High-Temperature Materials Needs for Power Generation

Ian G. Wright

Oak Ridge National Laboratory

Oak Ridge, Tennessee

Molybdenum Boro-silicide Workshop

Annapolis, Maryland, March 11-12, 2003

Major Drivers for Materials Development for Power Generation

Industry (gas turbines; advanced steam cycles)

EPRI

Office of Fossil Energy, US DOE

Office of Energy Efficiency, US DOE

Office of Nuclear Energy, US DOE

Power Generation Roadmaps

- **Vision 21** is aimed at effectively eliminating (at competitive costs) environmental concerns associated with the use of fossil fuels for producing electricity and transportation fuels. The approach is to develop technology modules that address specific functions required in an energy or fuels production plant (e.g. gasification; power generation modules); these are to be ready in the 2005-2015 timeframe.

- **Clean Coal Technology Roadmap** is a discussion document aimed at integrating the coal programs of DOE, EPRI, and the Coal Utilization Research Council (CURC). Its destinations involve major aiming points of 2010 and 2020 for advanced gasification and combustion cycles.

- **FutureGen** is a new initiative aimed at demonstrating Vision 21-type technologies, specifically for production of hydrogen, removal of air pollutants, and capture and sequestration of carbon. The demonstration plant is a 275 MWe-size unit, and will be ready for initial operation in the 2008-2010 timeframe.

Vision 21 *Performance Targets*

Capital & Operating Costs/RAM

Vision 21 must be competitive with other energy systems with comparable environmental performance

Emissions

- < 4.3 g/GJ SO_2 and NO_x
- < 2.2 g/GJ PM
- < 1/2 organic compounds in *Utility HAPS Report*
- < 0.4 mg/GJ Hg
- zero CO_2 option

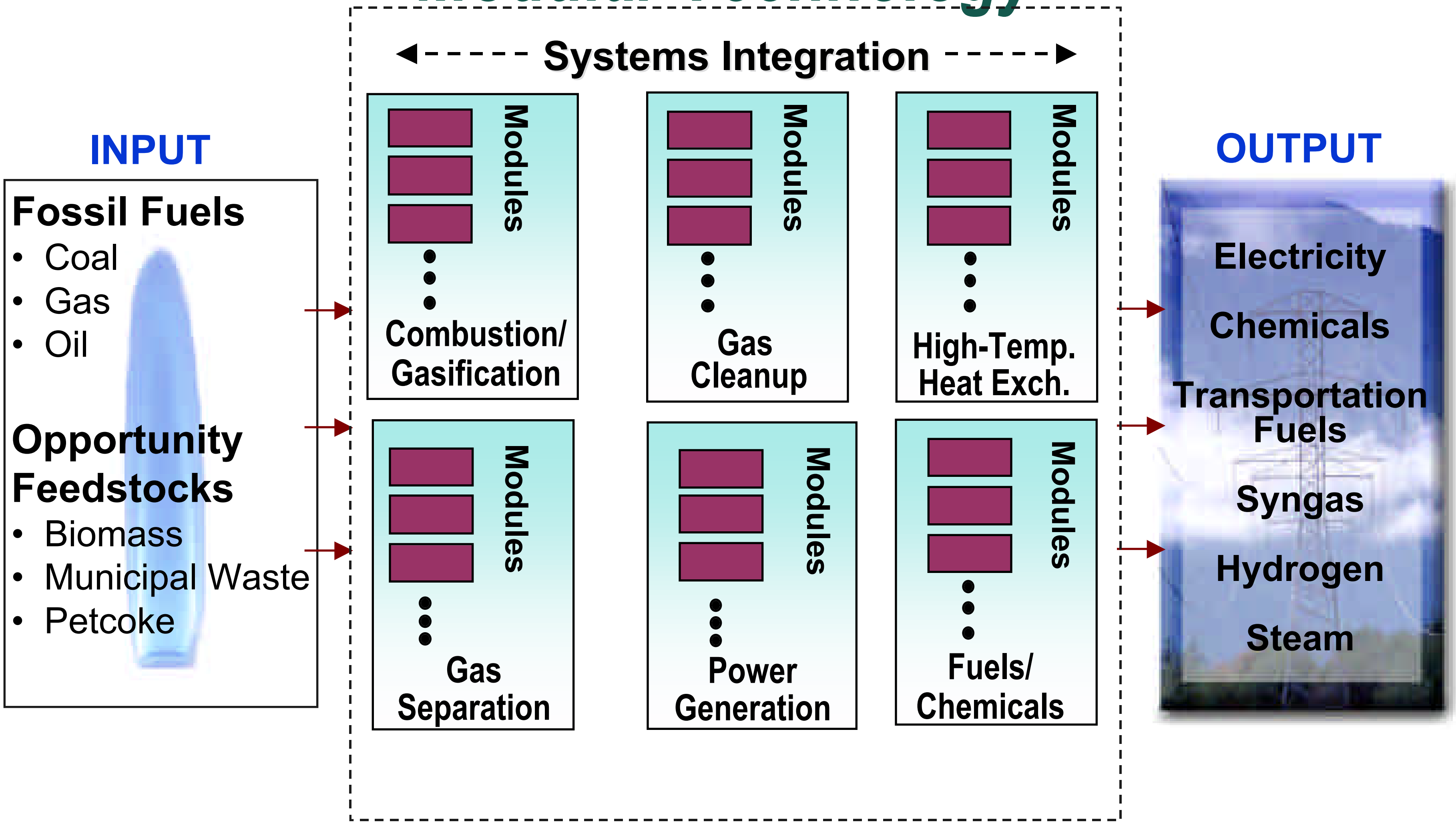
Efficiency

- Electricity generation
  - coal-based 60% (HHV)
  - gas-based 75% (LHV)
- Fuels-only plants 75%

Schedule of Benefits

- Technology spin-offs by 2005
- Designs for modules by 2012
- Commercial plant designs by 2015

VISION 21
Modular Technology

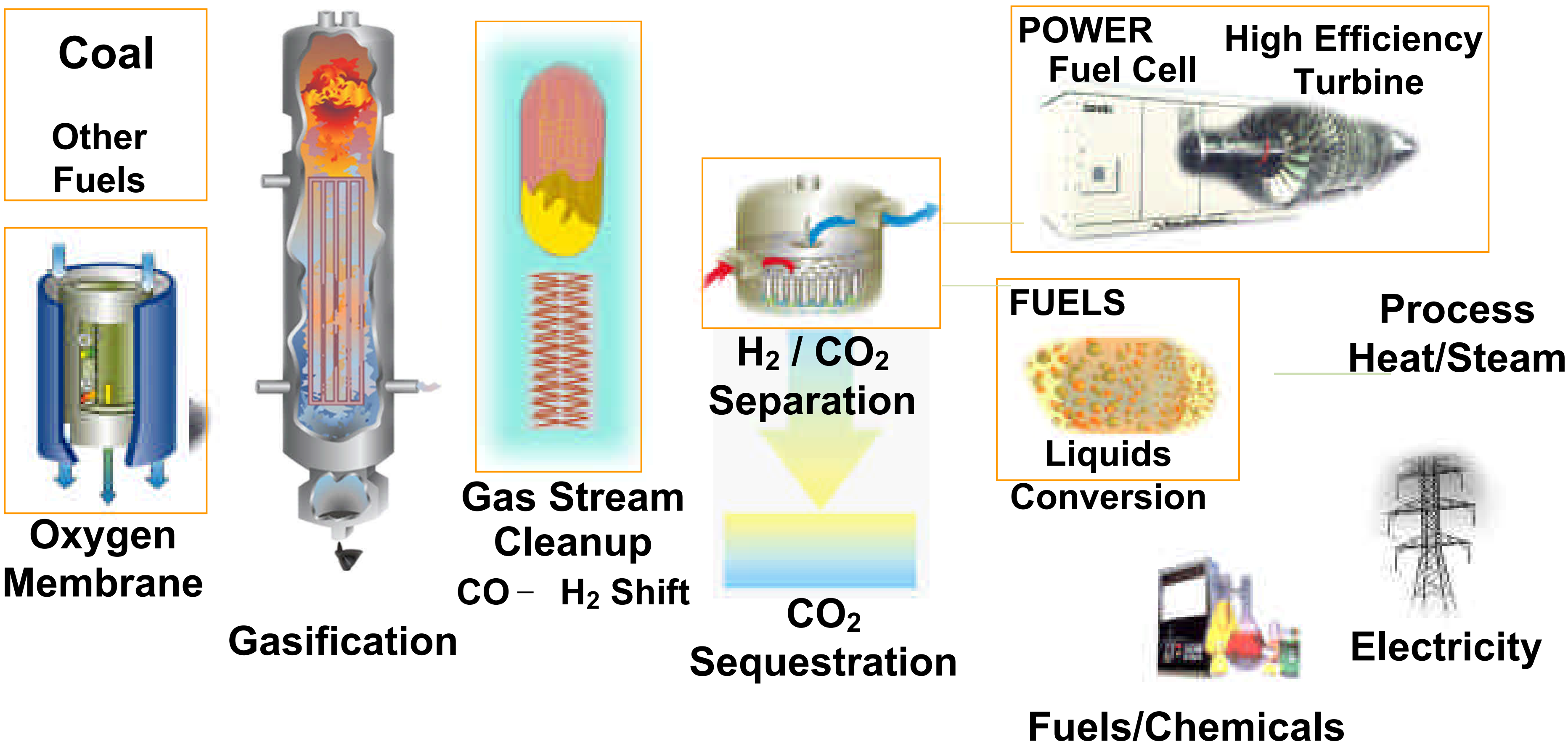


Future power plants will be different from today's plants

- Gasification will be more common
  - Gas turbines, fuel cells, catalysts are likely to be important components
  - Carbon management will be a major issue

- Higher temperatures   increased potential for materials degradation
  - Functional materials: -refractory linings
    - -gas cleaning systems (filters)
    - -gas separation membranes
  - Structural materials: -piping; heat exchangers (gas-gas; boiler tubes)
  - Specific components: -turbine airfoils; casings; bolting

VISION 21 *Modular Energy Plant*



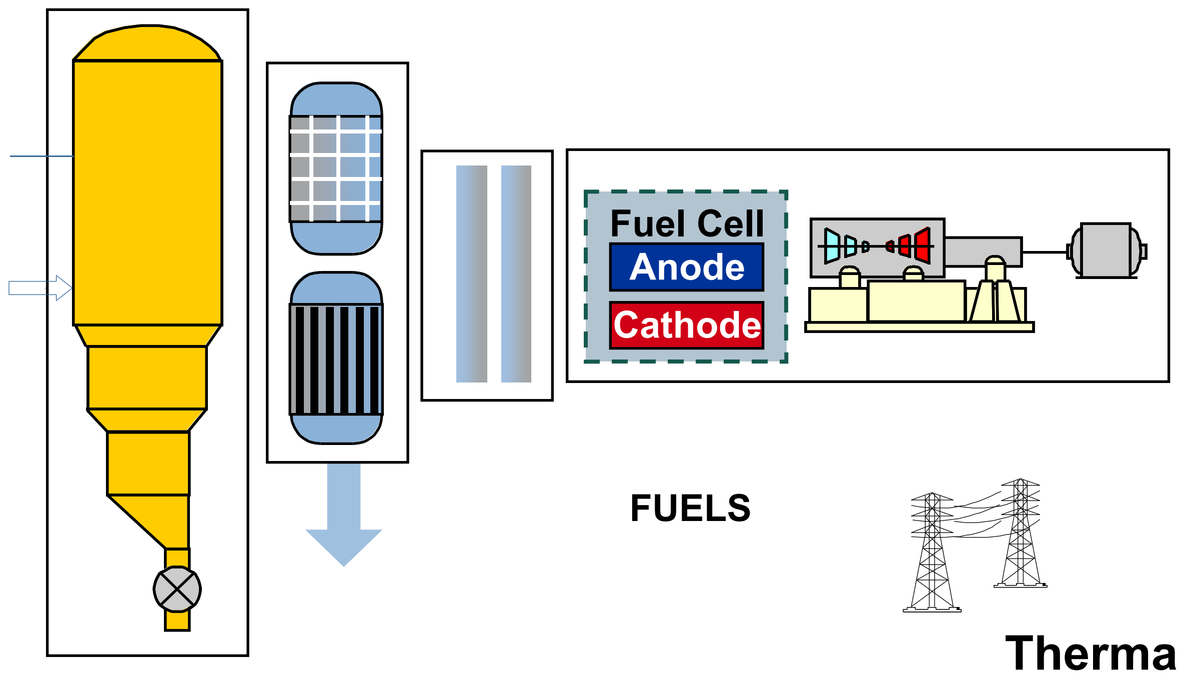
Vision 21 *Materials Issues*

Gas Stream Cleanup Devices

Hydrogen Separation Membranes

Fuel Cell Components

Sensors and Controls

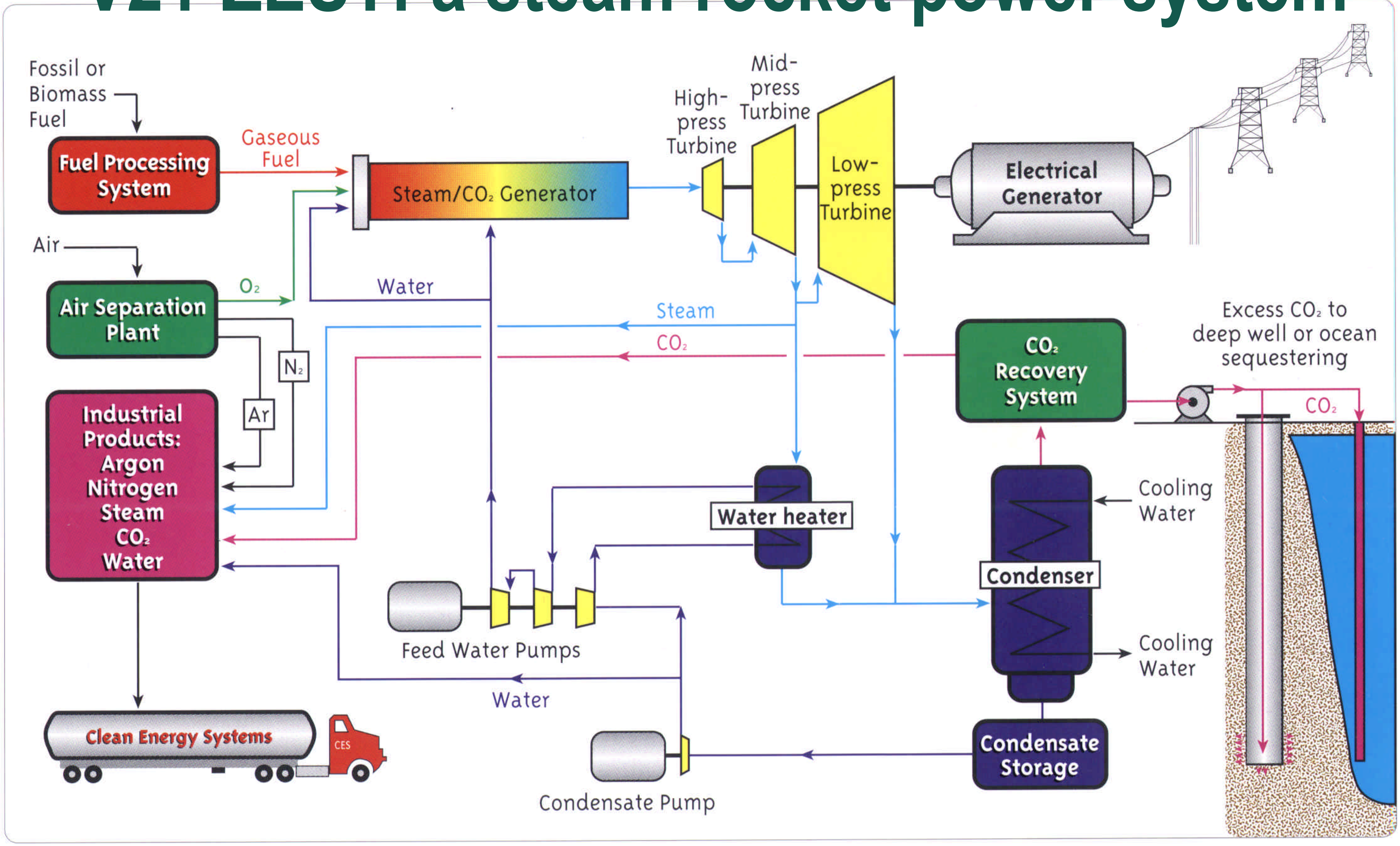


Oxygen Separation Membranes

Improved Refractories for Gasifiers

Thermal Barrier Coatings for Turbines

V21-ZEST: a steam rocket power system

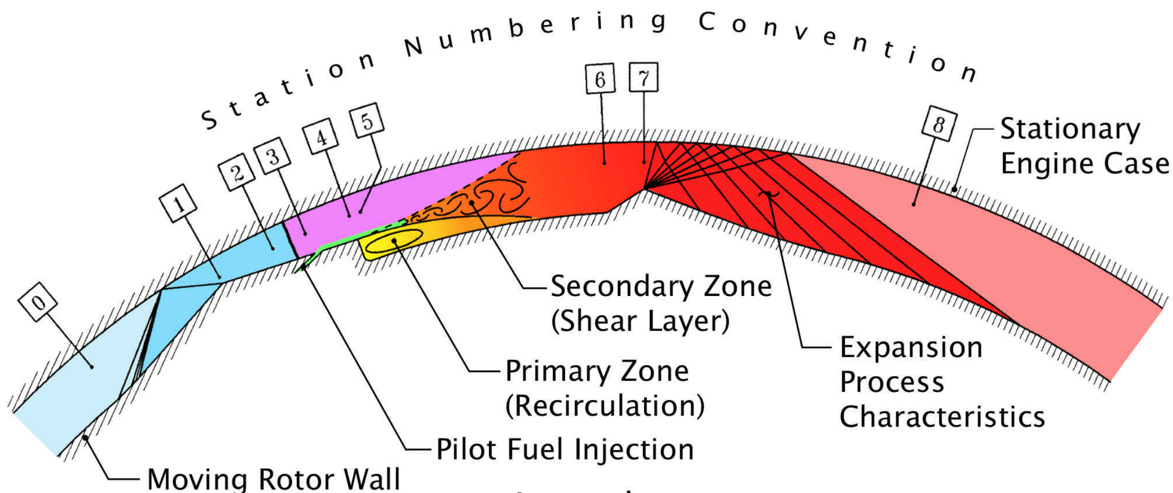


ZEST presents unprecedented materials challenges

• Steam generator:	Phase I:	1050°F/1200 psi steam/CO_2
	Near-term:	1600°F/1200 psi
	Long-Term:	3200°F/3200 psi
• Cool-down modules:	Inlet:	3200°F/3200psi
	Outlet:	1050°F/1200 psi
• Turbine (Phase I):	HP stage	1050°F/1200 psi
	IP stage:	2200°F/140 psi
	LP stage:	1200°F/14.7 psi

V21: Ramgen

- Based on supersonic shockwave compression technology
- Engine design with compressor, combustor and nozzle ‘modules’ on the rim of a disc rotating at supersonic speeds
- Practical design features, such as sealing, appear to be more pressing than materials capabilities



Legend

Station 0 - Inlet Flow
Station 1 – Post Oblique Shock
Station 2 – Pre Normal Shock
Station 3 – Post Normal Shock
Station 4 – Complete Subsonic Expansion
Station 5 – Combustor Inflow
Station 6 – Post Combustion
Station 7 – Nozzle Throat
Station 8 – Complete Expansion

DOE-EPRI-CURC Integrated Clean Coal Technology Roadmap

- Supports all the relevant initiatives: Clear Skies; Clean Coal Power; Climate Change; Homeland Security
- Destinations are based on current DOE and industry performance and cost targets (CURC, EPRI, DOE product lines)

	Current	2010	2020
Efficiency (HHV)	40	45-50	50-60
Availability (%)	>80	>85	≥90
Capital ($/kW)	1,000-3,000	900-1,000	800-900
CoE (¢/kWh)	3.5	3.0-3.2	<3.0

DOE-EPRI-CURC Roadmap
Materials Implications

- **Advanced combustion systems**
  - ultra-supercritical steam conditions:
    - 1250°F steam by 2010
    - 1400°F steam by 2020
  - oxygen-coal combustion
  - improved combustion sensors and controls
- **Advanced gasification systems**
  - improvements in gas separation: air; CO_2; H_2
  - fuel flexibility: pressurized feeding systems
  - improved gasifier availability: sensors and controls
  - gas cleaning under oxidizing and reducing conditions
  - syngas combustion in advanced gas turbines
  - hydrogen-fueled gas turbine
  - 100MWe fuel cell systems

Distributed Power

Micro-to-small gas turbines

- Recuperators are essential to achieve acceptable efficiencies
  - need to push recuperator operating temperatures > 1150°F
  - current alloys (type 347) inadequate
  - how to achieve creep strength and oxidation lifetime in thin foil sections?
  - cost is an important consideration
- Push for insertion of ceramic components:
  - silicon-containing CMC liners need coatings for environmental protection (H_2O)
  - ceramic airfoils have the usual problems

Fuel cells

- Issues:
  - metallic interconnectors (SOFC; MCFC)
  - manufacturing of electrodes, interconnectors, packaging

Generation IV Nuclear Power Options

- Supercritical steam (930°F)
  - double the steam circuit temperature of current nuclear plants
  - expect to use fossil experience…
- VHT gas-cooled reactor (1832°F)
  - He coolant
  - piping, heat exchanger, and expander turbine applications
  - some experience for piping alloys at lower temperatures
    - can a protective scale be formed and maintained?

Major HT Materials Needs for Power Generation Applications

- Turbines
  - Combustors: >3000°F (ODS alloys; CMCs)
  - Combustion turbines: >2700°F RIT (SC airfoils; TBCs; next generation materials)
  - Steam turbines: >1400°F; ZEST≈3200°F
  - VHTR turbines: He at 1832°F
- Piping, Heat Exchangers
  - USC steam cycles: >1150°F (ferritic steels?)
>1400°F (Ni-base alloys >15 ksi/100,000h)
  - V21 applications: >1650°F (ODS alloys; ceramics; where next?)
- Sensors
  - Flames/high heat flux applications: need breakthroughs
  - Molten slags; molten salts

Ongoing materials research in the DOE-ARM program is focused in four main areas:

- **Functional materials**
  - alloys & ceramics for gas filtration and separation; fuel cells; catalysts
- **New alloys**
  - extend high-temperature strength & environmental resistance of alloys for specific components
  - materials for increased steam cycle efficiency
- **Coatings**
  - corrosion protection for underlying structural components
- **Breakthrough materials technologies**
  - alloys & ceramics for severe service
  - ultra-high performance materials: future directions

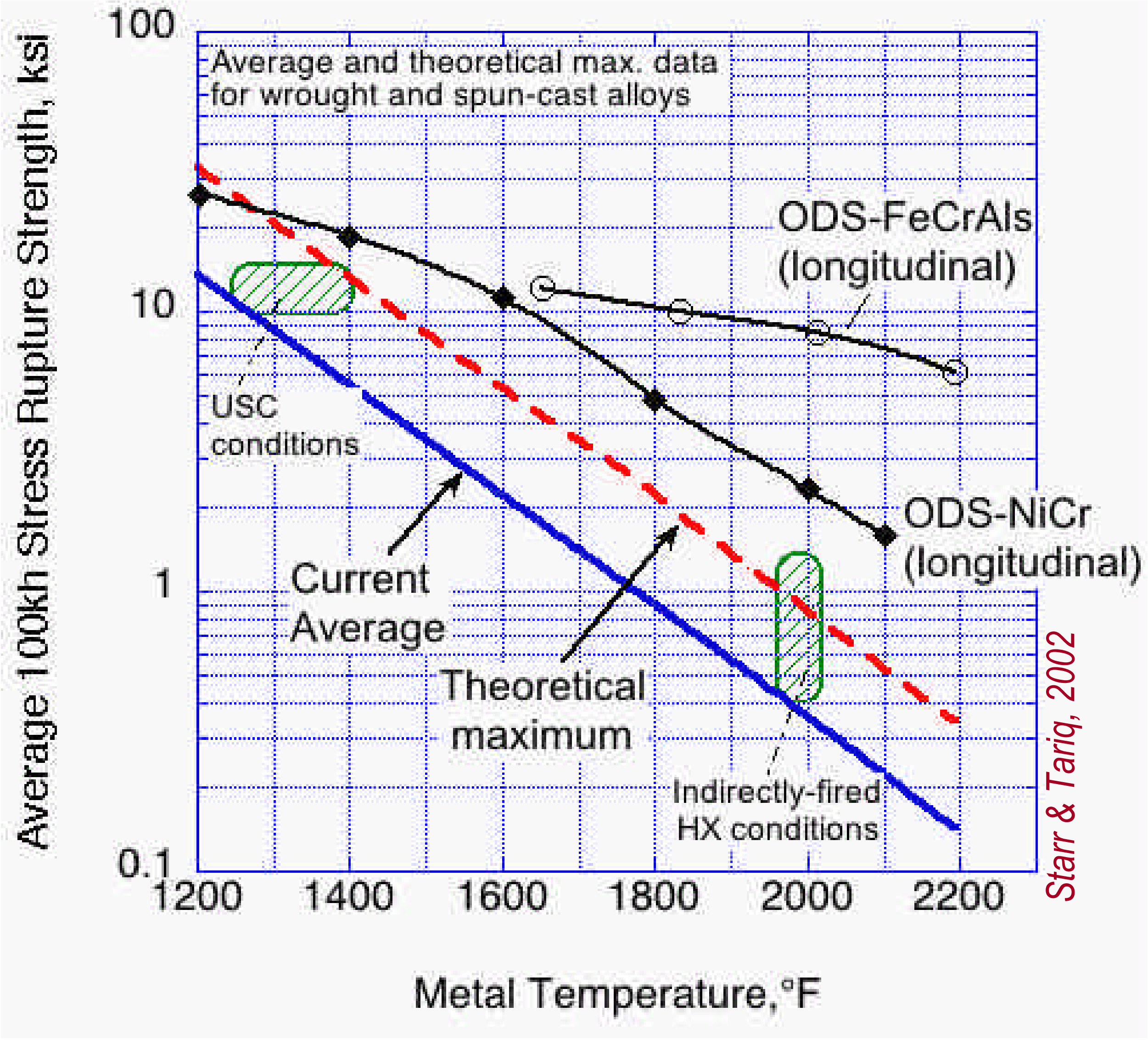
DOE-ARM Portfolio of Projects
Functional Materials

Participant	*Project*
Ames Lab	Metallic filters
LANL	H_2-separation Pd membranes
Sandia	H_2-separation membranes
ETTP	Inorganic membranes
Eltron Research	Proton-conducting membranes
ORNL	Proton-conducting membranes
ORNL	Sintering of thin, supported films
PNNL	Solid oxide seals
ORNL	Activated carbon composites

DOE-ARM Portfolio of Projects
New Alloys

Participant	*Project*
ORNL	High creep-strength alloys
Colorado SOM	Weldability for advanced alloys
Special Metals	ODS heat exchanger tubes
ORNL	ODS alloy development
UC San Diego	ODS alloy processing optimization
U. of Liverpool	Defect reduction in ODS processing
TWI	Friction welding of ODS alloys
Foster Wheeler	Field testing of adv. austenitic alloys
B&W Research	In-plant corrosion probe tests

Conventional, wrought alloys are marginal for next-generation applications



2002	2004	2006	2008	2010

Advanced Austenitic Alloys

DOE-ARM Portfolio of Projects
Coatings and Protection of Materials

Participant	*Project*
Lehigh U.	Iron aluminide weld overlays
Tennessee Tech	Aluminide coatings for power generation
INEEL	Coating microstructure and properties
ORNL	Slurry-based mullite coatings
ORNL	CVD zirconia coatings
U. of Louisville	Modeling CVD zirconia coatings
ANL	Fireside corrosion studies
NETL	Materials testing in combustors
UNDEERC	Materials testing in gasifiers

DOE-ARM Portfolio of Projects
Breakthrough Materials Technologies

Participant	*Project*
ARC	Refractories for gasifiers
ReMaxCo	Production of SiC fibrils
ANL	NDE for ceramics
ORNL	Multi-phase high-temperature alloys
U. Tennessee	Fatigue and fracture in intermetallics
WVU	Fracture of intermetallic alloys
ORNL	Functional surfaces/controlled oxidation
Ames Lab	Mo-Si alloys
ORNL	Mo-Si alloys
ORNL	Concepts for smart protective coatings

DOE-ARM projects on Mo-Si-B Alloys

- 1. Alloys based on $Mo-Mo_3Si-Mo_5SiB_2$ (ORNL)
- Trade-off between creep strength, fracture toughness, and oxidation resistance
    - reduction in α-Mo content increases oxidation resistance, but reduces fracture toughness
    - for a given α-Mo content, control of microstructural size scales and morphologies is very important
- Processing to modify structure so that Mo is present as a continuous binder phase
- Solid solution alloying can increase creep strength dramatically but, again, control of microstructural size scales and morphologies is very important

DOE-ARM projects on Mo-Si-B Alloys

2. Multiphase composites based on Mo-Si-B (Ames Lab)

- Novel processing
- Low-load structures capable of >1000 h at ≤2900°F
- Three alloys:
  - $Mo_5Si_3B_x$-$MoSi_2$-MoB
  - $Mo_5Si_3B_x$-Mo_5SiB_2-Mo_3Si
  - Mo-Mo_5SiB_2-Mo_3Si
- Oxidation at 1800-2000°F in dry and wet air
  - initial loss followed by protective SiO_2
  - some subscale formation

DOE-ARM projects on Mo-Si-B Alloys

3. Concepts for smart protective coatings (ORNL)

- Some results showing promising high-temperature corrosion results for silicides, $MoSi_2$ coatings

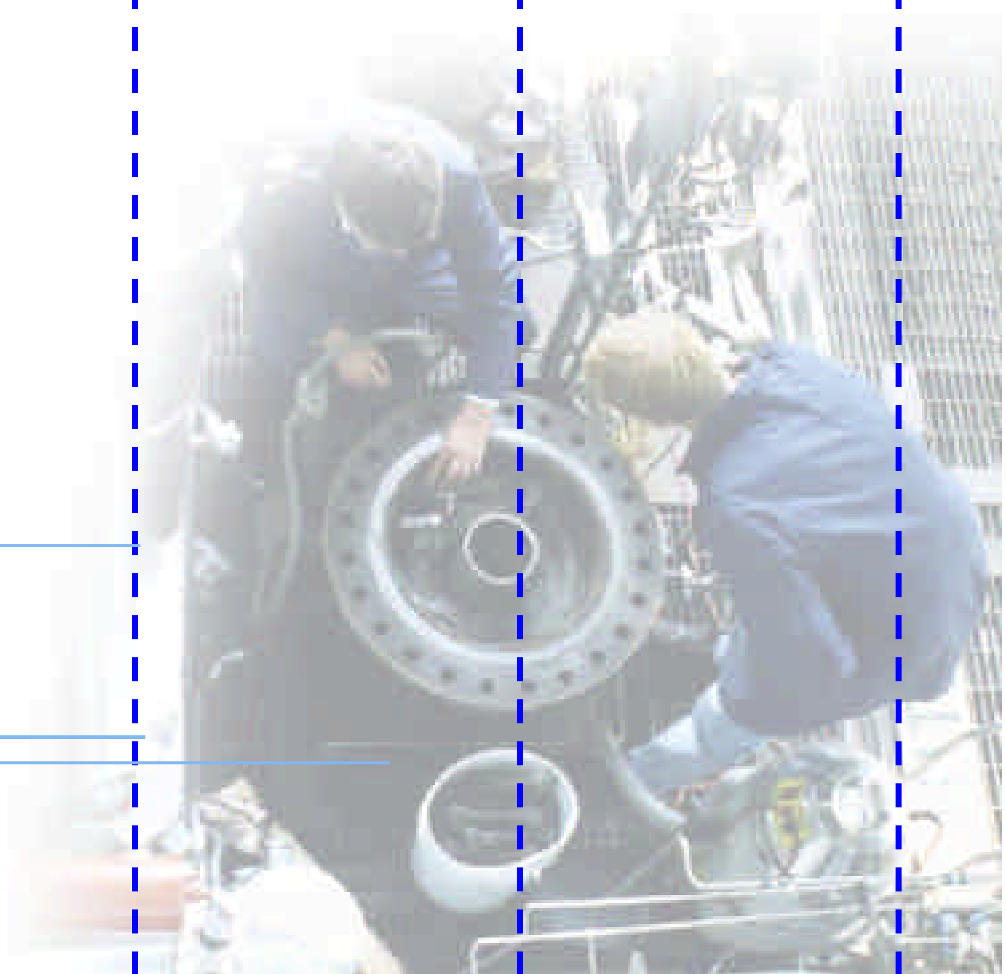
- Mo-Si-B is particularly attractive
  - Si can provide means to establish protective silica or borosilicate layers
  - Mo sulfidizes slowly

- Can we manipulate the phase assemblage of Mo-Si-B so that effective barrier layers form in different environments?
  - start with oxidation experiments
  - explore compositional/microstructural routes to protective oxide formation
  - follow with exposures in oxidizing/sulfidizing atmospheres

Timeline

Breakthrough Materials Technologies

Advanced refractories



Power Generation's need for Mo-Si-B-type Properties

1. Protection of instrumentation/sensors
   - Issues:
     - extreme temperatures
     - extreme corrosivity
2. Turbine first stage vanes
   - Issues:
     - D-E-C from dirty fuels/syngas (including water vapor)
     - lifetime/cost
     - reparability, availability, maintainability
3. Piping and heat exchangers
   - Issues:
     - volatile species; molten slag/salts
     - R-A-M; cost

Similarities & Differences in Materials Needs: Power Generation vs DoD

- History of extreme conservatism…
- Capabilities needed are nominally similar
  - high temperatures, difficult environments
    - strengthening mechanisms
    - resistance to deposition/erosion/corrosion
  - high efficiency, low emissions
- Service expectations are quite different
  - reliability, availability, maintainability
  - lifetimes > 30 years
- Cost is a major consideration in powergen

Acknowledgements

- Larry Ruth of NETL (Pittsburgh, PA): Vision 21 program
- Bob Romanosky Jr. of NETL (Morgantown, WV): ARM program
- Rod Judkins of ORNL: Fossil Energy Materials Program
- Bill Corwin of ORNL: Generation IV Materials Program