BorgWarner EFR Turbocharger Technical Training Guide

BorgWarner Turbo Systems

Table of Contents

Foreword

The first thing worth explaining is the strong connection between this exciting line of aftermarket turbos and our OEM commercial vehicle products. Commercial/industrial turbo products have extreme requirements for durability, reliability, and aerodynamic performance. Turbo sizing for the performance user more resembles what's in the commercial realm as compared to what comes from our (and others') OE passenger car developments. Since modern passenger car applications use turbos smaller than 55mm turbine wheel diameter, it's the larger components used on commercial applications that are more applicable to high-power aftermarket performance use. Commercial engines often utilize high boost pressures. Gage pressures of 45+ psi [3+ bar] are quite common even while retaining extreme durability.

Also required is resistance to abusive thrust loads, vibration, and robustness for a wide range of lubrication and cooling conditions. Our OE product validation standards are very tough, and many of these same practices were employed during the development of the EFR products.

That was the commonality, now here are the differences. Unlike commercial applications, high performance users want lightweight, compact, versatile designs. They also deliver the turbocharger very high exhaust gas temperatures and have high expectations for fast response. They also place value in cosmetic appearance and want integrated features that aid the installation process and remove the need for other accessories.

So, what happens when you combine all these requirements?
Something new is required, something that really changes the game.

Before a team was assembled, I selected the aerodynamics for the product line -- a range using only optimized combinations that would give our users turbo solutions anywhere between 200 and 1000 horsepower capability per turbo. I also made a list of every great design feature I could think of -- everything I had ever seen or heard of, new ideas that had never been taken from paper to hardware, and permutations of these that had never been integrated. Ninety percent of this content “stuck” and it was only the truly exotic that was excluded; features that would either take too long to develop across the size range or would be so expensive that nobody could afford them. Then, the program proposal was pitched to three of our top management staff. They got excited about the vision of giving this segment something remarkable and approved proceeding with the project. So, to them we all owe thanks.

After that, a talented and enthusiastic team was assembled and the rest of this text shares the detail of the design, development, and production launch process that followed.

The result is the new EFR Series of turbos from BorgWarner, and it’s our sincere hope that you enjoy them.

Brock Fraser
Global Director, Application Engineering
(Chief Engineer & Team Leader of EFR Project)
BorgWarner Turbo Systems

Chapter 2: EFR Product Introduction

Aerodynamic Selections

As mentioned, the primary goal was to provide optimized solutions for people in the 200-1000hp per turbo segment. Thankfully, this covers just about everyone except the hardcore drag racers. For those specialized customers, we still offer the highly popular S400SX and S500SX product lines. For the EFR products, the compressors range from 62mm OD (~50mm inducer) to 91mm OD (~68mm inducer). From this, the 70mm through 91mm compressors are designed for high-boost (40+ psi) capability. Born from our work in highly-boosted highly-efficient commercial engines, these compressors are top-shelf in terms of efficiency, range/width, and of course pressure ratio (boost) capability. On the turbine end of the machine, the range is from 55mm OD to 80mm OD. These turbine shapes are the newest "superback" and "fullback" designs from our work in high-boost high-efficiency applications. These are low-stress designs capable of high speeds and offering excellent efficiency. The compressor and turbine "pairing" is what it should be to maintain the best turbine inflow incidence, and the turbine housing A/R's are selected to also optimize turbine stage efficiency. A team has this kind of flexibility when you design a product line from scratch and aren't limited by availability of what already exists.

Wastegate System

Everyone knows that high performance applications need wastegating, and typically lots of it. This industry has been relying on external wastegates for many years out of necessity. As part of our "clean sheet" approach, we wanted to make internal wastegates that were capable of handling the flow requirements of high performance applications. This meant very large valve sizes (36mm and 42mm valve head) and aerodynamically-efficient porting. When you look at these designs, you won't see harsh corners, fabricated edges, or other losses. When as much as 40% of the flow needs to pass through the wastegate at maximum power, a flow-optimized solution is needed. You also won't see "fuse points" such as flexible diaphragms that have metal-to-metal contact with hot exhaust parts. In this industry, when an internal wastegate was employed for performance application, it was a typically a housing inherited from prior diesel use (with a low wastegate flow demand) and so it had to be a pretty special case to be able to flow enough exhaust and also a special case to be able to have enough orientation flexibility for the actuator canister. We hope you'll agree that the EFR product line changes this. Three actuator specifications are offered: low boost, medium boost, and high boost. Choosing the right actuator is the coarse adjustment and then the fine tuning can be done through a very handy rod-swivel joint.

Bearing System

Even though we have been long-time proponents of efficient journal bearing systems, for this product line we opted to use rolling element (dual row, ceramic ball) bearings. Once you have reached target boost, ball bearings offer little or no advantage in performance at full throttle. But, we absolutely recognize the benefits of getting up on boost quickly and having torque response that feels tightly linked to throttle movements. Ball bearings also reduce parasitic loss at low turbo speed and in the few (but growing!) instances of people who care about both fuel economy and performance, a benefit will be seen in consumption. Amongst OE's, this and other efficiency-enhancing tricks will be popular in coming years when coupled with engine downsizing. Ball bearings also offer greatly improved thrust capacity and can live with a lesser oil supply. Lastly, our EFR bearing system includes the latest in sealing technology, improving both resistance to oil leakage at light loads and intrusion of boost and exhaust pressures into the bearing housing while under heavy loads. The bearing housings are water-cooled for those who choose to (or are able to) plumb a water supply. Water cooling is recommended where possible to do so.

Turbine Wheel

The most exciting technology in the EFR package is the turbine wheel material. EFR turbine wheels are made from titanium aluminide. It's not the first time this material has been used, but it's the first time that it has been offered to the public across a range of size options. Titanium aluminide (or Gamma-Ti, for short) is a strange compound. One of those nice examples of the result being greater than the sum of the parts; this compound has temperature capability far in excess of aluminum and titanium as individual elements. Very difficult to cast, this compound is actually an inter-metallic which means that it's not quite ceramic and not quite metal. One major delivery of this project has been to commercialize this material to be able to introduce it at an acceptable price point. The technical advantage is very simple: low inertia. Since Gamma-Ti has roughly one-half the weight of a typical turbine wheel, the reduction in inertia is substantial *especially* on the larger wheel sizes such as 64mm and above. The turbine wheel is so light, it is very nearly the same weight as the compressor wheel that is on the other end of the shaft. When you feel one of these parts in your hand, it's hard to believe it's a turbine wheel. Then you drive the car and you feel what's been accomplished. When paired with the ball bearing system, it yields a turbocharger that has no rivals in terms of boost response.

Compressor Stage

As mentioned above, the series of compressors is from 62mm to 91mm OD which satisfies a wide range of applications. The compressor wheels are all FMW (forged milled wheels). We selected forged milled wheels not because they are pretty (even though they are) but because they do offer a strength improvement over cast wheels and because it provides speed and flexibility to the design process by not having to make casting tooling. Most high performance users won't benefit from the strength improvement because these applications are generally low turbo rotational speed and of relatively short mileage lifetime as compared to a commercial application. But, for the endurance racer or the uber-boost drag racer, the material might save your day. The compressor covers have been given our latest flow-range enhancement tricks such as treatment to the recirculation slot and optimization of the diffuser pinch and width.

Turbine Housing

When you look at the external appearance of the EFR product line, the first thing you will probably notice is the turbine housing. Unlike a milled compressor wheel that stays hidden inside, this outward-facing turbine housing looks like jewelry when installed. It's not all looks, however. The material is 300-series stainless steel for high temperature performance and corrosion resistance. The wall thicknesses are very thin, much thinner than a conventional casting, yielding low installed weight and low thermal mass. The manufacturing process is investment casting, which yields a cast surface that rivals a machined surface finish both inside and out. On the inside, this means lower gas friction losses. On the outside, this means people staring in your engine bay with jealousy. However, the housings are all-business when you get right down to it. With the initial product launch being comprised of four castings (with many machined variants), we are serving a variety of customers: wastegated or not, divided (twin scroll) or not, and of three different industry-standard mounting flange shapes. A v-band discharge flange comes standard. And, as mentioned above, they are aerodynamically designed as matched pairs with the turbine wheel choices.

Integrated Features

Why buy an external BOV? Why buy a boost control solenoid? In addition to buying these items separately and spending more money in the process, the user has needed to mount these parts which gives hassle and headache. The BorgWarner EFR turbos have these parts as integrated features. The CRV (compressor recirculation valve) vents boost quickly and efficiently when the throttle closes, and it is internally-recirculated to keep turbo speed high during the shift and to keep engine control systems (especially those with a MAF sensor) satisfied. The boost control solenoid valve (BCSV) is a convenience feature. Integrating the mounting of these valves onto the compressor cover is a trend we observed from the OE passcar side of the business. As such, you can trust that these are proven solutions that have worked for millions of customers for many years. For those that prefer an external blow-off valve, that's fine too. We will sell a block-off plate that disables the internal CRV.

“EFR” Name

Now that you have read the “EFR” letters a few times, you might wonder what the letters stand for or where the series name came from. Believe it or not, the process of determining the name was one of the more controversial elements of the program, but that just shows how much passion was put into this project by the team. Originally the name was derived from a contest entry held amongst BorgWarner's Asheville North Carolina facility (where the product is engineered and produced) employees. EFR^2 stood for Earth Friendly Race Ready series of turbochargers. The name struck a chord because it aligned with BorgWarner's strategy of being a technology leader in reducing fuel consumption and harmful emissions but also shows that they are well-heeled in the performance and racing scene. Many of the features in this product line will also migrate towards our OEM customers, especially those seeking the highest level of performance, efficiency, and feature content. Many of these customers are striking a healthy balance between powerful (fun) engines, yet also achieving extremely clean emissions and low fuel consumption. The name was later shortened to “Earth Friendly Racing” for a simpler look. After revealing the name within the organization and with some external advisors, it was apparent that tying “Earth Friendly” and “Racing” didn't go over well with many people. While many of the racing leagues are trying to produce a more “green” image, the vast majority of the performance market doesn't make a connection, at least not yet.

The EFR acronym remained the official name but it now more aligns with the true intent of the program. To find the name we needed only look back to the reason we started this project; to give the performance market a turbocharger that was engineered from a clean sheet with them in mind. Through the course of doing the work, we came to appreciate that the name "Engineered For Racing" (a.k.a EFR Series) would be known as the turbocharger that redefined the market's expectations.

<u>Summary</u>

All combined, the EFR turbocharger line is at the pinnacle of what can be done with the current state of the art while maintaining affordability. It raises the bar in every respect: performance, response, installation, appearance, and value. It is quite simply the best aftermarket turbo that money can buy, and we will continue to raise that bar and provide additional housing and feature options going forward.

Chapter 3: EFR Aerodynamic Selections

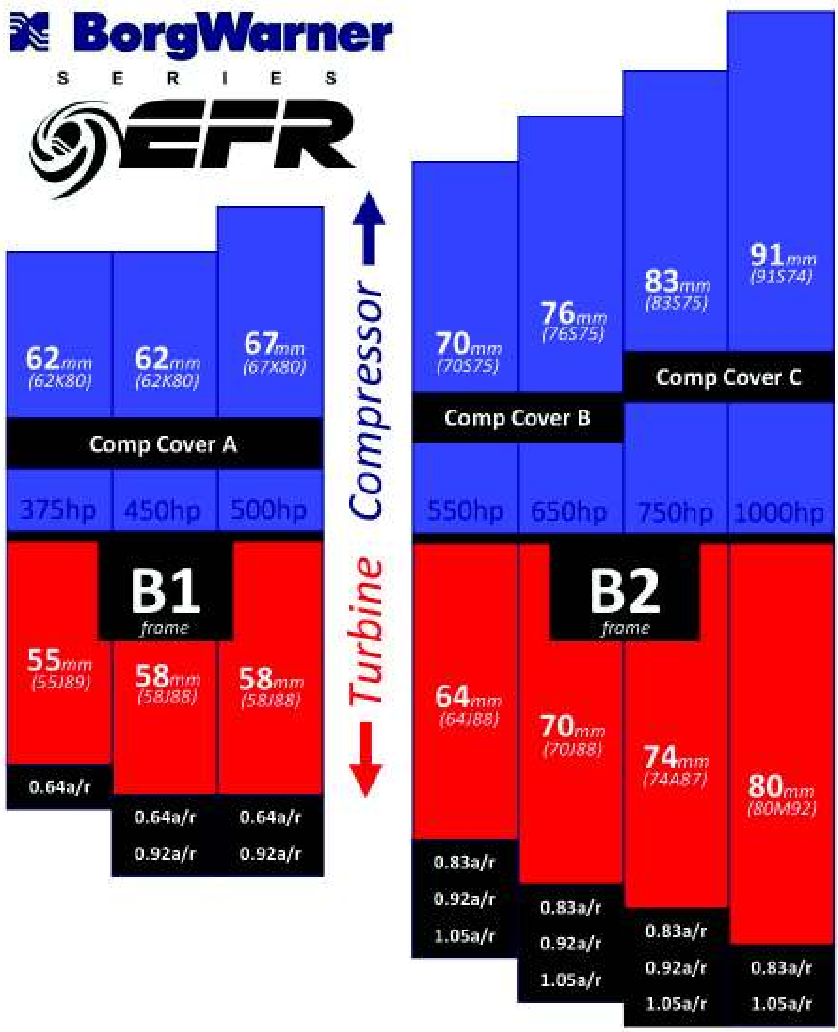


Figure 1: EFR Aerodynamic Options

Compressor Aerodynamics

There are six compressor wheel sizes within the EFR product range.
62mm, 67mm, 70mm, 76mm, 83mm, and 91mm.

Figure 2: Compressor Wheels 62mm-91mm

The two smallest wheels (62mm and 67mm) offer very large map width while still enabling high-boost operation. Very important for small engines striving for peak torque at streetable engine speeds, these compressors offer surge line positions that are far to the left on the map without needing a cover recirculation slot and cavity. The wheel itself is designed to not *need* an inducer recirculation slot, but furthermore it helps solve packaging problems due to the 2.5" inlet hose connection. Through a high backsweep angle on the blade outlet and our Extended Tip Technology on the exducer tip, these wheels offer excellent range (flow capacity) while still being capable of high boost at reliable turbo speeds. Both the 62mm wheel and 67mm wheel employ a large 80% inducer trim (64% on an area basis).

The rest of the compressor wheels (70mm through 91mm) are of a different design. These Extended Tip Technology wheels are very unique in that they are our highest-boost capable wheels but still give outstanding map width and flow capacity. The compressor cover treatment includes an inlet recirculation groove for maximum width and anti-surge characteristics. A new trim set was developed for this program on these wheels, which is 75% trim (56% on an area basis). This large trim gives up a very small amount of efficiency but for a significant gain in flow capacity. The only trim exception is the 91mm version. This part is released at 74% trim as to maintain an inducer diameter that is compliant to some specific drag racing class rules.

Figure 3: Extended Tip Technology

<u>Turbine Wheel Aerodynamics</u>

There are six turbine wheel sizes within the EFR product range. 55mm, 58mm, 64mm, 70mm, 74mm, and 80mm.

Figure 4: EFR Turbine Wheels 55mm - 80mm

The 55mm and 58mm turbines are targeted at street applications that need maximized boost response through smallest diameter and lowest inertia.   Still capable of 350-450hp when mated to the 62mm and 67mm compressors, they are a potent combination of quick response and respectable power capacity.   The 58mm turbine offers superior efficiency to the 55mm and when in doubt, should be the chosen one of the two.   The 55mm is offered for those people wanting the ultimate in small-rotor response, especially those who are used to 45-50mm turbos (such as our K03 and K04 products) who still want that "feel" but with a lot more top-end capability.

The 64mm and 70mm wheels are descendants from the same family of blade shape as the 55mm and 58mm, but are simply larger in size.   All four of these wheels use an 88-89% trim diameter, a good choice on this wheel for efficiency, flow capacity, and durability.

The 74mm wheel is of a very similar theme of those smaller sizes.   This wheel is a very potent performer and is used heavily in some of our most efficiency-focused applications on the OE side of the business.   It is cut to an 87% trim diameter.

The 80mm wheel really means business.   Made from our highest-flowing blade shape, this wheel is designed for maximum flow in view of our highest-power EFR customers.   This wheel has delivered the goods for up to 1000whp (per turbo) and comes with a 92% exducer trim.

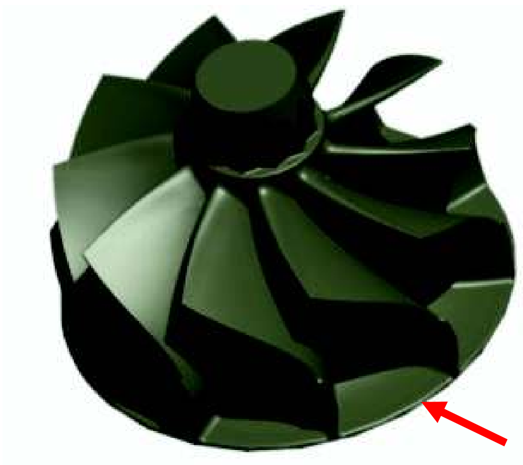


Figure 5: EFR Turbine Wheel, Showing "Fullback" (Full Diameter) Back Disk

All six turbine wheels use our latest hub shape definition. These hubs have a full aerodynamic back-disk, meaning that the hubline extends all the way to the inlet tip. Intuitively, this feature allows very smooth guidance of flow out of the housing and into the blade channels and this is exactly what is achieved. Impossible in the past due to material stress limitations, this exciting new "fullback" design is enabled by also having a "superback" on the part. Very similar to the curved surface on the backface of modern compressor wheels, the "superback" reduces centrifugal stress in the wheel by moving the locus of stress outwards from the core of the wheel. These two features work in concert to allow best possible efficiency, high speed capability, and durability.

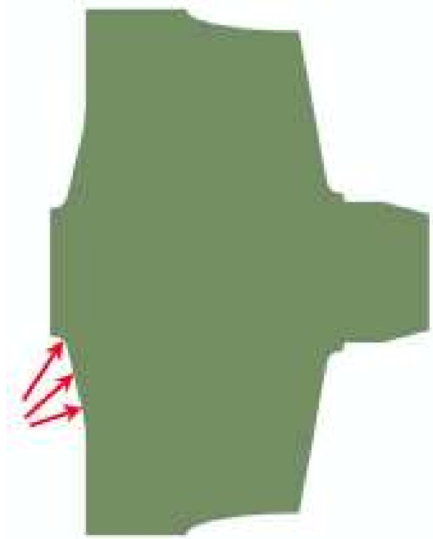


Figure 6: Turbine Wheel "Superback"

Turbine Housing Aerodynamics

Some of the most difficult program decisions were what design shapes to use for the turbine housings. The external features (and the decisions that led to them) will be discussed in a later chapter but here we will focus on the internal (volute) attributes. Every turbine wheel has a "sweet spot" in terms of what it likes to see for flow incidence angle. Keeping in mind that the wheel is always spinning, the incidence angle is formed by the rotational speed of the wheel and the angle of the gas leaving the turbine housing. Think of a garden hose that is spraying on a spinning paddle wheel. The wheel will achieve highest speed (greatest reaction) when the hose is pointed at the correct angle. It's tempting to think that the outflow from the housing volute dumps into one location, at the small end of the volute near the tongue (like the garden hose example). However, the actual purpose of the volute is to deposit an even distribution of flow (around the perimeter) leaving the volute and entering the wheel. Keep these principles in mind while we discuss a/r selection and the topic of "sweet spot".

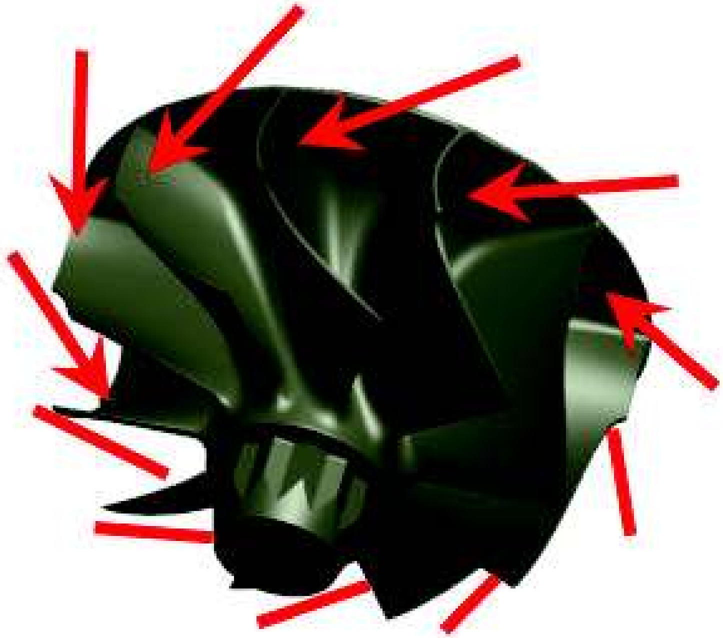


Figure 7: Turbine Wheel Inflow from Turbine Housing

Another important definition is the phi parameter. The phi parameter is nothing more than a numerical representation of the stage (wheel + housing) swallowing capacity. The number is calculated by knowing the mass flow, temperature, and pressure of the incoming gas.

$$\text{Turbine Flow Parameter (Phi)} = \frac{\text{mass flow} * \sqrt{\text{absolute temperature}}}{\text{absolute pressure}}$$

Figure 8: Phi Equation

Knowing the phi parameter for the stage and comparing that number to the engine exhaust manifold outlet conditions will describe whether or not the turbine can swallow what the engine is emitting. Any flow above and beyond the phi capacity must be wastegated. If the flow is less than the phi capacity, then the turbine is oversized and the boost target will not be achieved at that engine speed and load. This numerical comparison (point by point) is what is referred to as turbine matching and is substantially more involved than compressor matching. For that reason, turbine maps are often not published and sizing decisions are often based on rumor and tribal knowledge.

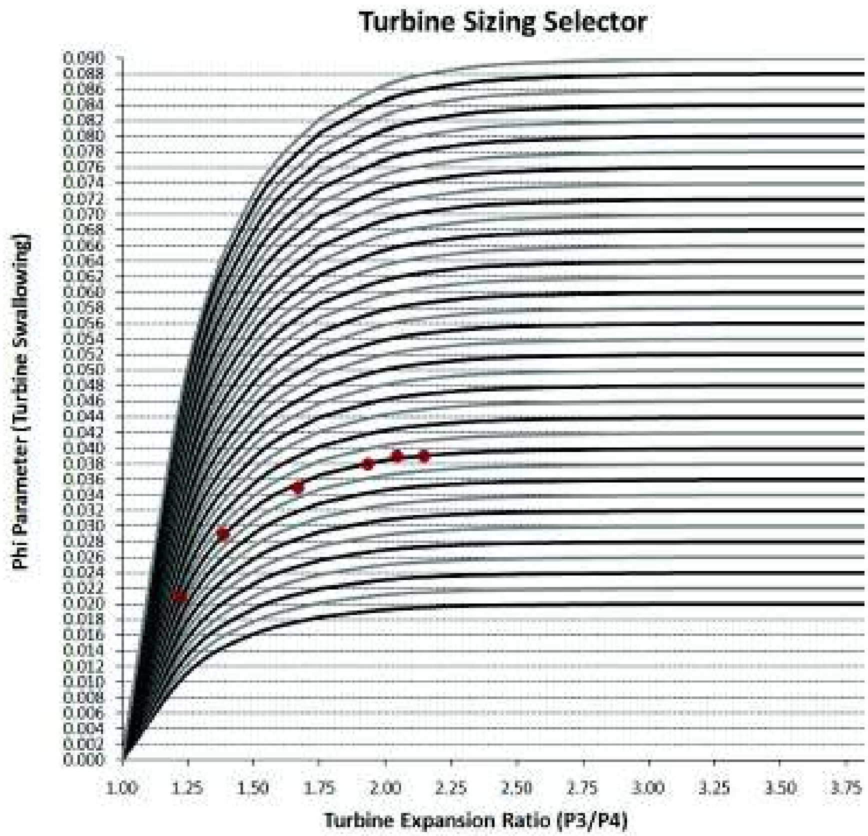


Figure 9: A Series of Phi Curves, (on which the operating points must fall, excluding the wastegate fraction)

The smallest housing in the EFR range was called “A” during the development phase and is optimized for the 55mm and 58mm turbine wheels. It uses a 0.64a/r which generates a volute outflow angle that is right in the sweet spot for these wheels. It is a suitable compromise of flow capacity while staying somewhat small and responsive. It has a large internal wastegate (31mm port, 36mm valve) which has flow capacity for roughly 38-40% of the turbine flow conditions for engine matches in the 350-450hp range.

Figure 10: Turbine Housing "A": 0.65a/r wastegated

The second housing “B” in the EFR range is similar in function to the “A” housing but designed for larger wheels. This housing has a 0.83a/r and is optimized for the 64mm, 70mm, 74mm, and 80mm wheels. This span of wheel diameters (16mm) yields a range of 8mm per side (at the tip radius) and the housing tongue position is designed for optimized yet durable positioning across this size range spectrum. This housing also has an internal wastegate, but is a bit larger in size than the “A” housing’s wastegate due to being targeted at the higher-power users. This wastegate has a port diameter of 36mm and a valve head diameter of 42mm which is the largest internal wastegate ever employed at the time of this writing. Wastegate flow fractions of 40-45% are possible with this design and combined with the range of wheel sizes, this housing is capable of very high power levels. The “B” housing does not have a divider wall, in other words it is a single-scroll design that will serve customers with non-divided manifolds.

Figure 11: Turbine Housing "B" - 0.83a/r wastegated

Let's pause on the EFR housing descriptions and spend a few moments on the subject of twin-scroll (divided) turbine housings. Twin-scroll housings are becoming very popular for performance use, and for good reason. By dividing the manifold and turbine housing into two flow paths, the engine firing order can be made to "alternate" the flow all the way to the turbine wheel inlet. The engine blow-down pulse is generated when the exhaust valve opens. During the blow-down, the engine power cylinder is still at very high pressure as a residual of combustion and the power stroke. This initial "pop" of energy travels at very high speed down the manifold runner, through the volute, and impacts the wheel. For this reason, the stream is very much a "pulsed flow" and the divided nature of the system simply amplifies and arranges those pulses. The engine firing order creates a "one-two" (alternating) punch on the wheel, keeping the pulses evenly spaced and in rapid succession. As the engine speed increases, this becomes a blur and the alternating nature loses its value. Hence, twin-scroll housings only benefit the low and medium speed operation of an engine. Within this range, it is a very effective way to improve turbine effectiveness. The wheel loves the high velocity evenly-spaced pulses of gas, and as long as they are “slow” enough in succession and duration, the wheel can make good reaction usage of the energy. What results is an improvement in “effective” efficiency, and at lower engine speeds more turbine power can be generated. The obvious result is quicker spool and better low-end boost response. As mentioned, the top-end operation is not improved, everything else being equal. Put into practice, a single-scroll housing of sufficiently large size is the recipe for a user that is seeking only top-end power optimization. That said, a very potent combination is a twin-scroll divided system that works to retain good low speed boost response, while sizing it large (aerodynamically) for the best top-end power. It’s the best of both worlds, in many cases.

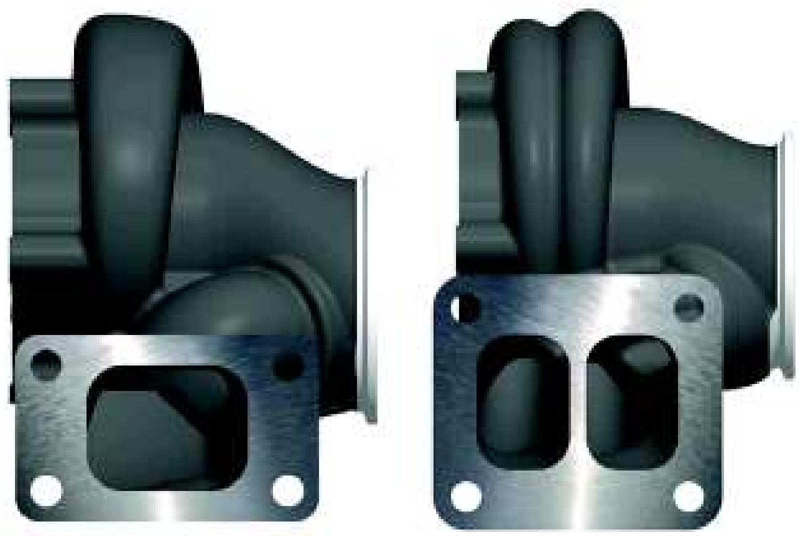


Figure 12: "Open" versus "Divided" Turbine Housings

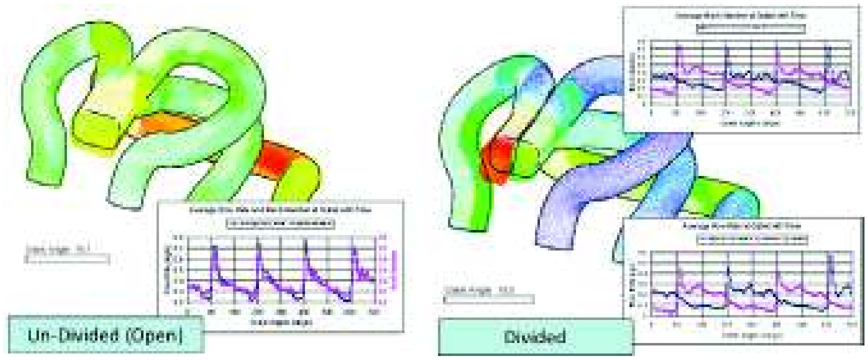


Figure 13: Open vs. Divided Manifold Pulsation (Courtesy: Ford Motor Company)

EFR turbine housing “C” is a very intricate part since it is not only a divided (twin-scroll) housing but is also internally wastegated. From a casting standpoint, this is quite difficult to do because the core shapes must not only divide the volute but also divide the wastegate path all the way up to the valve head. On OE diesel style housings, this can be accomplished with simple shapes and sometimes dual-valve arrangements but these are not good solutions for the performance application due to the limited wastegate flow capacity and high port flow losses. This “C” housing has a 0.92a/r and is optimized for the 58mm, 64mm, 70mm, and 74mm turbine wheels. Like on the “B” casting, this span of wheel diameters (16mm) yields a range of 8mm per side (at the tip radius) and the housing tongue position is designed for optimized yet durable positioning across this spectrum.

Figure 14: Turbine Housing "C" - 0.92a/r Wastegated

EFR turbine housing “D” is also a divided (twin-scroll) housing but is not wastegated. Targeted at those who are comfortable using two external wastegates or are already set up in such a configuration, this part will likely be the most popular on dedicated drag race machines. It is constructed with a larger volute than the “C” housing, this one being 1.05 a/r. It is also adjusted so that it can accommodate the largest of EFR wheel sizes, the 80mm. It is also offered for the 64mm, 70mm, and 74mm wheels. The housing has a very short axial length and is designed to be a “drop-in” for customers already running a T4-inlet divided housing with external wastegates.

Figure 15: Turbine Housing "D" - 1.05a/r Non-Wastegated

Summary

Turbine and compressor aerodynamics are truly “top shelf” in the EFR product line. Choices have been made that embody the current state of the art and include the latest and greatest techniques also being offered to our OE customers today. Combined with the other features like ball bearings, the compressor cover refinement, and Gamma-Ti turbine wheels (to be further discussed in other chapters), it has been our intention to maximize the performance of these turbos in every possible way.

Chapter 4: EFR Wastegate System

As mentioned in the introduction, internally-wastegated housings of the past have usually been castings that were handed down from prior diesel applications. As part of offering a diverse “performance” product line, it’s logical to make use of any casting that is available and might be of use to someone. However, these housings have had limitations. They have almost always had small wastegate ports that were quite suitable for diesel use but often not sufficient for “gasoline” levels of wastegating. Material specification has also been an issue, with most of these housing made from ductile cast iron of one flavor or another but rarely of a material truly suited for high-temperature operation. This is particularly noteworthy for wastegated housings, since the wastegate seat can be the “fuse” for thermal fatigue failure.

As part of our “clean sheet” approach, we wanted to make internal wastegates that were capable of handling the flow requirements of high performance applications. We use matching calculations that predict the level of wastegate flow required for any given match. By using a conservative flow coefficient assumption, we can predict how much flow will pass through a wastegate port of a specified diameter, motivated by the expansion (pressure) ratio across the turbine stage. Using this method, the wastegate can be sized on a match-by-match basis. This procedure was followed for a wide range of matches (displacements, power levels, engine speed ranges, turbo sizing) at the beginning of the project. It was decided that a 31mm port (36mm valve head) would be sufficient for the smaller turbine housing, and a 36mm port (42mm valve head) would be used for the larger housings. 36mm may not sound that much larger than 31mm but in fact it’s 35% more flow area.

Figure 16: Large Internal Wastegate

There are downsides with going too large, so we knew that we were walking a fine line. A wastegate that is too large can be fickle to control since a very small valve opening can then result in a very large increase of flow. In other words, if only 50% of the rod stroke is used for max wastegating flow need, then the control resolution is half of what it could have been. Also, packaging dimensions (housing physical size) suffers as the wastegate valve head grows in size.

Figure 17: Wastegate Valves - 36mm and 42mm

The wastegate valve, shaft, bushing, and lever materials are investment castings of premium materials. The valve heads have anti-rotation tabs to prevent vibration-induced skidding wear. Lever arm kinematics were selected to be a match with available rod stroke, yielding approximately

50 degrees of valve motion – sufficient to achieve maximum port flow. Another nice mechanical element is the lever's swivel-block due to the easy adjustment. The wastegate canister has an output rod and the end of this rod is threaded. The thread is M6 x 1.0 which means that each full turn of the nut equals a 1mm change in extension. By tightening the nut one turn at a time, a known preload (1mm) can be applied to the rod and canister spring. As preload is added, the spring inside the canister compresses and exerts more force to hold the wastegate flap closed. The downside of added preload is loss of stroke. In other words, the rod travel that is consumed by preload setting is no longer available for rod stroke motion (during use). The valve will not be able to open as far, so maximum wastegate valve flow will be limited.

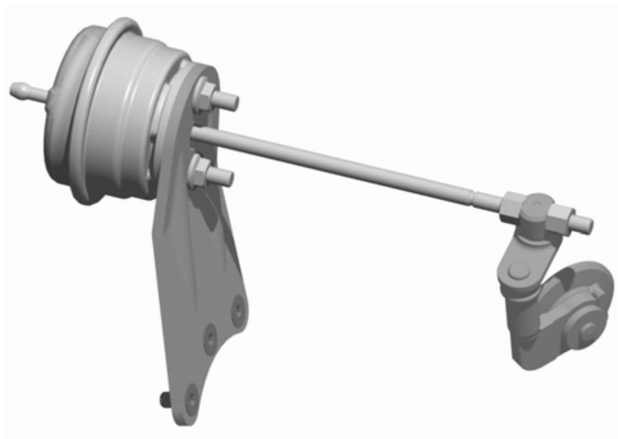
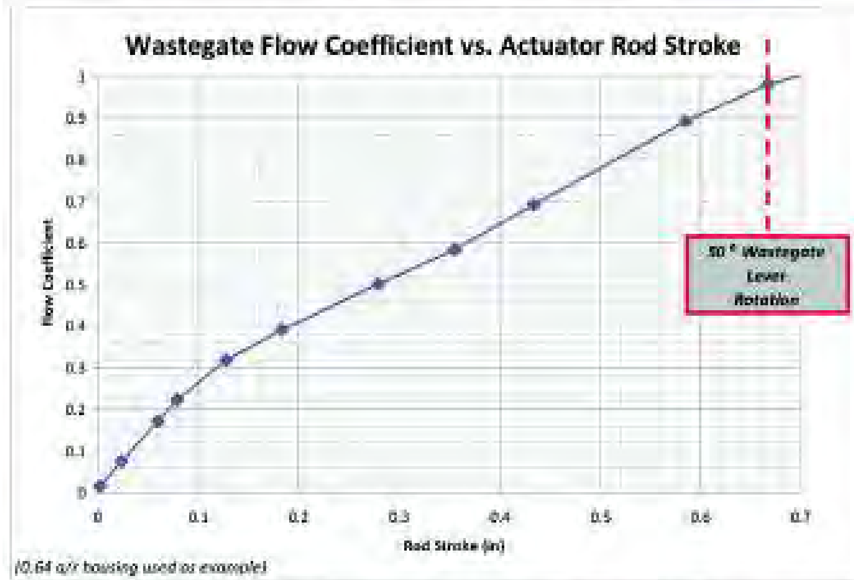


Figure 18: EFR Wastegate System



The flow coefficient is a measure of to what extent the wastegate port area is being used. When a pressure drop is applied to any orifice, orifice flow equations can be used to calculate what the theoretical maximum flow is through the hole. If the flow coefficient reaches 1.0, then that means that the port is being fed efficiently and that the port area is being used to the maximum extent. In this example, once the lever angle reaches about 50 degrees, the valve is sufficiently out of the way and the port is flowing at the max capability. From studying this plot, you can see why achieving a large stroke from the canister is important if the wastegate is being used for a large fraction of the total exhaust flow. This is particularly important with low-boost applications since higher wastegate flow fractions are required. More highly-boosted applications require less WG flow fraction since more work extraction (read: more turbine wheel energy) is required to power the compressor.

Figure 19: Wastegate Flow versus Opening Angle (Rod Stroke)

Turbine housing porting was also done with care, giving as much attention to the gate channel(s) as given to the rest of the volute entry throat. This is a compromise with outer elements such as overall housing height and stud/nut wrench access, but given these constraints the ports were smoothed, blended, and sized generously. Of particular challenge is integrating a smooth pair of wastegate channels into a twin-scroll housing. The "C" housing is of this type and requires bit of twist on the volute throats in order to wrap both wastegate channels towards the outlet, heading towards a Siamese (double-D) valve seat.

This is a superb housing for users of “divided” systems (with twin-scroll housing) since it avoids the need to buy, mount, and plumb two external wastegates.

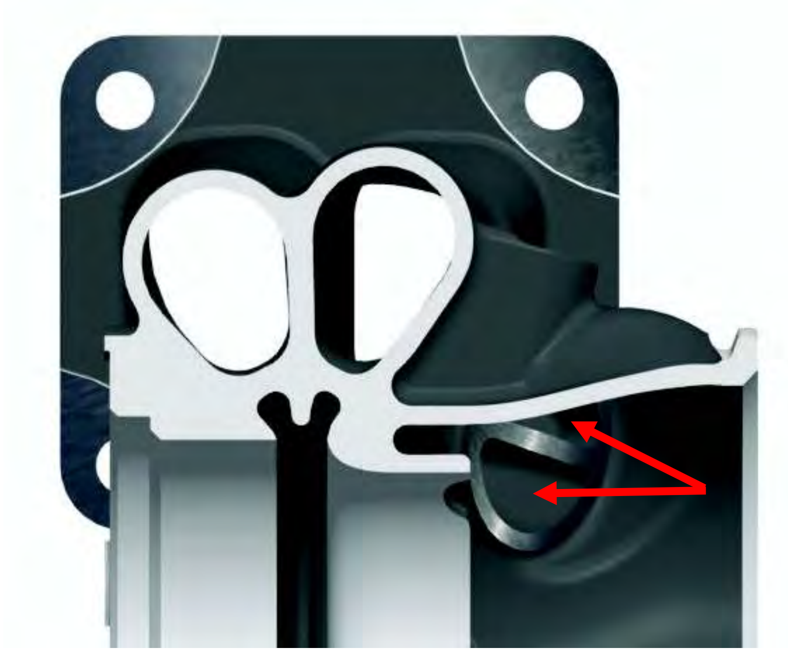


Figure 20: Turbine Housing "C" (0.92a/r) with Dual WG Passages

Wastegate behavior is tuned in two ways. First, the wastegate canister is selected. Second, the rod preload is set. There are three canisters offered, simply called “low boost”, “medium boost”, and “high boost”. As you would expect, the “low boost” actuator requires a low pressure to be applied before cracking the wastegate open. It is also sprung quite softly, so as canister applied pressure increases, the amount of rod movement increases quickly. This actuator is meant for vehicles running low boost pressures (less than 10psi) or vehicles running medium boost (10-15psi) that have an electronically-controlled spill valve (e.g BCSV) on the actuator line. The “medium” boost actuator is the default on EFR turbos and is targeted at the user running 12-18psi boost pressure straight off the supply hose or with mild amounts of electronic spill control. The “high” boost actuator is quite stiffly sprung and is reserved for those running 20-30psi boost (or higher, when using spill). The rod preload is the fine-tune adjustment, and as mentioned above it's easy to count turns and know how much preload (rod extension) is being added. Graphs are supplied that gives wastegate canister stroke response as a function of preload and applied pressure.

Rod & Spring Preload	Full Stroke Capability	179282, 179420, or 179285 Low Boost WG Canister		179283, 179421, or 179286 Medium Boost WG Canister		179284, 179422, or 179287 High Boost WG Canister	
[illegible]	[illegible]	Crack Open Pressure (psi)	Full Stroke Pressure (psi)	Crack Open Pressure (psi)	Full Stroke Pressure (psi)	Crack Open Pressure (psi)	Full Stroke Pressure (psi)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	0.59" (15mm)	5.7	14.0	10.8	20.6	17.6	32.4
3	0.55" (14mm)	6.1	14.1	11.2	20.6	17.8	32.3
4	0.51" (13mm)	6.8	14.3	11.9	20.6	17.9	32.3
5	0.47" (12mm)	7.3	14.4	12.3	20.6	18.1	32.3
6	0.43" (11mm)	8.0	14.4	13.2	20.6	18.6	32.3
7	0.39" (10mm)	8.5	14.6	14.0	20.6	19.0	32.3
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]		[illegible]		[illegible]	

Figure 21: Actuator Preload and Available Stroke Chart

The best control is achieved by using an electronic spill valve. This valve "vents" pressure from the wastegate canister's signal port. The net effect is that the canister can have a non-linear response to applied pressure and a more precise opening point and opening rate. When using a spill valve such as the one supplied with EFR turbos, the canister selected should be relatively softly-sprung. Why? With a valve, you can always lower the pressure making its way to the actuator, but you can't raise it. Also, the valve can vent <u>all</u> the signal pressure until it's time to open the wastegate. If you want a real punch in the mid-range, this is how to achieve it. The limiting factor for selecting a "softly sprung" canister (low boost) is the risk of premature wastegate valve opening. While not damaging in any way, it will soften up the boost response and can actually be a useful attribute on cars that are having traction problems when boost hits. Premature wastegate opening can be overcome by adding preload in most cases, but if extreme, the wastegate valve will blow open when exposed to turbine inlet pressures prior to when it is commanded to open by the actuator. The EFR actuators are sold separately, so if an alternate choice is needed, it's an inexpensive and easy swap.

EFR Wastegate Canister Selection Guide			
Core Assy	0.64a/r TH	0.83a/r TH	0.92a/r TH
6255	179282, 179283, or 179284	N/A	N/A
6258	179282, 179283, or 179284	N/A	179420, 179421, or 179422
6758	179282, 179283, or 179284	N/A	179420, 179421, or 179422
7064	N/A	179285, 179286, or 179287	179285, 179286, or 179287
7670	N/A	179285, 179286, or 179287	179285, 179286, or 179287
8374	N/A	179285, 179286, or 179287	179285, 179286, or 179287
9180	N/A	179285, 179286, or 179287	179285, 179286, or 179287

Figure 22: WG Actuator Canister Matrix

The most common problems occur at each end of the extreme:

Lazy boost onset or wastegate blowing open

- Canister spring too soft (use "medium" or "high")
- Not enough rod preload (tighten nut to add preload)
- No electronic intervention (spill valve can block pressure signal getting to WG can, hence delaying the opening)

Boost creep (overboost at high engine rpm's)

- Canister spring too stiff (use "low" or "medium")
- Too much rod preload (loosen nut to allow more rod stroke)
- Actuator/preload/spill combination not allowing full rod stroke at full boost condition
- Solution: Make sure actuator rod is achieving full stroke at max boost and high RPM (video-record, if required)

In extreme cases, the EFR wastegate port will not be large enough. It is sized to provide capacity for up to 40% of the engine mass flow to bypass the turbine wheel. However, on applications using very low boost pressures on large engines, little turbine power is required to satisfy the boosting task and as a result the need for wastegate flow is extremely high. In this type of scenario, there may be no other solution than a very large external wastegate. There are many on the market and the keys are to plumb the flow well and to buy a quality product. Keep in mind that these devices have an elastomer of some kind (either an o-ring or a diaphragm) that is in close proximity to exhaust gas heat. It's for this reason that we shy away from external wastegates, but if you do need one, buy the best you can afford.

The last topic is wastegate canister mounting. The canister bracket connects to the front face of the bearing housing, on the compressor end. This is a relatively cool location and keeps heat conduction (to the actuator) to a minimum. Furthermore, both the bracket and the output rod are stainless steel which further reduces the conducted heat. The bolt pattern on the bearing housing face is drilled in 15° increments which maximize the canister mounting options. Since the actuator mounts to the bearing housing, the bracket location will have to be adjusted simultaneously when the turbine housing to bearing housing orientation is adjusted.

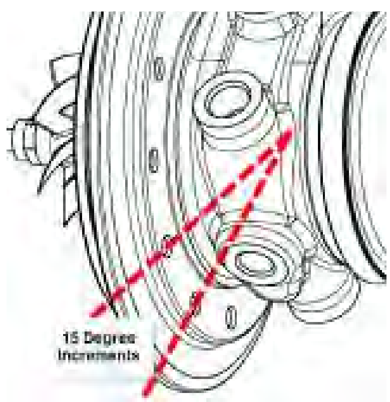


Figure 23: Actuator Bracket Able To Be Rotated in 15° Increments

Chapter 5: EFR Bearing Systems

The barrier for widespread use of turbocharger ball bearings continues to be cost. While the pricing is coming down amongst the global supply base, this is the primary reason as to why journal bearings continue to dominate worldwide OE turbo production. Current state of the art in rolling-element turbo bearings is to use ceramic balls and specialized race materials. EFR turbos use these premium materials and are designed and tested with commercial-duty longevity in mind.

Figure 24: Ball Bearing Cartridge

Figure 25: Bearing Disassembled; M50 Races, Metal Cages, Ceramic Balls

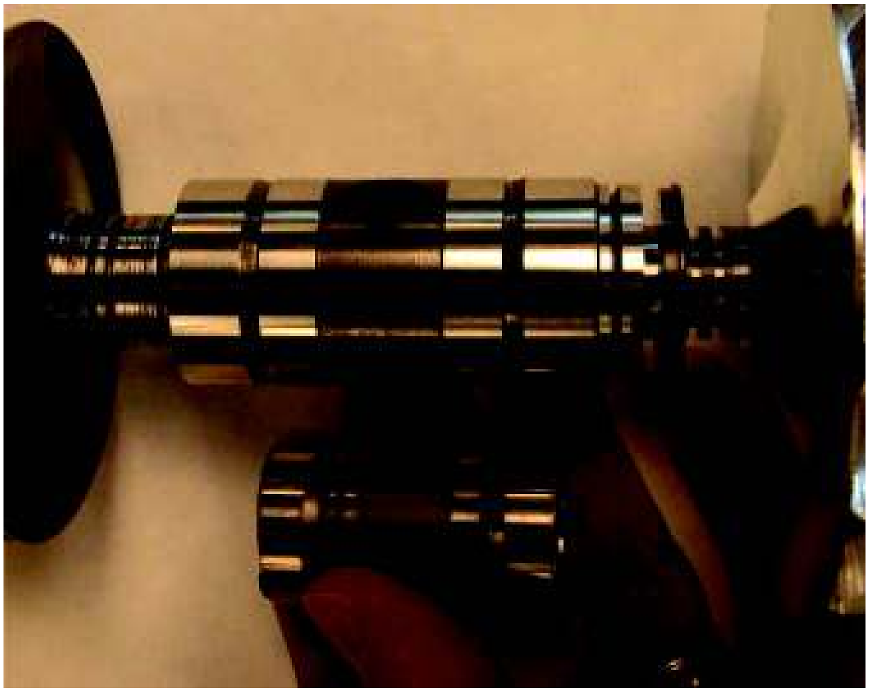


Figure 26: Which Would You Rather Have Supporting Your 500hp Application? (BorgWarner B2 vs. Competitor)

Figure 27: Competitor's Plastic Cage and Steel Balls

Ball bearing systems reduce friction losses as compared to their journal bearing counterparts. These friction losses are measureable on a combustion gas stand and are quantified by a gain in calculated turbine efficiency. Because it is difficult to separate the effects of mechanical efficiency (from the bearing system) and turbine efficiency, the SAE convention is to report the two as a "combined" efficiency. The combined efficiency is simply the multiplication of the thermodynamic turbine efficiency times the mechanical (bearing system) efficiency.

The friction loss is considerable at low turbo speeds and low shaft power. At these conditions, the power required to overcome friction is a larger fraction of the total power such that when reduced with ball bearings it accounts for a large improvement in combined efficiency. At higher speed and shaft power, the savings are a much smaller percent of total such that they become negligible. For this reason, the efficiency enhancement from a ball bearing system benefits the spool-up period and the light-load (low boost) regions of operation. The effect is most noticeable on a street machine coming in and out of boost and not as much at the drag strip. Using a drag race vehicle as an example, once it leaves the line it's always up on boost. Once on boost, the advantages of ball bearings erode so most drag race applications won't see much performance advantage from ball bearings. It's for this reason that our large S400SX and S500SX drag race turbos will likely retain conventional bearings for the foreseeable future.

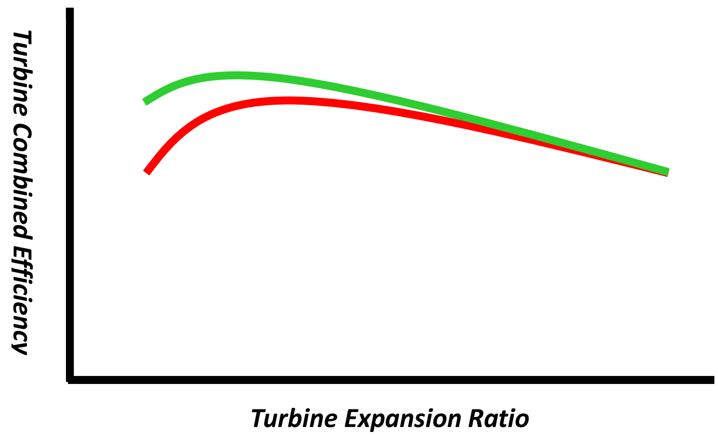


Figure 28: Low-End Efficiency Gain (Green) From Ball Bearings over Conventional System (Red)

The ball bearing system can survive substantially higher thrust loads than a hydrodynamic thrust bearing. The ball bearing is much better at surviving abuse such as compressor surge, marginal oil quality, low oil pressure, and harsh acceleration. The thrust capacity of a ball bearing is believed to be about 10X that of a conventional thrust bearing but to be honest we don't know the exact figure because our thrust load test rig cannot currently develop enough force to overload one. We do know that it has at least 5X the capacity. Unlike the conventional system where higher axial load capacity comes at the expense of friction losses, the thrust capacity of a ball bearing is "free", by comparison, when it's not heavily loaded.

Oil flow requirement is another key distinction. The ball bearing system does not require much oil to function properly. We have integrated an oil restrictor into the bearing housing so an external orifice SHOULD NOT BE ADDED. The oil does provide a cooling function in addition to keeping the ball raceways lubricated, so the oil flow will continue to be 25-50% of that required for a conventional system. A -4AN male fitting has been provided on the EFR turbo and a -4AN (1/4") line is sufficient as long as the engine supply pressure is healthy and the line(s) are kept short. If the line is longer than about 18” then it’s advised to step up to a -6 supply line. This is most critical for people living in cold climates.

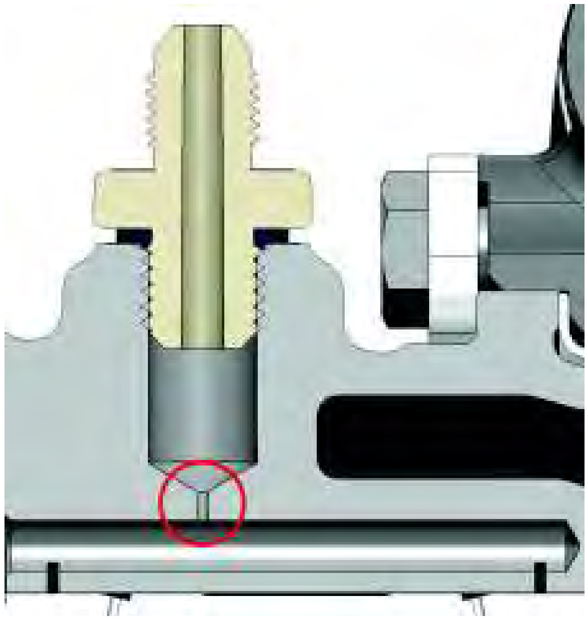


Figure 29: Oil Restrictor Integrated Into Bearing Housing

Figure 30: -4AN Oil Inlet Fitting (Supplied)

The EFR turbo also uses our top-shelf sealing system which includes two compressor piston rings placed in separate grooves as well as two turbine rings also placed in separate grooves. These features along with other geometric techniques provide a very effective oil sealing function as well as good blow-by resistance. Blow-by (the boost and exhaust pressure gases entering the bearing housing) has been reduced by 50% over the levels seen in prior generations of turbos. This sealing system along with the extended bearing span (for added stability) do make the center section quite long, and is the only drawback of the EFR internal component selections. This is a clear example of priorities: function and durability comes first.

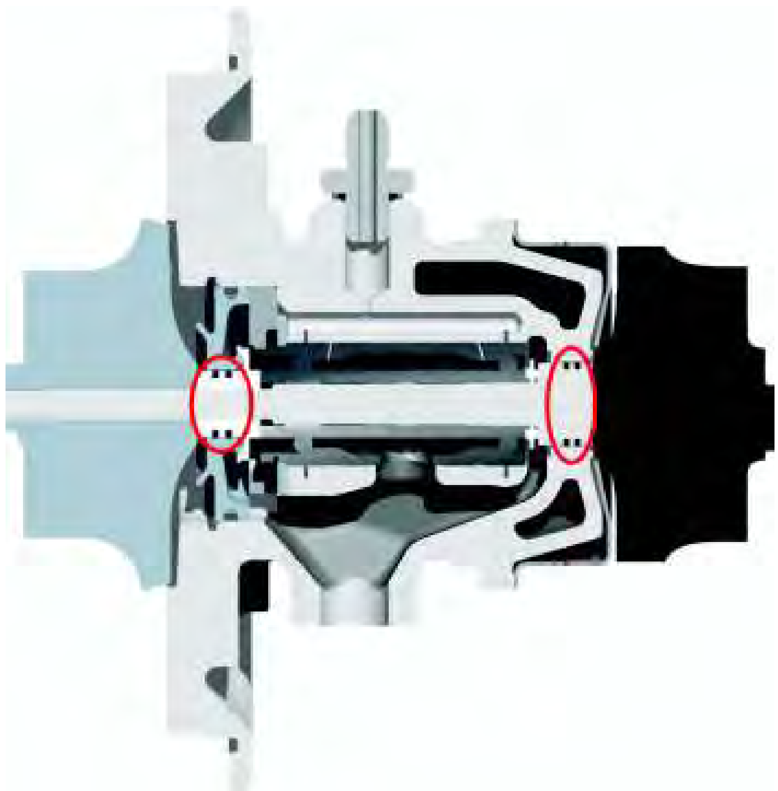


Figure 31: Dual Compressor and Turbine Piston Ring Seals

The bearing housing oil drain is machined for two connection types. The oil drain port is tapped with 3/8-NPT threads for those who want to install a fitting. A fitting with 3/8-NPT on one end and -8AN on the other makes for a very nice solution. The through-bore of such a fitting is about 0.42", which then spills into a 0.5" ID drain line. For those wanting to install a gasketed flange, two M8 holes are provided with a centerline span of 1.5".

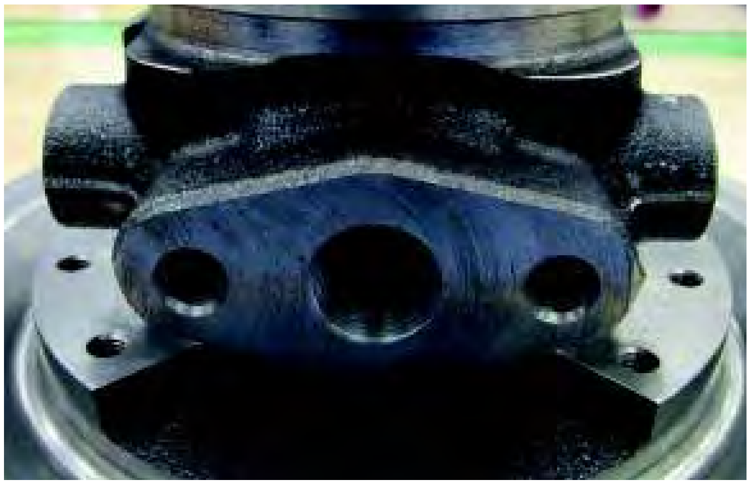


Figure 32: Oil Drain Pad Machined for Gasket and 3/8 NPT Fitting

Figure 33: Oil Drain Fitting Installed (-8AN)

The bearing housing castings are water-cooled, and four M14x1.5 ports are provided. Two plugs are also provided so that the ports not being used can be capped off. It does not matter which side of the bearing housing gets the inlet flow and which side gets the outlet flow, but the flow must be diagonal across the housing. Also, the inlet port needs to be on the bottom and the outlet port needs to be on the top. This is to encourage evacuation of air bubbles as well as to encourage auto-siphoning (flow movement through natural convection) during the shut down's heat soak.

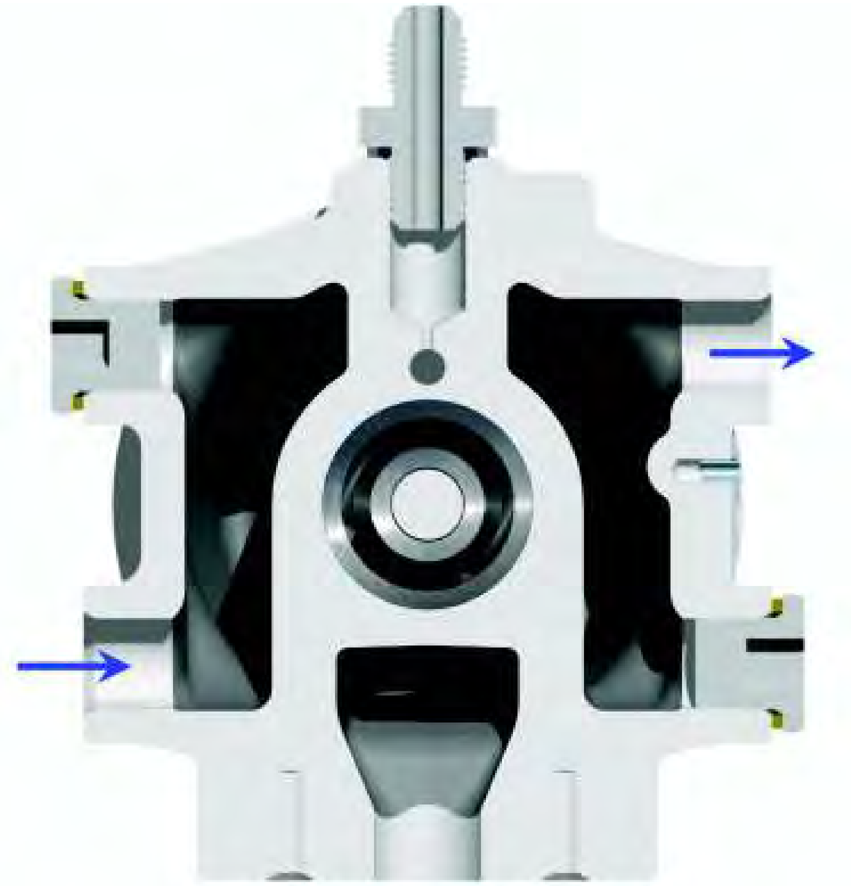


Figure 34: Cross-Flow (Bottom to Top and Side to Side) Nature of BH Water Cooling Plumbing

Figure 35: Series EFR Bearing Housings, B1 (back) and B2 (front)