Acronyms

A	Amp
AAS	Atomic Adsorption Spectroscopy
ACR	Autothermal Cyclic Reforming
ADVISOR	Advanced Vehicle Simulator
AES	Auger Electron Spectroscopy
AFC	Alkaline Fuel Cell
AFV	Alternative Fuel Vehicle
Ag	Silver
AHC	Ad Hoc Hydrogen Committee
AIAA	American Institute for Aeronautics and Astronautics
Al	Aluminum
Al/Si	Aluminosilicate
Al_2O_3	Aluminum Oxides
AMS	Accelerator Mass Spectrometry
ANL	Argonne National Laboratory
APCI	Air Products and Chemicals, Inc
APU	Auxiliary Power Unit
a-Si	Amorphous Silicon
a-Si:Ge	Amorphous Silicon/Germanium
a-SiC	Amorphous Silicon Carbide
ASNT	The American Society for Nondestructive Testing
ATDC	After Top Dead Center
atm	atmospheres
ATR	Autothermal Reformer
ATR	Auto-Thermal Reformer
Au	Gold
BDI	Boothroyd-Dewhurst, Inc.
BKI	Bevilacqua-Knight, Inc.
bmep	Brake Mean Effective Pressure
BN	Boron Nitride
BPSH	Bi-Phenol Sulfone
BTI	Breakthrough Technology Institute
C	Carbon
^oC	Degrees Celsius
C_2 plus	Hydrocarbon gases containing 2 or more carbon atoms
C_2H_4	Ethylene
CAD	Computer-Aided Drafting
CaFCP	California Fuel Cell Partnership
CaH_2	Calcium Hydride
CAM	Computer Aided Machining
CAM	Computer Aided Manufacture
CAO	Chlorophyll a Oxygenase
CARB	California Air Resources Board
CCD	Charge-Coupled Device
CCM	Catalyst Coated Membrane
CEM	Compressor Expander Module
CEM	Continuous Emissions Monitor
CESI	Catalystic Energy Systems, Inc.
CFD	Computational Fluid Dynamics
CGO	Gadolinium-Doped Ceria
CH_2	Compressed Hydrogen Gas
CH_2-ISS	Compressed Hydrogen Gas Integrated Storage System
CH_4	Methane
CIDI	Compressed Ignition Direct Injection
CIGS	Copper-Indium-Gallium-Diselenide
Chl	Chlorophyll
Cl	Chlorine
CLP	Corner Linked Polyhedral
cm	Centimeters
cm^2	Centimeters Squared
CMC	Carbonxymethylcellulose
CNG	Compressed Natural Gas
CO	Carbon Monoxide
Co	Cobalt
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CODH	Carbon Monoxide Dehydrogenase
Cr	Chromium
CSA	Canadian Standards Association
Cu	Copper
Cu/ZnO	Copper/zinc oxide
CVI	Chemical Vapor Infiltration
CWRU	Case Western Reserve University
DBM	Dibutyl Maleate
dc	Direct Current
DCM	Dichloromethane
DCSF	Diesel Combustion Simulation Facility
DECSE	Diesel Emission Control-Sulfur Effects
DEP®	Double Electrode Plate technology
DFMA	Design for Manufacturing and Assembly
DMAB	Dimethylamine Borane
DMFC	Direct Methanol Fuel Cell
DMI	Diversified Manufacturing Inc.
DOC	Diesel Oxidation Catalyst
DOE	Department of Energy
DPF	Diesel Particulate Filter

DPG	Distributed Power Generation
DSC	Differential Scanning Calorimeter
EC TC 105	International Electrotechnical Committee Technical Committee for Fuel
ECA	Electrochemical Surface Area
ECD	Energy Conversion Devices, Inc.
ECD-1	Emission Control Diesel-1
EDS	Energy Dispersive Spectroscopy
EDX	Electron Dispersive X-Ray
EGR	Exhaust Gas Recirculation
EIHP	European Integrated Hydrogen Project
ELV	End of Life Vehicle
EMC	Electro Magnetic Compatibility
EPAct	Energy Policy Act
ESR	Electron Spin Resonance
EtOH	Ethanol
eV	Electron Volts
EXAFS	Extended X-ray Absorption Fine Structure
^oF	Degrees Fahrenheit
FCC	Face-Centered Cubic
FCPS	Fuel Cell Power System
FCV	Fuel Cell Vehicle
Fe	Iron
FeO_2	Iron Oxide
FET	Field Effect Transistor
FG	Flared Gas
FHDS	Federal Highway Driving Schedule
Fl MH	Fluorinated Metal Hydride
FMEA	Failure Mode and Effects Analysis
FMEA	Failure Mode Evaluation and Analysis
FOS	Factor of Safety
FPS	Fuel Processing System
FreedomCAR	U.S. Department of Energy Automotive Research Partnership
FT	Fischer-Tropsch
FT100	Neat Fischer-Tropsch fuel
FTIR	Fourier Transform Infrared
FTP	Federal Test Procedure
FUDS	Federal Urban Driving Schedule
FY	Fiscal Year
g	Gas Phase
g/s	Gallons per Second
GA	General Atomics
Ga_2S_3	Gallium Sulfide
GeS_2	Germanium Sulfide
GeO_2	Germanium Oxide
GaN	Gallium Nitride
GC	Gas Chromatography
GC/MS	Gas Chromatography/Mass Spectrometry
GCG	Global Corporation Group
GDATP	General Dynamic Armaments and Technical Products
GDL	Gas Diffusion Layer
GE EER	GE Energy and Environmental Research Corporation
GHG	Greenhouse Gas
GHSV	Gas Hourly Space Velocity
GJ	Giga-Joule
GJ/t	Giga Joule per Metric Ton
gm	Gram
GRC	Global Research Center
GREET	Greenhouse gases, Regulated Emissions and Energy Use in Transportation
GTI	Gas Technology Institute
GTR	Global Technical Regulation
GV	Gasoline internal combustion engine Vehicle
h	Hours
H	Hydrogen
h^{-1}	per hour
$(H_2BNH_2)_x$	Polymeric Aminoborane
$(HBNH)_3$	Borazine
$(HBNH)_x$	Polyborazine
$H_2Ge_4S_9$	Dihydrogen Tetragermanium Sulfide
$H_4Ge_4S_{10}$	Tetrahydrogen Tetragermanium Sulfide
$H_4Ge_4S_{10} \cdot nH_2S$	Tetrahydrogen Tetragermanium Sulfide with n Molecules of H_2S
$H_4Ge_4S_{10} \cdot xH_2S$	Tetrahydrogen Tetragermanium Sulfide with x Molecules of H_2S
H_2-O_2	Hydrogen and Oxygen Gas Mixture
H_2	Hydrogen
H_2BNH_2	Monomeric Aminoborane
H_2O	Water
H_2S	Hydrogen Sulfide
H_2SO_4	Sulfuric Acid
H_3BNH_3	Ammonia-Borane Complex
HAD	Hydrogen Adsorption/Desorption
HALT	Highly Accelerated Life Testing
HAZOP	Hazardous Operations
HC	Hydrocarbon
$\Delta H_c°$	Heat of Combustion
HCI	Hydrochloric Acid

HCN	Hydrochloric Cyanide
HCNG	Hydrogen Enriched Natural Gas
hcp	Hexagonal Close Pack
HCSCC	Hydrogen Codes and Standards Coordinating Committee
HDPE	High Density Polyethylene
HEV	Hybrid Electric Vehicle
ΔH_f°	Heat of Formation
HFA	Hydrogen Fueling Appliance
HFSF	High-Flux-Solar Furnace
HGS	Hydrogen Generating System
HHV	Higher Heating Value
H-ICE	Hydrogen- Internal Combustion Engine
HOGEN	Hydrogen Oxygen Generator
HOR	Hydrogen Oxidation Reaction
ΔH_r	Heat of Reaction
HRT	Hydraulic Retention Time
HRTEM	High-Resolution Transmission Electron Microscopy
HTAP	Hydrogen Technical Advisory Panel
HTM	High Temperature Membrane
HTM	Hydrogen Transport Membrane
HTPMWG	High-Temperature Polymer Membrane Working Group
HTS	High Temperature Shift
I^2R	Ohmic Resistances
ICC	International Code Council
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
INEEL	Idaho National Engineering & Environmental Laboratory
IPA	Isopropyl Alcohol
ISO TC 197	International Organization of Standardization Technical Committee for Hydrogen Technologies
ISS	Integrated Storage System
ITM	Ion Transport Membrane
JEVA	Japanese Electric Vehicle Association
JHU/APL	Johns Hopkins University Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
K	Kelvin
K_2O	Potassium Oxide
kg	Kilogram
kj/mole	Kilo Joule
kJ/Mol-kilo	Joule per Mole
km	kilometers
KOH	Potassium Hydroxide
kPa	Kilopascal
Krpm	Thousands of Rotations per Minute
kW	Kilowatt
kWe	Kilowatt Electrical
L	Liter
LANL	Los Alamos National Laboratory
LCHPP	Low Cost Hydrogen Production Platform
LH_2	Cryogenic Liquid Hydrogen
LHV	Lower Heating Value
Li	Lithium
Li_2SO_4	Lithium Sulfate
$LiBH_4$	Lithium Borohydride
LiCl	Lithium Chloride
LiF	Lithium Flouride
LiH	Lithium Hydride
LII	Laser-Induced Incandescence
LME	London Metals Exchange
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas (Propane)
LPM I	Liters Per Minute
LTS	Low Temperature Shift
M	Molar
M $HCIO_4$	Molar Perchloric Acid
m^2Pa sec	Mole per Meter Squared Pascal Second (flux unit)
m^3/hr	Moles per hour cubed
mA	Milliamps
MBMS	Molecular-Beam Mass Spectrometer
MCH	Methylcyclohexane
MDSC	Modulated Differential Scanning Calorimetry
MEA	Membrane Electrode Assembly
MECA	Manufacturers of Emission Controls Association
MEMS	Micro Electro Mechanical Systems
MFC	Mass Flow Controller
Mg	Magnesium
mg	Milligram
MHSS	Metal Hydride Storage System
ML	Monolayer
mm	Millimeter
µm	Microns
MMSCFD	Million Standard Cubic Feet per Day Gas Flowrate
Mn	Manganese
Mo	Molybdenum
MOU	Memorandum of Understanding
MPR	Modular Pressurized Reformer

MSCFD	Thousand Standard Cubic Feet per Day Gas Flowrate
MSHA	Mine Safety and Health Administration
MSW	Municipal Solid Waste
MTS	Medium Temperature Shift
mV	Millivolt
mW	Megawatt
mW/mg	Milliwatts Per Milligram
N	Normal
N_2	Diatomic Nitrogen
NA	North American
NaCl	Sodium Chloride
NaF	Sodium Flouride
NADP	Nicotinamide Adenine Dinucleotide Phosphate
NaH	Sodium Hydride
$NaAlH_4$	Sodium Tetrahydroaluminate
Na_3AlH_6	TriSodium Hexahydroaluminate
Nb	Niobium
NCNR	NIST Center for Neutron Technology
NDIR	Non-Dispersive Infrared
NEDC	New European Drive Cycle
NETL	National Energy Technology Laboratory
NFC	Near Frictionless Carbon
NG	Natural Gas
NGASE	Natural-Gas-Assisted Steam Electrolyzer
NGCC	Natural Gas Combined-Cycle
NH_3	Ammonia
NH_4Cl	Ammonium Chloride
$(NH_4)_2SO_4$	Ammonium Sulfate
NHA	National Hydrogen Association
Ni	Nickel
NIST	National Institute of Standards and Technology
NL	Natural Luminosity
Nm	Nanometer
NMHC	Non-Methane Hydrocarbon
NMOG	Non-Methane Organic Gases
NMR	Nuclear Magnetic Resonance
NNA	Non-North American
NO_x	Nitrogen Oxides
NO_xEI	Nitrogen Oxide Index
NPD	Neutron Powder Diffractometer
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NRL	Naval Research Laboratory
O&M	Operating and Maintenance
O_2	Oxygen Gas or Diatomic Oxygen
OECD	Organization for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
OEP	Octaethyl Porphyrin
ORNL	Oak Ridge National Laboratory
ORR	Oxygen Reduction Reaction
OTM	Oxygen Transport Membrane
P&ID	Piping and Instrumentation Diagram
PADT	Phoenix Analysis and Design Technologies
PAH	Polycyclic Aromatic Hydrocarbon
PCR	Polymerase Chain Reaction
Pd	Palladium
PDF	Pair Distribution Function
PDF	Pair-Density Function
PDU	Process Development Unit
PEC	Photoelectrochemical
PECVD	Plasma-Enhanced Chemical Vapor Disposition
PEM	Polymer Electrolyte Membrane
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PFA	Personal Fuel Appliance
PFCT	Porvair Fuel Cell Technology, Inc.
PFD	Process Flow Diagram
$p\text{-}GaInP_2$	Gallium Indium Phosphide
PGM	Platinum Group Metal
PHA	Personal Hazard Analysis
PM	Particulate Matter
PM	Precious Metal
PMV	Personal Mobility Vehicle
PNNL	Pacific Northwest National Laboratory
POEM	Porous Oxide Electrolyte Membrane
PO_x	Partial Oxidation
POx/SR	Partial Oxidation/Steam Reformer
ppm	Parts per Million
ppmv	Parts per Million Volume
ppmw	Parts per Million Weight
PQ	Plastoquinone
PROX	Preferential Oxidation
PrOx	Preferential Oxidizer
PSA	Pressure Swing Adsorption
PSI	Photosystem I
Psi	Pounds per Square Inch
PSIA	Pounds Per Square Inch Absolute

PSIG	Pounds Per Square Inch Gauge
PSII	Photosystem II
Pt	Platinum
$Pt-FeO_x$	Platinum-iron oxide
PV	Photovoltaic
R&D	Research and Development
RDE	Rotating-Disk Electrode
Re	Rhenium
RFG	Reformulated Gasoline
RH	Relative Humidity
Rh	Rhodium
ROI	Record of Invention
RPECS	Rapid Prototyping Electronic Control System
Ru	Ruthenium
$RuCl_3$	Ruthenium Chloride
Rx	Rubrivivax
s	Solid Phase
S/C	Steam/Carbon
S/cm	Siemens per centimeter
S_2	Sulfur
SAE	Society of Automotive Engineers
scc/hr/l	Standard Cubic Centimeters per Hour per Liter
sccm	Standard Cubic Centimeters per Minute
scfd	Standard Cubic Feet per Day
scfh	Standard Cubic Feet per Hour
scfm	Standard Cubic Feet per Minute
SCORE	Sandia/Caterpillar Optical Research Engine
SCP	Single Cell Protein
SD	Sputter Deposition
SECA	Solid State Energy Conversion Alliance
SEM	Scanning Electron Microscope
SEP	Subscale Engineering Prototype
SESHA	Semiconductor Environmental, Safety, and Health Association
SET	Sustainable Energy Technologies
SF_6	Sulfur Hexafluoride
SFTP	Supplemental Federal Test Procedure
SHE	Standard Hydrogen Electrode
S-HTS	Scrubber-High Temperature Shift
SiC	Silicon Carbide
SINL	Spatially Integrated Natural Luminosity
SiO_2	Silica Dioxide
slpm	Standard Liters per Minute
SMR	Steam Methane Reformer
SO_2	Sulfur Dioxide
SOFC	Solid Oxide Fuel Cell
SR	Steam Reformer
STAR	Substrate based Transportation application Autothermal Reformer
SUV	Sport Utility Vehicle
SWNT	Single Walled Nanotube
SWOP	Supercritical Water Partial Oxidation
SwRI	Southwest Research Institute
t/yr	tonnes/year
Ta	Tantalum
TBD	To Be Determined
TCD	Thermal Conductivity Detector
TCD	Thermocatalytic Decomposition
TCR	Thermocatalytic Reactor
TCR	Total Capital Requirement
TCUF	Thermochemical User's Facility
TEA	Technoeconomic Analysis
TEM	Transmission Electron Microscopy
TEM	Transmission Electron Photomicrograh
TGA-DSC	Thermogravimetric Analyzer-Differential Scanning
TGA-FTIR	Thermogravimetric Analyzer-Fourier Transform Infrared
TGC	Tail Gas Combustor
THC	Total Hydrocarbons
Ti	Titanium
$(TiAl_{0.1}V_{0.04})$	Metal Hydride Alloy
$TiCl_2$	Titanium Dichloride
$TiCl_3$	Titanium Trichloride
TiF_3	Titanium Triflouride
TiO_2	Titanium Dioxide
tla	truncated light-harvesting Chl antenna
TMI	Technology Management, Inc.
TPC	Total Plant Cost
TPGME	Tripropylene Glycol Monomethyl Ether
TPR	Temperature-Programmed Reduction
T-RFLP	Terminal Restriction Fragment Length Polymorphism
TVA	Thermovolumetric analyzer
UH	University of Hawaii
UIC	University of Illinois at Chicago
UTRC	United Technologies Research Center

V	Vanadium
V	Volt
VC	Vulcan carbon, XC-72
VFA	Volatile Fatty Acids
VNT®	Variable Nozzle Turbine
VO_x	Vanadium Oxide
VRA	Vehicle Refueling Appliance
W	Tungsten
W	Watt
WGS	Water-Gas Shift
WHEC	World Hydrogen Energy Conference
WHSV	Weekly Hourly Space Velocity
WO_3	Tungsten Oxide
Wt	Weight
Wt%	Weight Percent
WTW	Well-to-Wheels
XAS	X-ray Absorption Spectroscopy
XPS	X-ray Photoelectron Spectroscopy
XRD	X-ray Diffraction
XRF	X-ray Fluorescense
ZEV	Zero-Emission Vehicle
Zn	Zinc
ZnO	Zinc Oxide
Zr	Zirconium
ZrO_x	Zirconia Dioxide
Ωcm^2	Ohm-centimeter-squared

Appendix A. Draft DOE Technical Targets

Tables 1 through 3 list the DOE technical targets for PEM fuel cell stack systems, fuel-flexible fuel processors, and integrated fuel cell power systems operating on gasoline. Target values listed in these tables represent a self-consistent set and must be achieved simultaneously. Targets for 2010 are R&D milestones for the purpose of measuring progress, not necessarily the targets required for successful commercialization of the technology. Table 4 lists the DOE technical targets for integrated fuel cell power systems running on direct hydrogen. Table 5 shows the technical targets for on-board hydrogen storage, and Table 6 lists the technical targets for off-board hydrogen production and dispensing infrastructure. Tables 7 through 10 list technical targets for fuel cell stack and fuel processor components. All targets were developed with industry through preliminary vehicle system analyses and will be refined further as the technology matures and power system trade-offs are identified. Targets for hydrocarbon-based systems are based on operation with reformulated gasoline containing an average of 30 ppm sulfur (80 ppm maximum); except for the hydrogen storage targets in Table 5, all power target values indicate electric power (We).

Targets are reviewed on an annual basis and updated as necessary based on new information.

Table 1. Technical targets: fuel cell stack systems operating on hydrogen-containing fuel from a fuel processor (gasoline reformate) in 50 kWe (net) fuel cell systems

(Excludes fuel processing/delivery system)
(Includes fuel cell ancillaries: thermal, water, air management systems)
All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2001 status	2005	2010
Stack system power density[a, b]	W/L	200	400	550
Stack system specific power	W/kg	200	400	550
Stack system efficiency[c] @ 25% of rated power	%	45	50	55
Stack system efficiency[c] @ rated power	%	40	42	44
Precious metal loading[d]	g/rated kW	2.0	0.6	0.2
Cost[e]	$/kW	200	100	35
Durability[f]	hours	1000[g]	>2000[h]	>5000[i]
Transient response (time for 10% to 90% of rated power)	sec	3	2	1
Cold start-up time to rated power @ –20°C ambient temperature @ +20°C ambient temperature	 min min	 2 1	 1 0.5	 0.5 0.25
Survivability[j]	°C	–20	–30	–40
CO tolerance[k] steady state (with 2% maximum air bleed) transient	 ppm ppm	 50 100	 500 500	 500 1000

[a]Power refers to net power (i.e., stack power minus auxiliary power requirements).

[b]Volume is "box" volume, including dead space, and is defined as the water-displaced volume times 1.5 (packaging factor). Power density includes ancillaries (sensors, controllers, electronics, radiator, compressor, expander, and air, thermal and water management) for stand alone operation.

[c]Ratio of output DC energy to lower heating value of hydrogen-rich fuel stream (includes converter for 300 V bus); ratio of rated power to 25% of rated power efficiencies unchanged, assuming continued proportional reduction in stack efficiency at higher current and proportional increase in compressor efficiency at higher flow rates.

[d]Equivalent total precious metal loading (anode+cathode): 0.1 mg/cm^2 by 2010 at rated power. Precious metal target based on cost target of <$3/kW precious metals in MEA [@$450/troy ounce ($15/g), <0.2 g/kW]

[e]High-volume production: 500,000 units per year.

[f]Performance targets must be achieved at the conclusion of the durability period; durability includes tolerance to CO, H_2S and NH_3 impurities.

[g]Continuous operation (pertains to full power spectrum).

[h]Includes thermal cycling.

[i]Includes thermal and realistic driving cycles.

[j]Performance targets must be achieved at the end of 8-hour cold-soak at temperature.

[k]CO tolerance requirements assume capability of fuel processor to reduce CO. Targets for the stack CO tolerance are subject to trade-offs between reducing CO in the fuel processor and enhancing CO tolerance in the stack. It is assumed that H_2S is removed in the fuel processor.

Table 2. Technical targets: fuel processors[a] to generate hydrogen-containing fuel gas from reformulated gasoline containing 30 ppm sulfur, average, for 50 kWe (net) fuel cell systems

(Excludes fuel storage; includes controls, shift reactors, CO cleanup, heat exchangers)
All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2001 status[b]	2005	2010
Energy efficiency[c]	%	78	78	80
Power density	W/L	500	700	800
Specific power	W/kg	450	700	800
Cost[d]	$/kW	85	25	10
Cold start-up time to maximum power				
@ –20°C ambient temperature	min	TBD	2.0	1.0
@+20°C ambient temperature	min	<10	<1	<0.5
Transient response (time for 10% to 90% power)	sec	15	5	1
Emissions[e]		<Tier 2 Bin 5	<Tier 2 Bin 5	<Tier 2 Bin 5
Durability[f]	hours	1000[g]	4000[h]	5000[i]
Survivability[j]	°C	TBD	–30	–40
CO content in product stream[k]				
steady state	ppm	10	10	10
transient	ppm	100	100	100
H_2S content in product stream	ppb	<200	<50	<10
NH_3 content in product stream	ppm	<10	<0.5	<0.1

[a]With catalyst system suitable for use in vehicles.
[b]Projected status for system to be delivered in late 2002: 80% efficiency, 900 W/L, 550 W/kg.
[c]Fuel processor efficiency = total fuel cell system efficiency/fuel cell stack system efficiency, where total fuel cell system efficiency accounts for thermal integration. For purposes of testing fuel-processor-only systems, the efficiency can be estimated by measuring the derated heating value efficiency (lower heating value of $H_2 \times 0.95$/ lower heating value of the fuel in) where the derating factor represents parasitic system power losses attributable to the fuel processor.
[d]High-volume production: 500,000 units per year.
[e]0.07 g/mile NO_x and 0.01 g/mile PM (particulate matter).
[f]Time between catalyst and major component replacement; performance targets must be achieved at the end of the durability period.
[g]Continuous operation.
[h]Includes thermal cycling.
[i]Includes thermal and realistic driving cycles.
[j]Performance targets must be achieved at the end of an 8-hour cold-soak at specified temperature.
[k]Dependent on stack development (CO tolerance) progress.

Table 3. Technical targets: 50 kWe (net) integrated fuel cell power systems operating on Tier 2 gasoline containing 30 ppm sulfur, average

(Including fuel processor, stack, auxiliaries)
(Excluding gasoline tank and vehicle traction electronics)
All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2001 status	2005	2010
Energy efficiency[a] @ 25% of rated power	%	34	40	45
Energy efficiency @ rated power	%	31	33	35
Power density	W/L	140	250	325
Specific power	W/kg	140	250	325
Cost[b]	$/kW	300	125	45
Transient response (time from 10 to 90% power)	sec	15	5	1
Cold start-up time to rated power @ –20°C ambient temperature @+20°C ambient temperature	 min min	 TBD <10	 2 1	 1 <0.5
Survivability[c]	°C	TBD	–30	–40
Emissions[d]		<Tier 2 Bin 5[e]	<Tier 2 Bin 5[e]	<Tier 2 Bin 5[e]
Durability[f]	hours	1000[g]	2000[h]	5000[i]
Greenhouse Gases	One-third reduction compared with conventional SI-IC engines in similar type vehicles			

[a]Ratio of dc output energy to the lower heating value of the input fuel (gasoline).
[b]Includes projected cost advantage of high-volume production (500,000 units per year) and includes cost for assembling/integrating the fuel cell system and fuel processor.
[c]Achieve performance targets at 8-hour cold-soak at temperature.
[d]Emissions levels will comply with emissions regulations projected to be in place when the technology is available for market introduction.
[e]0.07 NO_x g/mile and 0.01 PM g/mile.
[f]Performance targets must be achieved at the end of the durability time period.
[g]Continuous operation.
[h]Includes thermal cycling.
[i]Includes thermal and realistic drive cycles.

Table 4. Technical targets: 50 kWe (net) integrated fuel cell power systems operating on direct hydrogen[a]

All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2001 status	2005	2010
Energy efficiency[b] @ 25% of rated power	%	59	60	60
Energy efficiency @ rated power	%	50	50	50
Power density excluding H_2 storage including H_2 storage	 W/L W/L	 400 TBD	 500 150	 650 220
Specific power excluding H_2 storage including H_2 storage	 W/kg W/kg	 400 TBD	 500 250	 650 325
Cost[c] (including H_2 storage)	$/kW	200	125	45
Transient response (time from 10% to 90% of rated power)	sec	3	2	1
Cold start-up time to maximum power @ –20°C ambient temperature @+20°C ambient temperature	 sec sec	 120 60	 60 30	 30 15
Emissions		Zero	Zero	Zero
Durability[d]	hours	1000	2000[e]	5000[f]
Survivability[g]	°C	-20	–30	–40

[a]Targets are based on hydrogen storage targets in an aerodynamic 2500-lb vehicle.
[b]Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).
[c]Includes projected cost advantage of high-volume production (500,000 units per year).
[d]Performance targets must be achieved at the end of the durability time period.
[e]Includes thermal cycling.
[f]Includes thermal and realistic drive cycles.
[g]Achieve performance targets at 8-hour cold-soak at temperature.

Table 5. Technical targets for on-board hydrogen storage[a,b] subsystem

Characteristic	Units	Target	2001 Status Physical storage[c]	2001 Status Chemical storage[d]
Storage capacity[e]	wt%	6	5.2	3.4
Recoverable usable amount[f]	%	90	99.7	>90
Energy density[g]	Wh/L[h]	1100[h]	813	1300
Specific energy[i]	Wh/kg[h]	2000	1745	1080
Cost[j]	$/kWh	5	50[k]	18[l]
Cycle life	cycles	500	>500	20-50
Operating temperature[m]	°C	–40° to +50°C	–40° to +50°C	20°C to 50°C
Start-up time to full flow @+20°C @-20°C	 sec sec	 15 30	 <1 TBD	 <15 TBD
Refueling time	min	<5	TBD	TBD
Hydrogen loss	scc/hour/L	<1.0	<1.0	<1.0

[a]Based on lower heating value of hydrogen; includes both physical and chemical methods of hydrogen storage; enables greater than 300-mile range, based on an aerodynamic, 2500-lb vehicle.
[b]R&D carried out in collaboration with DOE Hydrogen Program.
[c]Includes compressed gas and cryogenic liquid tanks.
[d]Projected from laboratory-scale (100 g) test beds and proposed system designs.
[e]Weight percent H_2 is the weight of H_2 divided by the weight of (H_2 + tank).
[f]Recoverable stored hydrogen, e.g. in a 100-kg H_2 storage system containing 6 kg of stored hydrogen, at least 5.4 kg of useful hydrogen must be recoverable.
[g]Based on 5 kg hydrogen for >300 mile range at 10,000 psia (volume of stored hydrogen is 135 L). Allowing for 10% containment volume, system volume is 150 L..
[h]Watts thermal.
[i]Specific energy is the lower heating value energy of H_2 contained, divided by the weight of (H_2 + tank) .
[j]Based on high-volume production of 500,000 units per year.
[k]Based on individual tanks.
[l]Projected hydride material cost only; based on 100-200 kg alanate production.
[m]Hydrogen storage system must provide hydrogen to the fuel cell at these ambient temperatures.

Table 6. Technical targets for off-board hydrogen production and dispensing infrastructure

Component	Characteristic (LHV Basis)	Units	Current Status[a]	2005	2010
Reforming	Cost	$/GJ H_2	9.9	8.8	7.7[b]
	WTW GHGs	g/km	75	70	65
	Primary Energy Eff.	% (LHV)	80[c]	82	85
Purification	Cost	$/GJ H_2	0.56	0.56	0.56[d]
	WTW GHGs[e]	g/km	1.1	1.1	1.1
	Primary Energy Eff.	% (LHV)	75[f]	82	90
Compression	Cost	$/GJ H_2	2.6	2.3	2.0[g]
	WTW GHGs	g/km	14	11	8
	Primary Energy Eff.	% (LHV)	82[h]	85	88
Storage & Dispensing	Cost	$/GJ H_2	2.7[i]	2.7	2.7[j]
	WTW GHGs	g/km	0	0	0
	Primary Energy Eff.	% (LHV)	100[k]	100	100
Total	Cost[l]	$/GJ H_2	19.2	17.2	16.2[m]
	WTW GHGs	g/km	90	82	75
	Primary Energy Eff.	% (LHV)	62	68	75

Notes: Well-to-wheel greenhouse gas (WTW GHG) emissions are weighted by their global warming potential. Assumes 84-mpeg fuel economy in a direct hydrogen FCV and on-site power from the US average grid mix. Primary energy efficiency is defined as Hydrogen Output LHV / Primary Energy Input LHV of the process step. Primary energy associated with on-site power use assumes a 35% production and transmission efficiency penalty (typical US grid mix).

[a] Assumes state-of-the-art technology that is feasible but not necessarily available in a complete system today. This assumption is consistent with the automotive fuel cell performance target assumptions.

[B] Assumes energy cost reductions by way of higher efficiency and a 50% equipment cost reduction from the current scenario. Small-scale reformers are assumed to come down significantly in price with projected advances in materials and designs.

[C] Assuming a steam methane reformer operating at 10 atm.

[D] Assumes no equipment cost reduction from the current scenario. Conventional equipment (PSAs) will not likely come down significantly in price, especially with higher efficiency requirements. Advanced technologies may provide higher efficiencies, but are unlikely to be cheaper.

[E] Assumes 100% of the purification purge stream (primarily CO2, H2, CH4, and CO) is recycled to the production step, where the purge stream is burned to generate heat for the reforming process. There may be some additional purification emissions in other system configurations, but the total sum of emissions from the production and purification steps will remain the same.

[F] Assuming a small-scale PSA system operating at reformer outlet pressure.

[G] Assumes energy cost reductions by way of higher efficiency but no equipment cost reduction from the current scenario. Conventional equipment (gas compressors) will not likely come down significantly in price, especially with higher efficiency requirements. Advanced technologies may provide higher efficiencies, but are unlikely to be cheaper.

[H] Assuming conventional compressors are used from the PSA outlet pressure to 3600-psi maximum on-site storage pressure and accumulator-type compressors are used from the storage pressure to 5000 psi on-board storage.

[I] Based on 3600-psi on-site gas storage.

[J] Assumes no equipment cost reduction from the current scenario. Conventional equipment (high-pressure gas storage tanks) will not likely come down significantly in price. Advanced technologies may provide higher overall efficiencies, but are unlikely to be cheaper.

[K] Assuming high-pressure gas storage with no leaks during storage or dispensing.

[L] Includes operation, site prep, and central control costs.

[M] Costs are based on a hydrogen fueling station serving 300 vehicles per day (~10,000 std m3 per day) with on-site production. Capital equipment costs assume mature production volumes of 100 units per year. Production volumes of 100 units/year were also studied by DTI with analgous economic predictions. Production volumes of 10,000 units per year will reduce capital costs substantially to $13/GJ (See "Integrated Vehicle Analysis" DTI, 1998). Energy costs assume a natural gas price of $5/GJ (HHV) and power price of $0.07/kWh.

Table 7. Technical targets for fuel cell stack components

Component	Requirement
Membranes	Cost: \$5/kW Stability: <2 mV w/RH 20–100% , <10% swelling H_2 crossover: <1 mA/cm^2 O_2 crossover: <3 mA/cm^2 Area specific resistance: 0.1 ohm-cm^2
Electrodes	Cost: \$5/kW CO tolerance: 500 ppm steady state, 1000 ppm transient with 0.2 g Pt/rated kW Durability: 5000 hours Utilization: 85% H_2, 60% O_2
Membrane-Electrode Assembly	Performance: On hydrogen 400 mA/cm^2 at 0.80 V (at rated power) 100 mA/cm^2 at 0.85 V (at quarter power) On gasoline reformate 500 mA/cm^2 at 0.75 V (at rated power, 30 psig) 125 mA/cm^2 at 0.83 V (at quarter power, 9 psig) Cost: \$10/kW
Bipolar Plates	Cost: \$10/kW; <1kg/kW H_2 permeation rate: <2 $\times$ 10^{-6} cm^3 sec^{-1} cm^{-2} @ 80°C, 3 atm (Equivalent to <0.1 mA/cm^2) Corrosion limit: <16 microamps/cm^2 Resistivity: 0.02 ohm/cm^2

Table 8. Technical targets for sensors for automotive fuel cell systems[a]	
Sensor	Requirements
Carbon Monoxide	(a) 1–100 ppm reformate pre-stack sensor • Operational temperature: <150°C • Response time: 0.1–1 sec • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure • Accuracy: 1–10% full scale (b) 100–1000 ppm CO sensors • Operational temperature: 250 °C • Response time: 0.1–1 sec • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure • Accuracy: 1–10% full scale (c) 0.1–2% CO sensor 250–800°C • Operational temperature: 250–800°C. • Response time: 0.1–1 sec • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure • Accuracy: 1–10% full scale
Hydrogen in fuel processor output	• Measurement range: 1–100% • Operating temperature: 70–150°C • Response time: 0.1–1 sec for 90% response to step change • Gas environment: 1–3 atm total pressure, 10–30 mol % water, 30–75% total H_2 , CO_2, N_2 • Accuracy: 1–10% full scale
Hydrogen in ambient air (safety sensor)	• Measurement range: 0.1–10% • Temperature range: –30 to 80°C • Response time: under 1 sec • Accuracy: 5% • Gas environment: ambient air, 10–98% RH range • Lifetime: 5 years • Interference resistant (e.g., hydrocarbons)
Sulfur compounds (H_2S, SO_2, organic sulfur)	• Operating temperature: up to 400°C • Measurement range: 0.05–0.5 ppm • Response time: <1 min at 0.05 ppm • Gas environment: Hydrogen, CO, CO_2, hydrocarbons, water vapor
Flow rate of fuel processor output	• Flow rate range: 30–300 standard L/min • Temperature: 80°C • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure
Ammonia	• Operating temperature: 70–150°C • Measurement range: 1–10 ppm • Selectivity: <1 ppm from matrix gases • Lifetime: 5–10 years • Response time: seconds • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure

Table 8. Technical targets for sensors for automotive fuel cell systems[a]	
Sensor	Requirements
Temperature	• Operating range: –40 to 150°C • Response time: in the –40 to 100°C range <O.5 sec with 1.5% accuracy; in the 100–150°C range, a response time <1 sec with 2% accuracy • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure • Insensitive to flow velocity
Relative humidity for cathode and anode gas streams	• Operating temperature: 30–110°C • Relative humidity: 20–100% • Accuracy: 1% • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm
Oxygen in fuel processor and at cathode exit	(a) Oxygen sensors for fuel processor reactor control • Operating temperature: 200–800°C • Measurement range: 0–20% O_2 • Response time: <0.5 sec • Accuracy: 2% of full scale • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm (b) Oxygen sensors at the cathode exit • Measurement range: 0–50% O_2 • Operating temperature: 30–110°C • Response time: <0.5 sec • Accuracy: 1% of full scale • Gas environment: H_2, CO_2, N_2, H_2O at 1–3 atm total pressure
Differential pressure in fuel cell stack	• Range: 0–1 psi or (0–10 or 1–3 psi, depending on the design of the fuel cell system) • Temperature range: 30–100°C • Survivability: –40°C • Response time: <1 sec • Accuracy: 1% of full scale • Size: $\leq$1 in^2, usable in any orientation • Other: Withstand and measure liquid and gas phases

[a]Sensors must conform to size, weight, and cost constraints of automotive applications.

Table 9. Technical targets for compressor/expander (C/E) units for automotive fuel cell systems[a]

Characteristic	Units	Target
Input power[b] at full flow	kW	4.3
Efficiency at full flow Compressor (at 3.2 pressure ratio)[c] Expander	 % %	 75 90
Efficiency @ 20% of full flow Compressor (at 1.6 pressure ratio)[c] Expander	 % %	 65 80
Volume[d]	L	4
Weight[d]	kg	3
Cost[d,e]	$	200
Turndown ratio		10
Noise	db	<80

[a]Targets are being reviewed as a result of the Compressor Peer Review.

[b]Input power to the controller to power a compressor/expander system producing 76 g/sec (dry) maximum flow. This flow rate roughly corresponds to maximum power for a 50-kW fuel cell system. A 25% flow is 19 g/sec. Expander inlet conditions are assumed to be: 82 g/sec, 150°C, and 2.8 atm (at full flow).

[c]The pressure ratio is allowed to float as a function of load on the fuel cell system (i.e., as a function of the flow through the compressor/expander unit).

[d]Weight, volume, and cost do not include the motor/controller or heat rejection (if required).

[e]Cost target based on a manufacturing volume of 100,000 units per year.

Table 10. Technical targets for fuel processor catalysts and reactors (for reforming Tier II gasoline containing 30 ppm Sulfur)[a]

Characteristic	Units	Autothermal reformer	Sulfur removal	Water gas shift	CO preferential oxidation
GHSV[b]	per hour	200,000	50,000	30,000	150,000
Conversion[c]	%	>99.9	>99.95	>90	>99.8
H2 selectivity[d] (or consumption)	%	>80	<0.1	>99	<0.2
Volume[e]	L/kWe	<0.013	<0.06	<0.1	<0.02
Weight[e]	kg/kWe	<0.015	<0.06	<0.1	<0.03
Durability[f]	hours	5000	5000	5000	5000
Cost	$/kWe	<5	<1	<1	<1

[a]GHSV (gas hourly space velocity) = the volumetric flow rate of the product gases reduced to 25°C and 1 atm, divided by the bulk volume of the catalyst.
[b]Target values are guidelines for single reactor R&D; system/subsystem targets take precedence.
[c]Conversion: (moles of reactant in – moles of reactant out) × 100/(moles of reactant in).
[d]Selectivity: At the autothermal reformer: (moles of H_2 in product) × 100/(moles of H_2 “extractable” from the reformer feed); at the shift reactor: (moles CO converted to H_2) × 100/(total moles of CO converted).
[e]The volume and weight targets include only the catalysts, not the hardware needed to house the catalysts or any heat exchangers.
[f]Over standard driving cycles.

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