History in the Air Conditioning and Refrigeration Industry:

Breakthrough of Large Positive Displacement Rotary Compressors in the Second Half of the 20th Century

Introduction

Only two classes of compressors were offered at the end of the 1950s in the United States for large air conditioning and refrigeration applications: the positive displacement reciprocating and the dynamic centrifugal machines. Reviewing manufacturers' catalogs of water chillers showed that the capacity range of the two classes overlapped. The authors of a 1961 paper[1] came to the following conclusions:

"The hermetic reciprocating compressors should be competitive with centrifugals up to approximately 250 ton in normal comfort cooling applications…will best serve the purpose for applications where the compression ratios are high or highly variable…. and in all applied systems requiring direct expansion air-handling units, remote air cooled or evaporative condensers."

Anticipating future technical developments, the authors suggested that the capacity overlap might be bridged by nonreciprocating higher speed compressors combining the advantages of both reciprocating and centrifugal designs: positive displacement, i.e., no surging, wide applications range and use of high pressure refrigerants, as well as high speed capabilities due to the absence of reciprocating valves for maximum capacity per volume or weight of compressor. This forecast was based partially on recent trends in engine driven portable air compressors where the reciprocating had been gradually displaced by oil flooded rotary-machines, first of the sliding-vane then of the screw-design. Capacity control was achieved by varying the rpm of the driver without any compressor unloading device.

The concept of the screw compressor was patented in Sweden by Professor A. Lysholm in 1934. A prototype landed in the Holyoke, Mass., laboratory of the Worthington Pump Corp. in the fall of 1950. The writer, who had just joined the company, was given the job of testing and evaluating its potential in refrigeration applications; the verdict was definitely negative. This dry (oil free compression), extremely high-speed machine was very noisy and would require mechanical speed increasers even when directly coupled to two-pole electric motors at about 3,600 rpm, and the complex screw lobes and gullies were extremely difficult to manufacture. However, the Swedish engineering company, Svenska Rotor Maskiner AB (SRM), owning the Lysholm patent rights developed simpler manufacturable oil flooded

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During a 20-year period in the U.S. he was active in the air conditioning and refrigeration (AC&R) industry, first at the AC&R division of Worthington Corporation, leaving this company as chief engineer to join Dunham-Bush, Inc., West Hartford, Conn., as research, development and engineering director. During the latter period he introduced the hermetic rotary screw compressor systems for AC&R applications on the U.S and world market. This work provided the basis for several two-phase fluid flow and heat transfer papers published in international technical journals and his doctoral thesis at the ETHZ, titled: "Single Component Two-Phase Annular-Dispersed Flow in Horizontal Tubes without and with Heat Addition from a Constant or Variable Temperature Source."


Soumerai

He returned to Europe as technical director of the Industrial Products Group of ITT Europe, Inc., at their Brussels, Belgium headquarters. After seven years in the energy generation business with Brown Boveri & Cie., Switzerland, he became an independent consultant concluding his career by returning to the AC&R industry with Dunham-Bush and their welded hermetic Vertical Screw Compressors.

He is the owner of eleven U.S. patents, was active in numerous U.S. and overseas engineering/industry associations and committees (mainly with ASHRAE and IIR) and has authored many papers and textbook chapters in the field of thermal engineering and new products development, including a book with John Wiley & Sons, Interscience Division, titled "Practical Thermodynamic Tools for Heat Exchanger Design Engineers."

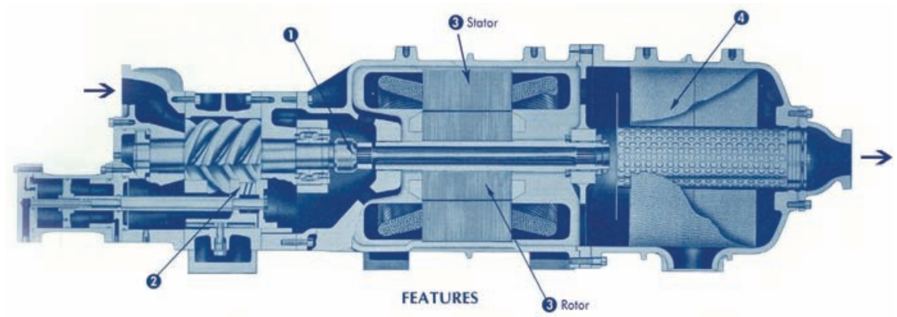


Figure 1: Design of first large hermetic screw compressors.

1 - Direct drive: compressor directly connected by flexible spline shaft to the rotor of the hermetic electric motor.

2 - Continuous stable capacity modulation: from 100 % down to 10 % by means of hydraulically actuated single slide valve assembly entirely within hermetic enclosure (no drive shaft extending through compressor housing to the outside required with open type screw-and centrifugal hermetic- compressors).

3 - Effective more efficient high pressure side hermetic motor cooling[6a] resulting, due to the constant ample flow of cool oil mist, in safe winding temperatures at full load and lower temperatures at part load in contrast to conventional suction gas cooled hermetic motors.[17,18] More importantly, by avoiding the second law of thermodynamic losses associated with suction gas cooling, the energy ratio, or kW/ton is moderately improved at full load but becomes more significant at part loads, i.e., under the conditions most frequently encountered in air conditioning applications.

4 - Integral effective two-stage oil separation[6a] by centrifugal forces, 3-rotor, followed by compact static separator 4.

5 - Force feed lubrication with separate hermetic motor driven oil pump (not shown) to provide lubrication prior to start up and during coast down periods in accordance with architect and engineering consultant specifications in the 1960s (based on centrifugal requirements).

versions without timing gears that could be directly coupled to two-pole electric motors together with other major design improvements, such as an unloading device necessary with fixed rpm electric drives. These improvements made this new technology quite suitable for air conditioning and refrigeration applications. The writer, who was then responsible for the high-speed single-stage centrifugal chiller program in the late 1950s at the air conditioning and refrigeration (AC&R) division of Worthington Corp., submitted and obtained approval for a feasibility study of hermetic screw compressors as an alternative up to 600 or 1,000 ton to the high-speed centrifugal program under way.

Initial Breakthrough in Europe: Large Open Type Screw Compressors

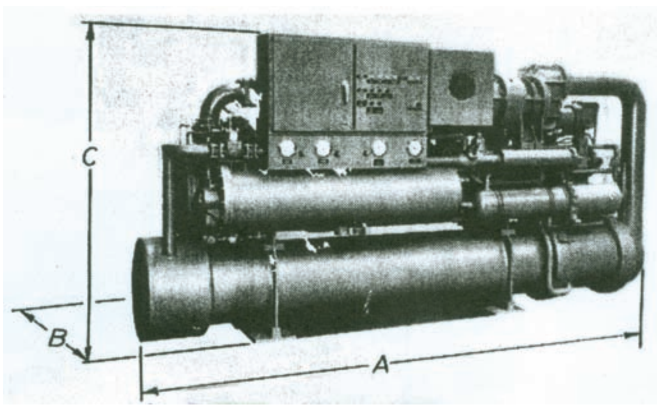
At the beginning of the 1960s three manufacturers had already pioneered this new technology, exclusively with open-type machines, mainly for pure refrigeration and a few industrial air conditioning applications. These manufacturers, STAL,[2] Howden[3] and Mayekawa were all licensees of SRM and initially used the same basic rotors design, the same rotor diameters and similar rotor lengths to diameter ratios ranging from 1.0 to 1.7. However, U.S. shipments of package chillers indicated that over 85% were of the hermetic type, therefore, to penetrate the large air conditioning market, hermetic screw compressors were necessary.

U.S. Breakthrough: Large Hermetic Type Screw Compressors (1967)

This new technology was pioneered by a medium-size U.S. manufacturer, Dunham-Bush (D/B), under the leadership of a dynamic entrepreneur named Cecil Boling, the first president of ASHRAE. He had the courage to enter the large air conditioning market with hermetic screw compressors in direct competition with the long established centrifugal systems offered by the leading U.S. manufacturers. The official launch of the new DBX line of screw compressor systems occurred during the 1967 ASHRAE Winter Meeting at the ARI show in Detroit where the first (worldwide) large hermetic screw compressors and package chillers commercially available were displayed.

Concurrently, a paper[4] was presented showing a typical European open-type version with an oil separator twice as large as what was sitting on it. A drastic oil separator size reduction was necessary to compete in the U.S. market. This was accomplished by placing the motor on the discharge side of the compressor and using the electric rotor as a dynamic oil separator, followed by a compact static oil separator **(Figure 1)**. As a result, the complete hermetic unit was smaller and lighter than the incomplete unit sitting on its separator. These open-type designs were not competitive with the compact hermetic compressors. More importantly, the compact DBX hermetic chillers **(Figure 2)** could compete with the most modern centrifugal chillers as discussed in a paper[5] in which key features of the DBX chillers were compared with the centrifugals of eight different manufacturers and concluded, predicting that future hermetic screw compressors would also penetrate the market below 100 ton.

Readers can find more detailed engineering information on several unique design features (some patented at the time) incorporated in the DBX package chillers in a 1987 Wiley Interscience publication.[6a]



CAPACITY TONS-NOM.	LENGTH A-FT.	WIDTH B-FT.	HEIGHT C-FT.	FLOOR SPACE FT.^{2}	FT.^{2}/TON
118	12.5	2.8	4.8	35	.30
170	12.5	3.0	5.2	38	.22
226	12.5	3.2	5.8	40	.18
327	12.5	3.5	6.2	44	.14

Figure 2: Compact DBX water chillers.

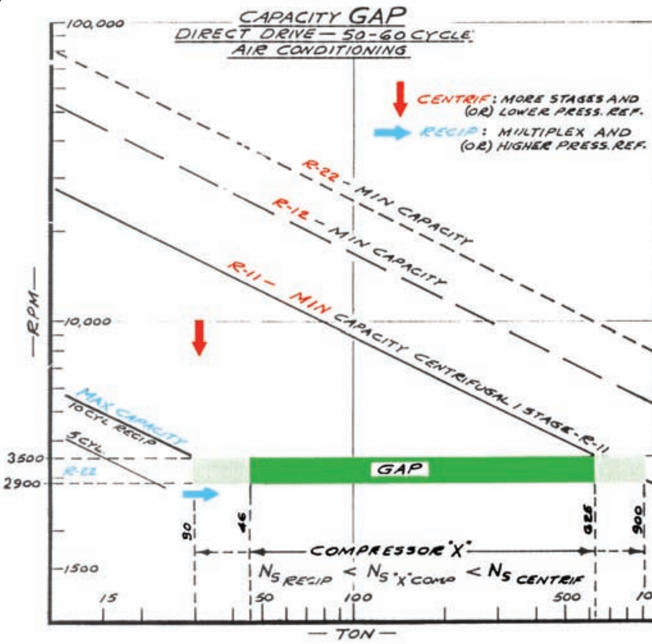


Figure 3: Gap chart.

Potential Market Penetration: The Gap Chart (1964)

Whilst in full agreement with the screw program, the D/B sales vice president was concerned that the architect and engineering consultants, the key decision makers in this market, might resist such a radical departure from established practice originating from a relatively minor manufacturer. Cecil Boling asked him to select a number of consultants and have the writer present this new technology to them. It was a pleasant surprise to find them very receptive to the new approach and even eager to participate in its field testing. The last slide presented to them was the so-called GAP graph **(Figure 3)**. This graph shows the attainable capacity as a function of compressor rpm for reciprocating and single-stage centrifugals. The green band named GAP identifies the competitive range of any new positive displacement compressor design (X) that could operate efficiently, directly driven by two-pole hermetic motors without speed increasers. The presentations were usually concluded by asking the consultant what features they would wish to find in this new compressor X. Their answers were consistently the same: rotary motion without reciprocating parts and automatic valves, like the centrifugals, plus the flexibility of the reciprocating compressors, which spelled out exactly the unique features of the screw machines.

During the field test period of the DBX line, similar oral presentations were made to engineering societies in the United States, Canada and Europe until Frank Versagi, the editor of ACH&R News, solicited a personal presentation. This was a more lengthy session than the previous presentations that Frank recorded and published verbatim under the title "Changing Picture in Large Tonnage Equipment"[7] followed by an epilogue.[8]

Design Targets/Solutions Below 100 Ton

It is clear that the first generation of DBX hermetics primarily intended to compete with centrifugals in large tonnage package chillers could not be competitive with the reciprocating machines below 100 ton, as luxury features of the centrifugals were incorporated in the design that were not necessary. In spite of this conservative design approach 1,800 screw compressor packages with capacities ranging from 120 to 650 ton had been delivered by the end of 1974[9]

To penetrate the market dominated by reciprocating hermetics the screw compressors had to be exclusively semi- or welded-hermetic with the electric rotor mounted on one of the shafts of the compressor rotors, thus eliminating two sets of bearings plus the internal spline coupling shown in Figure 1. Further significant cost reductions could be made such as the elimination of the independently motorized oil pump by taking advantage of the discharge pressure over the oil sump, as well as the additional costs associated with the dual open-hermetic design and the use of unnecessarily bulky and more expensive "Deglas" insulated motors, etc.

Furthermore, this technology had progressed to the point that the female instead of the male rotor could be directly coupled to the motor, thus providing 50% extra displacement with four male/six female rotors of unchanged dimensions. Additionally, a step-up gear could be used to reach higher compressor rpm and achieve better performance in the lower tonnage range (a minimum rotor tip speed is required) and further reduce the size of the rotors. A step-up gear would be quite acceptable in competition with multicylinder reciprocating machines. This approach would make it possible to reach capacities well below

*Table 1: Referigeration screw compressor manufacturers**

Country	Manufacturer	Mono Rotor	Twin Rotor	Open Type	Hermetic Type
USA	Carrier		✓	?	✓
	Dunham-Bush		✓	✓	✓
	Frick/York		✓	✓	
	Sullair		✓	✓	
	Trane		✓		✓
Germany	Bitzer		✓	✓	✓
	G.H.H.		✓	✓	
	Kuehlautomat**		✓	✓	
	Maschinenfabrik Halle**		✓	✓	
Japan	Daikin	✓			✓
	Hitachi		✓	?	✓
	Mitsubishi	✓			✓
	Mycom		✓	✓	✓ (?)
Denmark	Gram		✓	✓	
	Sabroe		✓	✓	
Great Britain	Hall	✓		✓	✓
	Howden		✓	✓	
Netherlands	Grasso		✓	✓	
Sweden	Stal		✓	✓	✓ (?)

* Several other manufacturers in former eastern bloc countries not included.

** Formerly part of ILKA (Volks Eigentum Kombinat) Group in GDR.

the 30 ton shown in Figure 3 As a result, the D/B sliding-vane compressor program[10] was put on ice and all research, development and engineering resources allocated to compressor developments were assigned to the completion of the largest DBX unit up to 650 ton and feasibility studies of small hermetic screw compressors as outlined previously.

The writer joined the staff of the Industrial Product Group of a multinational company in Belgium in 1969 and returned to D/B in 1988 as an independent consultant in Europe for their welded vertical screw compressors (VSCs). He had the opportunity to assess the state-of-the-art some 20 years after the introduction of the first large hermetic screw compressors.

Interim State-of-the-Art (1988-1992)

What became immediately apparent was the proliferation of screw compressor manufacturers **(Table 1)**. Worldwide, less than a handful of refrigeration compressor manufacturers were offering screw machines in the 1960s and their number[11] had exploded by 1988 to over 20, with five in the U.S. that included three centrifugal manufacturers. The commercial availability of screw compressors could be summarized on the basis of the 1988 ASHRAE Handbook as follows: 40 to 850 ton in package chillers, therefore, the estimated competitive range of rotary compressors shown in the 1960s Gap graph had already become a reality.

The range of 20 to 2,000 ton for compressor—or condensing—units in the Handbook could be extended downward to 8.5 ton in view of European designs displayed at the 1992 IKK Expo in Germany **(Figures 4a and 4b)**. Since other rotary compressors covered a capacity range from above 8.5 ton down to household applications, the following assessment could be made: positive displacement rotary compressors were commercially available from fractional hp up to 2,000 ton as of 1992, noting that the screw compressor alone occupied the lion's share of this range from 8.5 to 2,000 ton. The reciprocating and centrifugal machines were commercially available in only a portion of this capacity range at the lower and upper range respectively. **See sidebar, *Screw Compressor Advantages*,** for some of the technical reasons for the superiority of screw over the four-pole reciprocating-hermetics.

Favorable Impact of the CFC Issue

The fact that the oil flooded refrigeration screw compressors were designed from the start for high pressure refrigerants such as R22, an HCFC, and ammonia, rather than CFCs may also explain their increasing popularity since the signing of the Montreal Protocol. Because of their very low discharge temperatures screw compressors will be able to operate safely and efficiently with any future substitute refrigerant.[12]

Leading engineers were considering ammonia as an alternative refrigerant for AC applications with oil flooded screw compressors and work was under way to develop hermetic ammonia screw compressors of the canned-type design. This concept became a reality when a manufacturer displayed, **(Figure 4c)** an Eco friendly ammonia semi-hermetic reciprocating compressor at the 1992 IKK show.

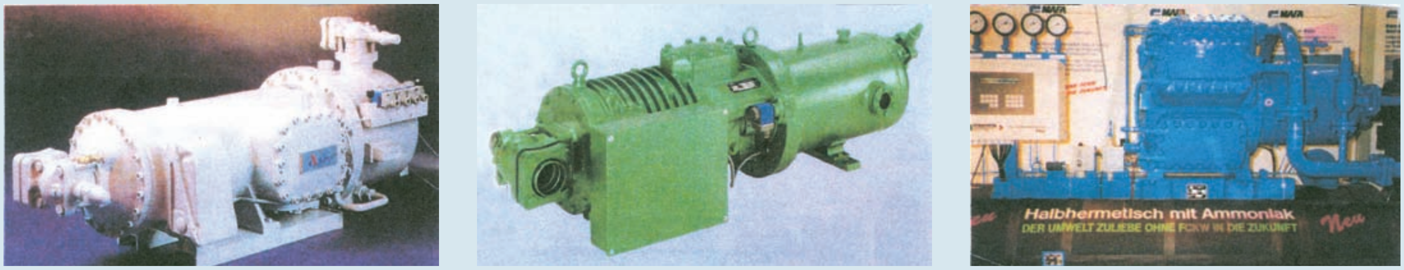


Figure 4: New products displayed at 1992 IKK show.[11b] More reliable small screw compressors with integral oil separator and Ammonia hermetic. 4a (left) Single rotor hermetic from the UK. 4b (center) Double-rotor hermetic from Germany. 4c (right) "Eco-friendly semi-hermetic ammonia reciprocating compressor" from the former German Democratic Republic.

This canned* hermetic design, developed in the early days of the refrigeration industry, was brought back to life around 1945 in a line of tiny low cost refrigerators produced by THERMA AG in Switzerland. Its chief refrigeration engineer, Herr Kaenel, developed a small version (<1/10 hp) of typical fully hermetic rotary compressors with a unique feature: He kept the stator outside the refrigerant ambient because he felt his Swiss motor suppliers had insufficient experience with the new insulations available in the U.S. He recognized that his solution was more expensive than the conventional designs (extra costs of the nonmagnetic stainless steel for a portion of the compressor shell, which had to be machined to minimize the air gap between stator and rotor). He felt these additional costs were offset by these advantages of the canned design: use of conventional insulation for the external stator, which could easily be replaced in case of a motor burnout and avoid contaminating the refrigerant circuit and the possibility to loosen the extremely tight manufacturing tolerances necessary to reduce the gas blow-by from the high to the low pressure side of the rotary compressor by "flooding" the compressor with more oil than necessary for lubrication.

The excess oil entrained with the discharged gas was effectively separated from the gas by centrifugal forces as the gas and oil mixture was flowing through the electric rotor. Unknowingly, Herr K. had anticipated some of the "novel" features incorporated in the DBX hermetics up to 600 hp such as oil flooding and first stage oil separation by centrifugal forces. In some respects the DBX hermetic was just a 600/1/10=6,000 fold extrapolation of Herr Kaenel's 1945 mini rotary compressor and his insulation problem/solution a good model for the design of small (<25 hp) eco-friendly ammonia hermetic compressors.

Screw Compressor Advantages

Smaller size, lighter weight and lower costs of both basic compressor and hermetic motor due to their ability to operate efficiently and reliably directly coupled to two-pole 60 or 50 cycle electric motors and higher rpm with step up gears .or variable frequency drives (VFDs). Flatter volumetric efficiency curves as a function of compression ratio (CR) resulting in significant reduction in the required compressor displacement compared to the reciprocating type at high CR typical of medium and low temperature refrigeration, as well as heat pump applications.

Use of an economizer system by injecting refrigerant vapor into the compressor at a suitable intermediate pressure level resulting in increased capacity and better energy ratio; noting that in the case of screw compressors equipped with a sliding valve unloader or other device based on the same principle the economizer effectiveness quickly vanishes below full load. The economizer system remains fully effective down to minimum load when capacity control is achieved exclusively by varying the compressor speed with VFD. This feature is also important at higher capacities in competition with centrifugals.

Current State-of-the-Art (2010)

The most recent and significant technical breakthroughs in large hermetic compressor designs are based on the availability of variable frequency drives (VFDs). The two main advantages of VFDs (besides others such as low inrush currents, etc.) are:

1. Optimized programmable continuous capacity modulation without mechanical unloading device; and
2. Higher design speeds without mechanical step up gears; the most compact lightweight hermetics are obtained as the size of the motor also decreases with increased design frequency.

To simplify this final update all types of refrigeration compressors are grouped in three major classes defined below:

First Class: RECIP, which stands for positive displacement reciprocating compressors, a very mature technology dating back to Perkins' 1834 mechanical refrigeration system, therefore, new technical breakthroughs are improbable. Because of

*Seal-less water circulators based on the same principle are called "wet rotor" pumps.

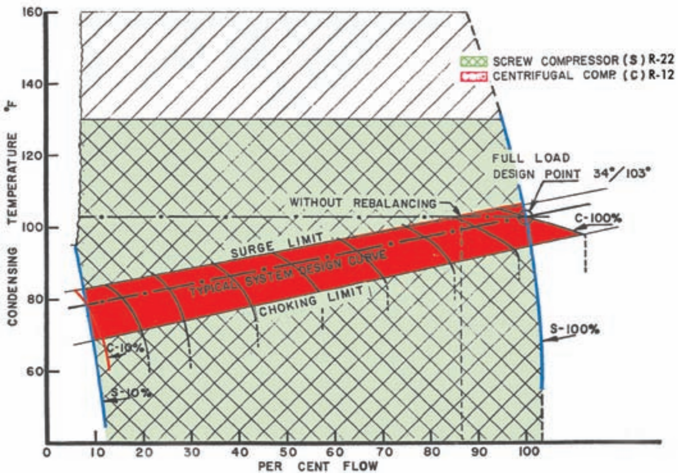


Figure 5: Allowable condensing temperature range of oil injected screw-and typical high speed centrifugal-compressors at fixed evaporating temperature.

the severe restrictions imposed by the use of automatic suction and discharge valves on the maximum piston speed (to keep the kW/ton within acceptable limits) this is the lowest speed class of the group. Like all other positive displacement compressors, it benefits fully with VFD from advantage number one, but there is no significant need for advantage number two, as the larger RECIP still operates with four-pole motors at a maximum speed of 1,800 rpm in the U.S.

Second Class: TURBO for dynamic centrifugal and axial machines, the theoretical basis for this technology goes as far back as Leonard Euler who published in 1754 a mémoire[6b] on a conceptually new and workable hydraulic turbine. It has benefited from developments in many industrial applications therefore, this technology is quite mature and new fundamental breakthroughs are unlikely. Because the impellers have no contact with any stationary walls, these dynamic machines operate at the highest speed of the group and benefit more from the higher speed feature (advantage number two) of VFD than the other classes.

The turbos are basically high flow machines, very competitive at the highest capacities (10,000 ton, so far) but their competitiveness at lower tonnages gradually fades out as indicated by the steadily increasing penetration of the screw compressors into their traditional capacity range. The reasons for this shift are highlighted in Figure 3 and illustrated in greater detail in Figures 6 through 11 of the compressor trend series.[7]

The most serious limitation of this class is its lack of flexibility. In contrast to positive displacement compressors, the turbos cannot be operated[13a] at a constant speed over a wide range of conditions. Further, they cannot physically operate at constant evaporating and condensing temperatures at various speeds since their "head" varies with the second power of the rpm, thus, limiting the use of VFD for capacity control so severely that mechanical unloaders usually are required in addition to the VFD. These limitations can be somewhat palliated as shown in a section of chapter 38 of the 2004 edition of the ASHRAE Handbook (from here on referred to as the Handbook) titled *Performance and Operating Characteristics*. However, this lack of flexibility has had a significant negative impact on the TURBOs competitiveness as shown in many papers and confirmed by the "wish list" of the consultants mentioned previously. In competition with positive displacement compressors, this vulnerability may aptly be described as the "Achilles' heel" of the TURBO. This lack of flexibility became particularly acute in the 1960s with the most compact high speed R-12 chillers[7] operating at an rpm ranging from a low of 8,500 at 1,000 ton up to a peak of 22,500 at 125 ton due to the turbo's extremely narrow operating range as shown in **Figure 5.** This graph, adapted from H. Loch,[14] was first presented at the 1967 IIR Congress to show why these most advanced designs could not compete with screw chillers in the growing market for air cooled water chillers. Figure 5 may also explain why today's most technically advanced line of water cooled R-134a turbo chillers with VFD was specifically designed for unusually low condensing temperatures. A leading German compressor manufacturer promptly reacted by offering a similarly customized line of hermetic screw compressors with integral VFD.

Third Class: ROTARY for positive displacement rotary compressors, which includes all nonreciprocating compressor designs shown in Figure 1 of chapter 34 of the Handbook. Their wide, useful speed range occupies a medium position between the lower speed RECIP and high speed TURBO. The technology of key members of this class— scroll and screw compressors—being relatively young, suggest that new technical breakthroughs are probable. As the rotary combines the best features of the RECIP and TURBO, it alone benefits fully from all the advantages of VFD. This is no doubt the reason for the recent surge of new hermetic screw compressor designs with integral VFD; three such units produced by major refrigeration compressor manufacturers in China, Germany and Italy were displayed at the HARI Show in the U.S. and EXPOCOMFORT in Italy in the first quarter of 2010.

Competitive Capacity Range of Each Compressor Class

The commercial availability of large rotary compressors (i.e., screws) progressed rapidly between the interim update and the 2000 Handbook, which already showed an increase of the upper limit for factory built package water chillers from 850 to 1,300 ton. However, no specific information was available to determine in which tonnage range each class was most competitive in air conditioning applications and this matter had not been addressed in the ASHRAE Journals and Handbooks until the 2004 Handbook edition. As a result, prior to 2004, only qualitative guidelines (GL) could be made on the basis of the increased availability of the screw compressors:

(GL 1) Low Tonnage Range: It is clear that the ROTARY has displaced, or at least reduced the market share of the RECIP since several RECIP manufacturers have expanded their pro-

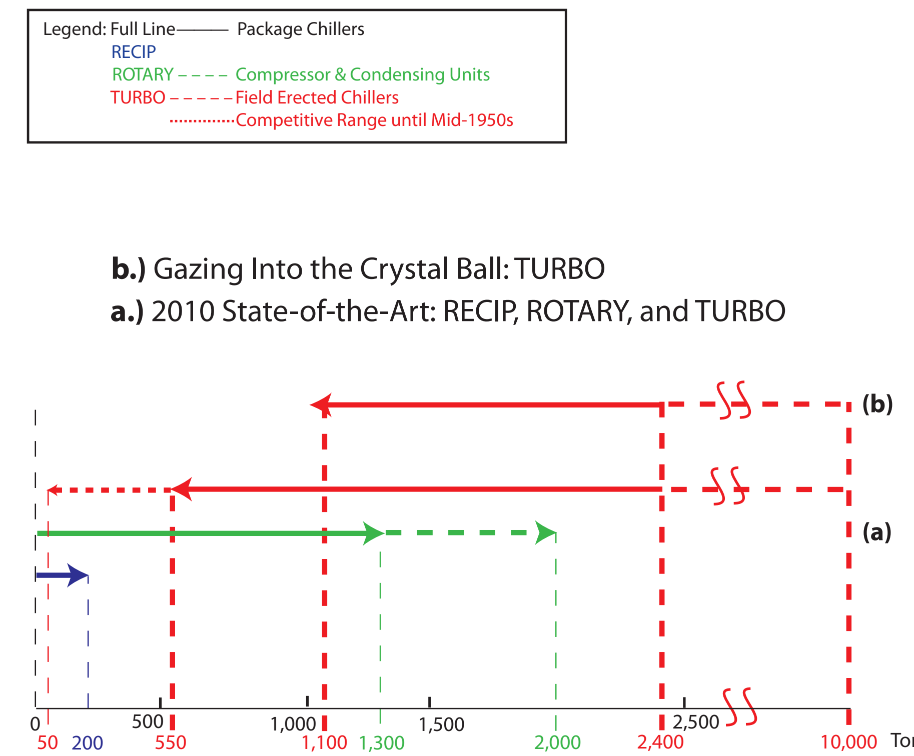


Figure 6: Most competitive capacity range of each compressor class.

gram to include ROTARYs and contributed to the obsolescence of the RECIP.

(GL 2) High Tonnage Range: The same argument can be made as for GL1 by substituting the word TURBO for RECIP since all leading centrifugal manufacturers have now joined the formerly restricted club of screw compressor manufacturers.

Fortunately, a first cautious attempt was made in a small table on page 38.4 of the Handbook to determine the application range, in terms of capacity, of all refrigeration compressor types used in liquid chillers. Below this table the authors give a reason for the fact that: *The reciprocating and screw liquid chillers are more frequently installed from 80 to 200 ton*, due to the lack of flexibility of the TURBO and therefore, valid above 200 ton, which, expressed in the author's own words, becomes:

(GL 3) Preferred Choice: positive displacement compressors for *air cooled condenser duty, brine chilling, or other high pressure applications.*

The bar chart in **Figure 6** indicates the most competitive tonnage range of each compressor class. This is based on data in the Handbook, as well as previous sections of the present paper and the above mentioned guidelines and table. The latter divides the capacity in five blocks starting with "up to 25 ton "and finishing with "above 1,000 ton." The absence of a compressor class from a block means it is not competitive in its range. As it is not in the fourth block of 200 to 1,000, the maximum value for the RECIP is 200. Similarly, the ROTARY upper limit should be 1,000 ton since it is present in the fourth but not in the last block; in view of the recent expansion of this class to 1,300 ton this is the value selected for chillers along with 2,000 ton for compressor—and condensing—units as shown in Figure 6a.

Because of the availability of competitive 550 ton hermetic screw compressors and (GL) 2 and 3 the most competitive range of the high flow turbo starts only at 550 ton. TURBO below 550 ton may still be competitive in special market niches, which however, represent a very small fraction of the available sales volume. The total 2007 sales value in EURO in seven European countries of water chillers for the large AC market was distributed as follows:[15] 2% absorption; 4% turbo; 94% RECIP and ROTARY. This significant dominance of positive displacement compressors in Europe is most likely valid, to a different degree, worldwide.

To an experienced compressor engineer the information conveyed by Figure 6 would seem quite normal as the competitive capacity ranges are decreasing from the higher to the lower speed machines as they should. The situation was radically different in the past until the mid 1950s when the hermetic turbo manufacturers enjoyed a "de facto" monopoly in the large chiller market and could produce and sell units with capacities as low as 50 ton. This ceased when large (>25 hp) reliable low cost hermetic RECIP became available with the results shown in the introduction of the present paper. Due to the wide customer acceptance of the screw chillers since the 1960s, the turbo manufacturers had only two choices: either accept losing the financially most significant part of the chiller business or join the screw compressor club. The market leaders chose the second alternative (see *Interim State-of-the-Art*) and, in so doing, accelerated the retreat of the high flow turbo toward higher tonnages where they normally belong.

Gazing Into the Crystal Ball

The title of the cover page of the November 1974 Journal issue dedicated to the "R" of ASHRAE seems a suitable way to conclude this historical survey of positive displacement rotary compressors in refrigeration and air conditioning applications. Two forecasts are proposed based on a rational assessment of the advantages and limitations of each compressor class. The first one suggests, as shown in Figure 6, that: The most competitive capacity range of centrifugal chillers will retreat further up the tonnage range as new hermetic screw compressor designs, up to 1,000 ton or higher, become available. The only question is whether the financial investment to develop and produce these machines can be justified in view of the rather small demand for such large compressors. A single chiller capacity of 1,100 ton could be rapidly produced† with multiple hermetic screw compressors already available before 2004,[13b] for instance, with two 550 ton machines updated to take advantage of the unique flexibility of this class of compressors and the availability of VFD to control capacity exclusively in terms of rpm (see *Sidebar*, and *Figure 5)*. This would make the screw compressors without the sliding valve unloader even more competitive pricewise than in the past and such a unit would offer part-load efficiencies and annual energy savings unmatched by any chiller equipped with one or two hermetic turbo, particularly when the two screw compressors operate on a single refrigerant circuit, thus allowing the system to rebalance at any load with the full heat exchange surface available in the evaporator and condenser as this has been done for two decades[16] with welded vertical screw compressors.[13c]

Lastly, a surprising forecast for many U.S. members of ASHRAE, because of the incompatibility of the refrigerant and electric motor materials,[13d] the commercial availability of eco-friendly ammonia hermetic rotary compressors. This trend should start in the lower tonnages in competition with the RECIP, probably in high compression ratio applications where the major advantages of the ROTARY (see *Sidebar*) may more easily offset the negative aspects of the canned hermetic design mentioned in connection with the THERMA mini rotary compressor. If the market demands it, one cannot altogether exclude the long shot probability that hermetic motors suitable for an ammonia environment may one day become available; this would remove the hp restrictions imposed by the canned design and make the conventional fully hermetic ammonia compressors as available as those with current refrigerants. This situation would again favor the screw compressors, which were designed from the start for ammonia, whereas this refrigerant has the wrong characteristics for high flow centrifugal machines and would shift their competitive capacity beyond 2,000 ton, the upper limit shown in Figure 6a for commercially available open-type screw compressor and condensing units.

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†Besides two water chillers.

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