Chapter Five

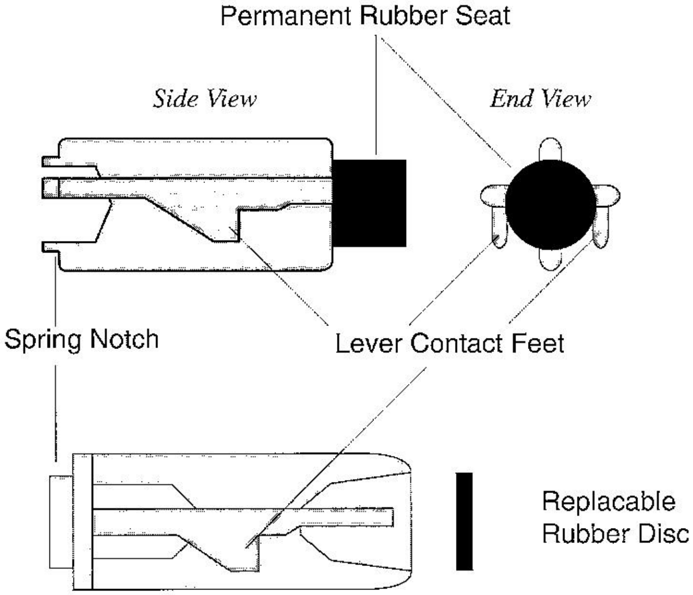
Air Balanced Second Stage..................Mechanical Principles

The majority of chapter five is devoted to air balanced demand valve designs. Before I delve into this subject, there is one more downstream mechanism that I would like to cover. The reason I waited until this chapter to discuss this particular downstream valve design is because it was converted from "downstream" to "air balanced" as it evolved over the years. This conversion is easy to understand when a direct comparison of the parts that were used to modified the design are analyzed.

The roots of this valve go all the way back to 1969. It was originally called the "Scubapro Adjustable" second stage and its presence dominated the market for many years. As I am sure you can imagine, there have been innumerous component changes, but the mechanical principles are the same. You will, undoubtedly, encounter a variety of different configurations of this downstream second stage. Most of these versions can be upgraded to current parts and performance standards, including the modifications that convert the function from downstream to air balanced. I felt it was only prudent to present this design evolution in the proper sequence, so that it is absolutely clear how to handle this second stage.

Figure #54

Adjustable Downstream Poppets



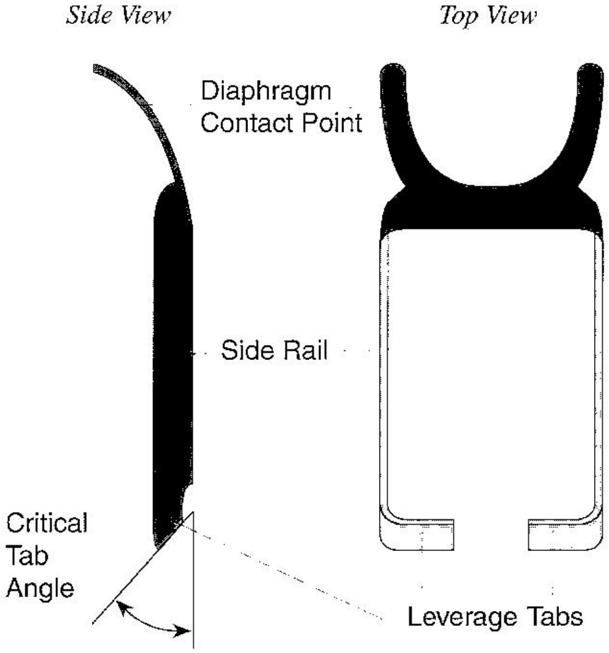
Poppet: The adjustable downstream valve has had 5 major poppet changes. Regardless of the actual shape and size, they all perform the same function. The current poppets fit nearly all of the older model units. The only reservation to this universal compatibility is that many times the demand lever must also be changed when a new poppet is retrofitted into an older second stage.

The figure to the left shows the version of the poppet that was used from 1982 -1994. At the time of this writing, a newer version is in the final stages of development. The new poppet features a replaceable rubber disc seat similar to the one shown in chapter four. For the purpose of the remaining illustrations, the 1982-1994 poppet will be used.

The poppet is illustrated in two views to better identify its shape. The seat on the 1982-1994 version is a rubber coated brass cap that is permanently bonded to the plastic molded body. Take special note of the lever contact feet that extend down from the cross web of the molded body. These two vertical ledges are the point at which the lever pushes on the poppet to open and close the valve. The rear of the poppet is formed to fit inside the spring. The cross web design (end view) provides minimum friction contact inside the air barrel, yet maintains consistent and repeatable seat to orifice alignment.

Figure #55

Demand Lever, Adjustable Second Stage



Demand Lever: Figure #55 shows the demand lever in two views. The top of the lever is formed to contact the underside of the diaphragm with a minimum amount of friction. The side rails are thin and flexible to permit the open end of the lever to be spread over the air barrel and then spring back to its original shape after it is installed. The leverage tabs are bent to precise angles that establish the attitude of the lever when the spring tension forces it forward in the air barrel. Lever angle is critical because it positions the top of the lever so that it is just barley touching the underside of the diaphragm. This "zero clearance" provides immediate lever response that is in concert with diaphragm movement. Take a few moments and study the various features of the demand lever. I will refer to these elements as we work our way through the mechanical principles of this valve.

Air Barrel: The air barrel shown in figure #56 is a machined brass tube that serves as the housing for the complete valve assembly. In newer Scubapro regulators, G250, G200, & G200B, the air barrel can be removed from the second stage as a complete unit. In older chrome plated brass cases, the air barrel was silver soldered into the housing and was not removable. The external features of the air barrel are reasonably straight forward. Pay particular attention to the square broached lever access hole. The tabs of the lever protrude into the inside of the air barrel to control poppet movement. The flat front edge serves to set the lever angle and form a pivot point for the lever fulcrum. The aspirator directs the air flow to take advantage of the internal geometry of the housing.

Figure #56

Air Barrel, Adjustable Second Stage

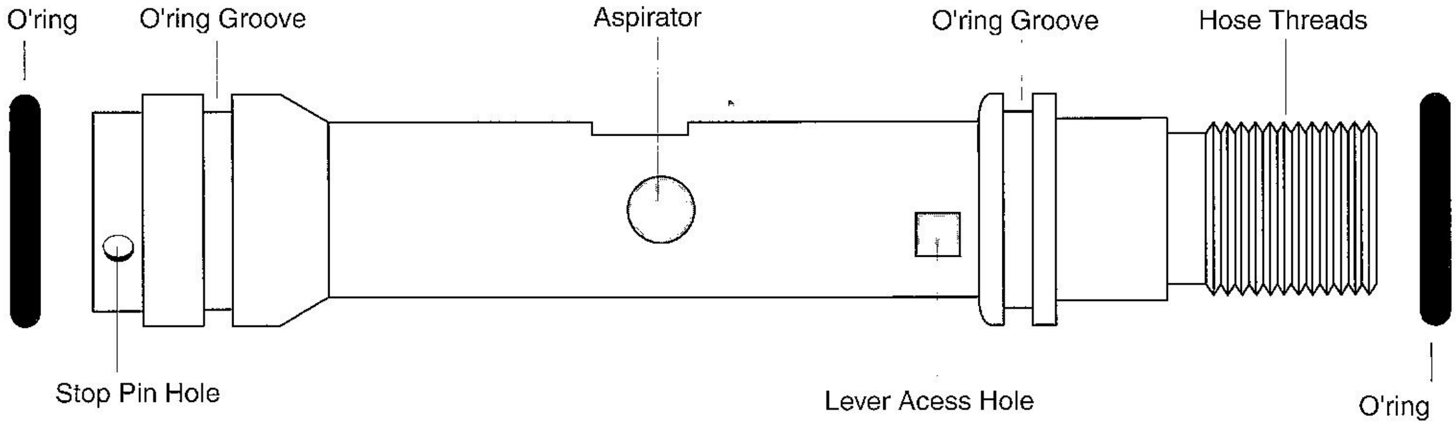


Figure #57
Adjustable Downstream Valve Components

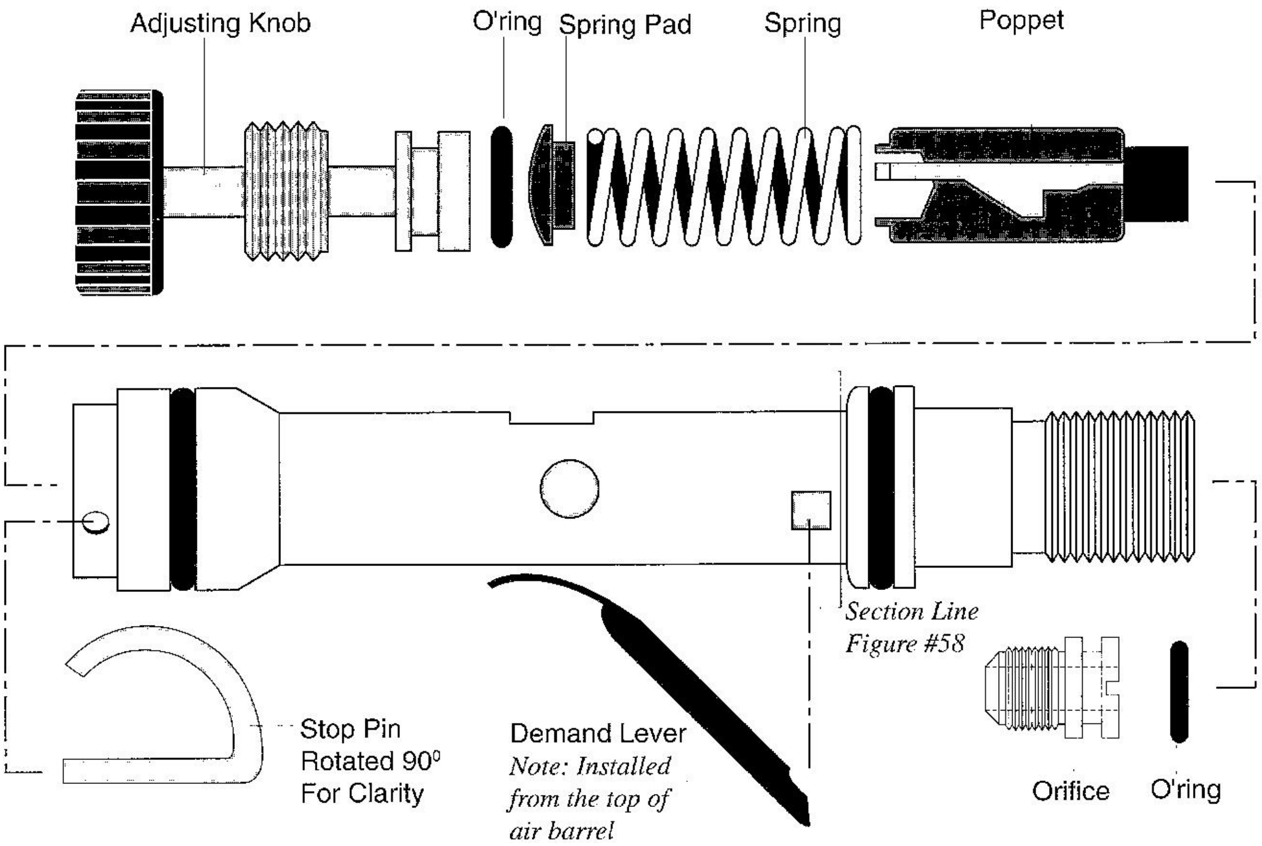
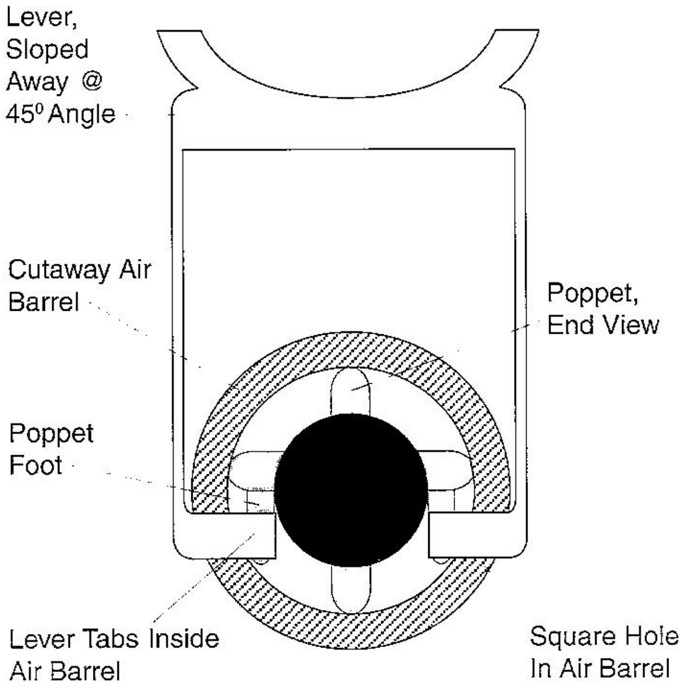


Figure #58
Poppet Alignment,
See Section Line Above



Order Of Assembly: Figure #57 shows an exploded view of all the downstream valve components. The order of assembly is as follows:

With the o'ring installed, the orifice is threaded into the air barrel from the hose end. The approximate location of the orifice is important and will be covered under adjusting procedures.

The lever is installed next by spreading the leverage tabs apart wide enough to pass over the outside diameter of the air barrel and snap into the square access holes.

The poppet is dropped into the air barrel from the stop pin end. Rotational alignment of the poppet is critical. The "poppet feet" must align with the "lever tabs" protruding inside the air barrel (see figure #58).

The spring and spring pad are dropped into the air barrel after the poppet. The adjusting knob is threaded into the air barrel until the outward edge of the threaded hub passes the stop pin hole.

The stop pin is installed by inserting the straight shank of the pin completely through the adjacent holes in the air barrel. The round portion of the pin is then snapped over the outer diameter of the air barrel. This pin prevents the adjusting knob from being backed all the way out after assembly.

Figure #59

Assembled Adjustable Downstream Valve, Full Cutaway

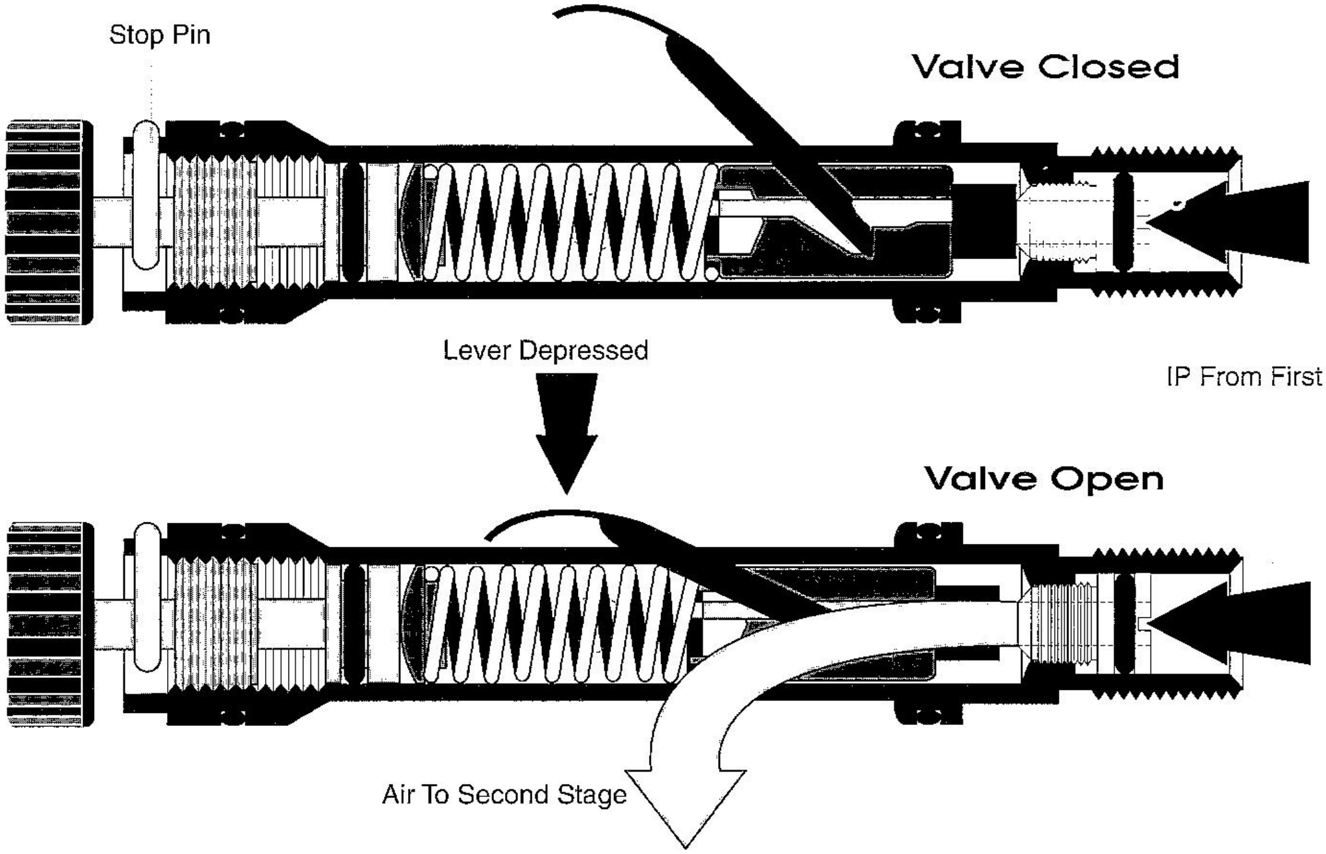


Figure #60

Lever Action Close-Up

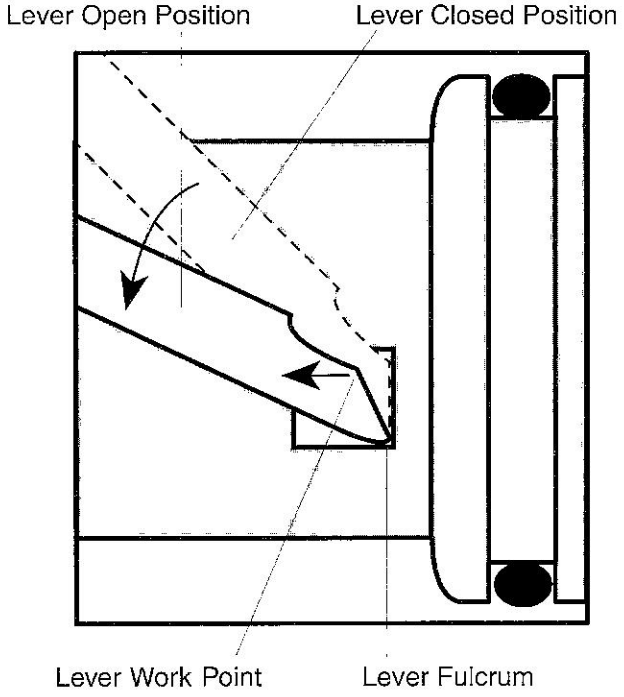


Figure #59 illustrates the adjustable downstream valve in both the open and closed positions. Its function is classic downstream as the force of the incoming air is directed to open the valve. The DSF is counterbalanced by a spring that seals the poppet against the orifice.

One new twist (I love it when a pun comes together) has been added to this valve. The spring force can be adjusted by the diver to control demand effort. This feature is primarily designed to help control water surge against the diaphragm causing the regulator to force air at the diver. These conditions are most prevalent when diving in heavy surf or strong currents.

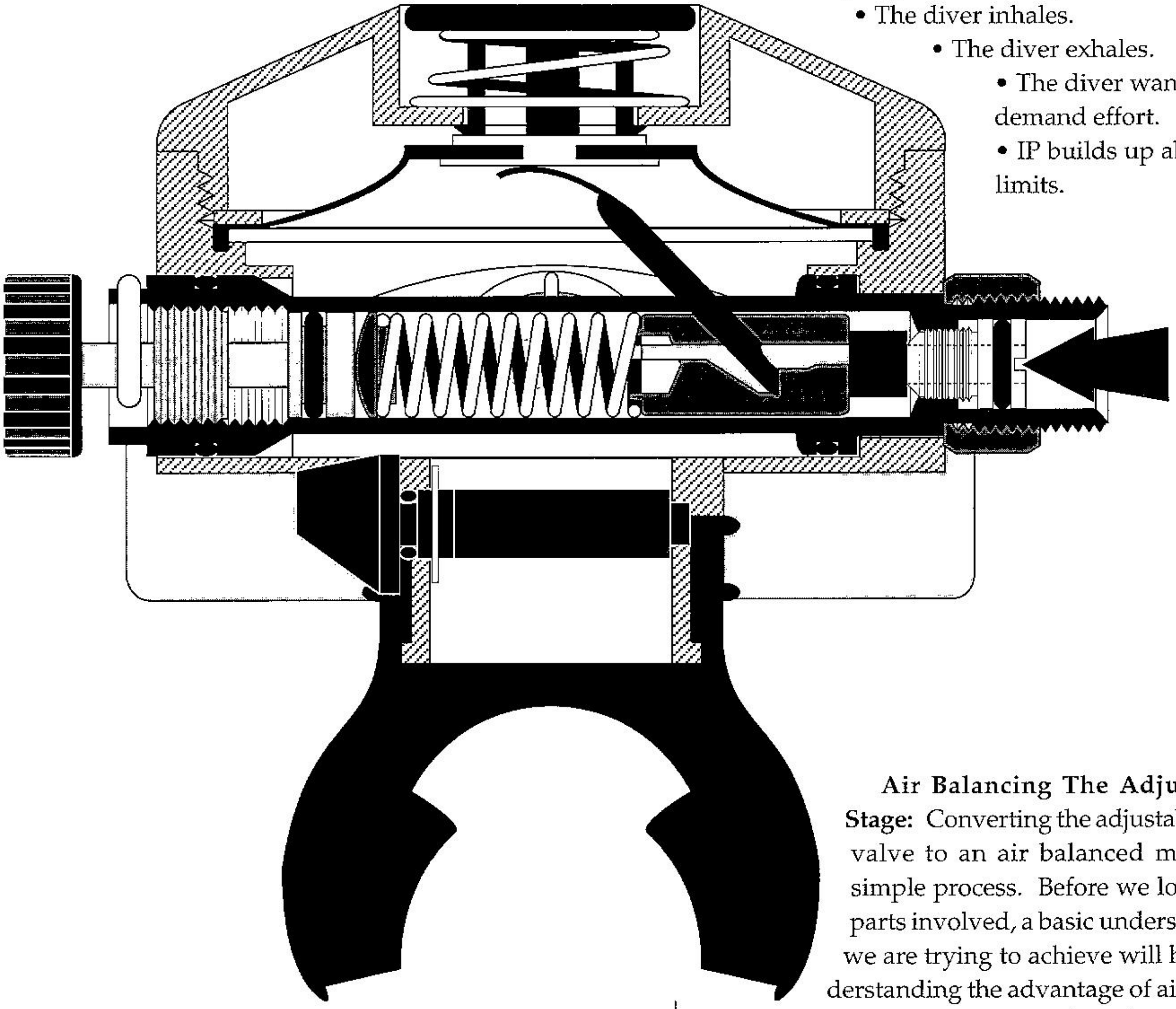
Figure #60 provides a close-up view of how the lever opens the poppet. Take special note that the angle of the lever tabs establish the "height" of the demand lever. This occurs because the spring forces the poppet forward against the lever tabs. This action causes the lever tab to align with the vertical side of the square hole in the air barrel. Lever height is seldom a problem, but may become important when new parts are retrofitted into older housings. If the lever is low, it will increase demand effort. The shortened stroke can also reduce the distance between the poppet and orifice and limit the flow performance of the second stage.

Figure #61

Complete Adjustable Downstream Second Stage

The relationship of this downstream valve and the other second stage components is the same as previously described. As a review, see if you can mentally trace the sequence of movements that occur under the following circumstances:

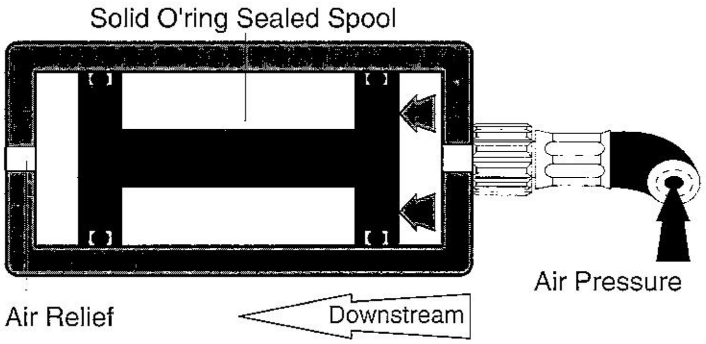
- The purge button is depressed.
- The diver inhales.
- The diver exhales.
- The diver wants to increase demand effort.
- IP builds up above acceptable limits.



Air Balancing The Adjustable Second Stage: Converting the adjustable downstream valve to an air balanced mechanism is a simple process. Before we look at the actual parts involved, a basic understanding of what we are trying to achieve will help in fully understanding the advantage of air balancing. Up to now, the spring has provided the only counter force that maintains a seal between the poppet and the orifice. It must be strong enough to overcome the DSF produced by the IP from the first stage. When the diver inhales, enough demand effort (vacuum) must be initiated to depress the spring further and open the valve. If we could eliminate the downstream force, a lighter more sensitive spring could be used reducing the amount of inhalation effort required to open the valve. So how do we eliminate the DSF? Simple, "we balance it against itself" and cancel its effect. In other words, if we can produce a valve where the DSF pushes on the poppet in opposite directions equally, it will no longer produce a force that moves the poppet in either direction. Let's take a look at two simplified illustrations that show the basic principles surrounding the air balancing process.

Figure #62

Downstream Spool Valve

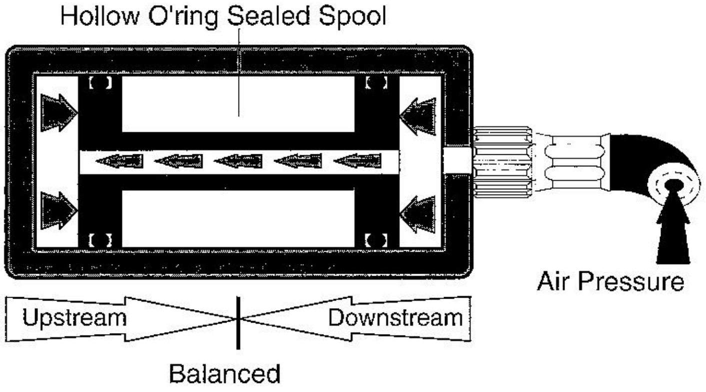


In explaining air balancing in the past, I have discovered that people think about the process in two different ways. Some understand it best by recognizing the stabilizing effect of two forces pushing equally in opposite directions, and others prefer to analyze the balancing process as a cancellation of force through the equalization of pressure. Both perspectives are valid. The illustrations to the left feature a classic "spool valve". The spool (piston) looks similar to the one mom used when she mended our jeans. I guess that's where the name came from. The ends of the spool are o'ring sealed to the inside diameter of a cylindrical housing.

In figure #62 the spool will be driven away from the incoming air pressure. We have provided an air relief hole in the far end of the housing to allow an exit port for the air compressed by the spool when it moves. This valve can be called a downstream spool. The force required to move the spool back toward the DSF will be equal to the surface area exposed to the pressure times the air pressure. For example: if the exposed surface is 1 sq. inch and the incoming pressure is 100 psi, a force greater than 100 lbs. would be necessary to move the spool "upstream" against the incoming air pressure.

Figure #63

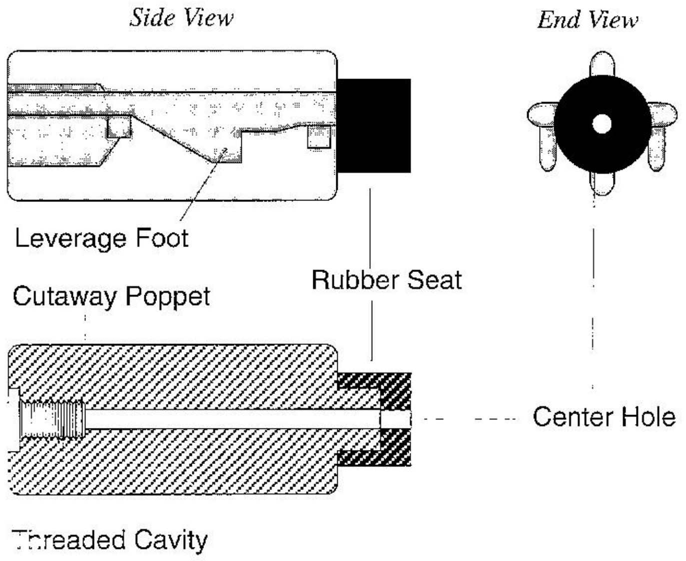
Air Balanced Spool Valve



In figure #63 we have plugged the relief port and drilled a hole completely through the center of the spool. The air can now travel freely to the opposite end. You can say that the spool is stable, because the two forces are pushing equally in both directions, or the force has been canceled by equalizing the pressure. Again, both statements are true. The most important fact is that the spool can be moved in both directions with a theoretical force of " 0 lbs". This valve has canceled the effect of the DSF by balancing it against itself.

Figure #64

Air Balanced Poppet



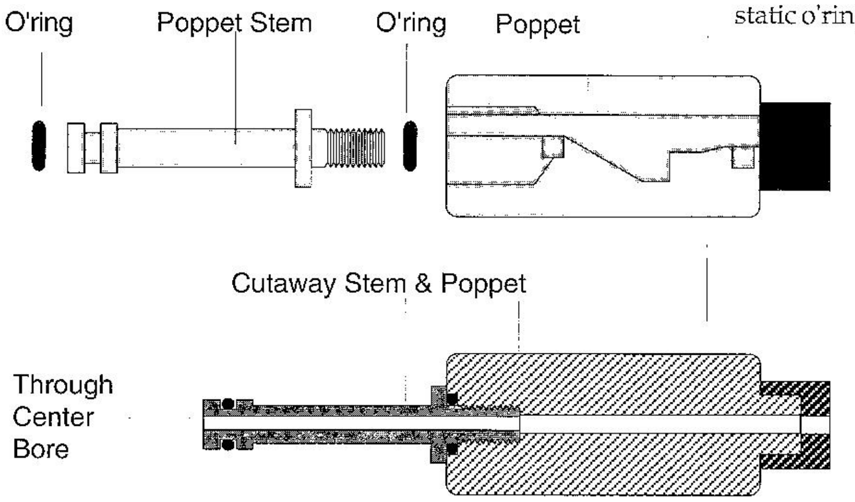
Let's take a close look at the actual parts used to air balance the adjustable downstream valve and see how this mechanical principle is utilized.

Balanced Poppet: At first glance, the balanced poppet looks identical to the downstream poppet. The cross webs are the same and the leverage feet are located in the same position. The end view, however, revels a hole in the center of the rubber seat. A cutaway side view shows that the hole extends all the way through to the back of the poppet. The back of the poppet is threaded internally and molded to accept an o'ring seal.

The composite rubber seat cap is permanently bonded to the body and the poppet must be replaced as a complete unit.

Figure #65

Balanced Poppet & Stem

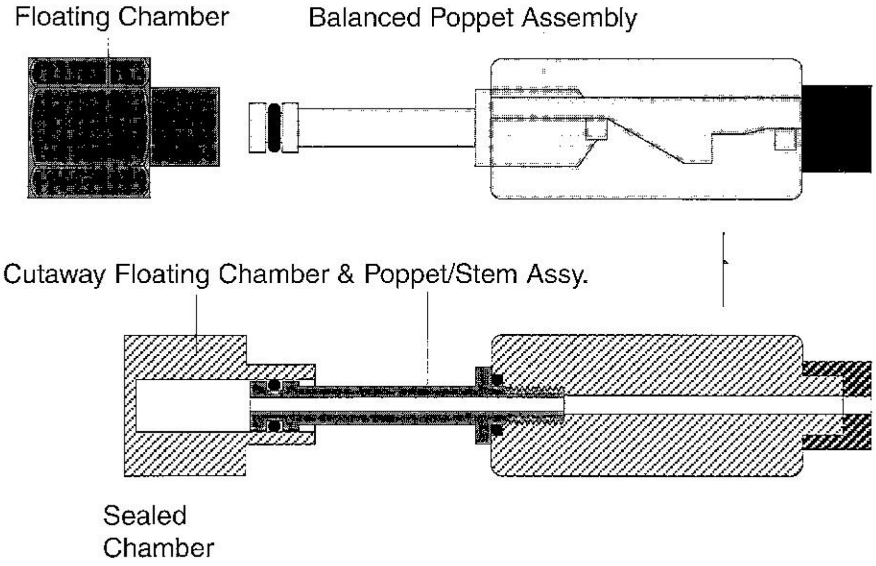


Poppet Stem: A chrome plated brass stem is threaded into the back of the poppet. It is sealed to the poppet by a static o'ring that is installed over the threads against the stem shoulder. The opposite end of the stem is grooved to accept a dynamic o'ring that seals the stem to the floating chamber.

The cutaway view shows that the stem is also center drilled. When the two parts are assembled, the center bore forms a sealed access hole that extends from the front of the poppet to the far end of the stem.

Figure #66

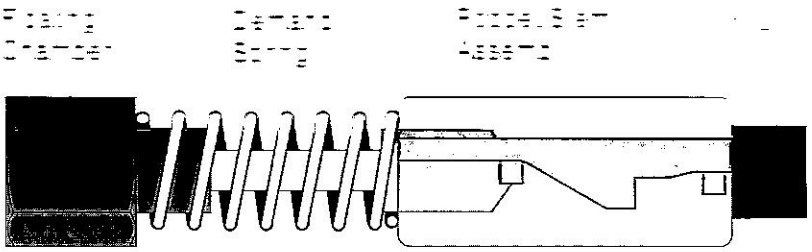
Floating Chamber & Poppet Assy.



Floating Chamber: The floating chamber is molded from high density plastic. It is hexagon in shape and the end nearest the poppet is machined round to a diameter that fits the inside of the demand spring coils. The floating chamber has a blind hole in the center that ends near the back of the part.

The diameter of the hole fits the end of the stem precisely. When the stem and o'ring are inserted into this hole, a small sealed chamber is formed. The stem can slide freely in both directions and the dynamic o'ring maintains an airtight seal as the stem moves. Air can now travel from the front of the poppet to the sealed chamber where it is trapped.

Complete Balanced Poppet Ass'y



Demand Spring [illegible] spring is assembled between the poppet and floating chamber. This spring reacts in the exact same way as the downstream spring. Its primary function is to apply the force required to seal the poppet against the orifice knife edge.

Complete Balanced Poppet Assembly, Cutaway

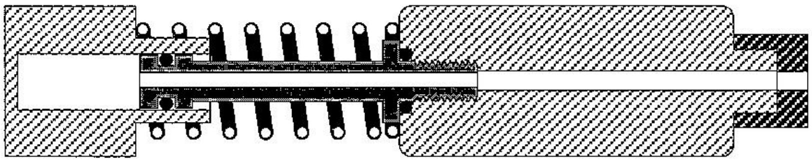
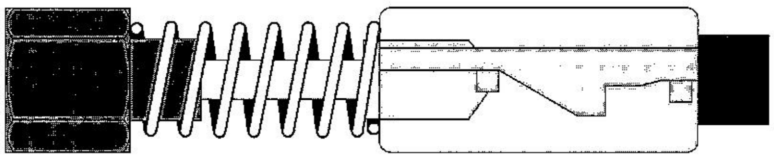


Figure #68

Balanced Vs. Downstream Comparison

Air Balanced Assembly



Downstream Assembly

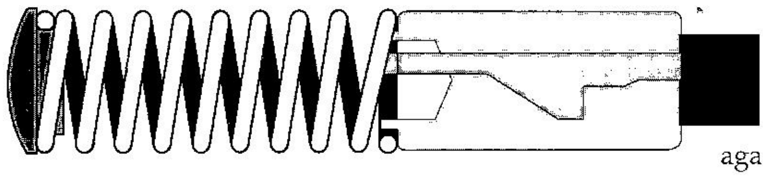


Figure #68 compares the downstream and balanced assemblies. Take special note of the relative difference in spring size. Remember, the spring must be compressed by inhalation effort. The stronger the spring, the higher the demand effort becomes. It only stands to reason that the air balanced valve will require less breathing effort because of the softer spring.

I can here you thinking ...."But the spring also supplies the force to seal the poppet against the orifice. How does the softer spring maintain this seal? Won't the downstream force push the poppet open and cause the valve to leak?" The answer would be, "Yes", if the DSF was the same; but the DSF has been reduced in the floating chamber by balancing it against itself. Read on!

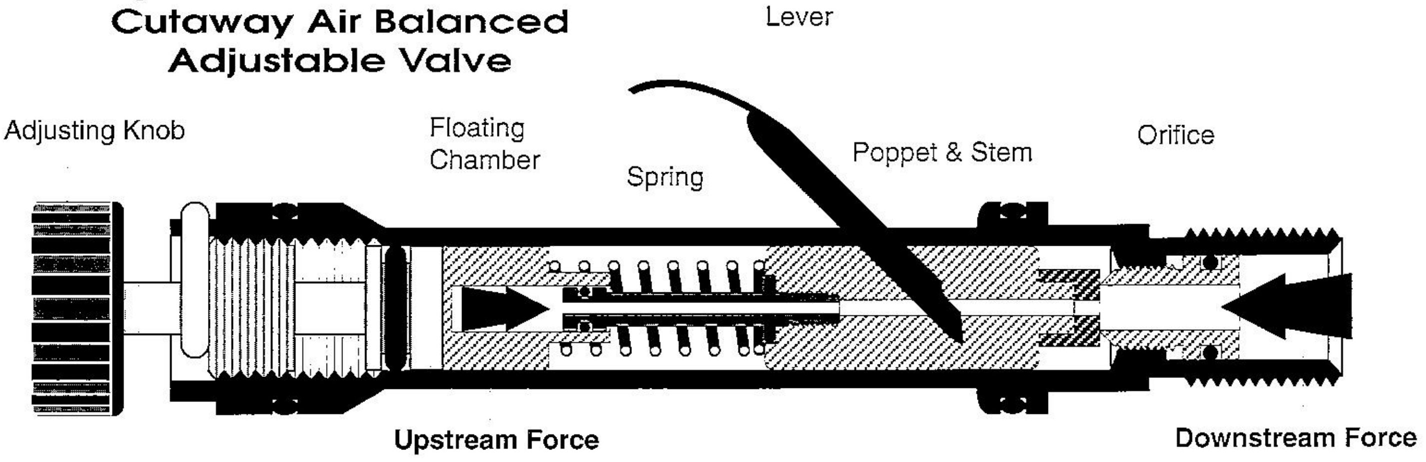


Figure #69

Cutaway Air Balanced Adjustable Valve

Figure #69 shows the complete cutaway air balanced valve assembly installed in the air barrel. Let's trace the forces that control poppet movement to discover how air balancing works.

Intermediate pressure air from the first stage passes through the orifice and applies a "downstream force" on the poppet seat. The same IP air also travels through the center bore of the poppet and stem to a sealed cavity in the floating chamber. The trapped air in the cavity applies an "upstream force" to the end of the poppet stem. If these two forces are "equal", they cancel one another suspending the poppet in a state of equilibrium between the two forces. If the downstream and upstream forces are "unequal", the poppet will move toward the weaker force. In this valve, the downstream force is" greater" than the upstream force (more detail on this later). To compensate for this difference, a spring is installed between the floating chamber and poppet. The spring supplements the upstream force and maintains contact between the poppet seat and orifice knife edge.

When the diver inhales, the force required to depress the lever is greatly reduced because of the lighter, more responsive spring. The diver can increase inhalation effort by fine tuning the external adjusting knob. Turning the knob inward increases spring compression and elevates demand effort.

You might be wondering why the Scubapro engineers did not go all the way and totally air balance this valve. Why didn't they match the downstream force with the upstream force and generate a state of total equilibrium? The main reason is because total air balancing would have eliminated downstream override. If you recall, this safety feature provided for an unusual increase in intermediate pressure. The added downstream force of the higher IP would push the poppet open and make the overflow air available to the diver to safely control his ascent. It was also discovered that a totally air balanced valve was unstable and did not produce smooth responsive breathing characteristics. The primary objective was to utilize the balancing principles to maximum advantage in reducing demand effort, yet maintain the safety and breathing characteristics of the downstream valve.

The most important point to remember is that all of these features are no longer a "trade off", but can be engineered to produce the best overall performance. For example, increasing the bore size of the orifice to produce more flow no longer requires the use of a larger spring. The increased downstream force produced by the larger orifice can be offset by increasing the upstream force to counterbalance its effect. The spring can then been engineered to produce minimum demand effort without limiting the flow.

The results are impressive to say the least. This valve is incorporated in the Scubapro G250 and a non adjustable version is used in the G200B. Scubapro did not forget about the customers who purchased earlier downstream versions of this "through air barrel" design. Scubapro second stages that were manufactured as far back as in the late 60s can be retrofitted with balanced components, upgrading their overall performance.

From a service and repair standpoint, this valve presents very few problems. The poppet and dynamic stem o'ring are always replaced during annual service. The years of research involving the precise seating effect between the poppet and orifice knife edge have been carried over from its downstream predecessor and is all but bullet proof. Adjustment procedures are also straight forward and will be covered in detail in the appendix section of this manual.

During this same time period, Scubapro was developing another balanced valve. The design originated with the "Pilot" second stage and evolved through the Air 1, D300, D350, and D400. The Pilot literally rewrote the record book for balanced second stage performance. Unfortunately, the intricate dual valve mechanism became cost prohibitive to produce. The skill level required to service the Pilot in the field also contributed to its demise. The "Air 1" second stage simplified the design and substantially reduced both manufacturing costs and the skill level required to work on the unit. The D300, D350, and D400 were a small evolution within the larger one, and each phase enhanced the breathing quality of this unique air balanced valve.

This valve has never been tagged with any particular name that precisely describes its function. The term "coaxial flow balanced demand valve" is often used to describe the overall characteristics of the mechanism. For the sake of our discussions, we will refer to it using this description.

Before we examine the actual parts used in the valve, a quick look at how air balancing is achieved, from a mechanical principle perspective, will help in understanding how the valve works.

Figure #70

Center Balanced Spool Valve

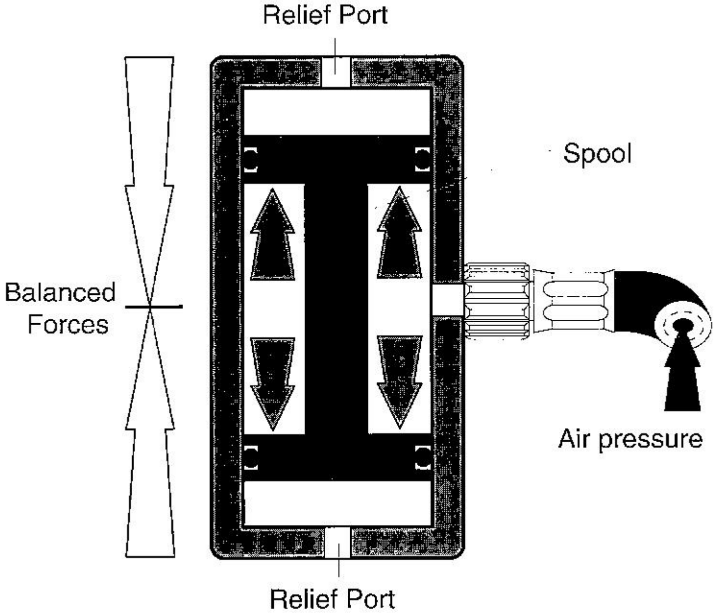
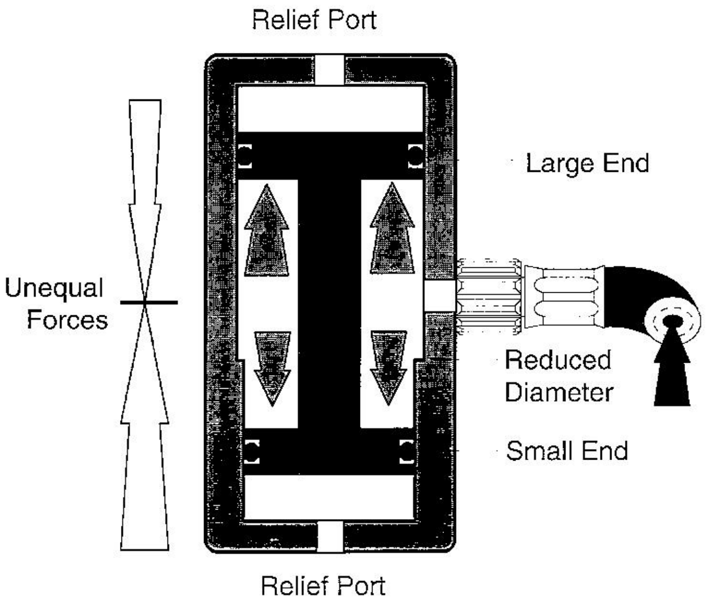


Figure #70 shows yet another way to air balance the spool valve. When air pressure is initiated in the center of the housing, between the two sealed ends of the spool, it will apply an equal force in both directions. The spool, in this example, is in a state of equilibrium and the air pressure does not produce a force that will move the spool in either direction. The force of the air pressure is, therefore, canceled or balanced. If we tried to move the spool, after the air pressure was administered, we would discover that it would take an equal amount of energy to move the spool in both directions.

Figure #71

Modified Spool Valve

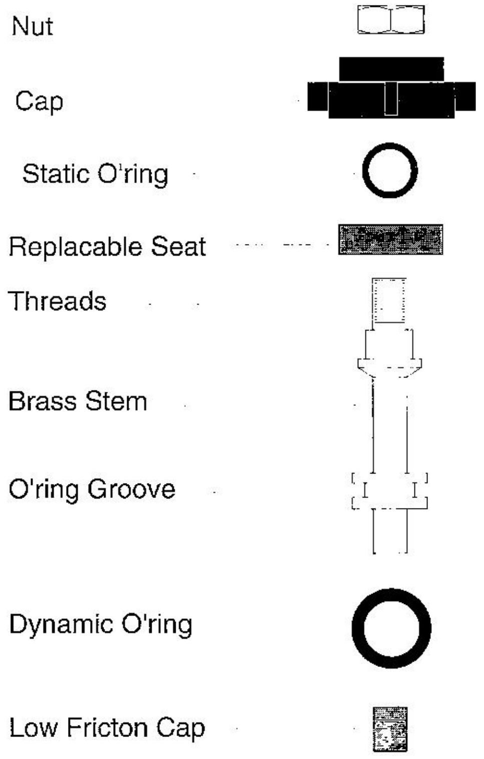


In figure #71 we have modified both the spool and the housing. The lower end of the spool has been reduced in diameter slightly. The lower end of the housing has also been reduced to fit the spool. When air pressure is initiated to this configuration, the spool will be pushed to the top of the housing because the area exposed to the pressure is less on the small end of the spool. If we attempted to move the spool downward, the amount of energy necessary would be a force equal to the difference of the two forces.

A close examination of the D400 parts will show how this principle is utilized in the actual valve mechanism.

Figure #72

D400 Poppet Components



Poppet Components: The balanced coaxial flow poppet is an escape from the traditional poppet designs used in the downstream valves and the air balanced units previously described. Several different poppet configurations have been used in the evolution of this valve. Regardless of the different appearance, it still is the primary moving part in the valve and supplies the sealing surface that mates with the knife as the valve opens and closes. For the purpose of this section of the manual, we will concentrate on this configuration used in the D400. Always be sure to keep up-to-date with current engineering and technical service bulletins for the latest modifications and compatibility information.

The primary feature of this poppet is the replaceable composite seat. It is a machined brass disc coated with a soft seating material. By removing the nut, cap, and static o'ring, a new seat can be installed to renew the poppet during service. Older versions were ultrasonically welded assemblies requiring replacement of the entire poppet.

The low friction cap is "press fit" to the brass poppet stem and can be replaced if necessary.

The dynamic o'ring is a critical component to this valve and should always be replaced and properly lubricated every time the unit is serviced.

Figure #73

D400 Poppet Assembly

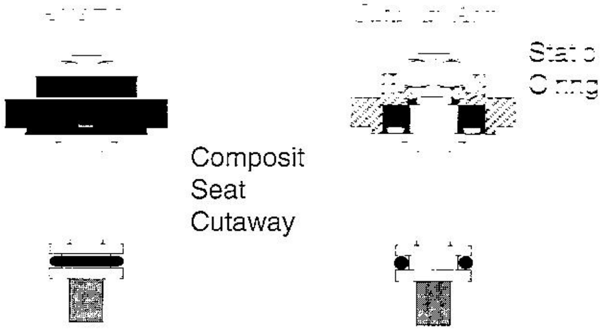


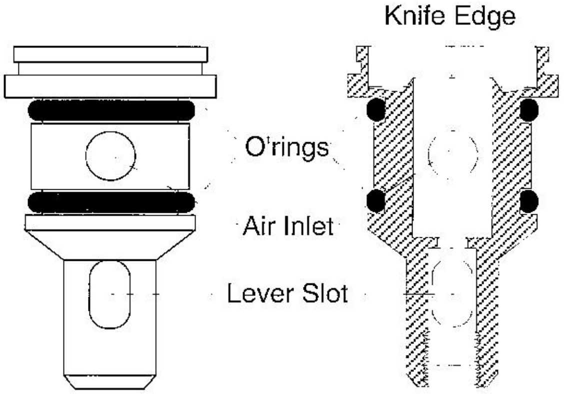
Figure #73 shows the assembled D400 poppet in two views. This illustration is self-explanatory except for two points.

The static o'ring not only serves as a seal between the composite seat and the cap, but when it is compressed it supplies tension between the nut and stem threads to keep the nut from loosening.

The cutaway view reveals a machined groove cut in the underside of the composite seat. This groove fills with the soft seating material when the brass disc is coated. This controlled thickness provides the proper compression for a compatible mating effect with the knife edge.

Figure #74

D400 Valve Body



The D400 valve body is machined from brass and chrome plated. The cutaway view shows that the knife edge is cut into the valve body itself eliminating the need for a separate orifice. Two static o'rings seal the valve body to an air tube in the main housing. Incoming air from the first stage enters the valve body in the center between the two o'rings.

Figure #75

D400 Poppet & Valve Body

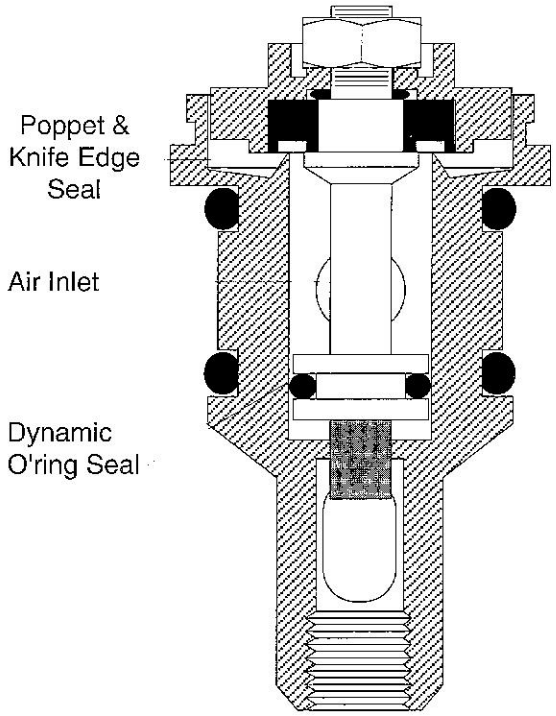


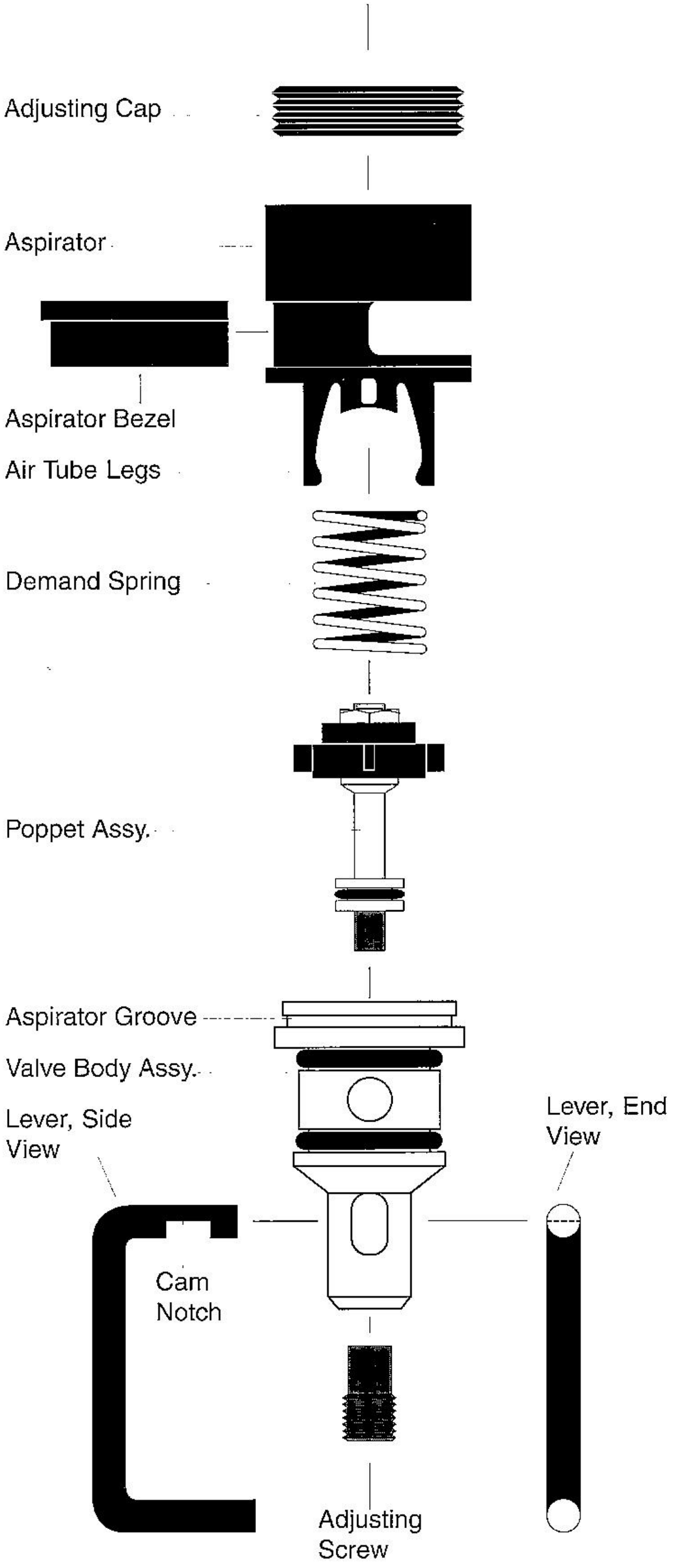
Figure #75 shows the poppet assembled in the valve body. The valve body knife edge and poppet seat form a seal that blocks the air from escaping out through the top and the dynamic o'ring prevents air from leaking around the stem and out the bottom. Air pressure enters the valve between these two sealed ends of the poppet. If the surface area exposed to the pressure was identical on both ends of the poppet, it would be totally air balanced (see figure #70).

As we learned in the analysis of the balanced adjustable second stage, total air balancing would eliminate downstream override.* The surface area at the bottom of the poppet is, therefore, slightly smaller than the area at the sealing point at the top of the poppet. This slight differential in pressure maintains the safety of downstream override without seriously affecting demand effort (see figure #71).

The D400 requires the lightest spring force of any regulator in the Scubapro line. The seating effect is very delicate and requires precision adjusting procedures. Pay particular attention to the adjusting sequence located in the appendix section of this manual.

* Pg. 46

Figure #76
Balanced Coaxial Flow Valve Components



The D400 valve assembly forms a removable module that can be completely assembled outside the main housing. The following brief descriptions identify the components that make-up this module.

Adjusting Cap: The adjusting cap is molded from plastic and is threaded into the aspirator to complete the module assembly. The distance the cap is threaded into the aspirator determines the adjusted load on the demand spring.

Aspirator: The job of the aspirator is to focus the flow of air from the valve into the main housing. The general direction of the flow can be adjusted by rotating the aspirator bezel. The position of the bezel is maintained by a series of detents located between the aspirator and the bezel (not shown). The forked legs on the bottom of the aspirator fit over the air tube in the main housing. They fix the rotational orientation of the valve assembly and keep the module from turning when the valve is adjusted. When the valve module is properly installed, the open side of the aspirator is facing the mouthpiece.

Demand Spring: The stainless steel coil spring supplies the force required to seal off the pressure of the downstream override. Tension is controlled by the adjusting cap.

Poppet Assembly: (See figure #72)

Valve Body Assembly: The valve body is described in figure #74 except for the aspirator groove. This horizontal groove joins with a ridge molded inside the aspirator. A vertical groove in the valve body aligns with a tab inside the aspirator to establish the rotational orientation of these two parts (not shown).

Demand Lever: The lever is shown in two views to better describe its shape. It is fabricated from stainless steel rod into a "C" shape and has a cam notch cut through the top leg. The cam action provided by the notch serves to raise the poppet when the lever is depressed (see figure #78).

Adjusting Screw: I prefer to call this screw the "clearance adjusting screw" because that is exactly what it does. It removes the space between the poppet and lever so that the slightest lever movement is transmitted to the poppet.

This screw has a similar feature to the "nylon locknut". A small plastic plug is imbedded in the threads. When the screw is installed initially, threads are cut in the plastic plug producing a locking effect. This prevents the screw from moving and altering the adjustment. Always replace this screw when the valve is serviced. Check to be sure that even a "new screw feels firm" when it is installed. Take no chances with the possibility of this screw backing out while the regulator is in use.

Figure #77

Balanced Coaxial Flow Valve, Closed

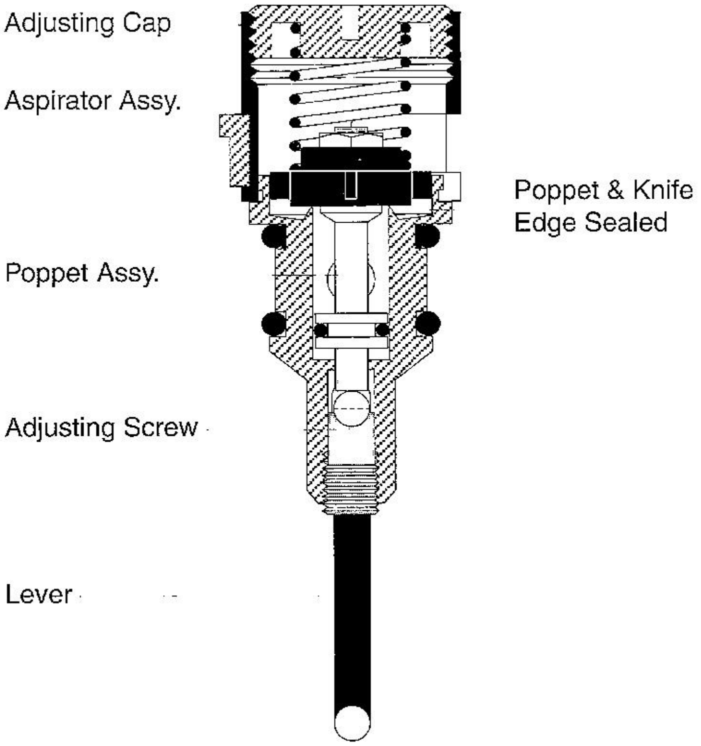
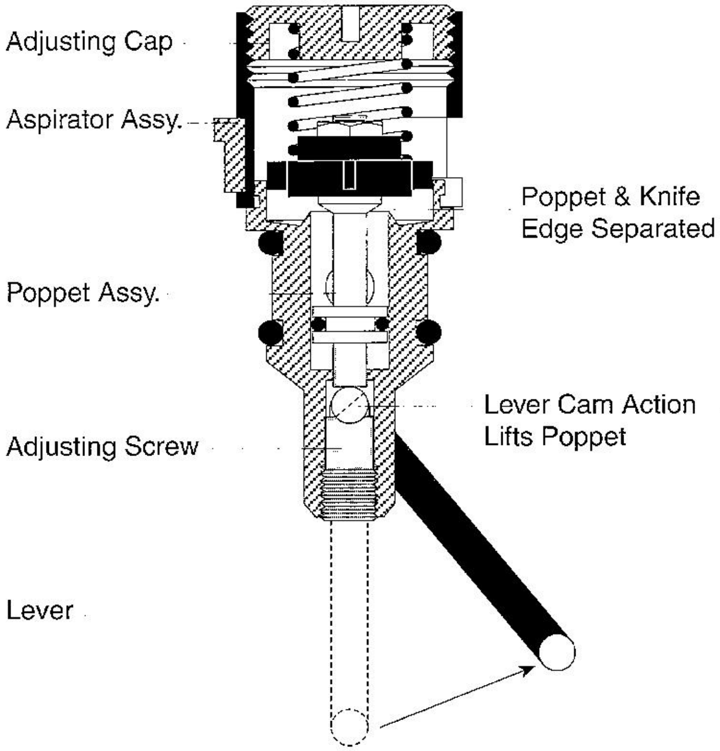


Figure #78

Balanced Coaxial Flow Valve, Open



Figures #77 & #78 show the D400 valve in "open" and "closed" positions. Take a few moments to familiarize yourself with the drawings before you read the following description.

The full technical name of the D400 valve is: "air balanced, coaxial flow, demand valve with downstream override".

Air balancing is achieved by exposing the air pressure to nearly equal size opposing surfaces. Air enters the valve in the center of the body. The force generated acts to both open and close the poppet. To preserve the safety feature of the downstream override, the opening surface area is slightly larger than the closing surface area. This differential will open the valve with force equal to the difference of the two opposing forces.

A spring is positioned on the top of the poppet to augment the closing force. The tension of this spring is adjustable to control the seating effect between the poppet and the knife edge and overcome the force of the downstream override. This variation in spring force is achieved by threading the adjusting cap in to increase spring tension, and out to reduce spring tension.

After the spring tension has been set, an adjusting screw is positioned to eliminate any remaining space between the lever and the poppet. With the clearance removed, the slightest lever movement will be transmitted to the poppet.

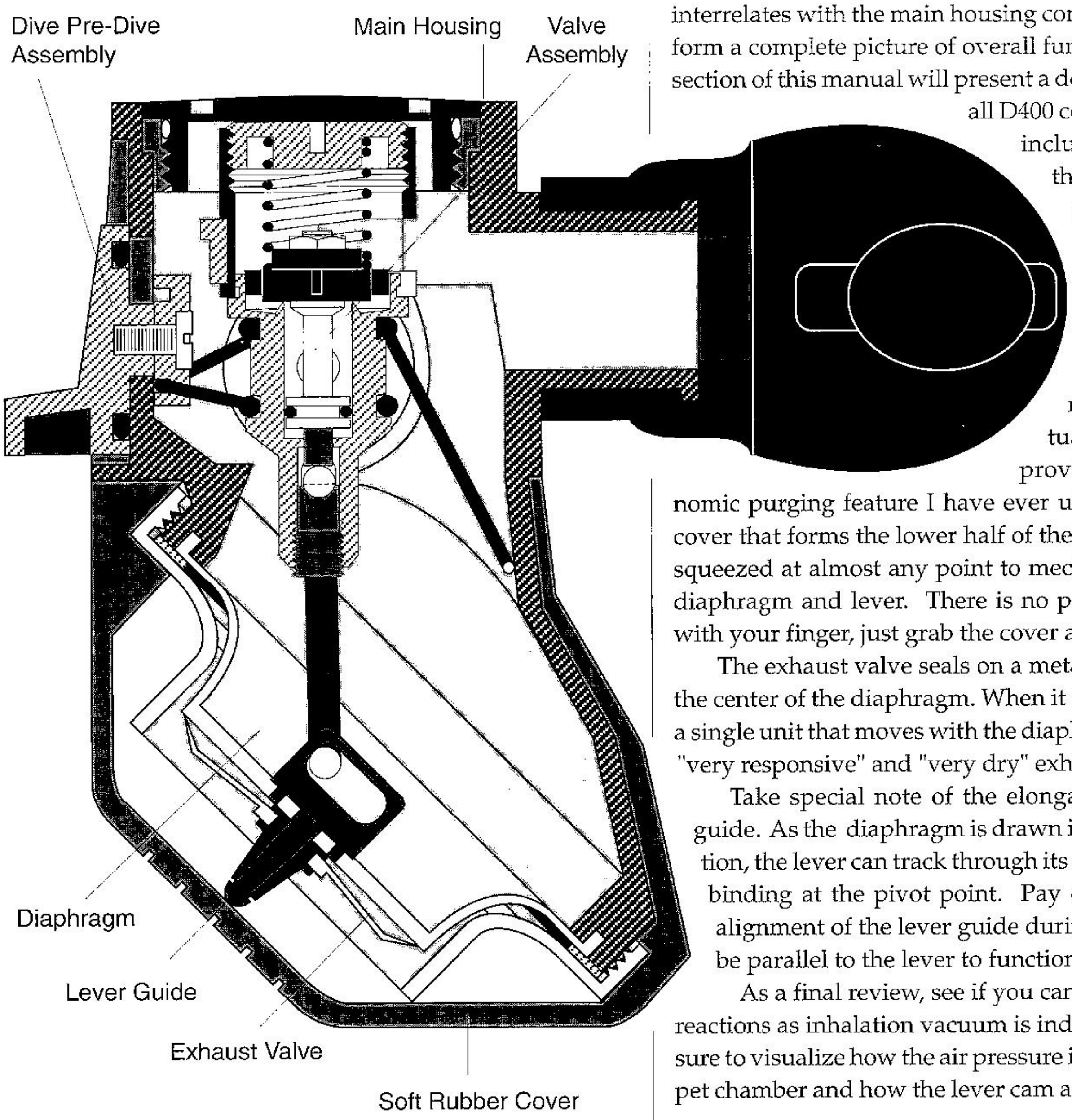
When the lever is depressed, the cam action generated by the rotating cam notch will lift the poppet and open the valve (see figure #78).

The resulting air flow is directed into the main housing through an adjustable aspirator.

This valve is a powerful player in the Scubapro regulator arsenal. It provides a smooth stable breathing response that is heralded by many as unequaled in the industry. Like the previously discussed air balanced valves, the D400 has no mechanical limitations that prevent it from being developed even further in the future. If history holds any indication of what's to come, the evolution will continue.

Figure #79

D400 Second Stage, Full Cutaway



Before leaving the D400, a general look at how the valve interrelates with the main housing components will help to form a complete picture of overall function. The appendix section of this manual will present a detailed explanation of all D400 components. This data includes a description of the "Dive Pre-Dive" feature and how it enhances the sensitive D400 valve.

At first glance, the D400 appears to be missing an external purge system. Actually, this second stage provides the most ergonomic purging feature I have ever used. The soft rubber cover that forms the lower half of the main housing can be squeezed at almost any point to mechanically depress the diaphragm and lever. There is no purge button to locate with your finger, just grab the cover and squeeze.

The exhaust valve seals on a metal spider molded into the center of the diaphragm. When it is assembled, it forms a single unit that moves with the diaphragm and provides a "very responsive" and "very dry" exhaust function.

Take special note of the elongated slot in the lever guide. As the diaphragm is drawn inward during inhalation, the lever can track through its opening arch without binding at the pivot point. Pay close attention to the alignment of the lever guide during assembly. It must be parallel to the lever to function properly.

As a final review, see if you can trace the component reactions as inhalation vacuum is induced by the diver. Be sure to visualize how the air pressure is balanced in the poppet chamber and how the lever cam action opens the valve.