PRESSURE SOLUTIONS

C202: Deadweight Testers

A deadweight tester is a primary standard for calibrating pressure instruments. What does that mean?

A primary standard is one that has no calibration adjustments, and hence is inherently accurate.

Pressure is defined as force per unit area. The reference standard for pressure is thus a piston and cylinder assembly (PCA). The piston is fitted with a weight carrier, which is loaded with weights. These generate a downward force due to gravity. Fluid is admitted to the base of the piston. When the weight carrier lifts and floats, the force generated by the weights is precisely balanced by the force generated by the pressure acting on the cross-sectional area of the piston. Pressure = Force/Area. Force = Pressure x Area. This is known as a pressure balance.

When a pressure balance is built into a device which has a means of generating or controlling pressure, coupled with connections to pressure attachment points, we call this a deadweight tester.

Dimensions:
Ascertaining the area of a PCA is difficult, because the effective area is larger than the piston diameter, and smaller than the cylinder diameter. We can make the piston very large, to reduce uncertainty in the determination of the area, but the weights would have to be very heavy. As an example, the 5111 has a repeatability of <1 part per million or 0,0001%. Using the 10 kPa/kg weight set, a 100 kPa weight would weigh 10 kg! That is not practical outside the lab.

On the other hand, looking at the 580DX, this has dual pistons, the LP with an effective area of 80,645mm², and the HP with an effective area of 8,0645mm². This means that a 1 000 kPa weight on the LP piston has a weight of 8,22474 kg. This is about the largest weight that can reasonably be man-handled repetitively.

Sealing:
Friction is the enemy of repeatability which is a component of accuracy. We cannot introduce conventional seals. Sealing is effected by extremely small clearance between the piston and cylinder. The weights are then spun to eliminate static friction. Dynamic friction we can do nothing about. To give you some ideas, the clearance between the piston and cylinder in the 5111 balance is nominally 0,2 micron. (1 micron = 0,001mm).

Dynamic Range:
The lower limit is determined by the amount of inertia required to spin the weights for a sufficient length of time for the pressure to stabilize. This is know as spin time. Viscous friction exerts a retarding force on the spinning piston and will bring it to a halt. The deceleration can be reduced by making the inertia of the weights larger, which is why on the 551 tester, we use annular weights to optimize the ratio of moment of inertia to mass.

The upper limit is determined by the increased leakage around the piston under pressure. This limits the amount of time the weights can spin for, and is known as float time. Both spin time and float time must be sufficient for a stable pressure to be generated.

In practice, a range of about 100 to 1 is typical. The 580L has a range of 120:1. The 580M has a range of 150:1, and each range on the 580DX is 70:1. The 552 which is the most common air tester, has a range of 70:1, and the 554 125:1

Causes of Uncertainty:

1. Measurement of the effective area. This is difficult because it is an indirect measurement. A PCA is compared with a known PCA. When both are in balance, the ratio of the areas can be determined from the ratio of the masses.
2. Measurement of the masspieces. This is relatively simple to do with high accuracy.
3. Correction for head effects. If the pressure connection is not at the same level as the base of the floating piston, the head difference has to be taken into account. This is why standardised oils must be used.
4. Correcting for piston buoyancy. The piston floats in fluid, and as such experiences an up-thrust proportional to the fluid density.
5. Correction for weight buoyancy. The weights normally float in air, and experience an up-thrust proportional to the air density.
6. Effects of temperature on the piston.
7. Effects of pressure on the piston. Under pressure, the piston will be squashed, and increase in area.
8. Effects of surface tension acting on the piston.
9. Variation in local gravity.
10. Effects of magnetic fields.
11. Departures from axial symmetry.
12. PCA rigidity.

Operating Fluids:

Reviewing our discussions on dynamic range, mineral oil is the most commonly used hydraulic fluid. It has sufficient viscosity to provide a good seal between the piston and cylinder, thus providing good float times, and sufficient lubricity to provide good spin times.

Air is commonly used at lower pressures. The practical lower limit for oil is 100 kPa with reduced accuracy, and typically 600 kPa for full accuracy. Air has minimal viscosity and excellent lubrication qualities, but requires extremely fine clearances, much better than oil. In practice, it is difficult to get acceptable float time above 7 000 kPa. In practice, because of the demands of cleanliness, air-operated testers tend to be used below 700 kPa, where oil-operated testers are less sensitive. Air does offer better uncertainties at low pressures, since the uncertainties caused by reasons 3, 4 and 8 above are effectively eliminated. Both oil and air are non-corrosive, and make no demands on the materials of construction.

Materials:

The materials of construction of the PCA need above all to be mechanically stable. The best material from a metrological point of view is tungsten carbide. In practical terms, its use requires a great deal of care, since it is a very brittle material, and easily chipped or broken, either of which event results in scrapping. Having said that, the D & H pressure balances used at the NML have tungsten carbide pistons. Then again, a Budenberg 380D is used for most commercial work, to reduce the risk of damage to the D & H where the available accuracy is not required. In practical terms, suitable selected tool steels can provide the dimensional stability in conjunction with a high degree of toughness which can tolerate the abuse expected by unskilled operators. Materials should thus be chosen with intended use in mind.

Accuracy Mode:

Time to state that deadweight balances have an accuracy expressed as a percentage of the actual pressure being generated. Unlike most devices, they are as accurate in percentage terms at the bottom of their range as they are at the top.

Benefits of DHB:

DHB was formed by the merger of Desgranges & Huot, and Budenberg Gauge Ltd.
In the eastern, non-American half of the world, Desgranges and Huot are the main providers of reference standards for National Pressure Laboratories with over 40 countries depending on D & H for their National Pressure Standard. All of the pressure laboratories in South Africa which are SANAS accredited to certify oil-operated deadweight testers, use D & H pressure balances.

Budenberg is the pre-eminent manufacturer of deadweight testers for industrial use. While less accurate than the D & H units, which typically cost R500 000,00 upwards, they are sufficiently accurate for industrial use, and built to a rugged yet ergonomic standard which has made them the reference of choice in virtually every significant pressure workshop. Think of a top name, and it is virtually certain that they use a Budenberg Deadweight Tester. Think AECI, Angloplats, CSIR, Caltex, Denel, Engen, Eskom, Natref, SABS, Sasol, Sappi, Zincor etc etc etc.

Peace of mind:
Budenberg purchasers know that there is a vast reservoir of satisfied customers who have proven over nearly 50 years that Budenberg takes it all and keeps on going. Part of that is service: Blanes is lucky to have the population to be able to offer a sound back-up service, with commonly required parts kept on the shelf. Blanes refuses to service non-DHB testers because of the difficulty in obtaining spares.

Something else needs to be said here. We did address above, the high degree of accuracy involved in making a deadweight tester, where 0,015% seems to be the current degree of uncertainty on offer. To the best of my knowledge, Budenberg remains the only manufacturer to make PCA components to tolerance. Competitors make a PCA to the best of their ability, and then adjust the weights to suit. If the PCA is damaged, the whole metrology set of weights and PCA has to be replaced. Not so with Budenberg. Even though the chances of a Budenberg PCA being damaged are remote, it does happen. Dropping the PCA off a bench is one reason, another reason is shipping the PCA and weights together without constraining the weights, so that in transit the PCA gets hit by 50 kgs of weights. When it happens, the whole PCA may be replaced, perhaps only the piston needs to be replaced, or perhaps only one weight needs to be replaced. Budenberg can do it without loss of accuracy, but I don’t think anyone else can. Bear in mind that the PCA and the weight set are the two most expensive components of the deadweight tester.

In this regard, we can point out that, although the 280 series bases have been discontinued for over 25 years, and are no longer supported by spares, customers can purchase the current 580 series base, and continue using their original PCA and weights.

A couple of comments on manufacturing. Making a piston takes a long time, because the ageing process is necessary for the degree of dimensional stability required. The final honing and lapping is done on state of the art machine tools. Budenberg have a standing order, and the machines are replaced every year. Only brand new state-of-the-art machines are good enough.

Making the weights is much simpler. A CNC machine is programmed to produce the final blank. The blank is then taken off the machine and placed on a computerised scale which weighs it to a high degree of accuracy, then calculates the size of the calibration cut required. The blank is put back in the machine, the final calibration cut is taken, and the weight is ready for final inspection. If you look underneath a modern Budenberg weight, you will see two concentric recesses. The larger one is the stacking register. The smaller one is the calibration cut. Any other holes automatically invalidate the weight. Most competitors adjust the weight to suit the piston by drilling holes to change the weight. Finally, the Budenberg range of piston areas and weights was carefully selected so that weight blanks can be used on more than one tester. The major weight, 8,224 kg is 1 000 kPa on a 1/8 in² PCA (D), 2 000 kPa on a 1/16 in² PCA (L), and 5 000 kPa on a 1/40in² PCA (M).

The weight blank is only stamped when it is sold. This improves service levels and reduces costs.

Accuracy:
Local certifying laboratories have shown that Budenberg delivers real accuracy, not theoretical accuracy. For example, referring again to the list of uncertainties above, Budenberg make their PCA and weights compensated for reasons 3 to 12, excluding 6 and 9 which are environmental causes beyond Budenberg's control. The customer does not have to make corrections for these items. Simple software is provided for environmental corrections.

A point to watch for in competitors is where the direction of rotation of the piston is defined. This is an admission that the piston is not radially symmetric, which means that the effective area of the piston differs according to the direction of rotation. Since the manufacturer does not have the capability of making a round piston, he has to choose one direction to obtain accuracy. Reversing the direction of the piston will cause significant inaccuracy.

No Budenberg piston has the direction of spin prescribed.

Budenberg has one of the best pressure laboratories in the world in-house, in the UK second only to the NPL, and thus offer their own certificate of accuracy. Most competitors have to send out their components for outside measurement, which is why they cannot build in the buoyancy compensation that Budenberg do, and why many other testers offered with a similar accuracy to Budenberg cannot demonstrate that accuracy when it comes to recertification.

Stability:
The PCA materials are selected for extreme stability. The weights are all made from austenitic stainless steel which is immune to magnetic fields, and corrosion. The expected life is at least 30 years. Note that weights which are made up by drilling and filling with lead, will be viewed askance by a competent auditor, because the stability of the weight is suspect. Was the weight modified before or after its last certification? Was the empty hole meant to be filled with lead? Also note that Budenberg weights have sufficient mass to provide stable spin times. The datum is usually 825g, and the large weights are 8 kg.

Ergonomics:
In addition to its metrological specification, which determines whether it is permissible as a reference standard, the deadweight tester has to be easy to use, and the more often it has to be used, the more important the ergonomics are.

Budenberg is only on its third generation of base, its second generation being superior to most competitors current versions. The current Budenberg hydraulic design dates from 1983, and is identical in the 380, 480 and 580 series testers. The current philosophy is to have a single base for each series. We have the 580 series of oil-operated deadweight testers, and the 550 series of air operated testers. These bases have the pressure capability of the highest range in the series, and have common attachment points for the PCA and the gauge connection. This means that the PCA can be removed and replaced with a second gauge connection, turning the base into a comparator.

The 580 series base has a pressure generating capacity of 120 MPa. The pressure generation is done by a dual area screw press. The large area is used for moving large quantities of oil quickly, to fill the system and build initial pressure to about 10 MPa. The small area is used to generate 120 MPa without much effort.

No competitors come close to this ease. I have seen many competitors with external pumps linked, because the user has lost patience with the need for repetitively screwing the capstan in, isolating, re-priming and starting all over again to build pressure.

The 550 base replaces the screw press with a volume adjuster and supply and release valves. External air is admitted to approximately the desired pressure using these valves, then finely adjusted to float the piston using the volume compensator.

Budenberg's Dual Concentric Pistons:
A word has to be given to the dual piston design. As we said earlier, a range of about 100:1 is about the limit on oil-operated deadweight tester. To obtain a wider range, we use two pistons. In the early sixties, Budenberg patented their "Ranger" design, which had the HP piston fitted inside the LP piston. The design incorporates an auxiliary piston which protects the delicate HP piston from shock. These HP protected pistons are the only example of tungsten carbide in the whole Budenberg range, made possible by this auxiliary piston design. Look at the illustration in the data sheet.

In operation, the LP piston lifts first, and its flotation range is indicated by a blue band. Increasing the pressure will bring the LP piston against its stops, when the HP piston comes into play without any external valving or other operations. The flotation range of the HP piston is indicated in red.

Each weight thus has two values. In the D PCA, these have a ratio of 10:1. In the H PCA, these have a ratio of 20:1. Thus, with a slight movement of the capstan, two pressures can be generated in an instant, which is ideal for checking span without any weight loading.

Although the patents expired 30 years ago, no-one has managed to copy or duplicate this design, with which most technicians are familiar.

Oxygen Service:
Oxygen reacts violently with oil. Oil cannot be used for calibrating oxygen instruments. There are two choices, either the air-operated range for pressures to 12 MPa, or the use of an oil seal for higher pressures. Budenberg has two oil seals available, one for 70 MPa, one for 120 MPa. The oil seals contain a bladder which separates the oil from the inert fluid, which may be water, which is applied to the instrument under test.

Some of our competitors offer water as an operating fluid. My first reaction to this is to suggest you read the pressure balance "bible", "The Pressure Balance: Theory and Practice" by Dadson, Lewis and Peggs, published by Britain's NPL. There is no reference in this book to water as an operating fluid. The reason is as simple as the reason we don't put water into our car's engine. It has no lubricating qualities whatsoever. You simply cannot get the sensitivity or spin time required for an effective pressure balance. It's a nice idea, since tungsten carbide is not corroded by water, and is hard enough to resist wear when run under water, but it doesn't work in practice.

Conclusion:
One last thought; of the deadweight testers sold in South Africa, only Ashcroft and Budenberg have retained their names over the years, indicating sound businesses. Virtually all other makes rise and fall, businesses fail, get bought out, taken over, merge, re-appear under different names and so on. Many people who bought these units have had to replace them prematurely.

There is no real competitor to Budenberg. There are many wannabees. Ashcroft is not in the same class at all, usually bought on price, and this is fair. Others come up with good looking specs, and good prices. To gain confidence, ask in the market place. If you take price out of the equation, try to find some-one for whom Budenberg would not be first choice.

The final problem is this; if a potential user cannot afford a Budenberg, let him think carefully about his reasons for buying a deadweight tester. Money spent on an inadequate unit is money wasted. Why is the other unit cheaper? Budenberg has the economies of scale, cheaper units are leaving something out!

In thirty years of selling Budenberg, I have not had one dissatisfied customer. It is a great product to sell, because you will never have a moment's trouble with your conscience, and your customer will never have to explain to his superiors why he wasted their money.

The Market Place:
In the pressure balance/deadweight tester market place, there are three tiers. At the top, National Standard Level, there are two main players, Desgranges and Huot (The DH in DHB) and Ruska, now owned by General Electric.

Slightly overlapping this top tier is Budenberg, which is used in many smaller National Pressure Laboratories (eg Botswana, Ethiopia, Mauritius), and in this country, is used by the NML as a working standard to preserve the D&H for critical work.

At the bottom is everybody else.

There may be competitors to Budenberg, but there are no equals.

Identifying Budenberg Deadweight Testers

This has become more difficult in later years.

The first generation of Budenberg deadweight testers had a semi-circular cast iron base, and a non-captive piston. The only one I know of is at Kelvin power station. We have no information on these, because in 1968 when I started, it was obsolete, and the only literature we had was for the 200 series.

The 200 series is easy to identify, because the serial number incorporates the model no. e.g. 8680/280D. The 200 series units all had bases with steel covers and sloping sides. 200 series weights were black cast iron.

The 200 series PCAs are still in use, and their markings are a reliable guide to model. Each PCA is marked with an area in in^2.

Fig. 240L was the low pressure air model with a hollow ½in^2 piston, with annular weights marked from 1,5 to 100 kPa. These weights can be used for vacuum by hanging the PCA upside down. This is today's 551.

Fig. 240 was the common air model with a ½in^2 piston, and weights marked from 10 to 700 kPa. This is today's 552. These are solid conventional weights.

Fig.241 was the mid range unit with a ⅛in^2 piston, and weights marked from 100 to 3 500 kPa. This has no direct modern equivalent, the closest would be today's Fig.554.

Fig.246 was the upper range unit with a 1/16 (0,0625) in^2 piston, and weights marked from 100 to 7 000 kPa. This is today's Fig.556.

Fig.247 was the upper range oil-lubricated unit with a 1/16 (0,0625) in^2 piston, and weights marked from 100 to 12 000 kPa. This is today's Fig.558.

Most of the testers you come across will be oil-operated.

Fig.279 was very popular, using a 1/16 in^2 piston, and weights from 100 kPa to either 1 500 or 4 000 kPa. This is still in the range because it has a couple of variants which are still in demand.

Fig. 279P puts the 279 with a short weight set into a portable package.

Fig. 278 uses the Fig. 279 base with the dual range piston, to provide a very compact tester with range to 7 000 kPa. This is extensively used on NATO submarines.

Fig. 280L was the first 200 series model continued through to the 500 series. It used the same 1/16 in² piston, with more weights to 14 000 kPa. The base was plain with a reservoir and isolating valve. The current version is the 580L.

Fig. 280D was the dual piston design, originally called the "Ranger", with pistons of 1/8 (0,125) and 1/80 (0,0125) in², and was originally weighted to 55 000 kPa. The base had a hand-grip type priming pump/reservoir. The current version is the 580DX.

Fig. 280H was the dual piston design, originally called the "High Ranger", with pistons of 1/8 (0,125) and 1/160 (0,00625) in², and was originally weighted to 110 000 kPa. The base was an up-rated 280D base. The current version is the 580HX.

Fig 283 is still current. This is the 400 MPa design with intensifier, using a 1/200 in² piston. The weight carrier is overhang design, so the weights are annular.

The 240 series, and the 280L, D and H were discontinued in 1983. The design philosophy on the replacements was to use a common base for the series, to which any piston could be fitted. The mounting posts were identical, and a G½ gauge connection was developed to fit these mounting posts, thus making the base suitable for use a a comparator when fitted with 2 mounting posts.

The air series was known as the 350 series. In addition to the supply and release valves which were all that the 240 series offered, a volume compensator was added, to make it much easier to generate the correct pressure.

The oil series was known as the 380 series. The base incorporated a unique dual area ram with change-over valves. The small area ram is permanently connected to the mounting posts. The large area ram can be vented back to the reservoir, or connected to the mounting posts. This provides a large area for moving large volumes quickly, eliminating the need for a separate priming pump; then when the operating effort starts to get a bit high, venting the large ram and using only the small ram enables high pressures to be generated with minimal effort. This design is very very easy to use, and has no competition!

Because the base was standard, and could have any piston fitted, or none, the model type no longer formed part of the base serial number. The pistons had always been identified by serial number, but you had to know where to look, usually under the rim of the head. Realising that advances in quality management made requirements for the measuring components to be identifiable, the piston serial number was moved to the base of the piston. A typical base serial number would be 15467/380.

A new model was introduced, the 380M. This was the first to have a metric weight carrier. The usual weight carrier is marked 10 lb/in² with a make-up weight to take it to 100 kPa, the M is 200 kPa with a make-up weight to take it to 30 lb/in². The piston area is 1/40 in² to stay a multiple of the other pistons.

The weights were designed in a modular format, and were made as blanks which could take different values depending on which PCA they were used with. The modern large weight is 1 000 kPa when used on a 1/8 in² PCA, 2 000 kPa when used on a 1/16 in² PCA and 5 000 kPa when used on a 1/40 in² PCA. . During the life of the 350/380 series, the weights were changed from cast iron to martensitic stainless steel.

The Budenberg family were very conservative, they only claimed accuracies that were very safe. They knew they were the best, and believed in delivering more than the customer expected. In 1995 or thereabouts, after the family had sold out, the new owners had the accuracies re-assessed, and decided that they could quite reasonably sell the range with better accuracies than were then claimed. They re-launched the 350/380 series as the 450/480 series, changed the paint colour on the base, from black to Burgundy, and called it the "Premium" range. The weights became austenitic stainless steel, non-magnetic to eliminate errors caused by stray magnetic fields. The weight sets were numbered. The HP piston on the dual range PCAs was made from tungsten carbide.

At the end of the twentieth century, the merger with Desgranges & Huot, and the formation of DHB, meant a marketing review. DHB noted that the stainless steel cover tended to show the age of the tester, as dropping weights on the cover caused a little ding. It was decided to change the cover material to ABS plastic, which would not deform under impact. It was also decided to change the valve handles, because some people had a tendency to over-tighten them, and damage the expensive manifold block. This slightly modified version was released as the DHB 550/580 series with a yellow colour scheme, and even better specs. It was labeled the "Industrial Series" and the D & H range became the "Metrology Series".

It is important to remember that these three generations are identical under the cover, the basic design is unchanged. 380 and 480 bases use 580 spares.

Now we come back to the question of identifying model numbers.

The modern base will give a serial number and series, e.g. 15467/380. This identifies the series as 380, but not the model.

One then has to look at the marking on the PCA. For the hydraulic range, the following applies:-

1/16 in² means *80L where * = 3, 4 or 5.
1/40 in² means *80M where * = 3, 4 or 5.
1/8 + 1/80 in² means 380D or *80DX where * = 4 or 5.
1/8 + 1/160 in² means 380H or *80HX where * = 4 or 5.

The picture gets muddied up a little when one realizes that 200 series testers may be upgraded with a more modern base, but in real life it doesn't matter much whether the unit you see is a 280D with a 580 base, or a 480DX. As a representative for Budenberg, you have to understand the range of the model before you. If you are booking a tester in for service, the model number is part of the identification process which links the tester to the owner. If the owner requires a new PCU, or a new weight set, you have to know what to order.

Maintaining 200 series bases

This applies to the 280L, D, & H in the main, and also the 240 series air testers.
No spares are available for these bases, which can no longer be repaired. When the PCA and weights are in good order, recommend that a current series base be purchased. The 280D/H will require an adaptor to match the revised datum level.

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