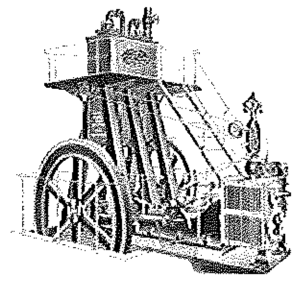
Manufacturing Cost Considerations in Compressor Design

60 RPM
York



Joseph Orosz

Torad Engineering

- Brief History of Compressors
- Compressor Manufacturing
  - » Yesterday and Today
  - » Enabling Technology Changes in Manufacturing N/C machining
- Design Considerations
  - » Performance
  - » Cost
  - » Future Trends

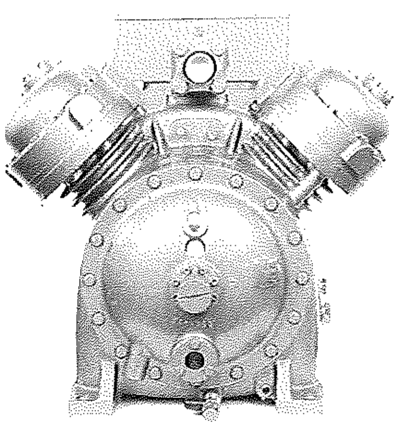
Herrick Laboratories Purdue University

A brief History of Compressors and Market Drivers over the last 30 years

Herrick Laboratories Purdue University

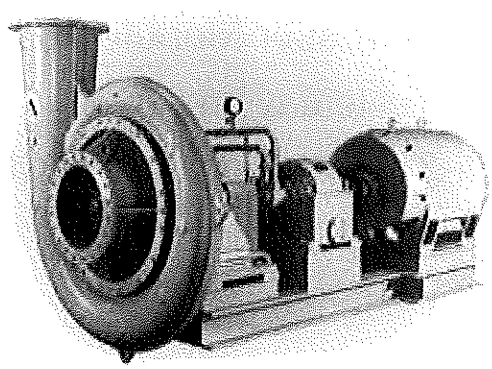
History of Compressors

What types of compressors existed prior to 1955? only 2 choices



Reciprocating
Open Drive
Semi – Hermetic
Hermetic

<150RT <250RT for AC
all wide P2/P1 apps

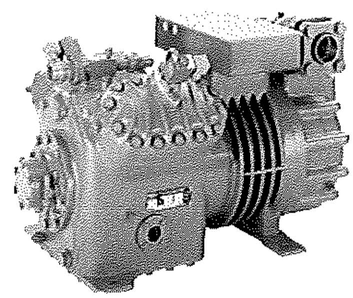


Centrifugal

>250RT

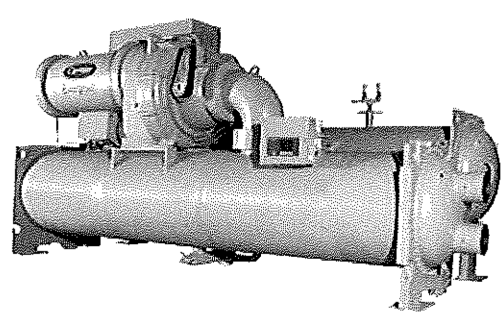
History of Compressors

- Reciprocating Compressors
  - » Applied in comfort cooling up to 250 tons
  - » Refrigeration Applications
  - » Best fit for applications with variable compression ratios
  - » All systems requiring
    - – Direct Expansion air handlers
    - – Remote air cooled units
    - – Evaporative condensers



History of Compressors

- Centrifugal Compressors
  - » Applied in comfort cooling greater then 150 tons
  - » Limited operating range wrt P_D/P_S = 1.5 ~ 2.5
  - » Low pressure refrigerants – R11, R12
  - » High Efficiency
  - » Cost effective in large sizes



Herrick Laboratories Purdue University

Market Forces

Market dynamics of the Mid 70's

- The oil Crises
- Increased Regulations
  - DOE
  - ASHRAE
  - ARI
- Increased energy cost

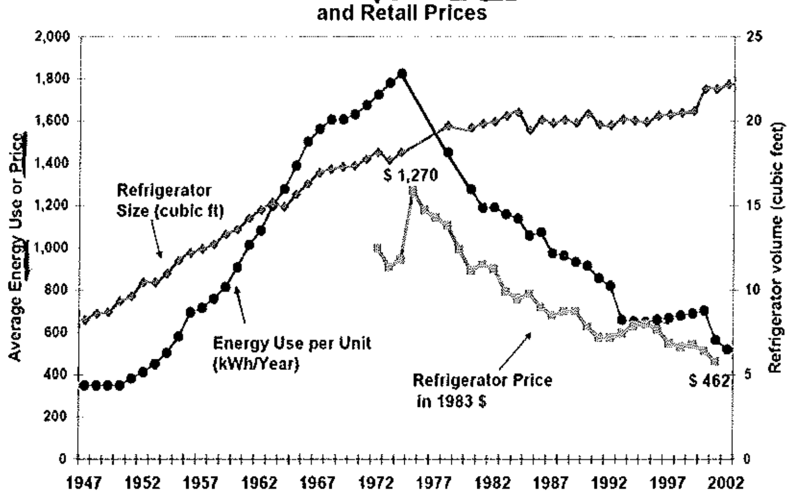
Take Issue - Efficiency improved not B/c compressors as much as System improvement

Refrigerators somewhat exception

Herrick Laboratories Purdue University

Appliance Market

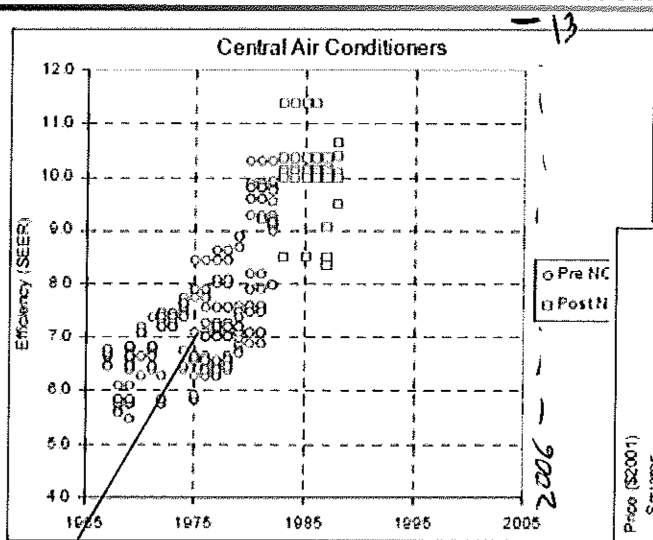
New United States Refrigerator Use v. Time and Retail Prices

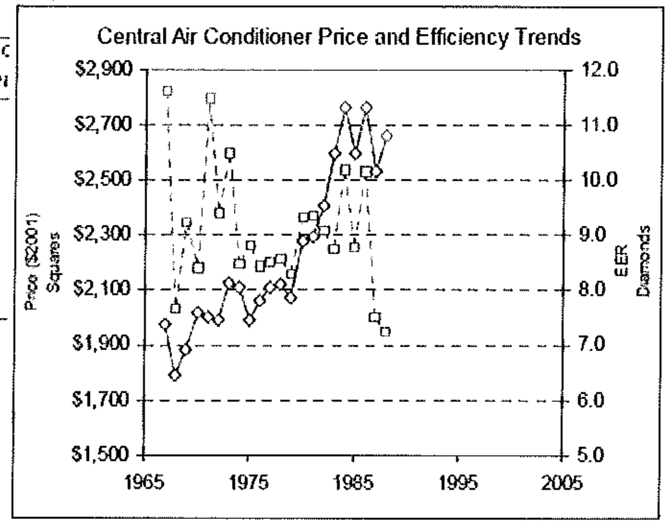


10

Source: David Goldstein

Central A/C





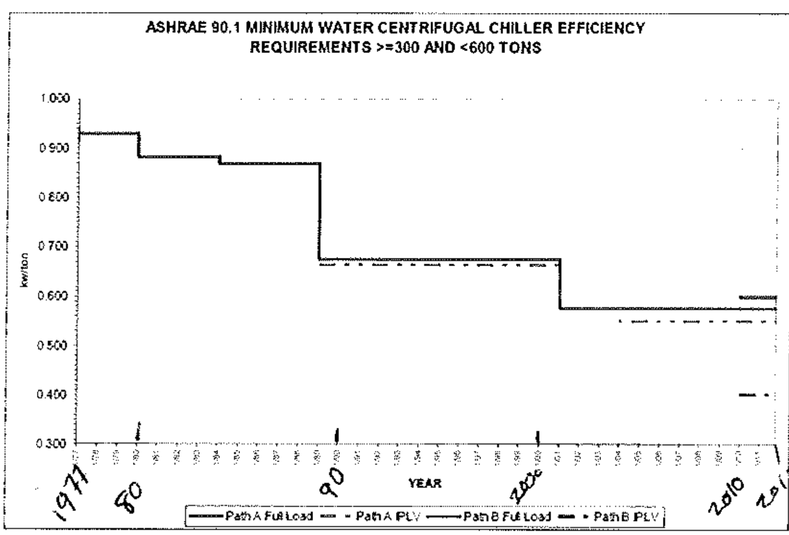
Average 7.0 SEER in 1975

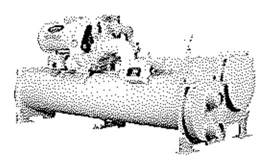
Average 13.5 SEER in 2010

when min SEER = 13.0

Large Water Chillers

Example of HVAC Historical Product Efficiency Improvements for Large Centrifugal Chillers





61% Improvement in Full Load Since 1977 on top of losses in cycle efficiency for changes in refrigerant from CFC to HCFC to HFC

Industry Drivers

What did the demand for increased efficiency and reduced cost look like over the last 30 years?

	Selling Price	Energy Efficiency
Domestic Refrigerators	⬇ -60%	⬆ +70%
Large Tonnage Chiller	⬇ -22%	⬆ +61%
Residential A/C	⬇ -24%	⬆ +68%

Cost and Efficiency improvements required new compression technologies

Manufacturing Technology of the past

Piston Compressors

What can we say about the manufacturing attributes of these two machines?

Piston Compressors

Easy to seal - Piston in a housing bore!
Capitalized on the existing Automobile supply chain
Rings, Pistons, Crankshafts, Rods, Blocks
Easy to Measure features
Experienced high volume production supply chain

Piston Compressors

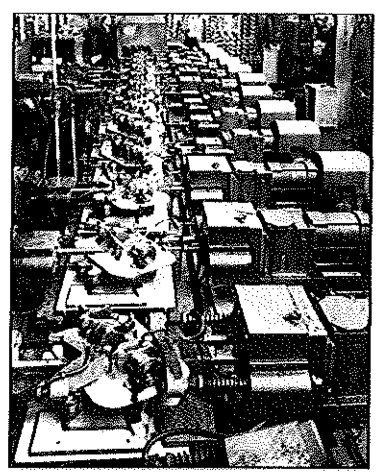
How did we manufacturer reciprocating parts?

Capital Equipment based on Automotive

Prior to CNC equipment most manufacturing was done by breaking down operations into discrete features and producing those on individual machines.

The automobile industry was producing machines to make all these parts.

After all a piston compressor is an engine running in reverse!

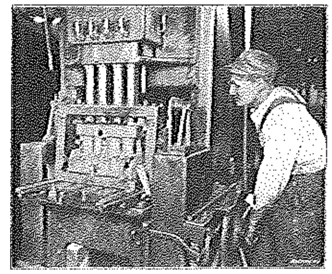


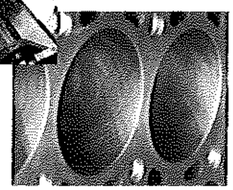
Drilling oil ports in crankshafts

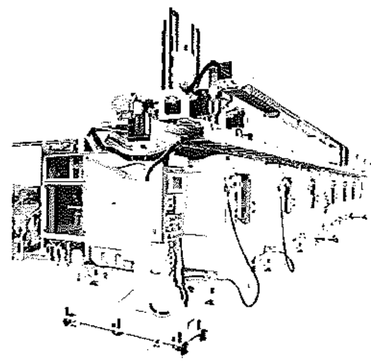
Piston Compressors

Piston Bore Feature Generation

- Cast Bore
- Rough Bore – Boring Bar
- Semi- Finish – Boring Bar
- Finish – Fine Boring Bar
- Finish Hone
- Measure for size
- Scan for Cylindricity







Centrifugal Compressors

What can we say about the attributes of these machines?

Centrifugal Compressors?

No Seals!
Large capacity and high speed
Well suited for high capacity chillers
Due to large internal clearances and the use of non-contacting high speed blades these machines could be made using the same equipment as other steam turbine equipment turbo equipment of the day.

Centrifugal Compressors

How did we manufacturer centrifugal parts?

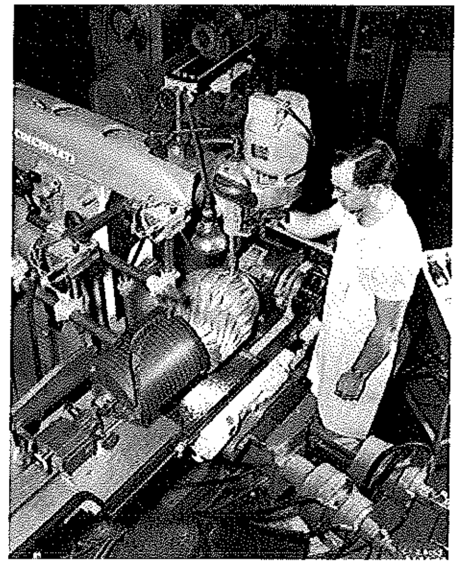
~1950 Tracing machine

Capital Equipment?

Production was based on the steam turbine business which developed in the early 20th century

Compressors were produced in low volume so cost was not the major issue.

Machine process was slow with hand fitting of parts.



New Compressor Technologies

New Technologies

What types of compressors evolved post 1950's

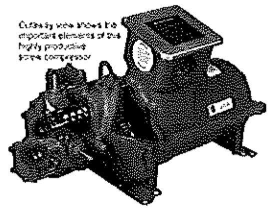
Twin Screw

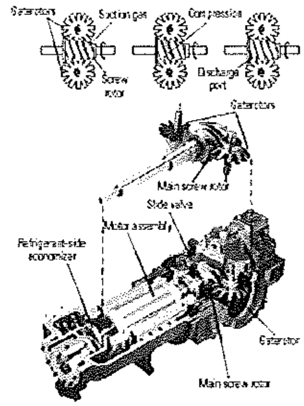
Mono-Screw

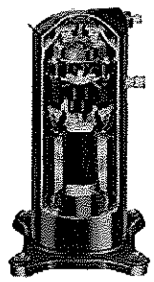
Rotary Vane

Scroll

Rolling Piston







New Technologies

Transition period

What can we say about the attributes of these machines?

Positive Displacement

High Speed *> 1750*

Rotating Motion

Complex Geometries

Difficult to Manufacturer

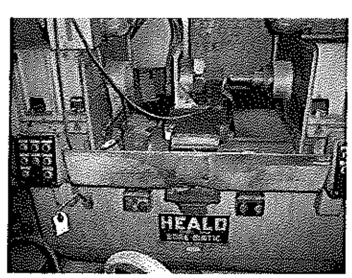
Difficult to Measure

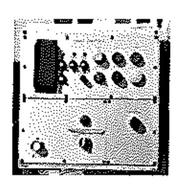
Hi~~/~~ Capital Equipment Cost *Mfg.*

Enabling Manufacturing Technology

Enabling Technology - Machining

Old Machine Tools →	Design Limitations
Multi Step Process (labor & shop space)	Holes
Hard Tooling	Lengths
Fixed Speeds	No Complex Forms
2 Dimensional (not 3-D)	Limited Surface Finish Control
Non flexible	Extra Processing
Long Set ups	Limited Design flexibility
Limited feature Geometry	

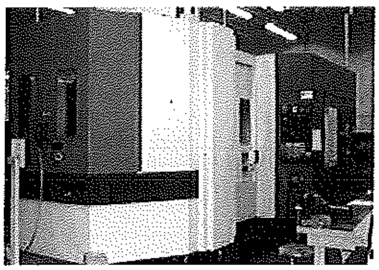


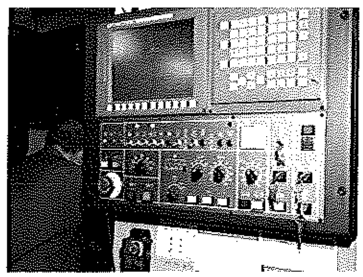


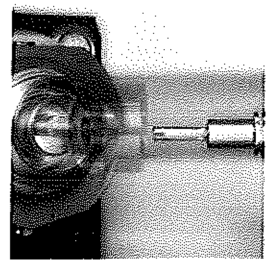
Herrick Laboratories Purdue University

Enabling Technology - Machining

New Machine Tools →	Design Opportunities
Flexible CNC Machines	Additional features for low cost
Many features in one machine	2D and 3D Contours
Variable speed for improved cutting conditions	Improved Surface Finishes
2d and 3D contour milling	Improved form
	Squarness
	Perpendicularity







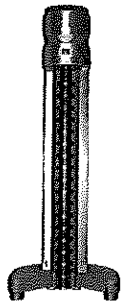
Herrick Laboratories Purdue University

Enabling Technology - Measurement

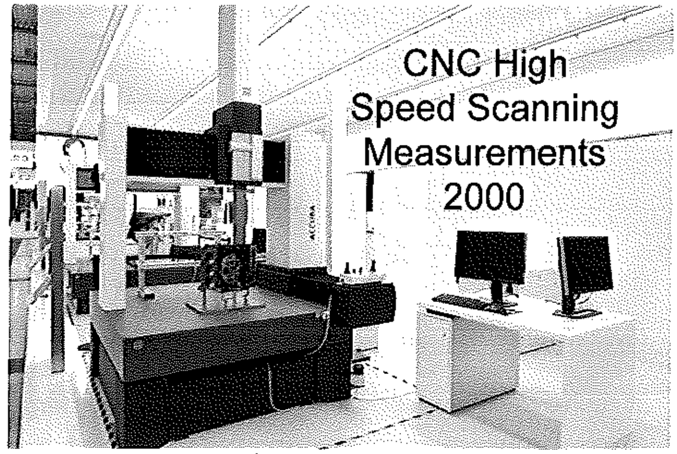
Old →	New
Diameters	Coordinate Measuring Machines
Lengths	Manual
Locations – Time Consuming	CNC
Form – Expensive	Scanning
No in process measurement	In Process Gaging – FDD of tool wear
2D complex curves	Optical Measurement
	In Machine-probing

Herrick Laboratories
Purdue University

Metrology Evolution



Manual Transfer Gage (1960's)



CNC High Speed Scanning Measurements 2000

Manual 3D Measuring (1970-1980)

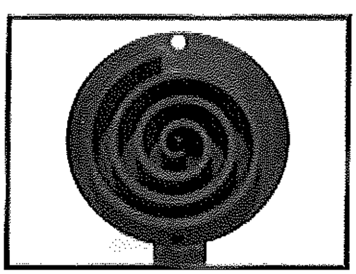
Herrick Laboratories
Purdue University

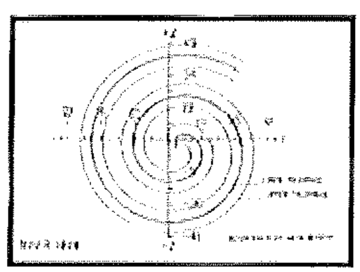
Metrology Evolution

Carl Zeiss IMT
Scroll Measurements

ZEISS

- Scan scrolls in minutes. previously 1 hour to 0.001 mm
- This process used to take over an hour.





Herrick Laboratories Purdue University

Design Considerations for Compressor Manufacturing

Herrick Laboratories Purdue University

Design Considerations

- Feature Control
  - » Size
  - » Location
  - » Form
- Tolerances vs Cost
- Design Influence
  - » Manufacturing
  - » Measurement
- Volume Effects

Design Considerations

- Feature Control diameters and lengths
  - » Features have a non-linear cost structure
  - » > +- .005 Size Tolerance – Process Capable – Tooling inexpensive with long tool lives
  - » > +- .001 Size Tolerance – Process Capable – Tooling reasonable
  - » > +- .0005 Size Tolerance – Process can be capable – Tooling and machines expensive
  - » < .0005 Size Tolerance – Process typical incapable
    - – In process controls
    - – Continues auditing adds cost

Herrick Laboratories Purdue University

Design Considerations

Mono screw much simpler than Twin

- Form Control
  - » Roundness
  - » Flatness
  - » Cylindricity
  - » Straightness
  - » Profile
- Form is not your friend!
  - » Complex 2D shapes – Scroll
  - » Complex 2D shape non constant Z – Twin Screw
  - » Complex 3D Shape – Mono Screw

Design Considerations

- Why is form so difficult?
  - » It is typically a refinement of a feature – i.e., Bore size with a roundness of .0002"
  - » Need high level of data to evaluate correctly
    - – Diameter Measurement - 2 points with a dial bore
    - – Roundness Evaluation at .0002" Tolerance – for a 3" bore would need about 1,000 points
  - » Non-Standard measuring tools
    - – Roundness Tester
    - – Scanning CMM's –
      - 100mm/sec with an acquisition rate of 4000 points/sec

Design Considerations

Part Tolerance	Gage Repeatability*
.005" (.127 mm)	0.000175" (0.0045mm)
.001" (.0254mm)	0.000035" (0.0009mm)
.0005" (.0127mm)	0.000018" (.00046mm)

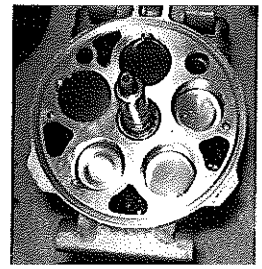
The Accuracy statement for the gauge is only PART of the answer. Remember.. numbers we are looking at are the AVERAGE REPEATABILITY of the GAUGE. This includes variation as a result of fixturing, probe flexing, thermal fluctuations, vibration influences, etc. So the gauge accuracy number is only a portion of the consideration.

*Average repeatability that is needed to assure ,10% manufacturing tolerance is lost to the gauge.

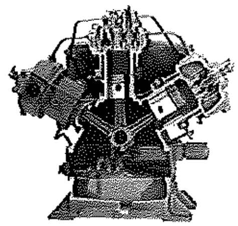
Herrick Laboratories
Purdue University

Design Considerations

- The Cost Hierarchy of Feature Generation
  1. Size – Diameters, lengths



  2. Location – X,Y



  3. 2D Form - Squareness Flatness, Roundness

  4. 3D From – Profiles, Cylindricity

Herrick Laboratories
Purdue University

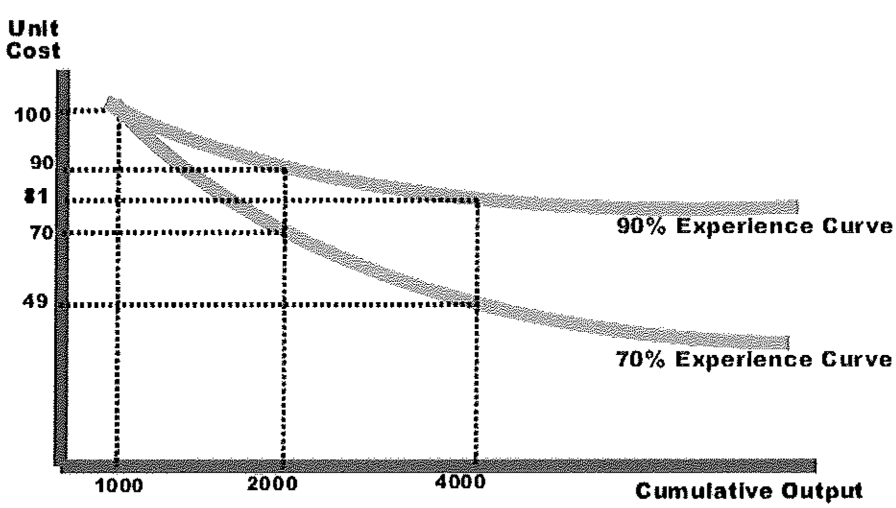
Volume and Experience

Volume Effects

- Volume and the Experience Curve
  - » Volume effects are real
  - » The higher the complexity the higher the experience curve
  - » First cost estimates are always high
  - » Low volume products move slowly along the curve – don't over-estimate the cost evolution

Volume Effects

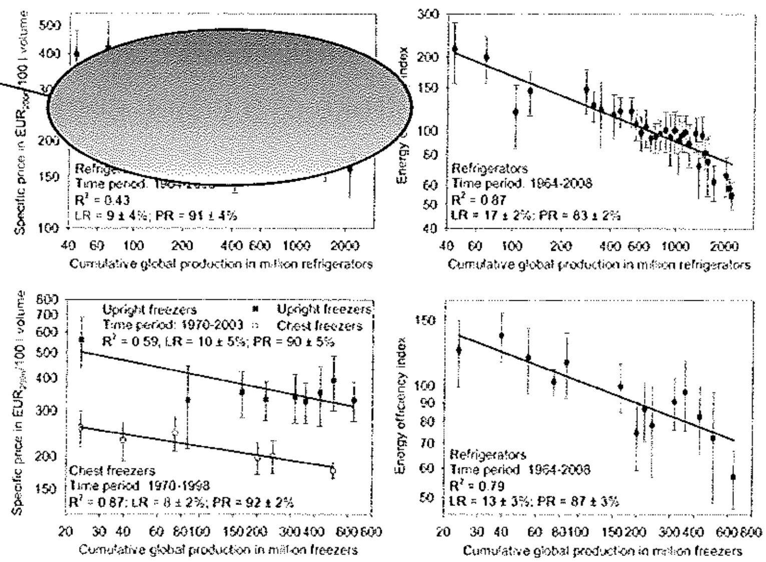
- Experience Curves



Volume Effects

- Experience Curves

40% Cost Reduction 1960-2008



Cost Drivers

Herrick Laboratories Purdue University

Manufacturing Cost Drivers

- The "Z" is free concept!
  - » What is the lowest cost dimension?
  - » Along the axis of the compressor
    - – Lengthening the stroke of a piston compressor
    - – Scroll involute height
    - – Screw rotor length
  - » Limit to exploiting the length is process capability
- Stay inside the motor diameter
  - » Minimize enclosure dimensions
  - » Give flexibility on the design

Herrick Laboratories Purdue University

Manufacturing Cost Drivers

- Minimize the interfaces
  - » Lower Cost
  - » Better Geometric control
  - » Easier assembly
  - » Less defects
- Control vs. Adaptation
  - » High volume selective assembly can make sense
  - » Lower volume can employ other methods
    - – Part adjustment
    - – Shimming End play gaps always used in screw machines
    - – Sacrificial coatings teflon

Future Trends and Practical Limits

Future Trends

- Cost Requirements – Direct/Indirect and Capital
  - » The winners will have a lower total cost
  - » Reduce material
  - » Reduce processing time
  - » Reduce capital outlay
    - – Rapid implementation of new designs
    - – Allow for recapitalization of the product to assure performance requirements are met throughout the life of the product.

shorter machine tool life

Future Trends

- Efficiency requirements
  - » They will continue to be stretched
  - » Due to unit requirements compressor variability must be minimal
  - » This means improved manufacture
  - » This means more tolerant designs
  - » Designs must be robust enough to allow consistent manufacture of the compressor at reasonably cost

Future Trends

- With compressor Overall Isentropic Efficiencies over 70% how far can we go?
- Mature technologies will see only incremental improvement
- Large Chillers market is pushing hard for a more holistic approach to building efficiency as discrete efficiency gains from equipment are limited.
- Efficiency gains still available in smaller sizes.
- Low cost compressor design will benefit by making dollars available for energy reducing technologies to be applied at better cost points, variable speed drives, controls etc.

Final thoughts

- Efficiency ⇧
  - Reduce sliding surfaces
  - Increase displacement density
- Cost ⇩
  - No complex geometry
  - Low tolerance levels
- Best Overall
  - Low raw material usage per displacement
  - Low capital requirements

Design Determines about 50% of the manufacturing cost

Bo Shen Heating as well as cooling

multi point eff over PLR + Pd/Ps + Psuction