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Scroll Corporation

DOE Compressor/Expander Module Development Program Merit Review Meeting

May 22, 2003

TIAX LLC
Acorn Park
Cambridge, Massachusetts
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Our objective for this meeting is to review the state of the technology and the plan to achieve the goals set forth for the Compressor/Expander Technology development program.

- We will review (briefly) the history of this line of Compressor/Expander Module development
- We will review the status of the current design versus the existing guidelines, especially with respect to packaging, cost and performance
- We will show designs that represent significant advances in reducing cost and package size and weight, while minimizing parasitic power consumption
- Review the current program status and the design challenges facing the turbo- and scroll- design teams

By way of introduction, TIAX LLC emerged intact from Arthur D. Little, Inc., advancing its 116-year heritage of helping clients realize the exponential power of technology & innovation.

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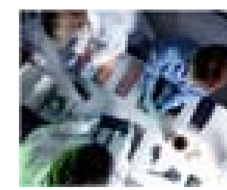
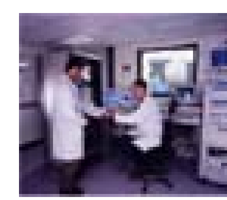
Arthur D Little

technology & innovation



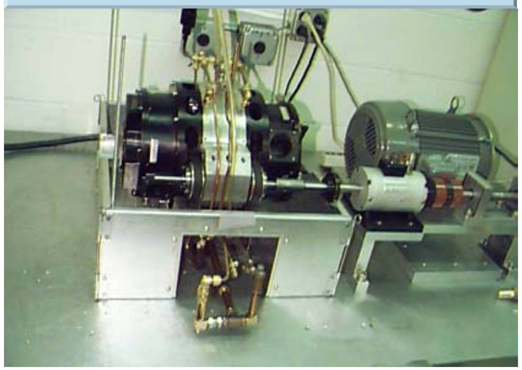
- Heritage
- T&I People
- T&I IP & Know-How
- T&I Facilities & Equipment
- T&I Resources & Relationships

- Independent company formed in May of 2002
- 300 staff of scientists, engineers, and industry experts
- Headquartered in Cambridge, MA
- West Coast offices in Cupertino, CA
- 50 laboratories
- ISO 9001:2000 Registered

The objective of this development program is to produce one working prototype system of a hybrid Compressor/Expander Module for an automotive fuel cell.

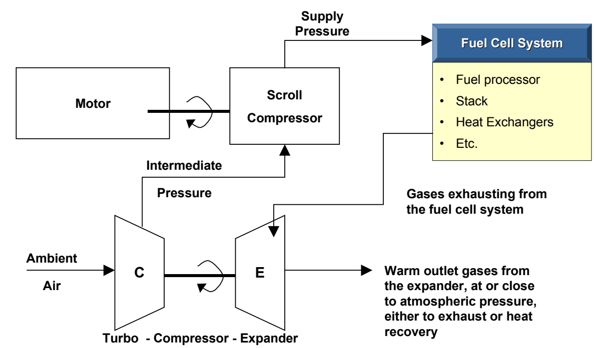
First Generation

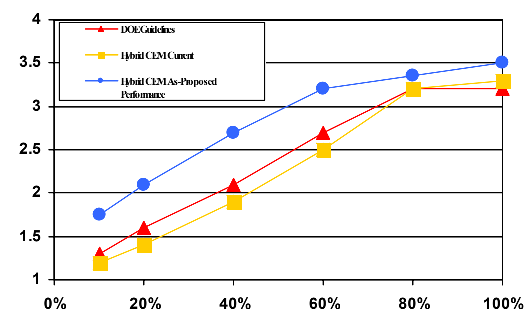


Second Generation

- A second generation scroll CEM met most of the DOE performance guidelines, but was substantially over target for weight and volume
- Turbomachines struggle off of their design point, but are much closer to the required weight and volume
- A hybrid system (essentially a turbocharged scroll compressor) was a logical compromise

As-Proposed Hybrid System Configuration





The hybrid approach offers significant improvements relative to the all-scroll second generation CEM previously developed and tested, while maintaining scroll-enabled pressure/flow and turndown performance.

	Parameter	DOE Guidelines	2nd Gen. Scroll Performance	Hybrid TurboScroll Targets
Compressor	Flow Rate: Dry Air (g/sec) Water Vapor (g/s)	64-76 0 to 4	61 See Note 1	64-76 0 to 4
	Stoichiometry	2.0	2.0	2.0
	Inlet Pressure (atm) Outlet Pressure (atm)	1.0 3.2	1.0 3.2	1.0 3.2
	Inlet Temperature: Design Point (°F) Extreme Range (°F)	68 to 77 -40 to 140	60 to 80 See Note 2	68 to 77 -40 to 140
	Maximum Shaft Power (kW) Turndown Ratio Stages	12.6 10:1 1 or 2	13.0 10:1 1	SC:~6 TC: ~6 10:1 2
	Contamination	oil-free <100 ppm	<50 ppm[3]	Grease-lubed
	Efficiency: 100% flow 3.2 PR 80% flow 3.2 PR 60% flow 2.7 PR 40% flow 2.1 PR 20% flow 1.6 PR 10% flow 1.3 PR	 75% 80% 75% 70% 65% 50%	 --- 71% 69% 64% 49% 52%	 SC:70% TC:70% SC:70% TC:75% SC:70% TC:70% SC:65% TC:65% SC:50%: TC: ----- SC:50%: TC: -----

[1]Testing was done with dry air [2]Extreme condition testing not performed [3]Worst case estimate

Comparison with DOE Guidelines (cont'd)

Expander

Parameter	DOE Guidelines	2nd Gen. Scroll Performance	Hybrid TurboScroll Targets
Flow Rate: Dry Air (g/sec) Water Vapor (g/sec)	56-70 9-16	77 See Note 1	Input
Stoichiometry	2.0	2.0	2.0
Inlet Pressure (atm) Outlet Pressure (atm)	2.8 1.0	2.7 to 3.2 1.0	Input Input
Inlet Temperature: Design Point (^{o}F) Extreme Range (^{o}F)	 244 to 302 149 to 302	 84 to 289 See Note 2	 Input
Maximum Shaft Power (kW) Turndown Ratio Stages	8.3 10:1 1	7.6 10:1 1	~6 10:1 1
Efficiency: 100% flow 3.2 PR 80% flow 3.2 PR 60% flow 2.7 PR 40% flow 2.1 PR 20% flow 1.6 PR 10% flow 1.3 PR	 90% 90% 86% 82% 80% 75%	 --- 81% 80% 77% 63% 74%	 86% 86% 86% 78% 60% -

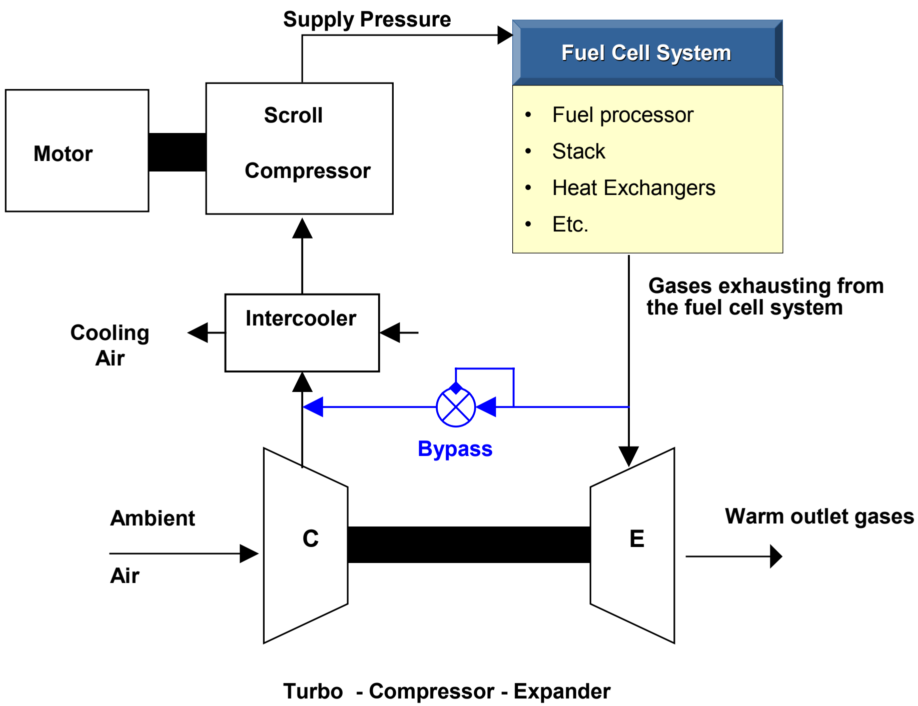
[1]Testing was done with dry air
[2]Extreme condition testing not performed
[3]Worst case estimate

Comparison with DOE Guidelines (cont'd)

	Parameter	DOE Guidelines	2nd Gen. Scroll Performance	Hybrid TurboScroll Targets
System	Maximum Overall Shaft Power (kW)	4.3	5.4	5.1
	Volume* (liters)	4	27	9
	Weight* (kg)	3	36.3	~12
	Production Costs* @ 100,000 Units/Yr	$200	$355	$300-$340[8]
	Start-up Response	<5s to 90% Max RPM	0.82 sec[6]	Stack capacity limited
	Transient Response	<4s for 20% to 90% max flow	0.72 sec[6]	Stack capacity limited
	Noise [7]	<80db	84dBA @40% 95dBA @80%	Speculative

*Without heat exchangers or motors/controllers
[6]Calculated value
[7]Noise measured at one meter without mufflers
[8]Using proprietary and Boothroyd-Dewhurst ground-up costing

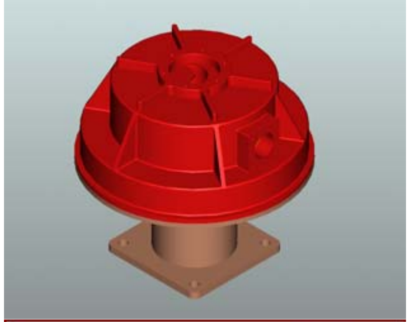
The latest System Block Diagram includes an intercooler between the turbo-compressor and the scroll, to reduce scroll operating temperatures and reject part of the heat of compression, and an optional bypass valve to redirect flow around the turbine and tailor the pressure/flow profile.



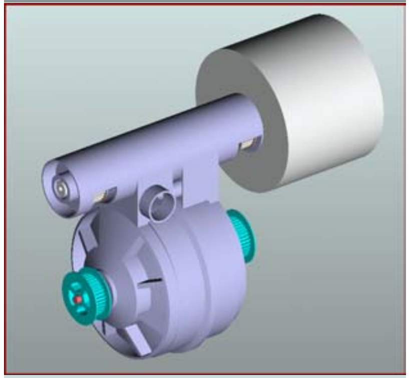
Hybrid TurboScroll Compressor/Expander Module

Three alternative configurations for the scroll compressor were studied in detail, resulting in complete layouts for all three designs.

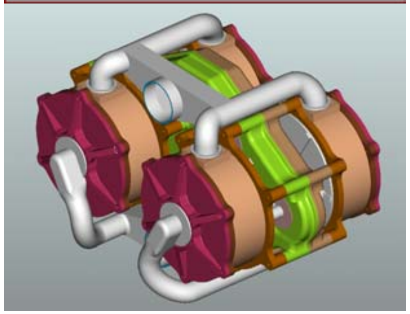
- **Single, back-to-back, co-rotating, and quad were in the preliminary concept list**
- **Relatively quick down-select to 3 alternatives**
- **Trade-offs are weakly linked to turbo-compressor configuration**
- **A relatively conservative approach is preferred, emphasizing compressor/expander system design over advancement of scroll design technology**



- **Single-Sided Orbiting Scroll Design (Conventional)**
  - Lowest Part Count
  - Acceptable Size and Weight
  - Acceptable Technical Risk



- **Co-Rotating Design (Unconventional Drive)**
  - Smallest Size and Weight
  - Acceptable Part Count
  - Best Potential for Low Speed Efficiency



- **Quad Orbiting Design (Unconventional Drive)**
  - Best Thermal and Lubricant Isolation
  - Potential Noise Advantage
  - Demonstrated and Proven Design Configuration

A set of selection criteria, defined and used to create a decision matrix, permitted efficient evaluation of the preliminary designs for the three configurations.

Design Configuration	Single Orbiting Scroll	Quad Orbiting Scroll	Co-Rotating Scroll
Maximum Speed	5,000 rpm or Less	6250-7000 rpm	6250 rpm or Higher
Size (5.0 L Goal)	7.2 L	11.0 L @ 6,250 rpm 8.3 L estimated @ 7,500 rpm	6.5 L
Weight (17 lb. goal)	18.8 lb	19.6 lb @ 6,250 rpm 16 lb estimated @ 7,500 rpm	17.3 lb
Cost Estimate (Drawing Count)	12 Fabrication drawings 4 Purchased drawings	30 Fabrication drawings 4 Purchased drawings	13 Fabrication drawing 8 Purchased drawings
Efficiency	- Main Crank Pin Bearing	- Flank length is 3-4 X's	- Windage loss - Shaft seals + Low Speed Efficiency
Noise	+ Lower Speed - Ball Thrust Bearing	+ Pulse Phasing of 4 scroll - Higher Speed	+ No ball thrust bearings - Two Rotating Rotors
Technical Risk	Medium	Low/Medium Proven Drive Mechanism	High

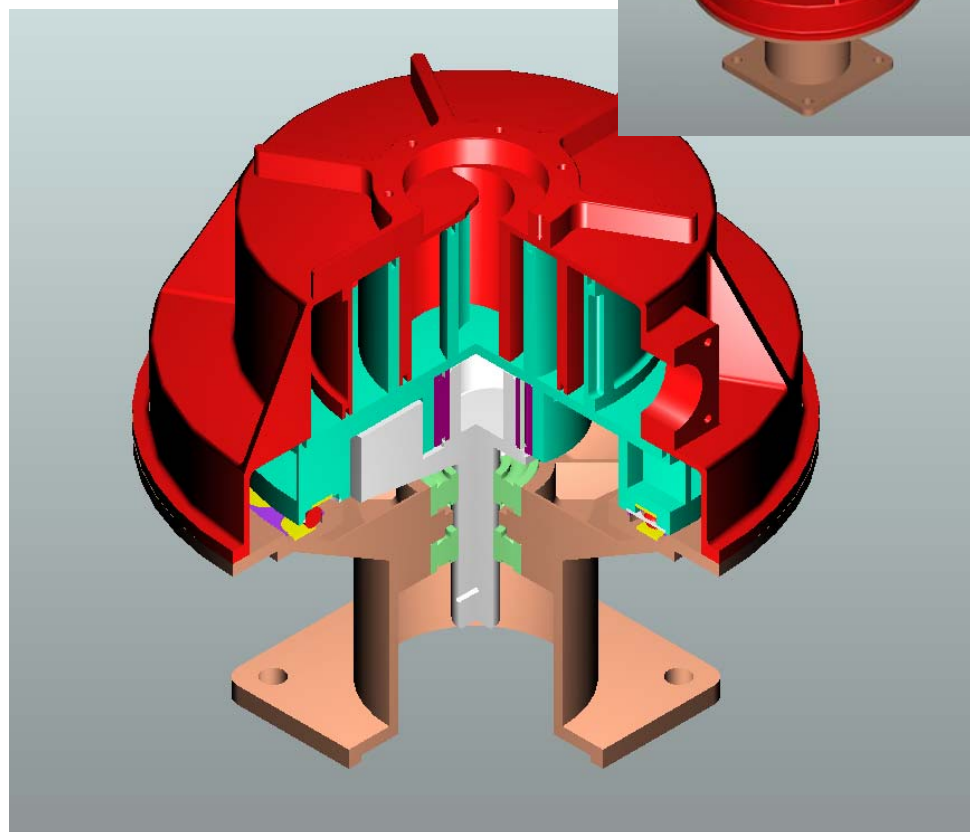
The Single-Sided orbiting scroll configuration was selected based on a decision matrix.

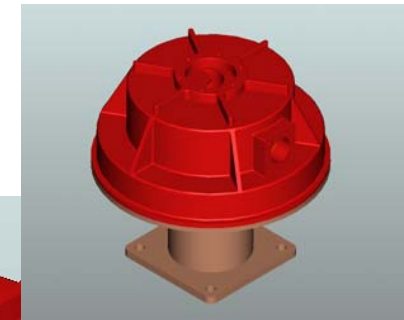
- Size and weight were not the lowest, but not far from being the best
- It had a significantly lower technical risk compared to the smallest/lightest design
- The lowest technical risk design was larger/heavier, with higher part count
- Performance was acceptable and comparable with the other concepts
- Noise was indistinguishable, with the Quad design having potential advantages

Technical Risk	Single Orbiting Scroll	Quad Orbiting Scroll	Co-Rotating Scroll
Lubricant Isolation	Isolating Grease in Thrust Bearing	Minimum Risk	Shaft Seal Failure
Thermal Management	Cooling Crank Pin Bearing	Cooling Fans Maybe Required	Needle Bearings at Gas Temp.
Lubricant Life & Service	Re-Greasing Crank Pin Bearing	Fully Isolated	Re-Greasing Needle Bearings
Volumetric Efficiency	Axial Deflection of Orbiting & Fixed scroll	•Long Flank Seal Length •Tolerance Stack up	•Deflections at High Speed •Tip Seal Performance •Shaft Seal Leakage
Mechanical Power Loss	•Main Crank Pin Bearing •Grease Seal Friction	•Multiple bearings •Grease Lube •Grease Seal Friction	•Windage loss • Shaft seal Friction
Obtaining 5000 hr life & Maximum Speed	•Main Crank Pin Bearing •Tipping of Scroll •Contact Stress on Balls	•Minimum Risk •Higher Risk @7250 rpm	•Life of Timing Teeth •Shaft Seals/Belts •Deflection of Shaft
Costly Purchased Parts Expensive Fabricated Parts	Main Crank Bearing	Conventional components	•Belts •Balancing •Quill Shaft Fabrication

The potential technical risks for the Single Scroll Configuration have been identified, and will be resolved as detail design continues.

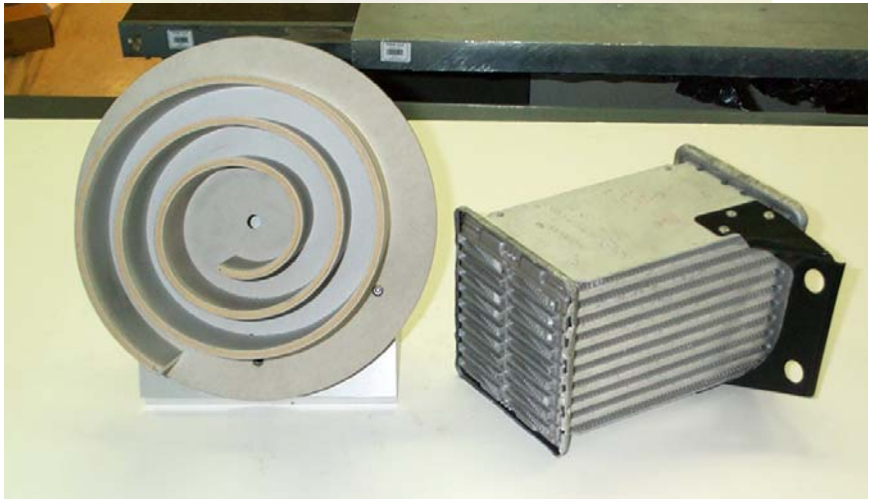
- **Maintenance of flank clearances over operating regime**
- **Tipping of scroll during transient conditions**
- **Lubrication of bearings**
- **Life of lubricant**
- **Lubricant isolation**
- **Cooling crank pin bearing**
- **Bearing cost**
- **Stiffness of scroll support structures**
- **Contact stress on Oldham/thrust balls and retainer**



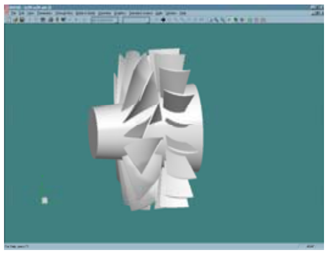


An off-the-shelf intercooler will be used, intact or modified, to provide rejection of the heat of compression of the turbo-compressor.

- The heat exchanger has excess heat rejection capability for our purposes
- Estimated turbo-compressor discharge conditions are as high as 215°F at a 2:1 pressure ratio
- Estimated reduction in inter-stage temperature to 120°F with intercooler
- ~4 kW of heat of compression will have to be rejected to the ambient through the inter-cooler
- This heat rejection contributes to the fuel cell system heat rejection

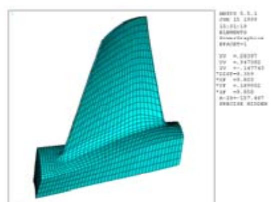


Concepts NREC, the turbo-machinery subcontractor for this program, has combined about 70 years in business, developing advanced turbo-machinery to meet demanding commercial and military requirements.



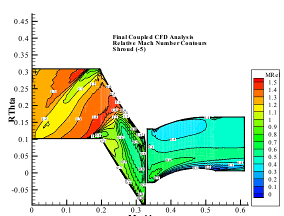
Fluid Dynamic Design

Manufacturing



Thermo-Mechanical Analysis

Testing

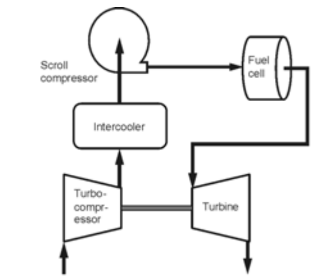


Computational Fluid Dynamics

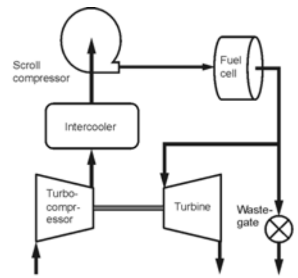
Wilder, VT Facility

Woburn, MA Facility

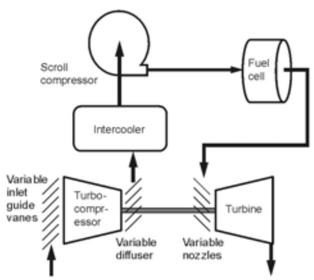
After establishing basic system requirements, a substantial variety of turbo-compressor combinations were studied.



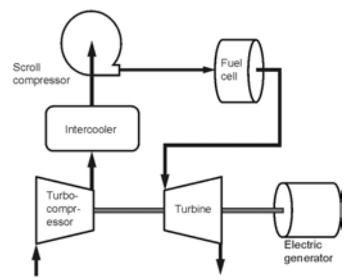
(a) Baseline fixed geometry turbine



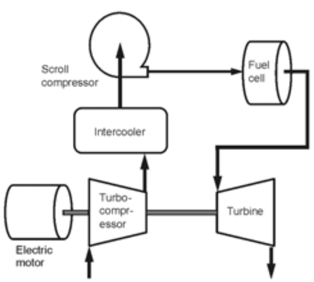
(b) Turbine with wastegate



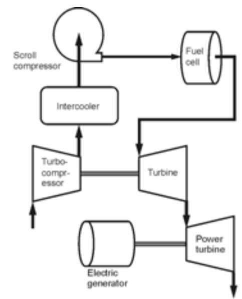
(c) Variable geometry turbo-compressor



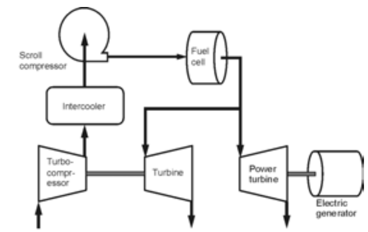
(d) Turbine with turbine-driven generator



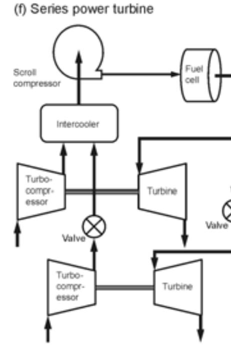
(e) Turbo-compressor with motor drive to compressor



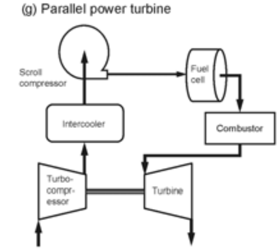
(f) Series power turbine



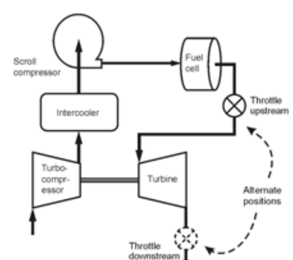
(g) Parallel power turbine



(h) Twin parallel turbo-compressors

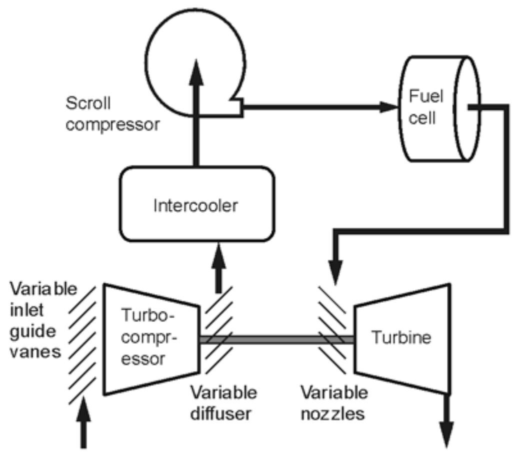


(i) Turbo-compressor with exhaust gas combustor

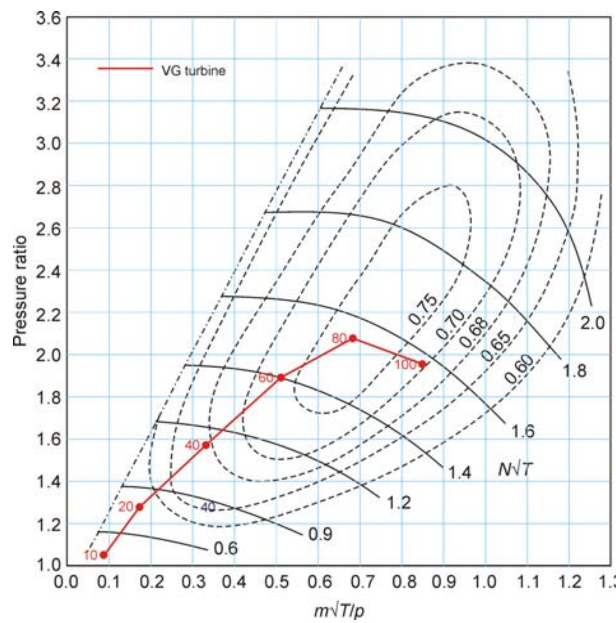


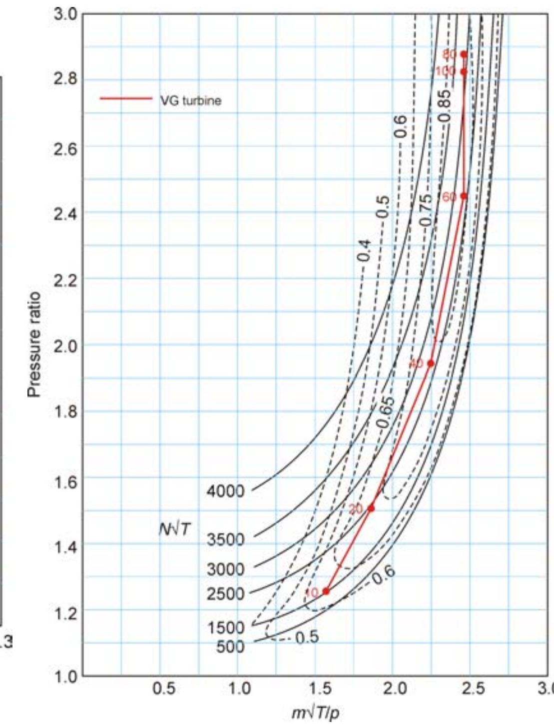
(j) Throttle valve upstream or downstream of turbine

Under the constraints governed by the DOE Guidelines, what would it take to get the most efficient air supply?



(c) Variable geometry turbo-compressor

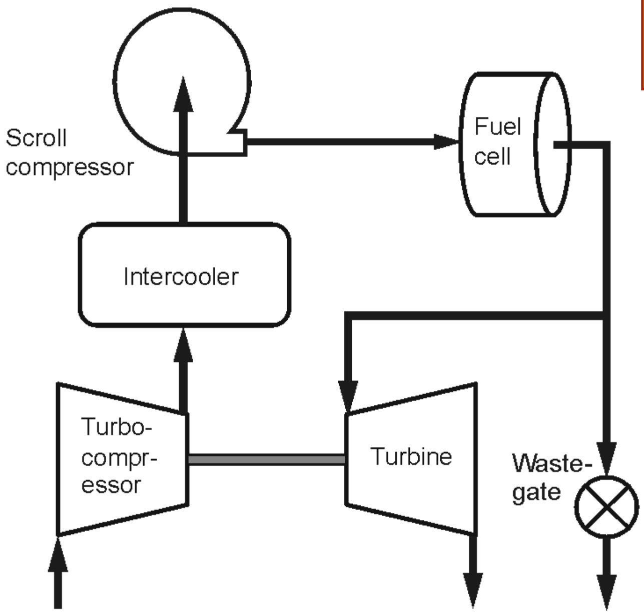




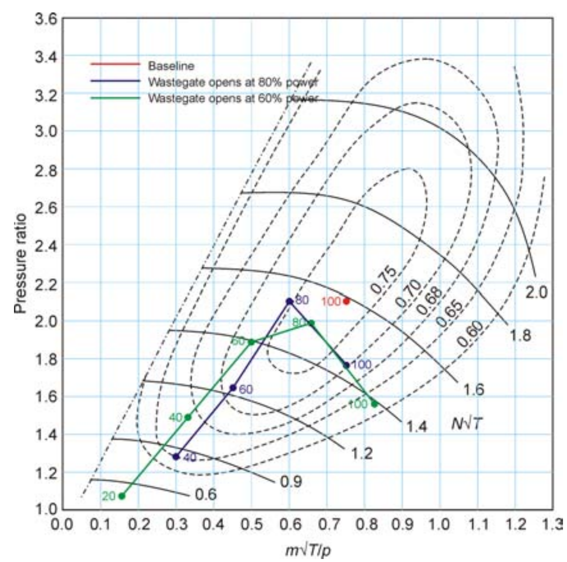
Variable geometries for compressor and turbine provide optimum flow adaptation to match operating regime with high efficiency regions, but…...

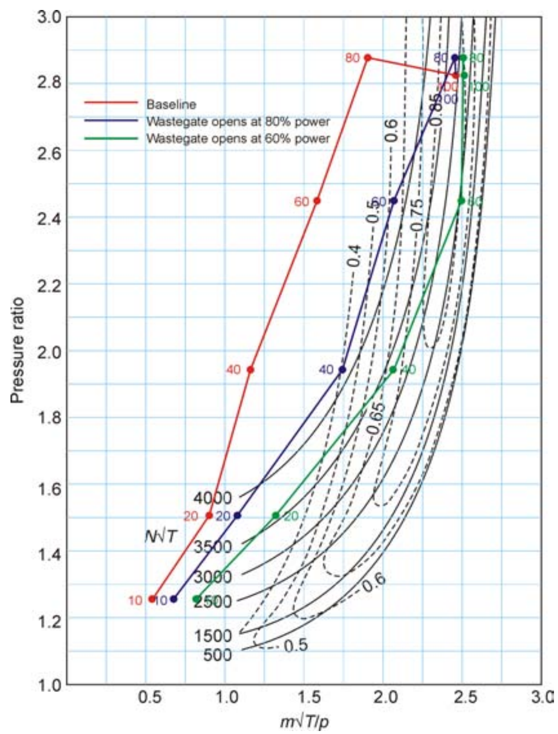
variable geometry components present mechanism size problems due to the small application.

How would a simple fixed geometry configuration compare in terms of power, cost and complexity?



Incorporating a wastegate allows us to meet DOE Guideline at high flows, but...

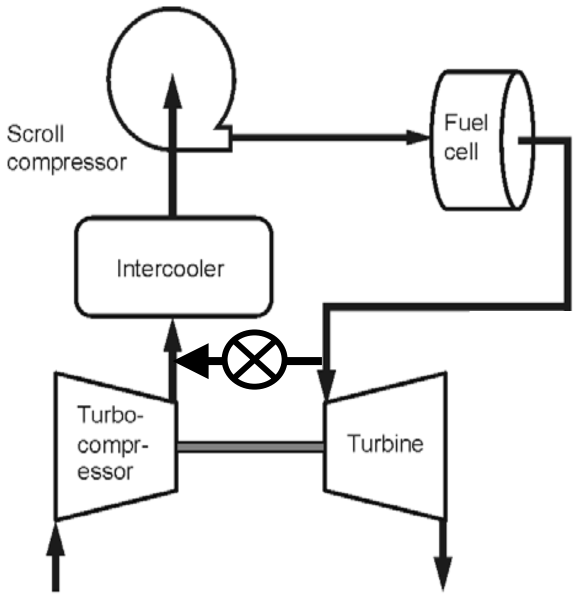


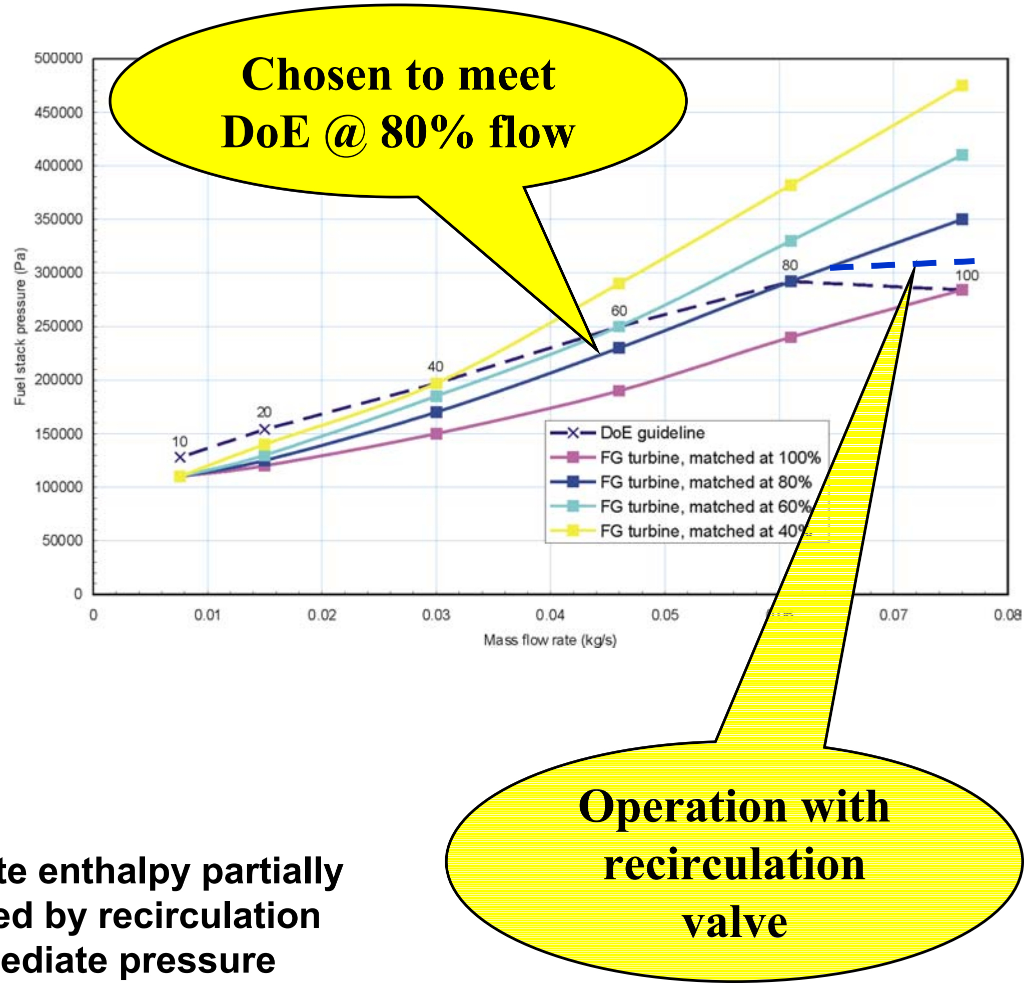


system efficiencies are compromised for certain operating regimes.

Recovering the bypassed enthalpy by recirculating part of the discharge gas may offer important advantages.

- **DoE guideline is met with some deviation at low flows**

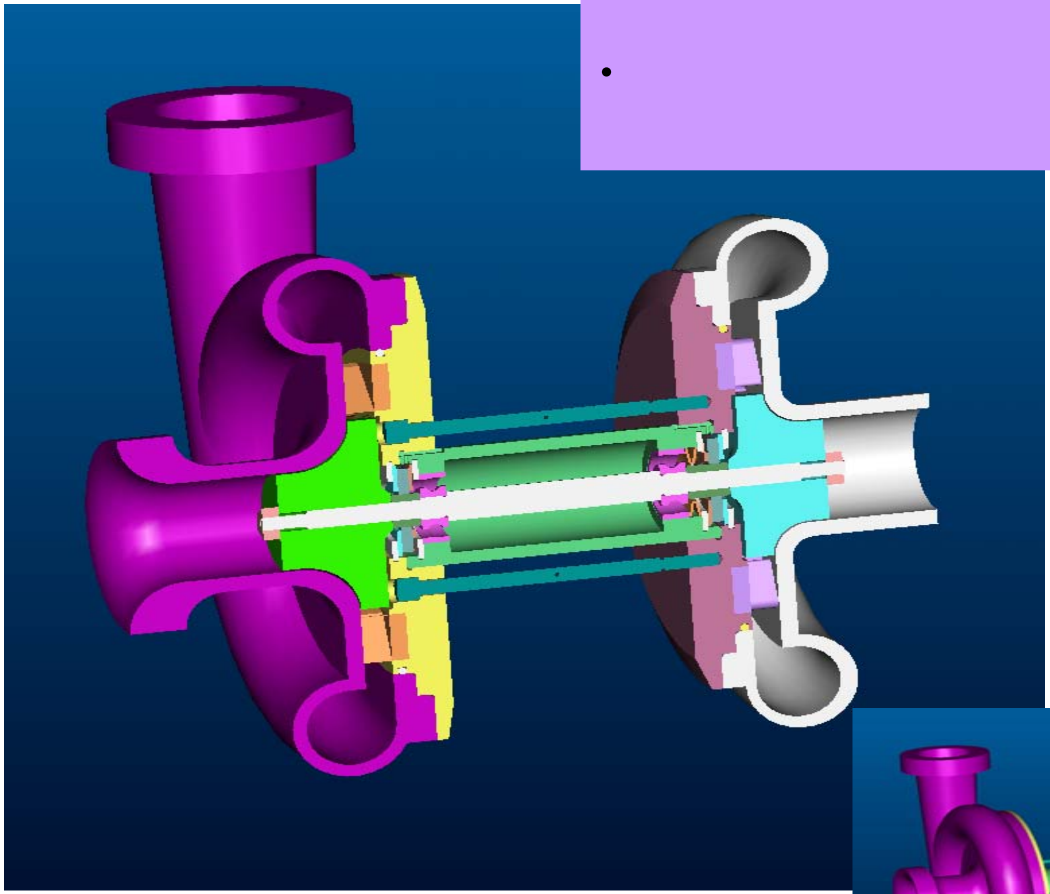


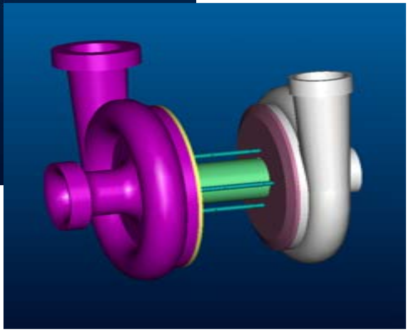


Wastegate enthalpy partially recaptured by recirculation to intermediate pressure

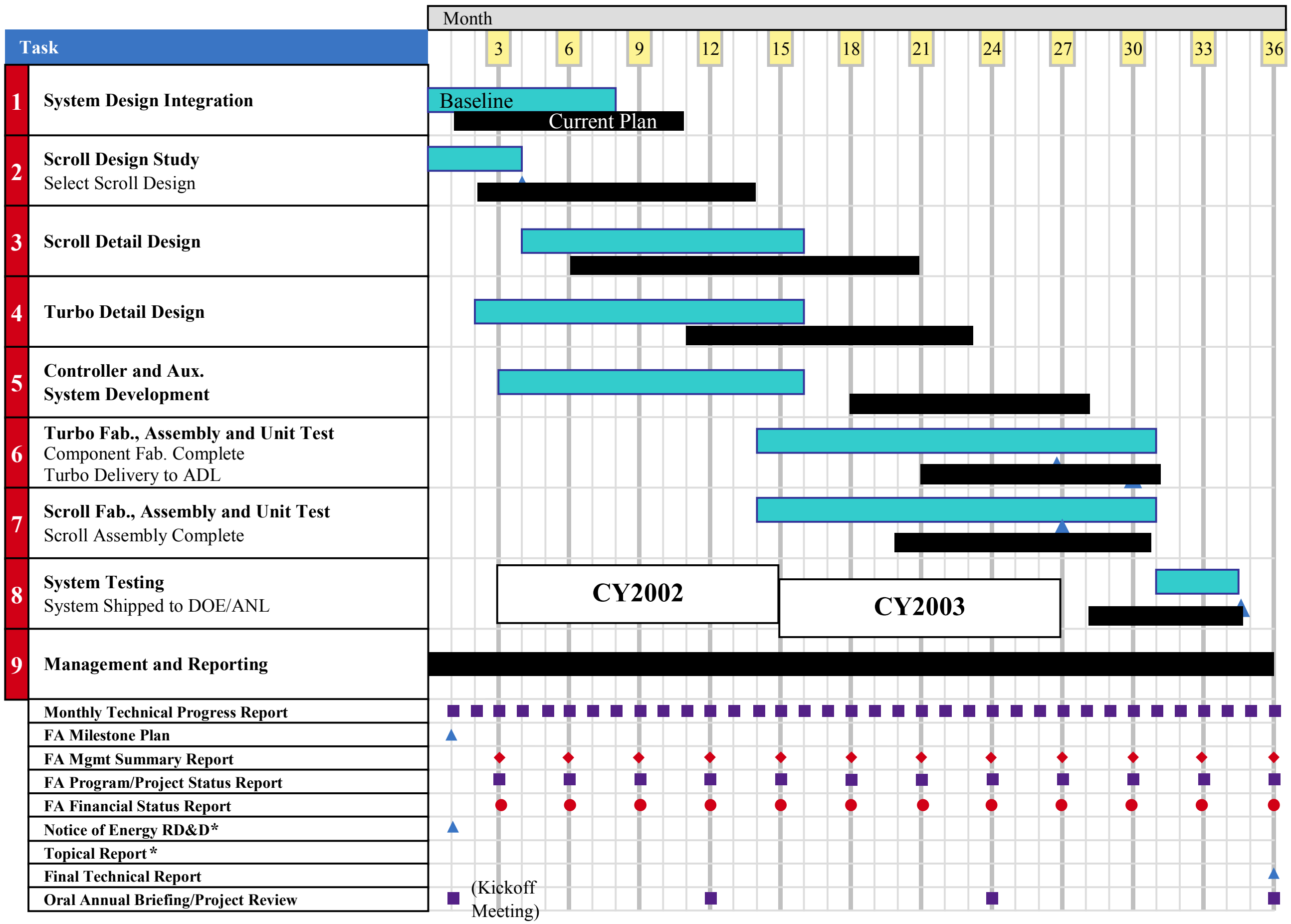
A simplified design, adapted from turbocharger technology, strikes a balance between cost, complexity, performance and risk.

- **Aluminum wheels / housings: 1.7” Ø turbine, 2.0” Ø compressor**
- **Operating speed range up to 140,000 rpm**
- **Grease lubricated bearings: max. speed 150,000 rpm. No contamination of gas path**
- **Steel shaft**
- **‘Stiff’ shaft design (first critical speed ~ 160,000 rpm**
- **Simple seals (labyrinths)**





The overall program covers a span of thirty-six months, generally divided into design, fabrication and test phases.



Some key technical issues & risks, identified early in the program, have been addressed; some remain as issues for our near-term activities.

- **Several key issues…**
  - Lubricant selection and management
  - Inter-Cooler Integration
  - Size & Weight
  - Manufacturing Cost
  - Noise behavior
  - Stability & control
- **… will drive our near-term activity plan**
  - Development of final designs and drawings for turbo-compressor and scroll compressor
  - Development of final layouts for “production configuration” and “test configuration” systems
  - Development of control and auxiliary systems
  - Development of test programs for scroll compressor, turbo-compressor and system
  - Continuing assessment of key system technical risks & issues