2014 Purdue Conferences
Compressor Engineering
Refrigeration and Air Conditioning
High Performance Buildings

SCREW COMPRESSORS

PAST, PRESENT AND FUTURE

Jack Sauls
Ingersoll Rand / Trane
Retired

INTRODUCTION

1

- What I learned from researching the history of screw compressors.
- How that influenced this presentation.
- The familiar and often repeated short historical narrative.

- Stories from some of the people involved.

WHAT I LEARNED

It is too big to do it all

- Too much information
- Too long a time
- Too many participants
- Too broadly characterized

Google “screw compressor” to see what I mean

WHAT I LEARNED

It has been done before

1965-66 **Trends in Compressor Design**

Henri Soumerai

Professor Ian Smith

Screw Compressors for
eration

crew C
opmen

Professor Nikola Stosic

2010 **Three Decades of Modern Screw Compressor Practice**

N. Stosic
A. Kovacevic
I. Smith
E. Mujic

2014 **Screw Compressors and Chillers**
A History of development

APPROACH

How I organized this talk…

~~The Unabridged Version~~

The Limited Scope Version

- Twin screw only
- Follow personal experience
- Focus on technical development

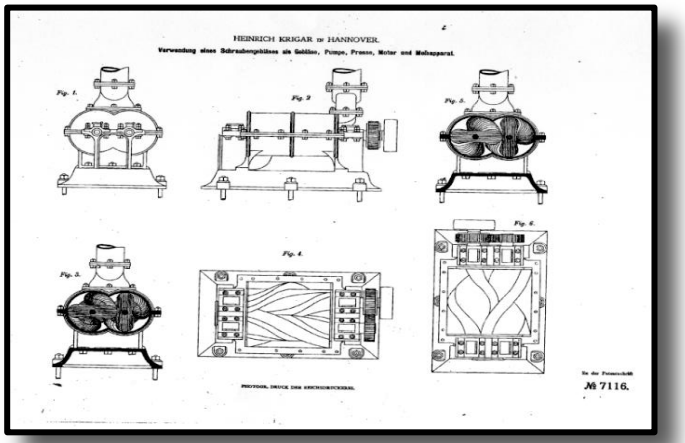
Divide Timeline into Phases

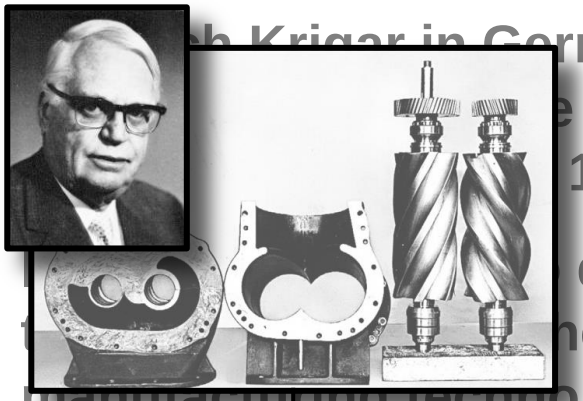
- Beginnings
- Re-invention
- Growth and Development

End up with a Useful Result

- How we got to where we are
- How we will define the future

OVERVIEW





Krigar in Germa first
of
18
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he I
manufacturing technology.

SRM

1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Beginnings

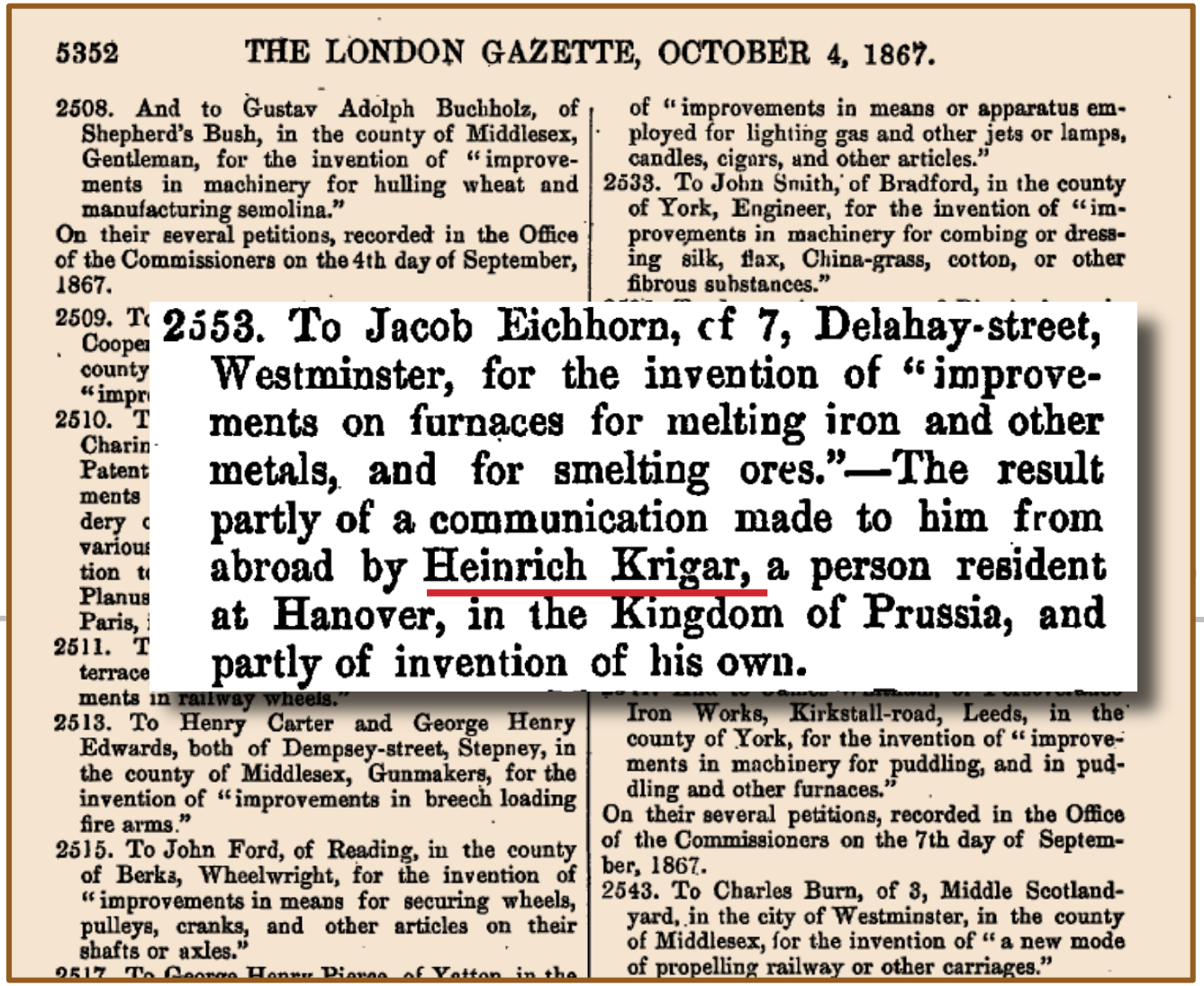
Reinvention

Growth and Development

BEGINNINGS

- What was Heinrich Krigar known for?
- Why did he even need a screw compressor?
- What does a woolen mill in Connersville, Indiana have to do with this story?

BEGINNINGS



5352 THE LONDON GAZETTE, OCTOBER 4, 1867.

2508. And to Gustav Adolph Buchholz, of Shepherd's Bush, in the county of Middlesex, Gentleman, for the invention of "improvements in machinery for hulling wheat and manufacturing semolina."

On their several petitions, recorded in the Office of the Commissioners on the 4th day of September, 1867.

2509. To Cooper county "impr

2510. T Charin Patent ments dery various tion t Planus Paris,

2511. T terrace ments in railway wheels."

2513. To Henry Carter and George Henry Edwards, both of Dempsey-street, Stepney, in the county of Middlesex, Gunmakers, for the invention of "improvements in breech loading fire arms."

2515. To John Ford, of Reading, in the county of Berks, Wheelwright, for the invention of "improvements in means for securing wheels, pulleys, cranks, and other articles on their shafts or axles."

2517. To George Henry Pierce, of Yatton, in the

of "improvements in means or apparatus employed for lighting gas and other jets or lamps, candles, cigars, and other articles."

2533. To John Smith, of Bradford, in the county of York, Engineer, for the invention of "improvements in machinery for combing or dressing silk, flax, China-grass, cotton, or other fibrous substances."

2553. To Jacob Eichhorn, of 7, Delahay-street, Westminster, for the invention of "improvements on furnaces for melting iron and other metals, and for smelting ores."—The result partly of a communication made to him from abroad by Heinrich Krigar, a person resident at Hanover, in the Kingdom of Prussia, and partly of invention of his own.

Iron Works, Kirkstall-road, Leeds, in the county of York, for the invention of "improvements in machinery for puddling, and in puddling and other furnaces."

On their several petitions, recorded in the Office of the Commissioners on the 7th day of September, 1867.

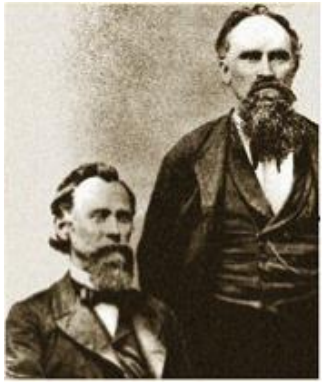
2543. To Charles Burn, of 3, Middle Scotland-yard, in the city of Westminster, in the county of Middlesex, for the invention of "a new mode of propelling railway or other carriages."

1870 1880 1890

Heinrich Krigar (1867)

Heinrich Krigar (1878)

BEGINNINGS



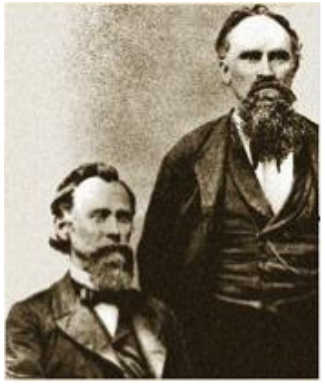
Francis & Philander…

…had a woolen mill in Connersville, Indiana…

1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

…that was powered by flowing water.

BEGINNINGS



THE CUPOLA FURNACE:

A PRACTICAL TREATISE ON THE

CONSTRUCTION AND MANAGEMENT

OF

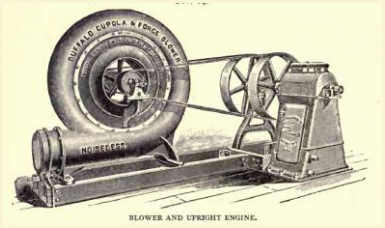
FOUNDRY CUPOLAS.

COMPRISING

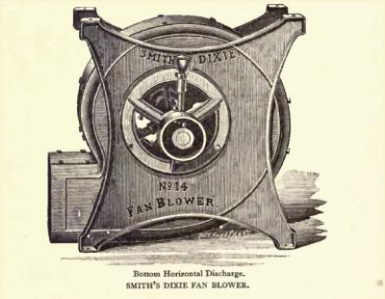
THE BEST METHODS OF CONSTRUCTION AND MANAGEMENT OF CUPOLAS; DIFFERENT SHAPED CUPOLAS; HEIGHT OF CUPOLAS; PLACING TUYERES; SHAPES OF TUYERES; LINING; SPARK CATCHING DEVICES; BLOWERS; BLAST PIPES; AIR GAUGES; CHARGING; DIRECTIONS FOR THE MELTING OF IRON, TIN-PLATE SCRAP, AND OTHER METALS IN CUPOLAS; EXPERIMENTS IN MELTING; WHAT A CUPOLA WILL MELT; ETC.

The first application of the Roots blower was in iron foundry cupolas.

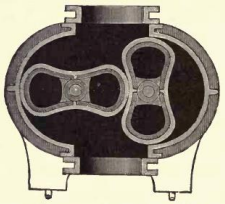
PHILADELPHIA:
HENRY CAREY BAIRD & CO.,
INDUSTRIAL PUBLISHERS, BOOKSELLERS AND IMPORTERS,
810 WALNUT STREET.
LONDON:
E. & F. N. SPON, LTD.,
125 STRAND.
1899.



BLOWER AND UPRIGHT ENGINE.

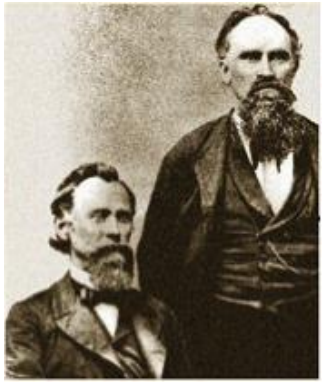


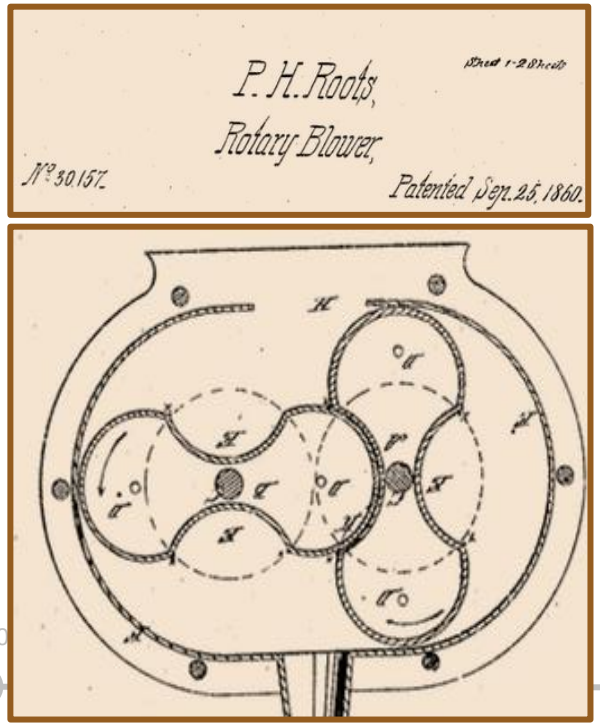
Bottom Horizontal Discharge.
SMITH'S DIXIE FAN BLOWER.

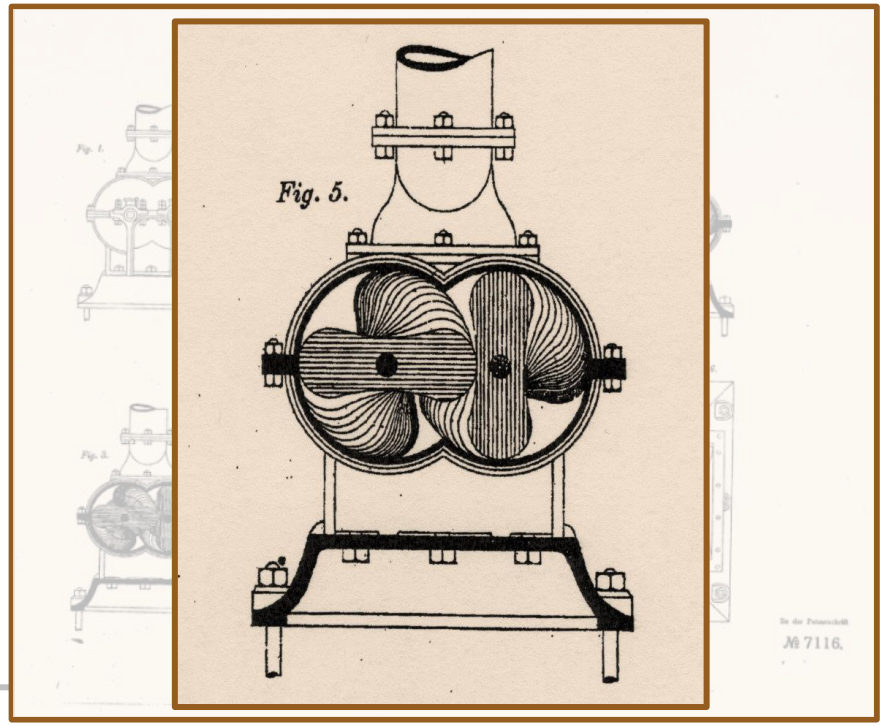


SECTIONAL VIEW OF CONNERSVILLE CYCLOIDAL BLOWER.

BEGINNINGS







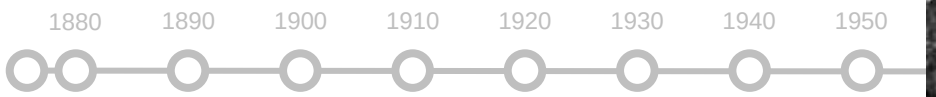
Roots
1860

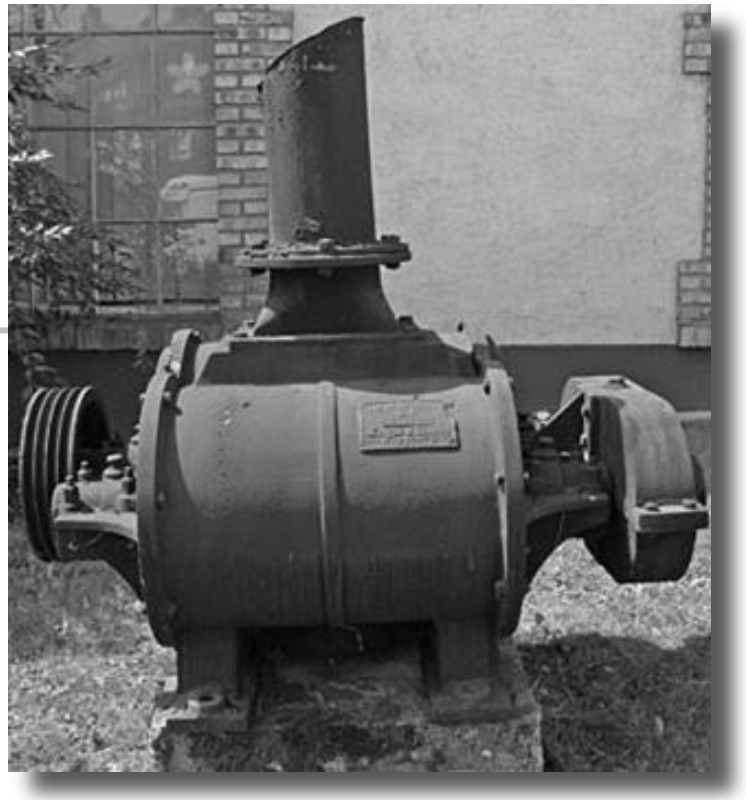
Krigar
1878

Putting these pieces together…

BEGINNINGS

- Krigar was an expert in foundry furnace design.
- New furnaces needed more flow and pressure.
- He modified the Roots brothers' invention to satisfy requirements.
- Success…





A Krigar "helical screw blower" at a Foundry in Ettelbrück, Luxembourg.

REINVENTION

- Gustav de Laval plants a seed.
- Two brothers from Sweden build a business.
- Alf Lysholm enters the picture.

REINVENTION

Gustav De Laval

Birger and Frederick Ljungström

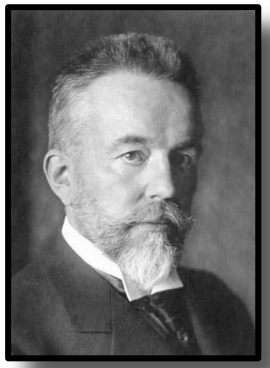
1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Heinrich Krigar

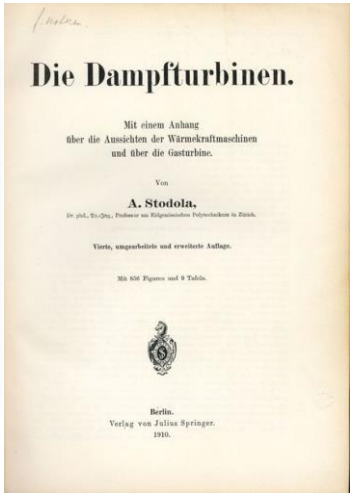
Francis & Philander Roots

Birger & Fredrick Ljungström

REINVENTION



Aurel Stodola



Die Dampfturbinen.

Mit einem Anhang
über die Aussichten der Wärmekraftmaschinen
und über die Gasturbine.

Von

A. Stodola,

Vierte, umgearbeitete und erweiterte Auflage.

Mit 856 Figuren und 9 Tafeln.

Berlin.
Verlag von Julius Springer.
1910.

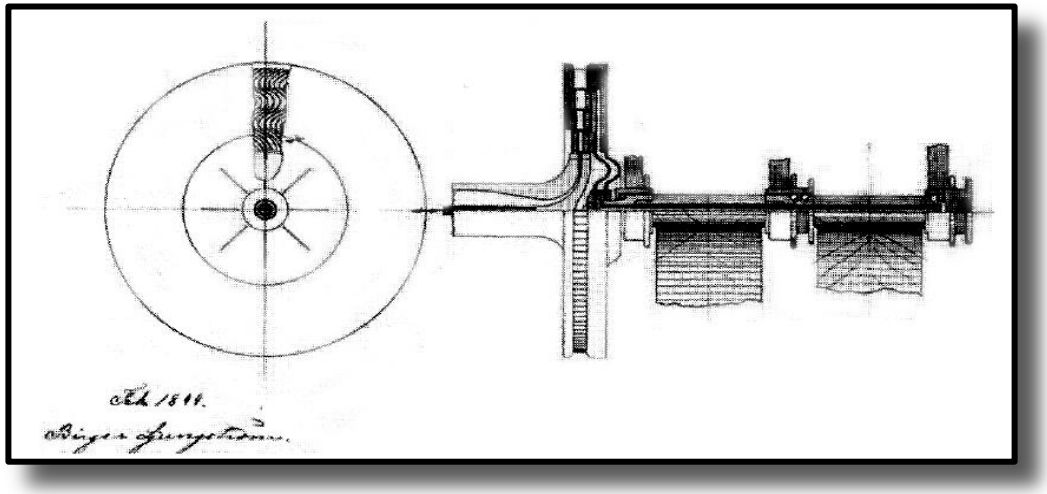
AB Ljungströms Ångturbin (ALÅ)

1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Heinrich Krigar

Francis & Philander Roots

Birger &Fredrick Ljungström



REINVENTION

Soren Edström

Alf Lysholm

Krigar's concept has gone from cupolas to gas turbines.

REINVENTION

- Ljungströms' interest in steam engineering led to the foundation of ALÅ and hiring of Alf Lysholm.
- Lysholm became an expert in steam turbines.
- He helped develop ALÅ's gas turbine concept.
- To avoid surge, he proposed using a positive displacement compressor.
- Success….

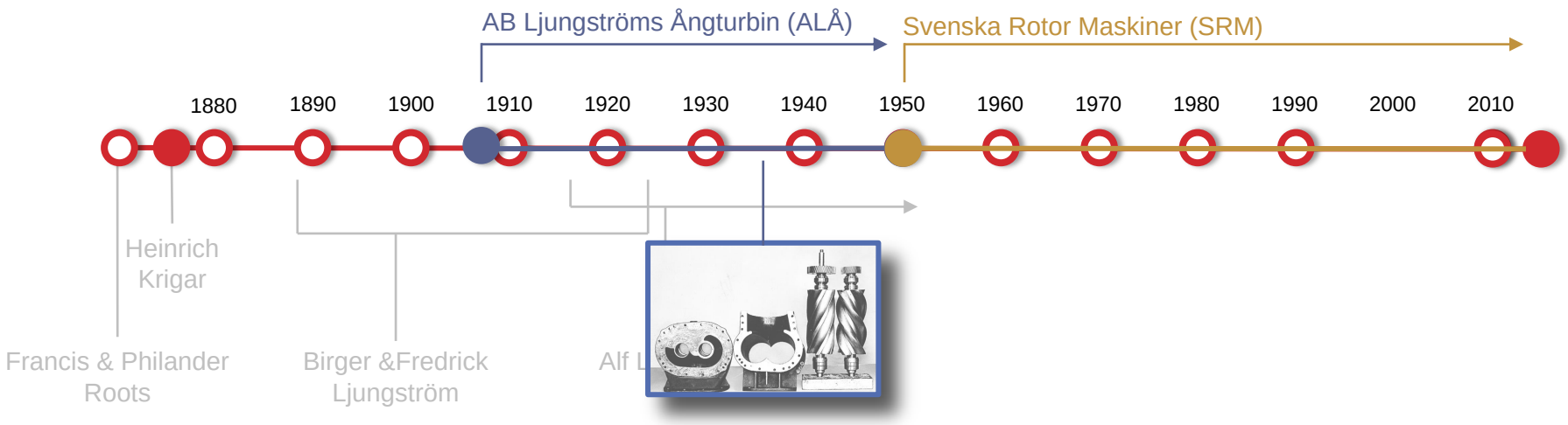
Not in gas turbines, but Lysholm's implementation of Krigar's 60 year old idea was the beginning of our screw compressor industry.

GROWTH AND DEVELOPMENT

- The appearance and growth of SRM.
- Seeds of commercialization.
- Building and using the body of knowledge.
- Manufacturing technology evolves.
- Success.

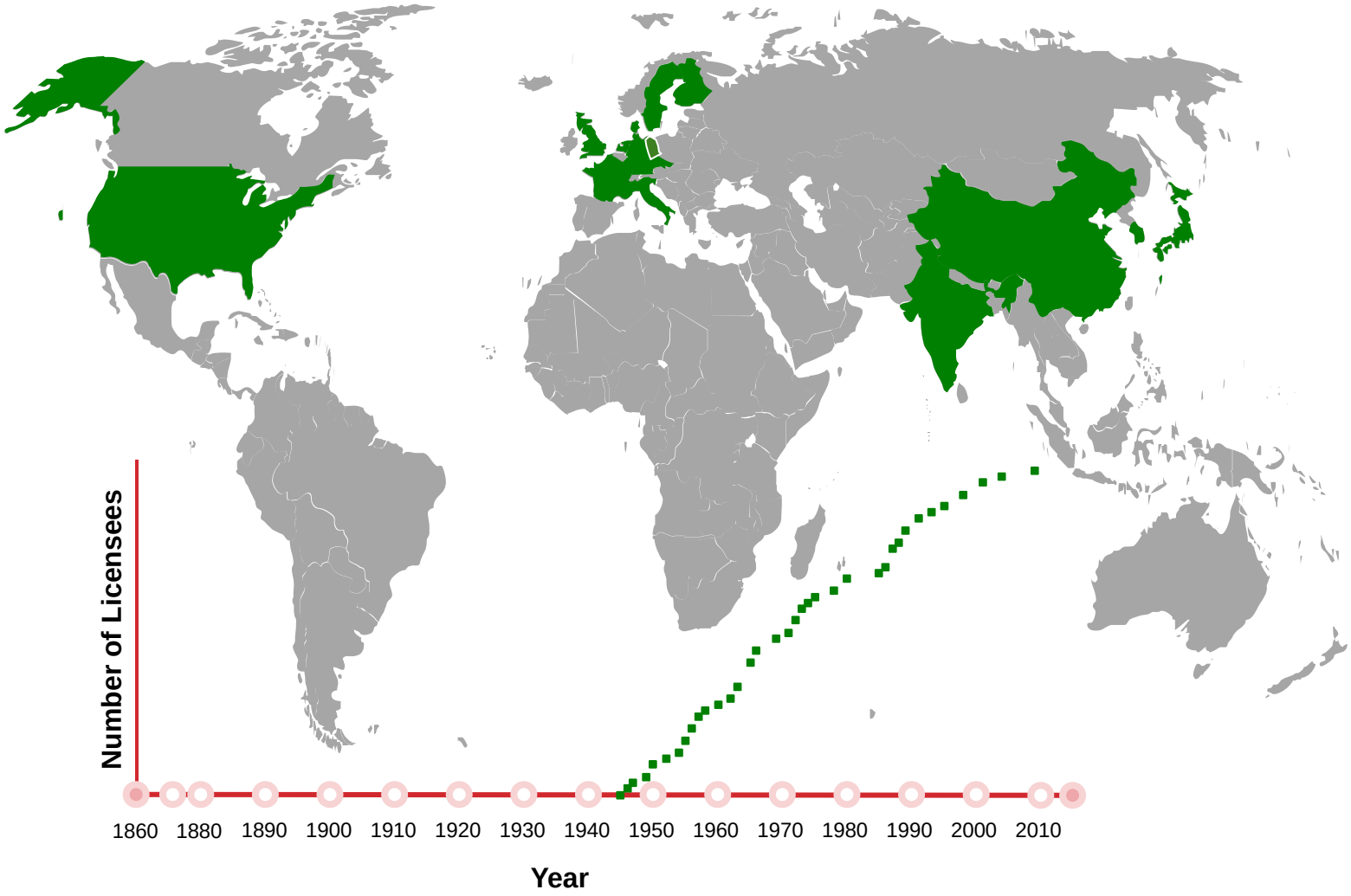
GROWTH AND DEVELOPMENT

Turbines to screw compressors & the appearance of SRM



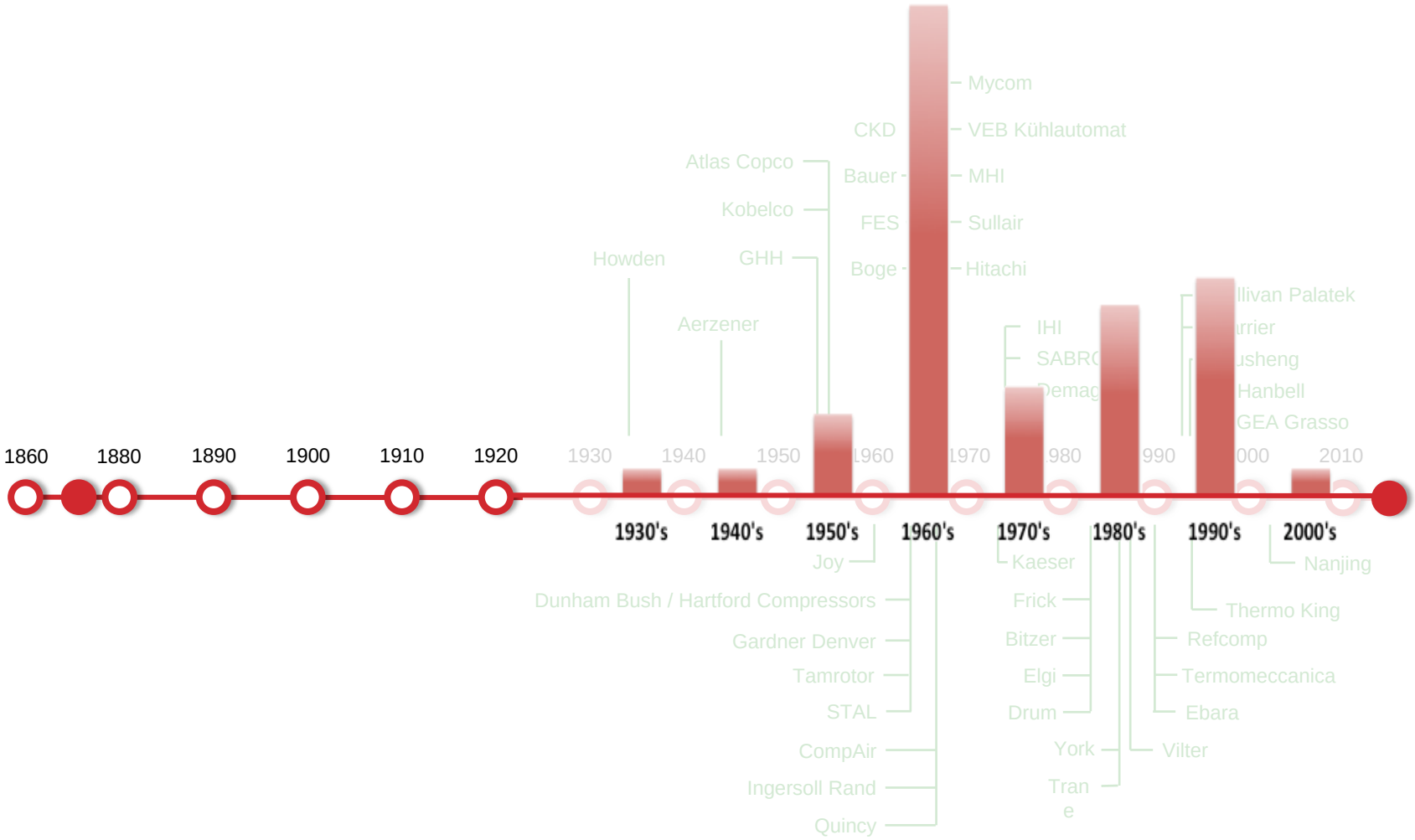
GROWTH AND DEVELOPMENT

Building up of SRM licensee involvement



GROWTH AND DEVELOPMENT

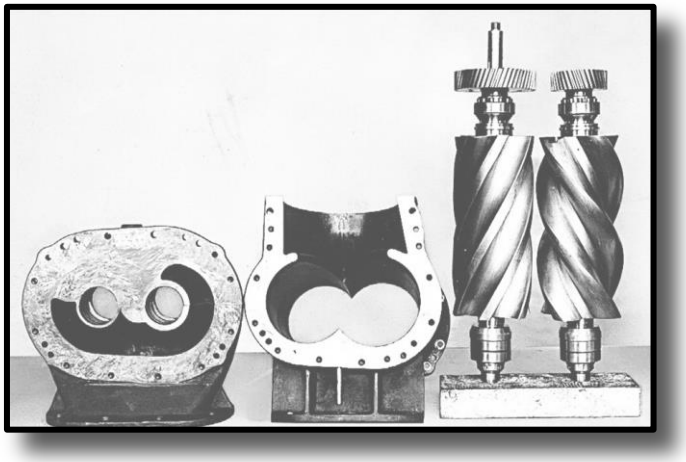
Commercial enterprises



Rapid Expansion in the 1960's

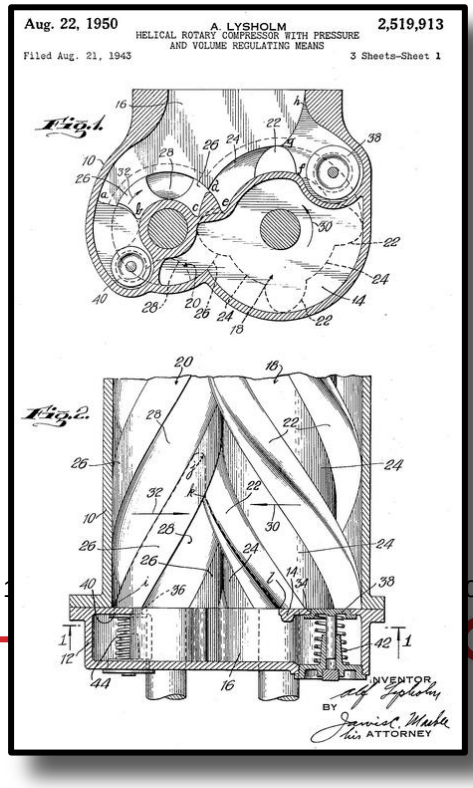
GROWTH AND DEVELOPMENT

1935 to 1950



Prototype dry running screw tests

70 options 25 options



Alf Lysholm

1860 1880 1890 1900 1910 1920 1930 1940 1950 1960 ... 010

Port type displacement and volume ratio control

GROWTH AND DEVELOPMENT

Building up the body of knowledge

Prototype dry running screw tests

70 options

25 options

1860 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

SRM begins publishing screw compressor reports

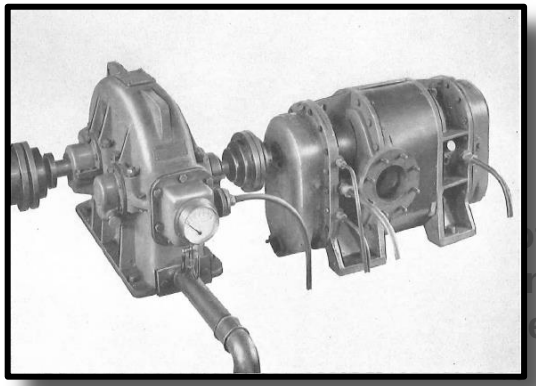
GROWTH AND DEVELOPMENT

Using the body of knowledge – Early adopters

Howden

"James Howden & Co Ltd … first company to commercialise the technology."

Howden.com



Guttehofnungshütte (GHH)

1952
"First oil-free screw compressor stage."

1953
"First two stage oil-free industrial compressor module."

ghhrand.com

type dry
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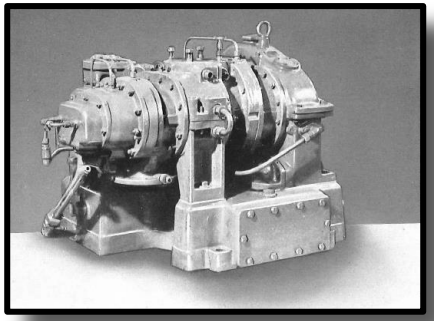
25 options

1860 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010



AERZEN

1943
"Production start for screw compressors."

Aerzen.com

KOBELCO

1955
"Completed Japan's first oil-free screw compressor."

kobelco.co.jp

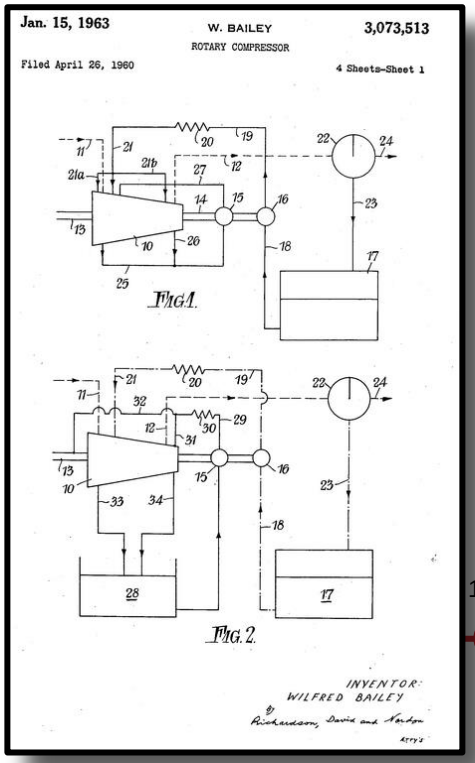
Atlas Copco

1955
"The first screw compressor is delivered."

atlascopco.com

GROWTH AND DEVELOPMENT

Building a body of knowledge



W. Bailey

1910 1920 1930 1940 1950 1960 1970

Oil flooded compressors

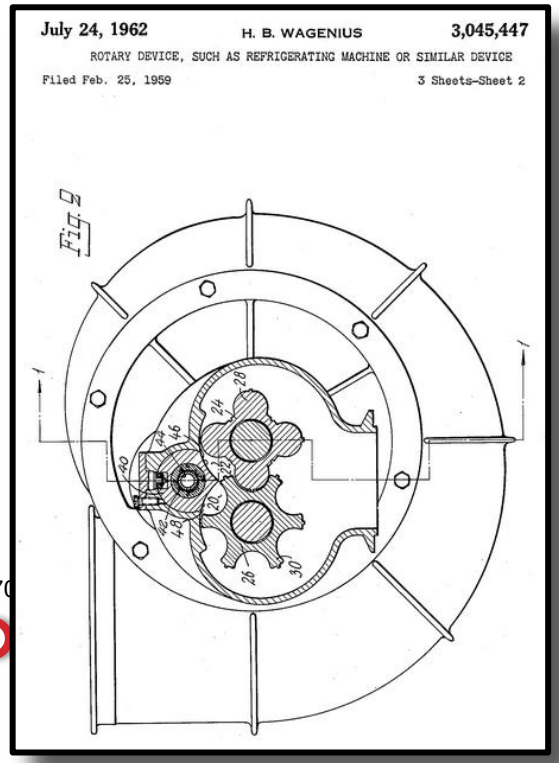
Prototype dry running screw tests

70 options

25 options

Port type displacement and volume ratio control

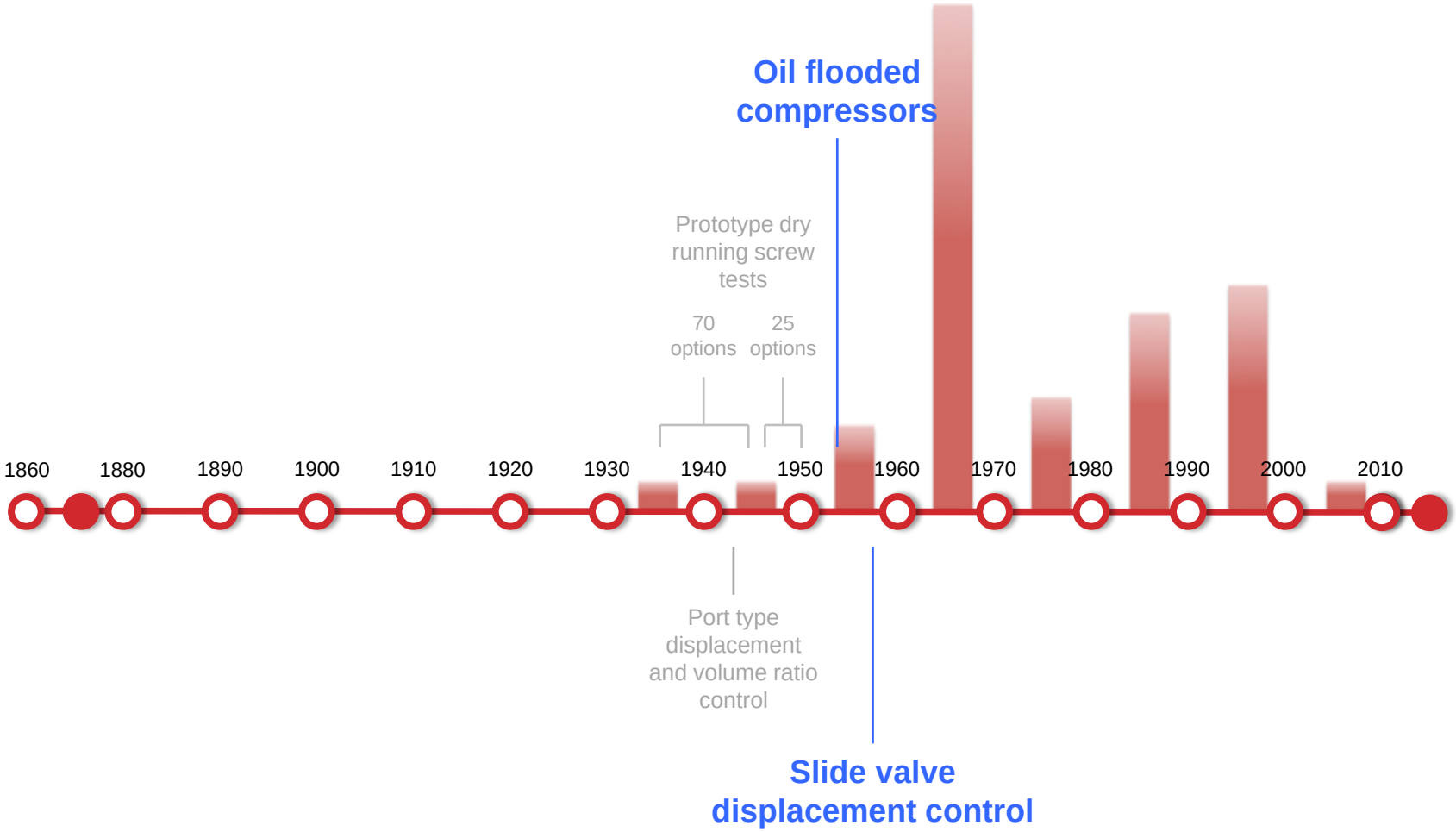
Slide valve displacement control



H. B. Wagenius

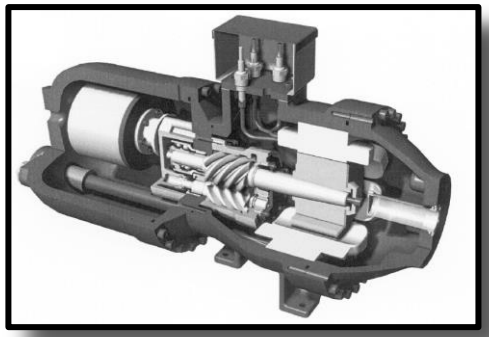
GROWTH AND DEVELOPMENT

Significant effect of developments in the 1950's



GROWTH AND DEVELOPMENT

1950's



SRM Refrigerant Compressor

Oil flooded compressors

Prototype dry running screw tests

70 options

25 options

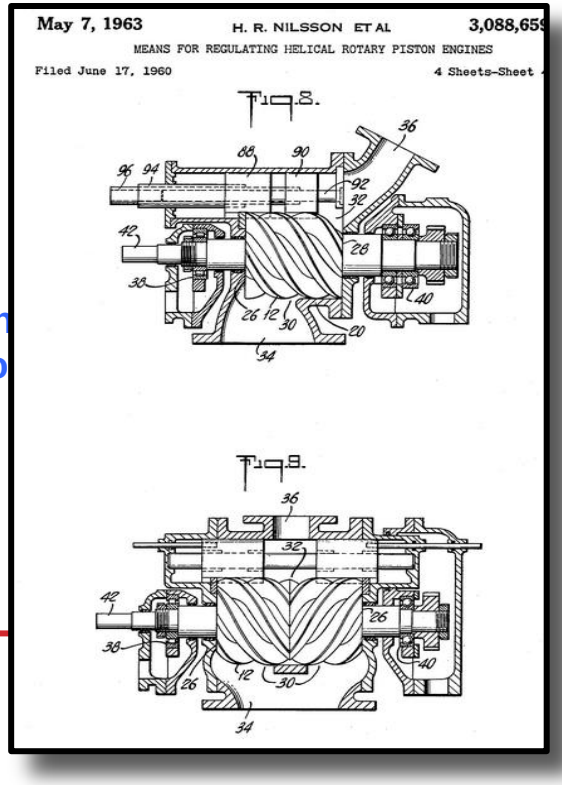
Refrigeran compresso

1860 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970

Port type displacement and volume ratio control

Slide valve displacement control

Slide valve volume ratio control

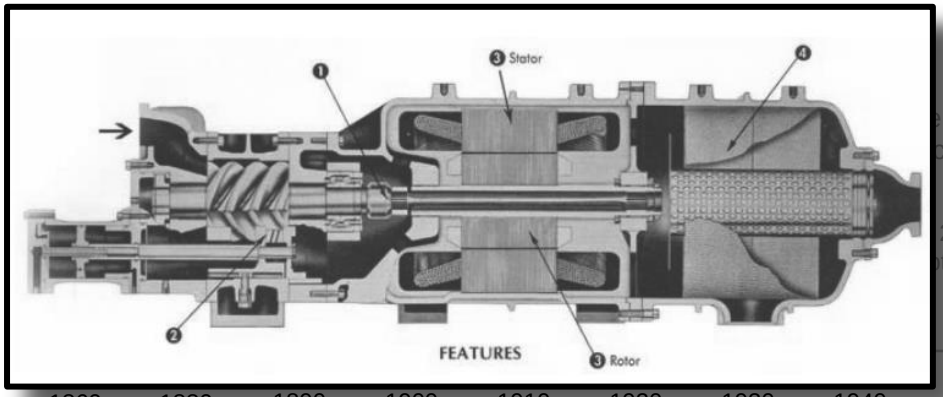


H. R. Nilsson

GROWTH AND DEVELOPMENT

1960's

Dunham Bush
First Semi-Hermetic Screw Compressor
For Air Conditioning Chillers



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Semi-her
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Refrigerant compressors

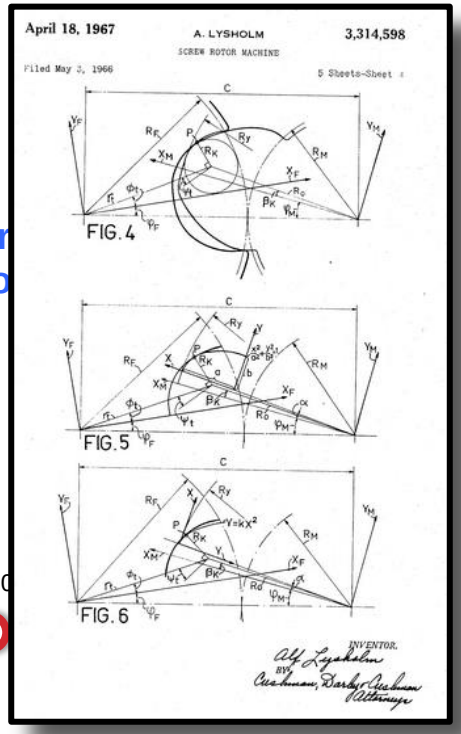
1860 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980

Port type displacement and volume ratio control

Slide valve displacement control

Slide valve volume ratio control

Asymmetric profile reintroduced



Alf Lysholm

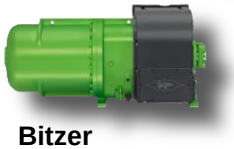
GROWTH AND DEVELOPMENT

1970's and onward

Ingersoll Rand

Trane

Atlas Copco



Bitzer

Frascold

Oil flooded compressors

Semi-hermetic screw for A/C

Refrigerant compressors

Prototype dry running screw tests

70 options

25 options

1860 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

Variable speed

Port type displacement and volume ratio control

Slide valve displacement control

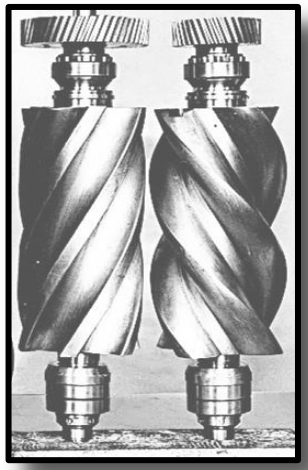
Slide valve volume ratio control

Asymmetric profile reintroduced

GROWTH AND DEVELOPMENT

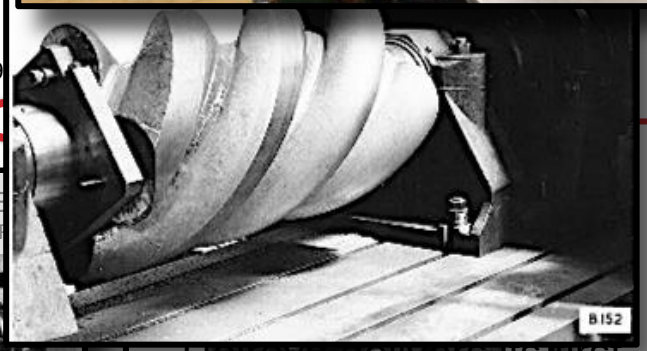
Manufacturing

Early SRM Prototype Rotors

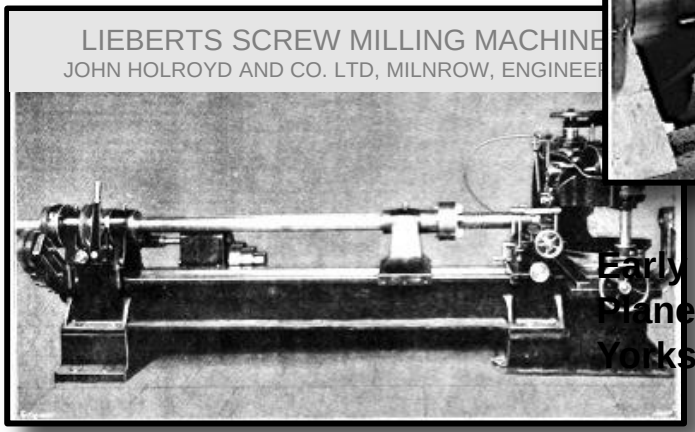


Holroyd 2A Profile Milling

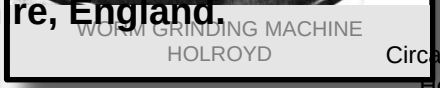
1860 1880 1890 1900 1910 19 1980 1990 2000 2010



Holroyd delivers its first milling machine to Howden



Early attempt at rotor manufacture. Planer made by Swift-Summerskill, Yorkshire, England.



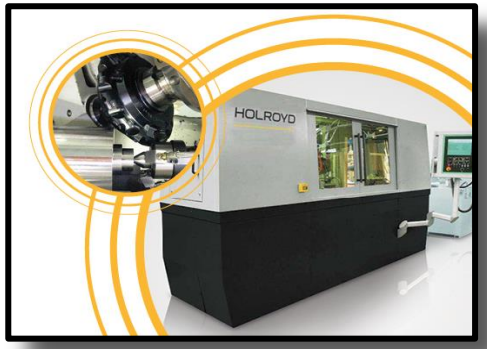
Circa 1950
Holroyd

GROWTH AND DEVELOPMENT

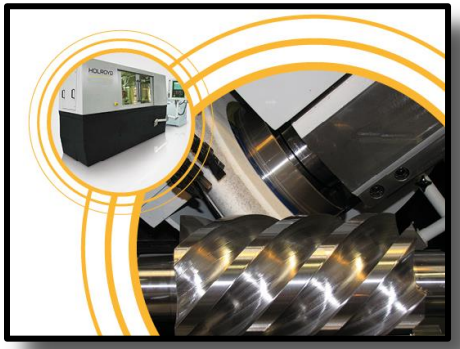
Manufacturing

Holroyd 2A
Profile Milling

1993
Holroyd EX
Profile Milling



2011
Holroyd TG
Dressable Wheel Grinding

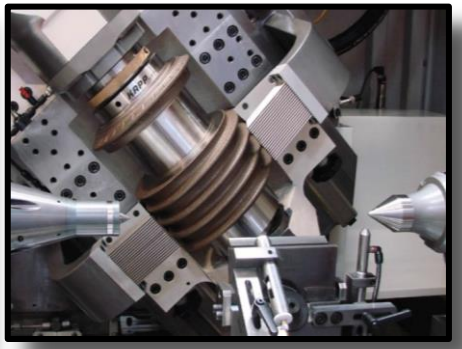


1880 1890 **1983** 1920 1930 1940 **2005** 1970 1980 1 **2013** 2010

Kapp RNS Series
CBN Profile Grinding

Kapp RX59
CBN Profile Grinding

Kapp RX120
CBN Profile & Generating Grinding



GROWTH AND DEVELOPMENT

- SRM begins building body of knowledge.
- Early adopters use the information, take risks, demonstrate viability and identify shortcomings.
- Technical solutions lead to acceptance.
- Manufacturing technology advances.
- Success…

The number of firms engaged in commercial activity more than triples in the 1960's.

More than 3 million compressors manufactured by SRM licensees since the mid 1940's.

Over 400,000 compressors produced in 2013.

GETTING MEANINGFUL RESULTS

- Examples of the body of knowledge available today.
- Development of screw compressor simulations.

5

GETTING MEANINGFUL RESULTS

The body of knowledge

Sakun

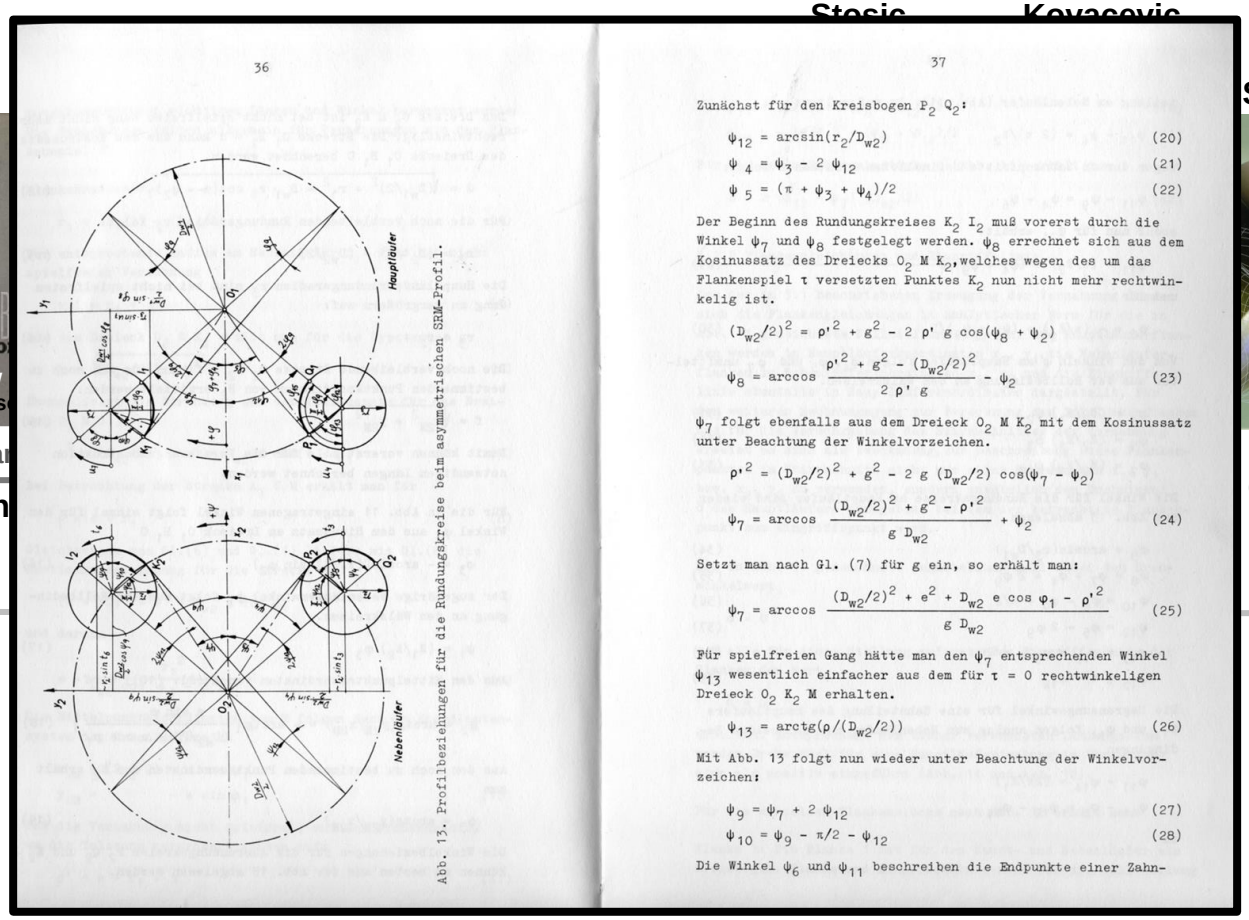
Russian

Compreh

1880

Stosic

Kovacevic



36

Abb. 13. Profilbeziehungen für die Rundungskreise beim asymmetrischen SRM-Profil.

37

Zunächst für den Kreisbogen P_2 Q_2:

$$\psi_{12} = \arcsin(r_2/D_{w2}) \quad (20)$$

$$\psi_4 = \psi_3 - 2\,\psi_{12} \quad (21)$$

$$\psi_5 = (\pi + \psi_3 + \psi_4)/2 \quad (22)$$

Der Beginn des Rundungskreises K_2 I_2 muß vorerst durch die Winkel ψ_7 und ψ_8 festgelegt werden. ψ_8 errechnet sich aus dem Kosinussatz des Dreiecks O_2 M K_2, welches wegen des um das Flankenspiel τ versetzten Punktes K_2 nun nicht mehr rechtwinkelig ist.

$$(D_{w2}/2)^2 = \rho'^2 + g^2 - 2\,\rho'\,g\cos(\psi_8 + \psi_2)$$

$$\psi_8 = \arccos\frac{\rho'^2 + g^2 - (D_{w2}/2)^2}{2\,\rho'\,g} - \psi_2 \quad (23)$$

ψ_7 folgt ebenfalls aus dem Dreieck O_2 M K_2 mit dem Kosinussatz unter Beachtung der Winkelvorzeichen.

$$\rho'^2 = (D_{w2}/2)^2 + g^2 - 2\,g\,(D_{w2}/2)\cos(\psi_7 - \psi_2)$$

$$\psi_7 = \arccos\frac{(D_{w2}/2)^2 + g^2 - \rho'^2}{g\,D_{w2}} + \psi_2 \quad (24)$$

Setzt man nach Gl. (7) für g ein, so erhält man:

$$\psi_7 = \arccos\frac{(D_{w2}/2)^2 + e^2 + D_{w2}\,e\cos\varphi_1 - \rho'^2}{g\,D_{w2}} \quad (25)$$

Für spielfreien Gang hätte man den ψ_7 entsprechenden Winkel ψ_{13} wesentlich einfacher aus dem für $\tau = 0$ rechtwinkeligen Dreieck O_2 K_2 M erhalten.

$$\psi_{13} = \operatorname{arctg}(\rho/(D_{w2}/2)) \quad (26)$$

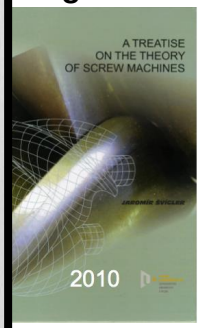
Mit Abb. 13 folgt nun wieder unter Beachtung der Winkelvorzeichen:

$$\psi_9 = \psi_7 + 2\,\psi_{12} \quad (27)$$

$$\psi_{10} = \psi_9 - \pi/2 - \psi_{12} \quad (28)$$

Die Winkel ψ_6 und ψ_{11} beschreiben die Endpunkte einer Zahn-

Svigler



Extensive geometrical analyses

2000 2010

GETTING MEANINGFUL RESULTS

The body of knowledge

Professor Laurenz Rinder

GETTING MEANINGFUL RESULTS

The body of knowledge

1880 1890 1900 1910 1960 1970 1980 1990 2000 2010

Professor Andreas Brümmer

Purdue
1972
21 Conferences
158 screw papers

VDI / TU Dortmund
1984
8 Conferences
212 screw papers

IMechE / CU London
1999
8 Conferences
95 screw papers

37 Conference Events Offered Since 1972
465 Screw Compressor Papers Now Contained in the Proceedings

GETTING MEANINGFUL RESULTS

Building and using the body of knowledge

PREDICTION OF THE OIL-FREE SCREW COMPRESSOR PERFORMANCE USING DIGITAL COMPUTER

M. Fujiwara, H. Mori and T. Suwama
Mechanical Engineering Research Laboratory, Hitachi Ltd., Japan

Well developed reciprocating compressor simulations provide model for screw

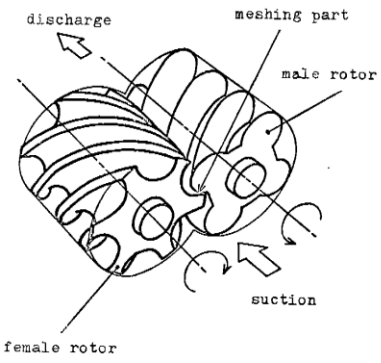


Fig.1 The rotors of the screw compressor

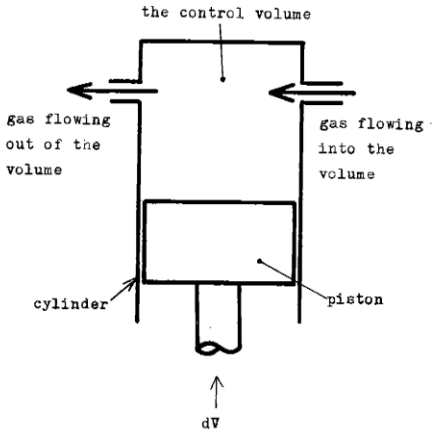


Fig.2 Model of the compression process

Simulation provides insights into screw-specific issues

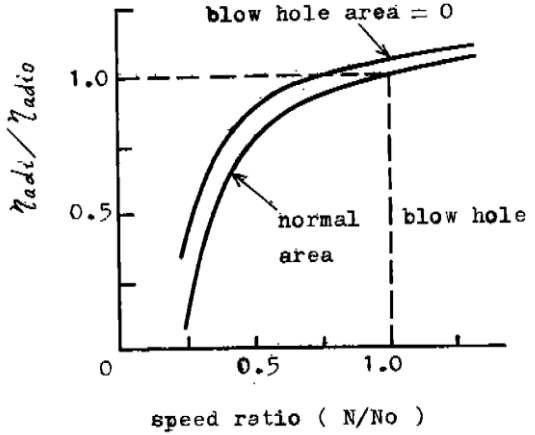


Fig. 6 η_{adi} as function of speed.
(parameter : blow hole area)

GETTING MEANINGFUL RESULTS

Building and using the body of knowledge

MODELING AND SIMULATION OF ROTARY SCREW COMPRESSORS

Mark A. Firnhaber
Industrial Division, Joy Machinery Company
900 Woodland Avenue, Michigan City, Indiana

Donald S. Szarkowicz, Ph.D.

REFERENCES

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2. Hamilton, J.F., "Extensions of Mathematical Modeling of Positive Displacement Type Compressors", Ray W. Herrick Laboratories, Purdue University, July, 1974.

3. Schwerzler, D.D., "Mathematical Modeling of a Multiple Cylinder Refrigeration Compressor", Ph.D. Thesis, Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University, June, 1971.

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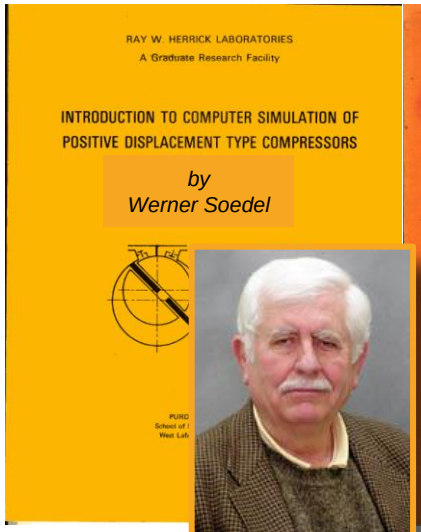

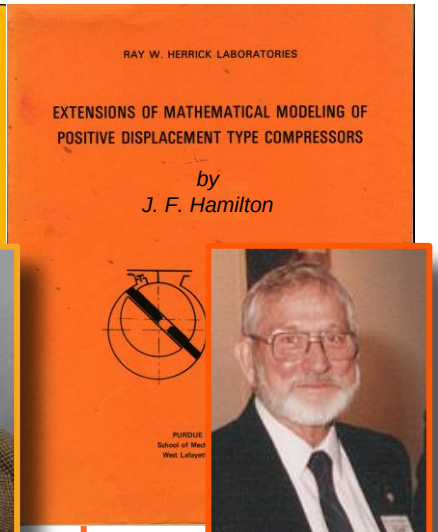

1880 18 1940 1950 1960 1970 1980 1990 2000 2010

MATHEMATICAL MODELING AND DESIGN EVALUATION OF HIGH-SPEED RECIPROCATING COMPRESSORS

A Thesis
Submitted to the Faculty
of
Purdue University

by

Martin William Wambsganss, Jr.

A Partial Fulfillment of the
Requirements for the Degree
of
Doctor of Philosophy

January, 1966

GETTING MEANINGFUL RESULTS

Building and using the body of knowledge

1940 1950 1960 1970 1980 1990 2000 2010

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GETTING MEANINGFUL RESULTS

Building and using the body of knowledge

1982

Analytical Modeling of Helical Screw Machine for Analysis and Performance Prediction

B. Sangfors

1984

Computer Simulation of the Oil Injected Screw Compressor

B. Sangfors

1998

Computer Simulation of Effects From Inj Different Liquids in Screw Compressors

B. Sangfors
Svenska Rotor Maskiner AB

2000

Modeling, Measurements and Analysis of Gas-Flow Generated Noise From Twin-Screw Compressors

B. Sangfors
Svenska Rotor Maskiner AB

REFERENCES

1. D.L. Margolis
"Analytical Modeling of Helical Screw Turbines for Performance Prediction" ASME Journal of Engineering for Power, vol. 100, July 1978,

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roke Internal Combustion g the Bond Graph Technique" pp 2263-2275 September 1975.

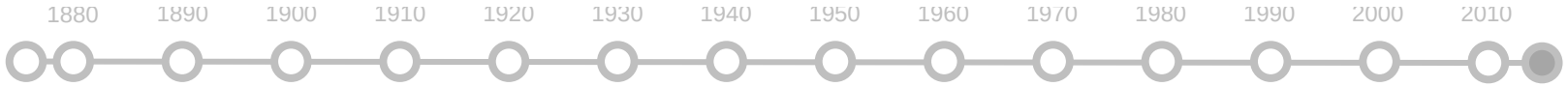
. Rosenberg Unified Approach" York, 1975.

1980 1990 2000 2010

Bo Sångfors

GETTING MEANINGFUL RESULTS

- **Large body of knowledge available.**
- **Contributions from academia, technology organizations, industrial firms.**
- **Various degrees of accessibility.**
- **Existing information used as basis for advances.**
- **Success illustrated in Purdue Conferences…**



24 papers on screw compressor simulation.

Based on my experience, this is a significant contribution to industry designers.

THE FUTURE DEFINED

- What I think we will see.
- What I k[illegible]ow it will happen.

1880 1890 1900 1910 1960 1970 1980 1990 2000 2010

Professor Knut Kauder

THE FUTURE DEFINED

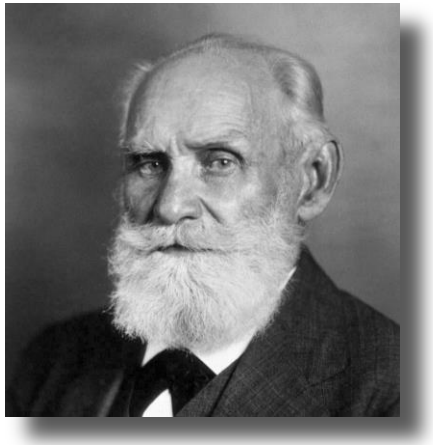
What I think we will see

- **CFD for “everyday” design**
  - Multi-phase flow
  - Fluid-structure interaction
- **Full spectrum optimization**
  - System models to simulate application stress
  - Manufacturing models to include variation stress
- **Manufacturing process simulation**
  - Model variation in machine functions
- **Adaptable, tolerant designs and smart systems**
  - Adjustable or condition tolerant configurations
  - Sensors, controls and materials

It’s hard to make predictions, especially about the future

THE FUTURE DEFINED

What I know about how it will be done



"If you want new ideas, read old books."

Ivan Petrovich Pavlov

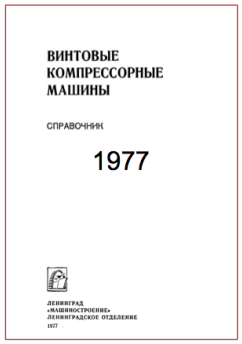
"If I have seen further it is by standing on the shoulders of giants."

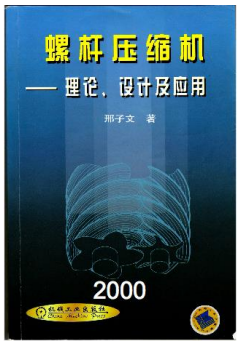
Isaac Newton

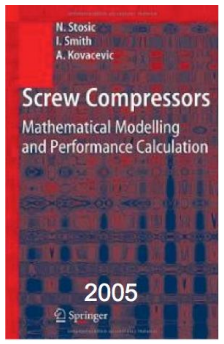
So, we should find the old books and giants…

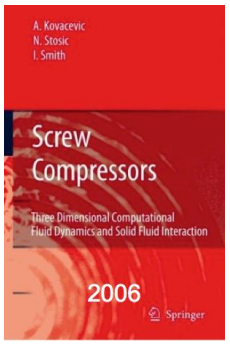
THE FUTURE DEFINED

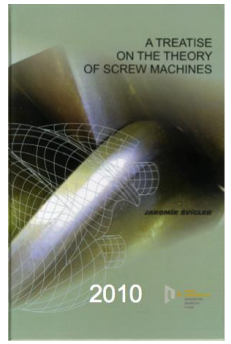
Here are just a few of the old books…

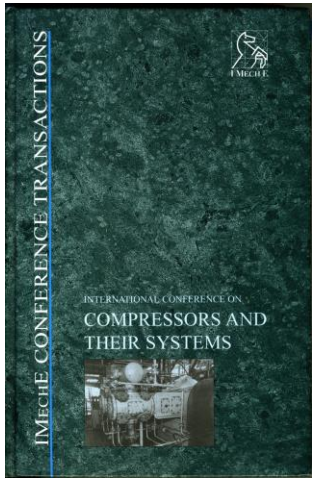












Use and contribute to the body of knowledge

THE FUTURE DEFINED

… and the giants are right here.

… that is exactly how the future of screw compressors will be determined.

Take the opportunity to share ideas and results with others

THANKS

Purdue / Herrick Labs
Compressor Conference Organizing Committee
Professor Eckhard Groll
Kimberly Stockment
Christian Bach
Stephen Caskey
Donna Cackley
Ingersoll Rand (Trane, Thermo King)
Matt Cambio
Drew Turner
Lars Sjoholm
John Crouse
Jeanne Harshaw
Joe Riemer
Gang Wang
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Bright Wei Liang Sun
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Frascold
Matteo Iobbi
TU Wien
Professor Laurenz Rinder
Dresser Roots Connersville

QUESTIONS OR COMMENTS?

2014 Purdue Conferences
Compressor Engineering
Refrigeration and Air Conditioning
High Performance Buildings

SCREW COMPRESSORS

PAST, PRESENT AND FUTURE

Want to offer your opinions on going forward with screw compressor technology?

You can do so by completing a short survey using the link below. Results will be compiled for review by the conference organizing and advisory committees. Results will be shared as appropriate based on responses.

https://purdue.qualtrics.com/SE/?SID=SV_88MJjihtfoxk7e5

Survey closes on July 31, 2014

COFFEE BREAK

9:30 – 9:45