

TLC of Your Valves — Temperatures, Loads and Corrosive Environment

By Ted Tunnecliffe

The operating conditions that valves must endure dictate many things about the design and alloys to be used, the heat treatments needed, the finishes required, the necessary hardness at various areas, the method of construction and a host of other things. So it is vital for us to know just what those conditions are in every application.

What conditions are we talking about? To put it in a nutshell, we need to know the valve operating temperatures, the loads or stress that it will be under, and the corrosive environment that the valve will be exposed to. In addition, we need to know just how long the valve is expected to live. So, let's address some of these questions, just how we go about determining them and how we use this information.

Temperatures during operation

This is a biggie. As I'm sure you know, different valve materials have different properties at various temperatures. Once we know these properties for the alloy, then we need to learn what they are for the valve. With that information, we can then decide which particular alloy will do the job to meet the durability requirements but without overkill. And, when we talk about valve temperatures, we must recognize that different areas of the valve operate at different temperatures, so different properties may be necessary.

Valve head temperatures

Usually the center of the valve head is the hottest place on the valve. In a spark-ignited (SI) engine, that temperature is typically very similar, if not identical to, that in the throat or underhead area. But, in a diesel or compression-ignited (CI) engine, the throat area is cooler because the exhaust gas in such engines is cooler than in the SI jobs. So, the bottom line is that we design the valve of a material or materials that will live at that temperature adding whatever safety factors we have decided upon.

But, how do we find out what the temperatures are? There are several ways. Although it's a tricky technique, the best way to instrument a valve is by putting thermocouples on it at the points where we want to know the temperature.

With thermocouples, we can run the engine at whatever conditions we are interested in and read exactly what the temperature is at any given moment. Of course, that assumes the thermocouples last long enough, and that's the tricky part.

Another technique for getting the operating temperature of a valve is to use "temperature check" valves. These are valves of a hardenable steel that have been fully hardened then only stress relieved to keep them from failing prematurely. The valves are put into an engine and run for a specific period of time. Afterward they are removed, cut up and checked for hardness at various points.

That hardness can then be related directly to the operating temperature by comparing it to a tempering curve of the alloy. I understand that some piston makers have picked up on the technique and use it by putting hardened plugs into aluminum pistons and checking their hardness after engine operation.

In **Figure 1**, a sketch can be seen of a temperature survey made on a temperature check valve. It shows the cross-sectioned valve and where the hardness indentations have been made across the head and up the stem. It also shows readings taken at several points around the head O.D. At the side and above, graphs show the hardness data after it has been converted to temperature. This particular test was run on a diesel so the throat temperatures did not go up in that location as they would have if it was a gasoline or other type of spark-ignited engine.

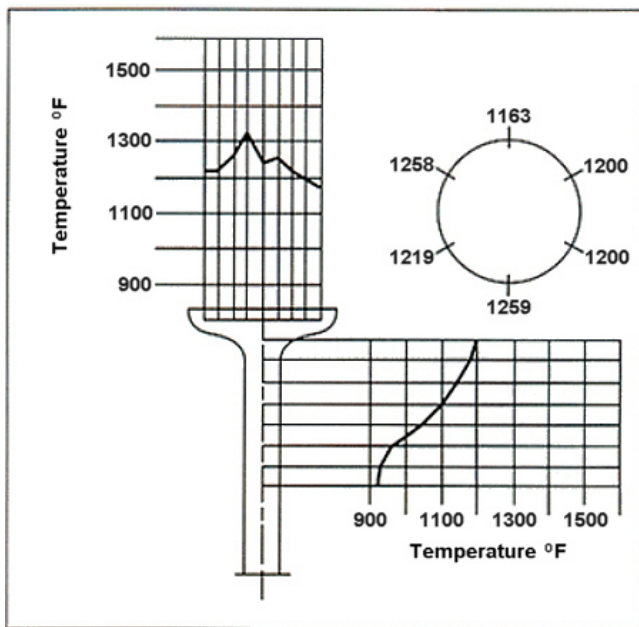


Figure 1. This is an actual example of a temperature survey test run on a diesel engine exhaust valve. It was one of a group run to determine which cylinder had the hottest exhaust valves and just what the temperature level was at maximum output. Thermocouples were then run in the hot cylinder to get operating temperature data at various speeds and loads.

The temperatures in Figure 1 are typical of those that exist on a diesel exhaust valve, but spark ignited engine exhaust gas usually runs hotter. In days past, the typical exhaust valve temperature for an SI engine was about 1350°-1400° F, but these days that level has moved up to about 1450°-1500° F. That is for the hottest point on the valve which is at the center of the head and the throat area.

The levels are important because it means that data on valve alloys must now be taken at that level in order to know the properties of the material. But, it is usually done the other way around; we know the alloy characteristics before we know what the valve wants. Although SI engine temperatures have changed, those for CI engines have not changed significantly. Since some of the alloys are common for the two types of engines, however, strength data is usually taken at the higher levels anyway. For comparison with a CI let's look at the temperatures of an SI exhaust valve. **Figure 2** shows what one of those looks like.

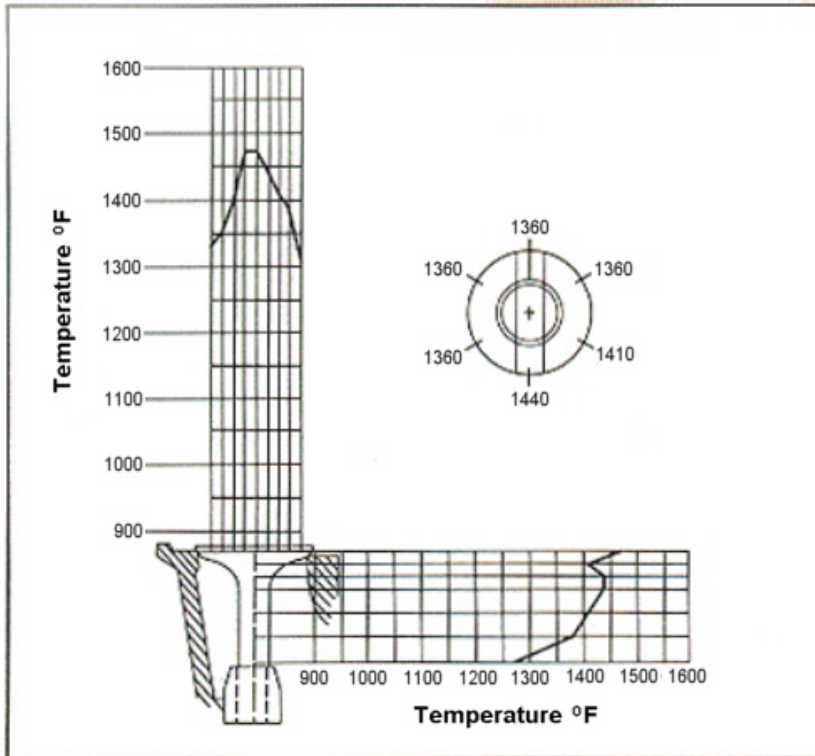


Figure 2. This gasoline engine exhaust temperature survey is characteristic of the data developed from such an engine. It shows the typical “hot spot” at the center of the head with a drop just below the head, then an increase further up the stem. That increase is normally due to the afterburning in spark-ignited engines. Note that the outside diameter temperatures are considerably below that of the center head due to heat dissipation in that zone when it is sealing properly.

Valve stem temperatures

In engines running normally, the valve stem temperature drops drastically and suddenly as the valve stem enters the guide. Typically, in about a one-inch distance or less, the temperature of a solid valve – not an internally-cooled valve – drops to oil temperature. So, the hot end of the guide must accept a lot of heat in a short distance. And that’s where the 24% being conducted out of the valve goes.

Because of this rapid drop in so short a distance, I have never understood the logic behind the use of a tapered valve stem. The typical taper varies only about 0.001" over the stem length, and it changes at a constant rate supposedly to accommodate thermal expansion. Since the temperature drops so quickly, I don’t see how a constant taper can help. Also, considering the fact that the hot end of the guide is expanding as well, it just doesn’t add up.

Seat face temperatures

This area is the most important for heat dissipation on any exhaust valve and another reason why good sealing is so vital. If the valve is sealing well, the heat that this area dissipates is about 76% of the total going out of the valve. Some day maybe we’ll talk about valve seat inserts and how they affect valve temperatures.

Typically the seat face area may run about 150° F lower than the center head, assuming it is sealing properly. If it leaks, the temperature can be anywhere from that of the center head to a lot hotter. So hot, in fact, that it will gutter. Remember, guttering is not melting – it is corrosion.

Since steel valve alloys melt at perhaps 2600°-3000° F, the only time they melt is when the engine has been running in pre-ignition. But, that's a subject for another article.

Intake valve temperatures

So far, we've been talking only about exhaust valve temperatures because they are the ones that usually give us the most headaches. It might seem as though intake valves should be hotter, given the fact that they are in that same combustion chamber with the exhaust, but the cooling charge lowers the combustion influences to the point that we cannot even measure the skin effect from that 4500° F typical peak combustion point.

Normal temperatures on intakes range from 600° to 800° F in the center of the head of a light duty job to 800°-1000° F for a heavy-duty application. At the seat face, those temperatures range from 200°-400° F on light duty engines, to 400°-600° F on heavy-duty engines. As with seat faces, the overhead areas are relatively mild on both types — about 200°-300° F on light duty to 300°-400° F on heavy-duty jobs.

Loading and operating stress

Let's get on to another subject — valve loading and stress. First of all, what is meant by "stress"? Fundamentally, it is load per unit of area, and there are a number of different kinds of stress that are generally recognized.

We'll stick to the basics: Tensile stress (pulling something apart) and compressive stress (squeezing something until it ruptures). It might be argued that torsional stress is actually a form of tensile and compressive stresses, but let's not get into that. Actual stresses will usually be some combination of tensile and compressive in a given area of the valve, but we look for the dominant one.

Compressive stress

Let's start at the tip end of the valve. The action of the rocker pad, or whatever mechanism acts to open the valve, applies a load to that tip which, over the area to which it is applied, is a stress. Because the load tends to compress the valve tip, it is obviously compressive.

If a round surface such as a rocker pad or a roller contacts the valve tip, it is essentially a line contact and is a much higher stress than if it were being contacted over the full width of the tip as some direct acting valve gear systems do. With line contact, such stresses are typically in the neighborhood of 120,000 psi. That's a lot of stress but, fortunately, since it is compressive, materials have a great amount of resistance to such loading. That is especially true of hardened steel, and is one of the main reasons why we harden valve tips.

The load on a valve tip is made up of both the spring load and the inertial load that must be overcome to get the valve open. And that is the biggie. It's just like getting a car or an electric motor going to begin with. It takes a lot more to get it moving than it does to keep it going.

Inertia is the reason why we have gearboxes in cars and starting windings in electric motors. Spring load is a relatively minor component of the total load.

Another compressive load that a valve has is at the seat face. The cam should seat the valve nice and easy on the seating or closing ramp and therefore a spring load of only about 100 pounds or so is applied (maybe 50 psi). Even if you're using a heavier spring, it is still relatively low compared to the combustion loads. After the valve is down, the fire goes off, and the peak combustion pressures on SI engines are bad enough at normal levels of perhaps 400-800 psi. But in diesels, they can be in the range of 2000-3500 psi. So, the valve can be under a significant compressive load at the seat face dependent on seat contact width and peak combustion load. Such loads are at least partially responsible for the wear and indentive peening that can take place at the valve seat face.

Tensile stresses

The valve keeper groove area is under a tensile load just by virtue of its reduced diameter. So it tends to be a stress concentration zone. That is one of the reasons I favor grooves that do not have sharp corners, as do the conventional flat bottom types. To me, the best design is the one that keeps stresses to a minimum and the radius type fits that description best. The stress in that area of a valve will vary from perhaps 15 to about 45 ksi (15,000-45,000 psi) depending on the groove design.

The stress at the underhead area of a valve can range from perhaps 20 to 60 ksi on the underhead fillet and 10 to 30 ksi at the end of the guide depending on a number of factors. Combustion load (face) and seating velocity (throat) are two important ones. That entire area is of course subject to failure more frequently perhaps than are others because of the combination of high loading and elevated temperature.

Another less obvious area of tensile stress is at the valve head O.D. So how do we get tensile stress on the outer area of the valve head? Well, stop and think about it. Remember that the head area has a significant temperature difference between the center and its outer diameter. Such a difference causes the hotter center to try to expand a greater amount than the cooler outer area and that creates a tensile or "hoop" stress at the O.D.

Such stresses can, and have, caused radial cracks at valve heads at the O.D. They can be in the range of 5 to 30 ksi. Similarly, a sharp corner at the head O.D. of an exhaust valve will get hotter than the area adjacent to it and expand to a greater degree. That expansion causes a stress that can produce radial fatigue cracking initiated at that corner.

Stress from uncontrolled valve motion

Valve "toss" is an undesirable condition in any engine but it can and does occur. That is especially true in high performance applications. In some engines such as dragsters, the application demands it, and it is almost impossible to design a valve that will live under such seating velocities and temperatures. The only good part of it that I can see is that it only lasts for a very few seconds—poor consolation.

As far as I know, there is no metal other than perhaps straight tungsten that would hold up under those conditions. I assume that the engine builders of those cars have tried about everything, including ceramics. When somebody comes up with a ductile ceramic, I want to buy stock in that company.

Corrosive environment

There are four major corrosives that valves can be exposed to: oxygen, lead oxide, sulfur and vanadium pentoxide. The last two are primarily encountered in diesel fuels, since sulfur is present in most gasolines only in minimal amounts, and I have never heard of vanadium pentoxide in gasoline. I also have never confirmed corrosive attack on a valve by oil, oil components or even fuel additives other than TEL for that matter. So let's take the corrosives we know of one at a time.

Oxygen corrosion (oxidation)

Oxygen is the one that, no matter what we do, can't be avoided. And it can be a killer since almost all metals oxidize to one extent or another. So how do we deal with it? We typically design alloys to tolerate it by adding elements that form protective coatings – coatings which are oxides themselves.

Stainless steel for example is "stainless" because it contains chromium and possibly nickel as well. The presence of the chromium allows an oxide to form on the exposed surfaces, which is very thin, forms rapidly, and is very adherent. This chromium oxide protects the metal surface by preventing further oxidation. And, of course, most valve steels are derived from stainless steels.

Lead oxide corrosion

Lead oxide, a very active metal corrosive, results from the combustion of tetraethyl lead (TEL) which is added to gasoline to improve octane level. In recent years we have seen a significant reduction in the use of TEL because of the detrimental effect it can have on human beings that breathe its fumes. So this corrosion problem has been taken care of for the most part already.

The exhaust valve alloy 21-4N was developed specifically to endure attack by TEL. It was not developed for intake valves nor for diesel engine exhaust valves, but it is sometimes used in both of those due to its low price because of high volume usage.

I recall an extreme case of lead oxide corrosion that I saw a number of years ago. At the time, I was wondering how the valve could stay together as much as it had corroded when it occurred to me that the seating dynamics must have been extremely mild or it would have broken long ago. So it doesn't take much of a diameter to hold a valve head on if the valve gear dynamics are good.

Sulfur corrosion (sulfidation)

In gasolines, sulfur may be present in amounts of up to about 0.1%, and even this small amount is being reduced by improved refining practices so it is not normally a problem in SI engine valves. In diesel fuels, however, it may be present at levels of 3% to 6% or higher in some grades, especially outside of the U.S. Some diesel off-highway engine builders pride themselves on the fact that they can burn anything you can pump. That may be necessary if you're building a dam in Lower Slobovia. But sulfur is a severe corrodant and is much more of a threat if part temperatures exceed 1000° F.

Sulfidation attack on valves is a fairly common problem where high levels of sulfur are present in the fuel. Nickel and nickel-based alloys are especially susceptible to attack by sulfur compounds produced by the burning of sulfur in fuels. Because of that susceptibility and the need for high strength non-nickel based alloys, an alloy was developed by Eaton called 23-8N. This material has replaced some of the iron-based alloys previously used and many of the nickel-based superalloys used in CI engines.

Vanadium pentoxide

Although vanadium pentoxide corrosion is rare due to good refining practices of crude, this stuff can really raise hell with the valves in a diesel engine. It is extremely corrosive and will attack most any valve alloy that I know of. Fortunately, it is ordinarily removed during refining so we don't usually have to worry about it.

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