THE INSTITUTE OF REFRIGERATION

The Road to Reality: Invention to Commercialisation of the Rotating Spool Compressor

by

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(Session 2013-2014)

To be presented before the Institute of Refrigeration at the Arden Hotel, Bickenhill Parkway, Birmingham On Thursday 6th March 2013 at 5.45pm

Abstract

People have ideas for new products every day. The successful journey from idea to a commercial product is truly a road less traveled. A road scattered with the ideas, companies and careers that succumb to the scrutiny of mature products and markets. TORAD's spool compressor has achieved many of the milestones necessary to make the final assent to having a significant impact on the refrigerant compression marketplace. This paper shares some of the experiences and answers the common question TORAD hears from others contemplating the road from invention to commercialization.

Introduction

Birthing of a new technology is exciting while frightening, disappointing yet rewarding but mostly it is just very hard to accomplish. As we meet people across the industry we are often asked a lot of "how did you do…" questions. These questions range from personal and business to technical and market considerations. There seems however to be one core understanding at the root of most questions; people understand what we are trying to accomplish is very hard. Following are answers to some of the questions we hear most often.

What is your (Greg Kemp) background?

The inventor of the spool machine is Greg Kemp, founder and CEO of TORAD Engineering. I graduated with a BS in Mechanical Engineering from the University of Illinois at Champaign/Urbana in 1986. I started my career in industrial automation sales with the Allen Bradley Company (Rockwell Automation). Several years later I moved to sales and marketing of enterprise software. I continued to work in the enterprise software market until the late 90's. By then the internet was blooming and I was bitten with the entrepreneur bug. In 1998 I founded Knolwedgestorm.com a high-tech software and services product search engine. I left the company in 2002 after the internet bubble burst. KnowledgeStorm was later purchased by TechTarget in 2007. I share this background to make an important point. While I was educated as a mechanical engineer I was never a practicing engineer until I founded TORAD in 2006. It was nearly 20 years after graduating engineering school before I directly used my engineering education.

How did you get the idea?

Being it was nearly 20 years from the time I had last said the word thermodynamics, it was more than a little odd that I would have an idea for such a machine. The original idea came to me while standing in my garage in early 2006 in what I believe was a vision from God. Why me, I have no idea other than I asked.

After my departure from KnowledgeStorm I was lost, like a man without a country. I had committed myself to KnowledgeStorm and suddenly found myself out of the company I had started and poured my life into. I started to spend significant time in prayer and reflection seeking answers to common questions most of us ask at some point in our life. What is my purpose, what is my relevance, and what do I do next? After several months of prayer out of the blue I had a vision. It was for this machine. The only way I know how to describe the vision is, "I woke up standing in my garage". If someone would have been there to observe that moment they would have seen me standing there, looking upward, in a state that would commonly be described as day dreaming. I have no idea how long I was standing there; I have no idea what sparked the vision. I could not remember why I was even in the garage. I had immediate and vivid recollection of the vision that I had seen while standing there. The vision was not completely clear but I recognized that it could be a new machine. I distinctly remember saying out loud, "hum… that could work". It is certainly not remarkable that a mechanical engineer would have an idea or vision for a machine. However, while I have a mechanical engineering degree I had not practiced or worked in the field of mechanical engineering ever. For the previous 18 years I was in sales and marketing, the last 13 years in the enterprise software market and an internet business. All I can say is I believe that the vision was from God and an answer to my prayers for purpose and relevance.

How did the development unfold?

Telling the entire story is beyond the scope of this paper. However I do need to mention some key contributors and bellwether events along the way. Charlie Paparelli has been my friend, partner, advisor, lead investor and managing partner from the beginning of the project. He has lifted the financial burden from our path and provided excellent business and personal advice. Early on Norman Garrett, Lonnie Elwood, and Eckhard Groll contributed to the effort. Cayce Washington and his team at Valley Tool were critical in helping keep the early prototypes financially obtainable and TORAD alive.

The real path to market viability started in September of 2010 when Joe Orosz joined the team. Joe has a wealth of experience in the rotary machine and refrigerant compressor industry. His engineering skills, manufacturing and market knowledge along with his business and operations acumen have been pivotal to TORAD's Success. Joe's first major contribution was recognition of the Zsoro number. Joe realized early on that the relationship between the machines displacement and sliding side seal frictional losses would be key to performance. He created a formula that considered these elements and yielded a dimensionless number that would help judge the compressors theoretical performance. I looked at his formula and realized that the best machines would have a dimensionless number that would grow very large. So I flipped the number over such that a smaller number was better. I named it after him but flipped the spelling of his name just as his number had been flipped. The Zsoro number has proven to be a simple and very good guide post for designing spool compressors.

In 2010 Craig Bradshaw was a PhD student working with Professor Eckhard Groll at Purdue University studying numerical modeling of compressors. I met Craig in the summer of 2010 at the biannual International Compressor Engineering Conferences at Purdue. Soon after Joe Orosz joined TORAD he met Craig and knew right away that he wanted Craig on the team. I was in complete agreement. Craig contracted with us developing a numerical model of the spool compressor while finishing his PhD. Craig joined TORAD after graduation in 2012. Craig has the amazing ability to contribute from turning wrenches and assembling machines to solving complex differential equations with numerical simulation. He has created analytical tools that have provided us with deep insights to the machines characteristics and keys to performance.

After Craig joined team the team really start moving forward quickly. I mainly contributed new ideas and learned to machine the parts. Joe provided the real understanding of what could and could not work in production. He also knew how to bring the metrology and precision necessary for any machine to approach market performance. Craig brought the ability to measure, model and predict the compressors performance. From this we are quickly learning how the geometry and components are optimized for given applications. There would not be a TORAD Engineering today if not for the contributions of Charlie, Joe, and Craig. We continue to collaborate together, everyone sharing in the generation of new ideas and solutions. This partnership is ongoing, as is the development, so the story isn't over. However, I can share what we have learned so far and what we hope for the future of the spool compressor in the remainder of this paper.

How does the spool compressor work?

The rotating spool compressor is a novel rotary compressor mechanism most similar to the sliding vane compressor. Primary differences are described by Kemp et al. [1, 2] and include three key differences from a sliding vane compressor, as shown in Figure 1.

- The vane is constrained by means of an eccentric cam allowing its distal end to be held in very close proximity to the housing bore while never contacting the bore.
- The rotor has affixed endplates that rotate with the central hub and vane forming a rotating spool.
- The use of dynamic sealing elements to minimize leakage between the suction and compression pockets as well as between the process pockets and the compressor containment.

The movement of the rotor is purely rotary with only the vane and tip seals performing any oscillating movement. The eccentric cam will force the movement of the vane to oscillate by twice the eccentricity during a single rotation. The tip seals will oscillate relative to the vane two times per rotation by an amount proportional to the ratio of diameters of the rotor to the housing bore (also known as the eccentricity ratio). The tip seal movement amount is roughly an order of magnitude smaller than the eccentricity and follows a sinusoidal path. Analytical details regarding the geometry, including the mathematical expressions describing the chamber volumes, is presented in Bradshaw and Groll [3].

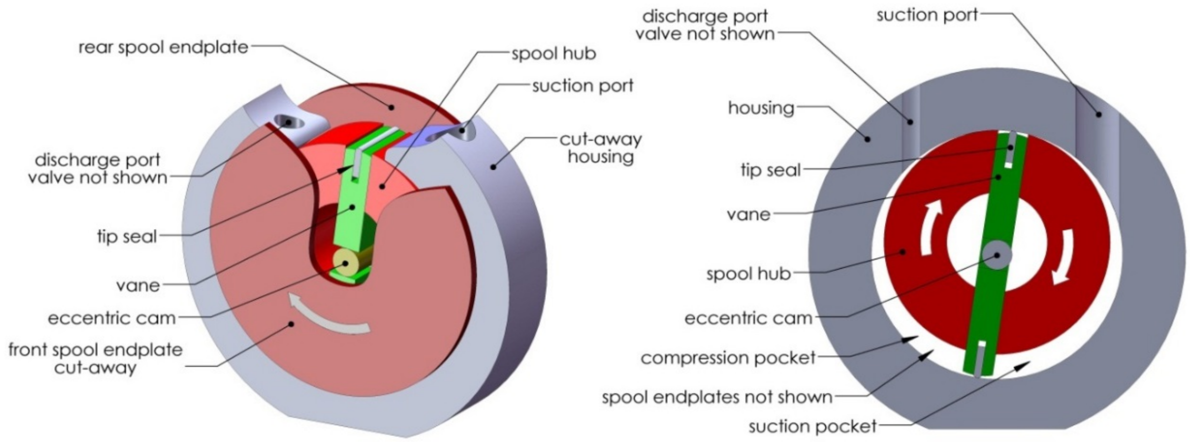

Figure 1: Cutaway view of rotating spool compressor mechanism with key components highlighted.

What differentiates the spool compressor from existing technologies?

A traditional vane machine (either sliding vane or rotary vane) are relatively difficult platforms scale into larger capacity ranges (larger displacement). This problem stems from the interface between the vane and the housing bore and/or the interface between the vane and the end walls of machine. The spool compressor mechanism reduces these problems by constraining the vane at the center of rotation and also rotating the endplate with the vane.

By constraining the vane as close to its center of mass the sliding velocity and kinematic forces are kept at a minimum. In addition, the vane itself is restricted from sliding on the housing bore. Instead, a secondary sealing element, the tip seal, is required to take up the gap between the end of the vane and the housing bore. The tip seal size and weight can be configured to reduce the frictional losses due to the contact between the housing bore and tip seal. A study of the tip seal design parameters was presented by Bradshaw [4].

The rotation of the endplates of the spool compressor mechanism greatly reduces the friction generated by the vane. It is not completely eliminated because the vane must slide radially relative to the endplate by an amount equal to the eccentricity. Since the endplate is rotating relative to the compressor housing the gap between these two parts requires sealing. This is accomplished with an additional dynamic sealing element called the spool seal. An overview of the spool seal design constraints has been presented by Kemp et al. [5]. The spool seal can be designed to accommodate various machine applications, such as a seal which can handle a wide operating envelope with adequate sealing. Alternatively, the seal can be designed with lower frictional power loss for applications which have high efficiency demands and a relatively small operating envelope, such as a water-cooled chiller.

The combination of these dynamic sealing elements give the spool compressor the flexibility to scale to sizes that have historically proven difficult for other vane machines. Additionally, this provides platform flexibility with a specific displacement that is also difficult with traditional vane machines due to the ability to modify the seal designs.

Performance Evolution of the Spool Compressor

Some of the first prototypes were designed based on rules of thumb which applied to other technology, some intuition based on experience, and some guessing. This yielded machine performance which was not ideal. However, during the testing of the 4th generation prototype, a useful nondimensional number was developed to aid in compressor design, as presented in Orosz et al. [6]). The number, called the Zsoro number, is given as the ratio of spool seal losses to the displaced volume. As shown in Figure 2, the initial overall isentropic efficiencies achieved for the 2nd through 5th generation prototype plotted against Zsoro number. This relationship has provided a benchmark to start from when designing a new compressor.

The Zsoro number does not account for all phenomenon, such as porting, valves, leakage, heat transfer, and tip seal friction to name a few items. Therefore, it was imperative to develop a more comprehensive compressor model to aid in designing and optimizing the spool compressor. A comprehensive compressor model was developed and presented by Bradshaw and Groll [3]. This model sets a framework which has been matured over the last three years and has been used to predict compressor performance for many other types of compressors in addition to the spool [7]. It models the open drive spool compressor prototypes and includes all major phenomenon including valve dynamics, heat transfer, leakage, friction and sub-models for the dynamic sealing elements. The model has predicted volumetric and overall isentropic efficiency of the 5th generation prototype to within 2% and 5%, respectively. While the model is continuously evolving, it has an accuracy level that yields confidence in its predictive power. These predictions have allowed great progress in understanding the potential of the spool compressor.

Potential of the Spool Compressor

Using the comprehensive model a series of studies have been conducted to understand the potential of the spool compressor with respect to an optimized geometry, operating conditions, and displacement.

Geometry Improvements

There are two major parameters to adjust to develop a particular spool compressor design. One is the eccentricity ratio (ε), which is the ratio between the rotor radius and the spool stator radius. The other parameter is the ratio of the axial length of the spool stator and the spool stator diameter (L/D). Using these two parameters a rough compressor size and shape can be calculated. To study this, the comprehensive model was exercised using a fixed displacement of 54cc (3.3in^3) with various eccentricity ratios and L/D ratios. Additionally, the operating conditions, port, and valve sizing remained fixed for all cases.

Figure 3 shows the volumetric efficiency of various L/D ratios and four eccentricity ratios. Below an L/D ratio of roughly 0.5 the volumetric efficiency is reduced rapidly with small changes in L/D. This is a result of the spool seal leakage area increasing compared with the displaced volume. Alternatively, as the L/D ratio increases beyond roughly 1.25 the volumetric efficiency decreases. This is a result of an increase in tip seal leakage as a proportion to the displaced volume. The design is less sensitive to tip seal leakage because the spool compressor picks up volume linearly with axial length but with the square of the diameter. For similar reasons the volumetric efficiency increases with eccentricity ratio. Figure 3 also shows the 6th generation prototype as well as the 5th generation prototype compressors.

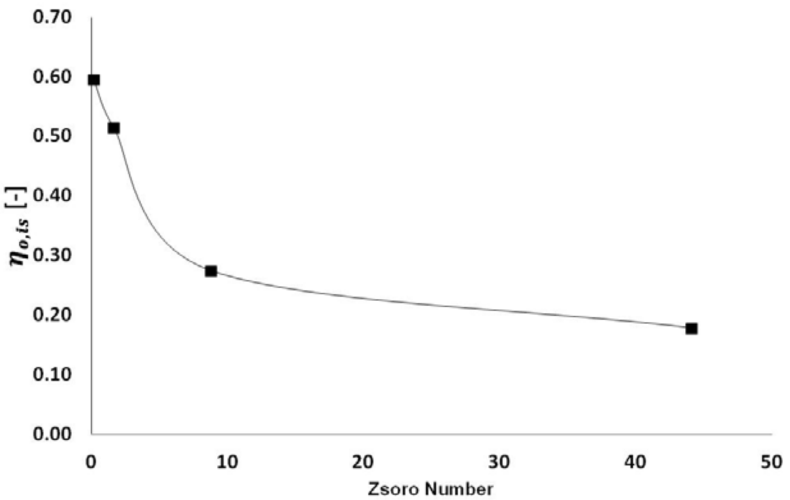

Figure 2: Evolution of Compressor Efficiency as a Function of Zsoro Number as Presented in Orosz et al. [6]

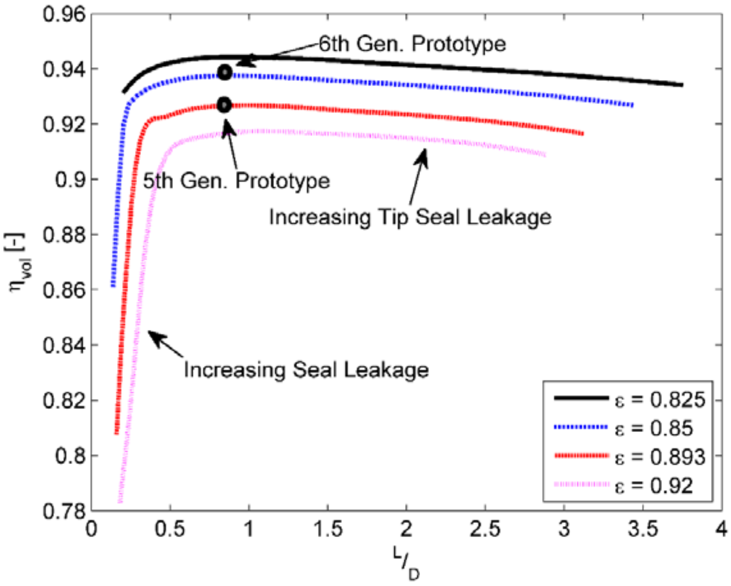

Figure 3: Model Predicted Volumetric Efficiency of a 54cc (3.3in3) Machine at Various Eccentricity Ratios and Length to Bore Diameter Ratios and a Fixed Operating Condition.

Figure 4 shows the overall isentropic efficiency for various eccentricity and L/D ratios. Similar to the volumetric efficiency the seal leakage greatly reduces the efficiency of any design below an L/D ratio of roughly 0.5. However, at larger L/D ratios the overall isentropic efficiency does not show a peak efficiency, rather generally increases. This is a result of the side seal friction dominating the losses compared with the tip seal friction as the L/D ratio increases. However, beyond certain L/D ratios the manufacturing becomes impractical or even impossible. This limitation is dictated by the need to be able to reach into the rotor with the eccentric cam to position the vane. As the rotor radius decreases this becomes more difficult with adequate mechanical integrity.

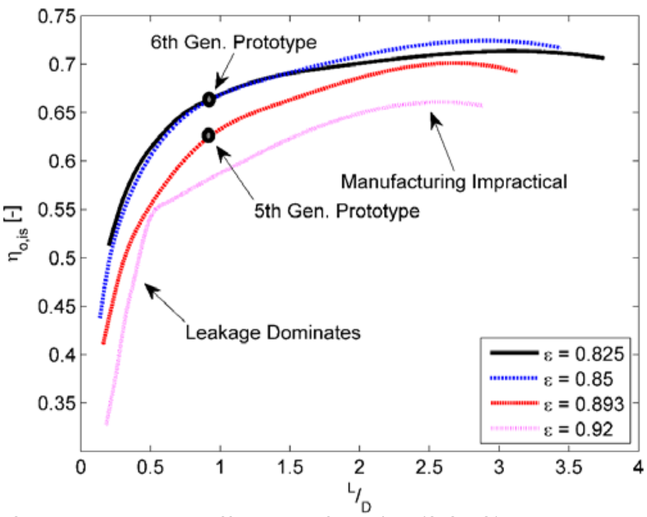

Figure 4: Model Predicted Overall Isentropic Efficiency of a 54cc (3.3in3) Machine at Various Eccentricity Ratios and Length to Bore Diameter Ratios and a Fixed Operating Condition.

Spool Compared Against Commercial Technology

The prototype and model predicted prototype performance is presented compared against two commercial compressor products, shown in Figure 5. The commercial scroll and rotary data is taken from hermetic compressors. However, for a fair comparison, the efficiency of the hermetic machines is adjusted using a motor efficiency curve to convert the overall isentropic efficiency of these devices to an efficiency based on shaft power instead of electrical power.

Figure 5 shows the volumetric efficiencies of the four compressors at a fixed condensing pressure and suction superheat (37.7C and 8.9K, respectively) and various evaporating pressures. The 5th generation prototype shows volumetric efficiencies similar to that of a commercial rotary and less than a scroll. Based on the previous analysis the 6th generation prototype is predicted to improve and show volumetric performance that is similar to a scroll.

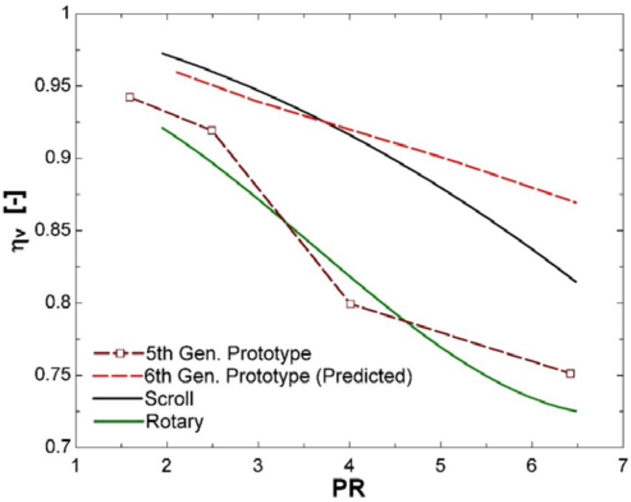

Figure 5: Comparison of Commercial Rotary and Scroll Volumetric Efficiency to Prototype Experimental and Predicted Prototype Volumetric Efficiency at 37.7C (100F) Condensing and Various Evaporating Pressures

Figure 6 shows the overall isentropic efficiencies of the four compressors under the same operating conditions shown in Figure 5. The 5th generation prototype displays efficiency levels which are similar to the rotary yet less than the scroll. The predicted performance of the 6th generation prototype will improve on that efficiency to approach the scroll.

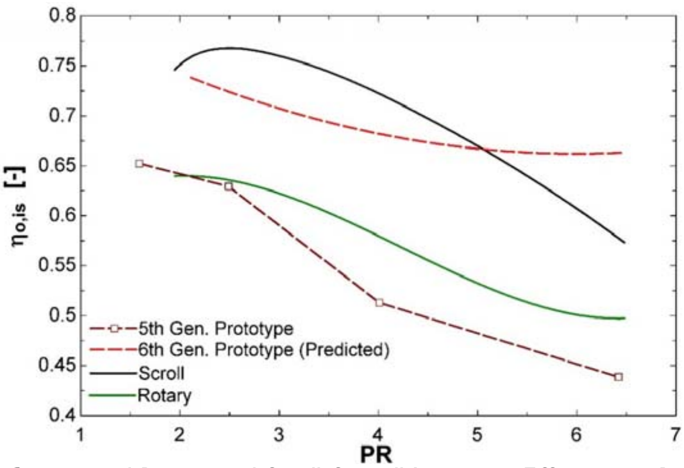

Figure 6: Comparison of Commercial Rotary and Scroll Overall Isentropic Efficiency to Prototype Experimental and Predicted Prototype Overall Isentropic Efficiency at 37.7C (100F) Condensing and Various Evaporating Pressures.

Spool Scaling

It was also important to understand how well the spool compressor will scale. Certain technologies often have displacement ranges that perform better than others. So to help ensure some commercial success it has been important to try and understand where the spool compressor fits into the market. The best chance of that are places where the potential efficiency of the machine is the greatest.

A study was carried out to predict the performance over displacements that achieve an ideal air conditioning capacity from roughly 2 to 95 tons. Figure 7 shows the results of this study in both volumetric and overall isentropic efficiencies of the compressor. The volumetric efficiency asymptotically increases with capacity. This increase is a result of the displaced volume increases faster than the leakage areas and the volumetric efficiency has nearly hit a maximum by 15 tons. The overall isentropic efficiency increases rapidly from 2 to 15 tons, picking up over 5% in efficiency points. Then near 70 tons the performance starts to fade as it becomes more difficult to manage heat and include an appropriate amount of discharge port area. Since all of these studies were performed at 3550 rpm, a potential solution to the port area losses would be to slow the rotational speed of the machines at the higher tonnage range.

This study has shown that there appears to be a region where the spool compressor can achieve even higher performance levels than the 6th generation prototype has shown. This has prompted a proposal to develop a 7th generation prototype within this 'sweet spot' for commercial air-conditioning markets.

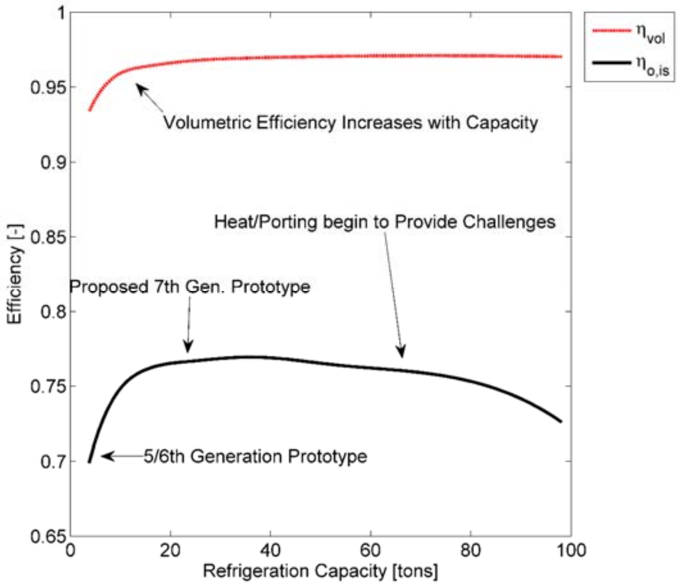

Figure 7: Model Predicted Efficiencies as a Function of Refrigeration Capacity.

Future of the Spool Compressor

An overview of the story behind the spool compressor has been presented from inception in a garage to performance levels that are close to market levels. This is a partial story with an ending that is yet undetermined but filled with promise. In just a few short years, with minimal capital investment, this technology has made incredible strides. Its simplicity suggests it will have a production cost that is far lower than current technologies. The performance predictions show promise to achieve similar efficiency compared to current technology with the flexibility to achieve multiple applications within the same product family just by changing the sealing elements. The device scales into larger sizes far better than traditional rotary devices which could provide both a cost and energy efficiency advantage in many markets.

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