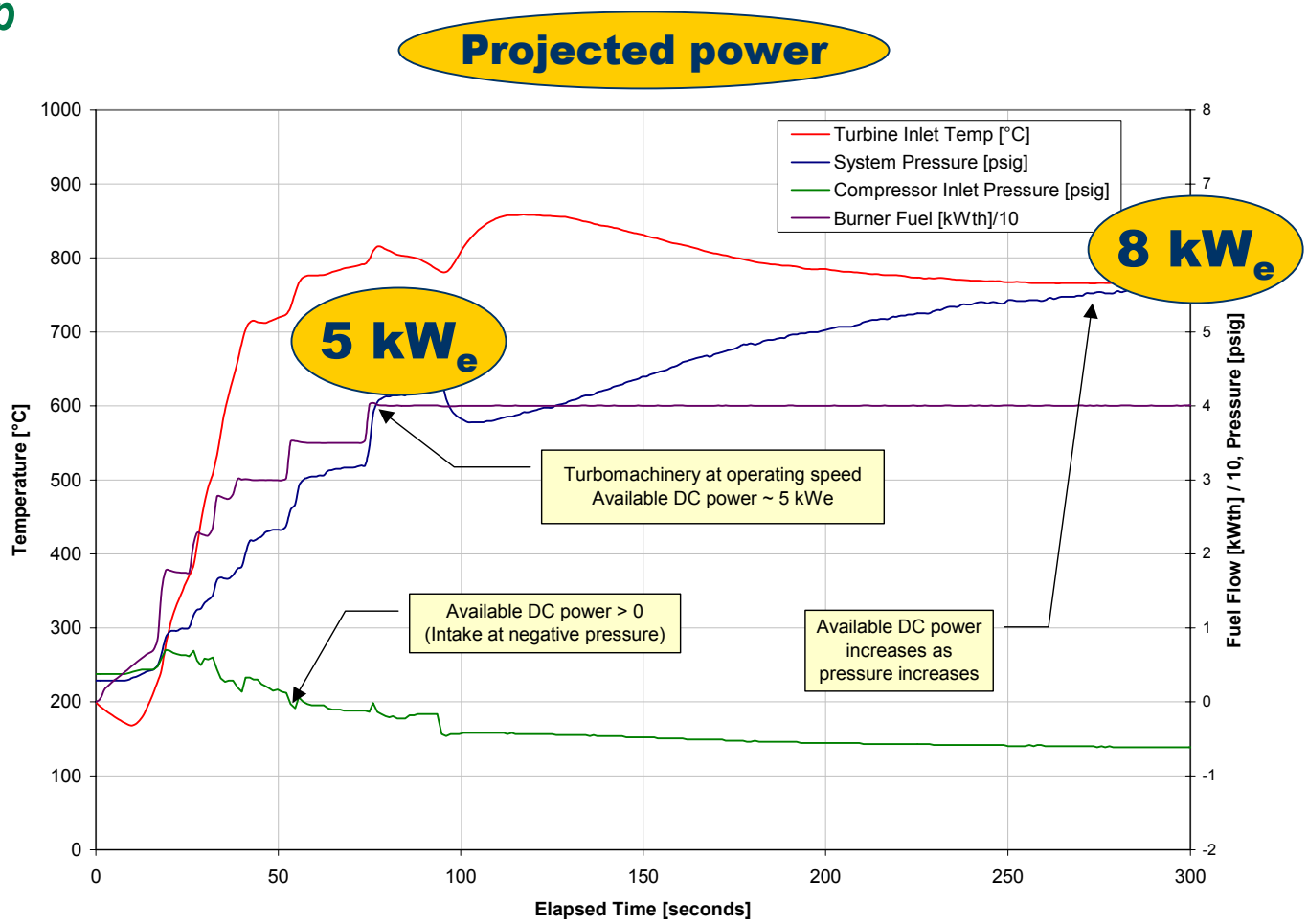
Automotive HiQ FP

- **Gasoline / Multi Fuel Substrate-Based Fuel Processor**
  - Incorporate high power density STAR technology
  - HiQ system configuration
- **Turbocompressor / Integrated Motor-Generator**
  - Show actual power < 30 sec after startup
- **Compatible with 50 kW_e elevated temperature stack**
  - Fuel processor will not depend on any one stack technology, only on general operating conditions

Startup Time Demonstration

At startup, the HiQ fuel processor system can operate in a Brayton cycle (gas-turbine) mode to provide partial power while the fuel processor catalysts are still warming up

- Automotive turbocharger is used to simulate turbogenerator
- External compressor drives turbocharger to simulate motor
- Net power is available when intake pressure is less than atmospheric
- About 25% power available at start-up in optimized system from turbo



HiQ Projections

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Future Plans

- **Proof-of-concept fuel processor testing** — **Q2-Q3 2003**
  - Startup optimization
  - Emissions testing
  - Control development and optimization
- **High-power density fuel processor development** — **Q2-Q4 2003**
  - Incorporate STAR technology developments
  - New design based on proven HiQ cycle
  - Build on results of new subscale catalyst testing and development
- **Turbo-generator system development** — **Q2-Q4 2003**
  - Joint development program with vendor
  - Testing with proof-of-concept reformer in Q4 2003
- **Construction of HiQ fuel processor** — **Q1 2004**
  - Testing in early 2004
  - Automotive power density targets