Design of Displacement Provers

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Introduction

Since, in any measurement system, there is always some error present, it is desirable to have a method for determining the amount of error and correcting for it. In recent years, displacement type meter provers are being used more frequently to calibrate liquid flow meters. Displacement meter provers operate on the principle of displacing a known volume of liquid. This displacement of liquid is accomplished by forcing a displacer through a calibrated section of pipe commonly referred to as the Prover Measuring Section. Since the entire stream of fluid being metered flows through both the meter and the prover, a ratio (meter factor) can be determined between the known volume and the volume register by the meter. This meter factor is used as a multiplier and applied to the volume shown on the meter registered to determine the true quantity of fluid passing through the meter.

Of the various types of proving methods available, displacement meter provers are generally accepted as the most practical, economical, and accurate means of proving, especially for large capacity meters. This includes metering installations for pipelines, tanker and barge loading operations, refineries, etc. There are several advantages of displacement meter provers which have given them wide acceptance. Some of these are:

1. Proving of the meter is done under actual operating conditions and the meter runs continuously. This eliminates errors resulting from starting and stopping flow. It also reduces proving time.
2. The fluid flow through the prover during the proving cycle is continuous. Thus, prover temperature is more easily stabilized.
3. The displacement method lends itself to automation.

Types of Displacement Provers

There are two general types of displacement meter provers: Unidirectional and Bidirectional. As the name implies in the Unidirectional Type, the displacer travels in only one direction through the measuring section; whereas, in the Bidirectional Type the displacer can travel through the measuring section in either direction by reversal of the flow stream through the prover. These types of provers are shown in Figures 1 and 2.

The calibrated volume (i.e., known volume between detector switches) in Bidirectional Type Provers is usually expressed as twice the volume between detector switches or a "round trip." The volume in the Unidirectional Type Prover is simply the volume between detector switches.

Unidirectional Provers

In general, Unidirectional Type Provers can operate with a much higher displacer velocity and, thus, may use a smaller diameter, longer calibrated section. Increased length between detector switches improves prover repeatability by reducing the significance of switch non-repeatability. No pre-run is required in the Unidirectional Type Prover since the transfer valve is sealed prior to launching of the displacer. However, since the displacer travels in only one direction in the unidirectional prover, care is required when replacing detector switches. The switches must be pre-calibrated or the prover will require recalibration.

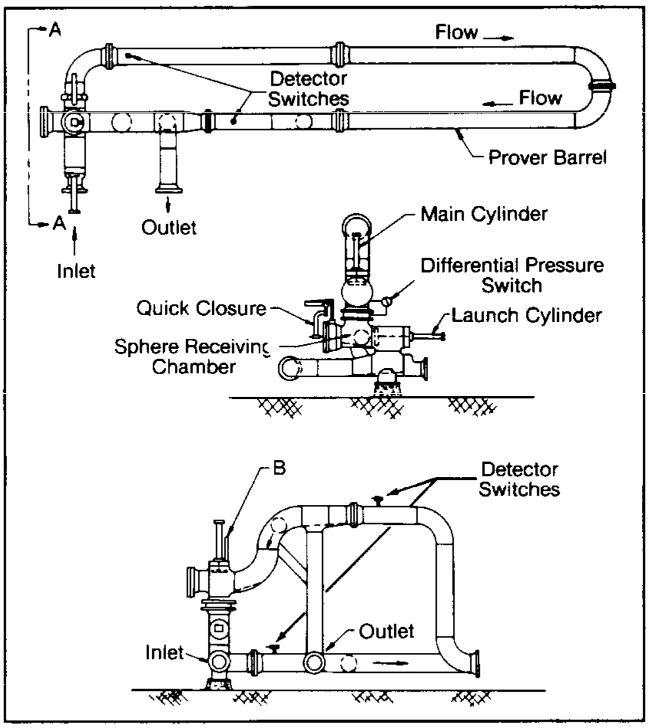

Figure 1 — Unidirectional Prover

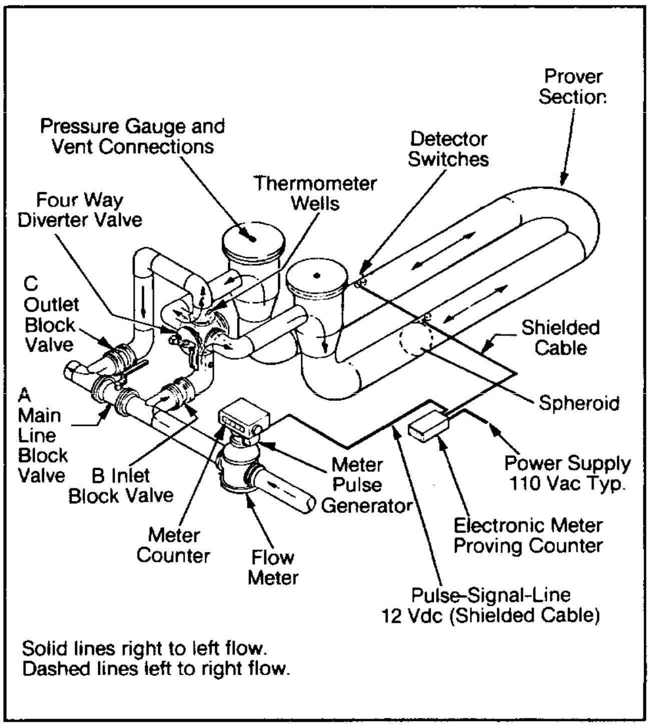

Figure 2 — Bidirectional Prover

Bidirectional Provers

With the Bidirectional Prover, recalibration is not necessary after detector switch replacement since any change in detector switch actuation time will be canceled out by the round trip of the displacer. Also, the Bidirectional Prover is much more adaptable, especially on lower flow rates, to being made portable (truck or trailer mounted). Pre-run becomes necessary in a Bidirectional Prover to assure complete flow direction reversal prior to the displacer entering the calibrated section. By the use of three or more detector switches, the Bidirectional Type Prover can be made into a multiple volume prover reducing the proving time on low flow rates. This is not possible with the Unidirectional Type because the displacer must always go through the entire length of the prover and return to the transfer valve.

Design and Construction

On the surface, the displacement meter prover appears to be a relatively simple device for calibrating meters over a wide range of flow rates. However, no matter what size displacement meter prover is being considered, it must be regarded as an extremely accurate instrument and must be designed, manufactured, calibrated, and used with great emphasis on detail if accurate measurement is to be achieved.

The major components of displacement meter provers and their primary design considerations are summarized below:

Prover Measuring Section

1. **Sizing the Prover Volume**

   The volume of the displacement prover must be selected so that it will provide the desired repeatability when considering the resolution of the detector switches and meter proving counters. The conventional method for determining the required prover volume is to use the recommendation set forth in Standard API 2531 "Mechanical Displacement Meter Provers" dated May 28, 1965, which suggests the calibrated volume of the displacement prover (i.e., volume between detector switches) be approximately 0.5 percent of the maximum hourly flow rate. For example, if the maximum hourly flow rate is 5,000 BPH, then the calibrated volume required is 25 barrels. This is true for either the Unidirectional or Bidirectional Prover. However, in the case of the Bidirectional Prover, it must be remembered that the calibrated prover volume is represented by the complete "round trip" travel of the displacer. This, then, results in a total calibrated volume of 1.0 percent of the maximum hourly flow rate (i.e., 50 barrels in our example). In many instances, especially on portable provers, the calibrated volume has been less (e.g., 0.25 percent of the maximum hourly flow rate) to allow for a more compact design but still giving the desired repeatability.

   If a more technically precise approach to determining required prover volume is desired, the following factors must be considered:

   a. The resolution of the meter pulse generator (i.e., the number of pulses per unit volume). It is generally recommended that the calibrated volume between switches be large enough to provide a minimum of 10,000 pulses. Therefore, a signal generator which provides 1,000 pulses per barrel requires a prover volume of 10 barrels, whereas, a signal generator providing only 500 pulses per barrel requires a prover volume of 20 barrels.
   b. The resolution of the detector switches, which is normally expressed in linear units.
   c. The sphere position repeatability at time of detector switch actuation. Currently, no published data exists on the dynamic sphere position repeatability for calculating the sphere/detector switch actuation repeatability relationship.

2. **Construction of the Measuring Section**

   The measuring section of a displacement prover is made up of pipe, fittings, and flanges. It can be a straight section of pipe or include smooth bends if a spheroid type displacer is used. Several items which should be considered when designing and fabricating the prover measuring section are:

   Pipe:

   a. The pipe used must be selected for roundness and uniformity of cross-section.
   b. The most efficient and economical length should be used to eliminate any unnecessary welds. If welding of pipe or fittings is required, the weld must be a full penetration weld and must be ground smooth. Welds which are not full penetration can cause leakage across the displacer and/or displacer damage, as well as not meeting the required Construction Codes (ANSI B31.4, etc.)

   Flanges:

   a. Flanges used in the measuring section should be match bored and machined for metal to metal surface contact with a tongue and groove O-Ring fit (see Figure 3). The metal to metal surface contact allows for disassembly and reassembly of the measuring section without the need for recalibration. The original factory "waterdrawn" certified volume is maintained even when the measuring chamber is disassembled for shipment or inspection. The possibility of flange gasket compression

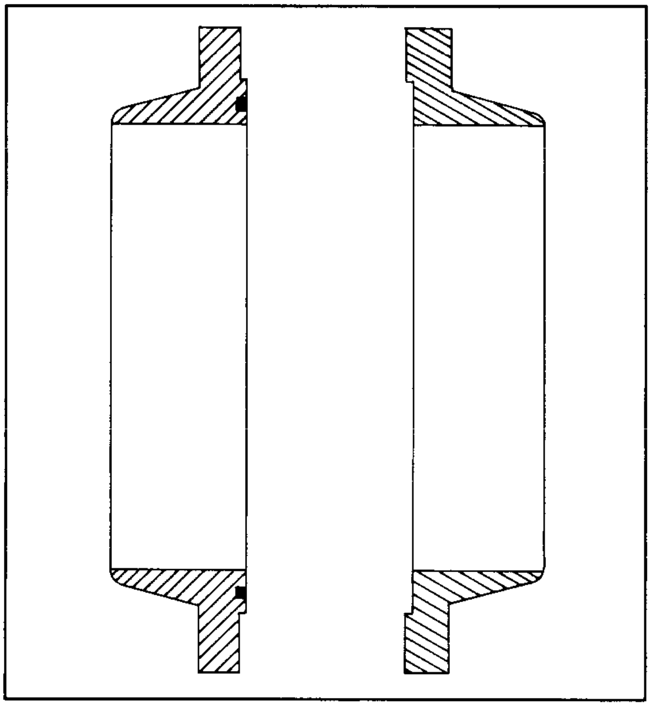

Figure 3 — Match Bored - Tongue and Groove O-Ring Flanges

which would change the calibrated volume is eliminated. The match bored, tongue and groove arrangement insures precise alignment between pipe spools. Misalignment can possibly cause displacer damage and/or reduce prover accuracy.

b. The measuring section should incorporate the necessary number of flanges to:
   1. Ensure full penetration welds and smoothly ground internal surfaces to protect against leakage and excessive displacer wear.
   2. Reduce pipe lengths between sections to ensure that the internal surfaces are properly sandblasted and coated.
   3. Allow for easy access into the measuring section for inspection and maintenance, such as recoating the internal surface.

Detector Switches

Detector switches should have the ability to detect when the displacer enters or exits the calibrated measuring section with a resolution comparable to that of the pulse generator and pulse counter. The detector switches act as a gating switch triggering the pulse counter on and off. The two basic types of detector switches used on displacement provers are:

1. **Proximity Type**

   The proximity type operates on the principle of the displacer entering into an electrical or magnetic field. No portion of the switch enters into the measuring section; thus, there is no seal required. But, this switch can only be used with a metal piston displacer with piston cups and a straight type prover.

2. **Mechanical Type**

   The mechanical type utilizes a plunger which makes contact with the displacer and transmits motion to a switch. In this type of switch, the plunger does enter into the measuring section and is subject to operating pressures. Therefore, a means must be provided for pressure balancing the switch to eliminate effects of pressure changes.

Detector switch parts which are critical to repeatability must be corrosion resistant. Switches should be serviceable under pressure to eliminate any need for isolating or draining the prover when servicing the switches. As mentioned earlier, calibrated volume changes resulting from field adjustment or replacement of detector switches is canceled out on a Bidirectoinal Type Prover. However, detector switches on a Unidirectional Type Prover must be factory calibrated and certified and must be sealed in place in the prover to prevent any field adjustment which will alter the calibrated volume.

Coating

1. **Internal**

   Some of the reasons for providing an internal coating on the prover barrel of the displacement prover are:

   a. To reduce frictional drag on the displacer, thus, prolonging displacer life and reducing prover pressure drop.
   b. To protect the measuring section from rust or pitting both prior to installation and during periods of non-use.
   c. To help ensure smooth, non-jerking displacer motion when handling liquids with little or no lubricity, such as gasoline or LPG.

   The coating must have a hard, smooth, long-lasting finish and must be applied only after the internal surface of the prover barrel has been sandblasted to a white metal base. This sandblasting will also remove undesirable laminations from the interior of the pipe wall. The two most commonly used types of internal coating are:

   a. Phenolic - this is a baked-on coating usually requiring several coats. The baked-on coating can become very costly and require considerable time for application, especially on large provers.
   b. Air-Cured Epoxy - this is an air-dried epoxy which usually requires only one or two coats. The process of application is often quicker and much less expensive than the baked-on Phenolic.

   Coating thickness is typically in the range of 4-6 Mils (.004-.006 inches) and both types of coating have been used on a wide variety of displacement prover applications. It must be emphasized that any change in the thickness of the internal coating affects the calibrated volume. Therefore, when considering prover design, the ease of access into the prover barrel is critical for future repair. Also, when selecting the type of coating to be used, consideration must be given to the ease with which the coating can be reapplied in the field.

2. **External**

   Many types of protective coating, such as primers, paints, and epoxies, are used on the external surface of the prover. Purchaser preference and ambient conditions usually dictate the type specified.

   In many cases, where large fluctuations in the ambient or prover surface temperature can occur, 1-1/2" to 2" of insulation is recommended on the prover to keep the effects of these temperature fluctuations on the prover volume to a minimum. Also, provers are often buried to obtain thermal stability.

Displacer

The displacer is the device which travels through the calibrated measuring section displacing the known quantity of liquid and tripping the detector switches.

1. **Types**

   Early mechanical displacement provers were of the straight type and used cylindrical pistons with piston cup seals on either end. However, these were later replaced by the elastometric spheroid which allowed for the manufacture of the more commonly used folded prover configurations. The spheroid-type displacer is hollow and is hydrostatically filled with water or a mixture of glycol and water (to prevent freezing) under pressure.

   The advantage of using the resilient spheroid is that it acts as a "squeegee." This action creates a good seal and also prevents the build-up of scale on the walls of the calibrated section. During the proving run the spheroid rotates, if properly inflated, thus equalizing wear about the entire surface of the spheroid. Spheroids also readily lend themselves to being inflated to the optimum size to suit different pipe wall thickness. A typical spheroid is schematically illustrated in Figure 4.

2. **Sizing**

   The spheroid is normally inflated to a diameter approximately 2% larger than the inside diameter of the measuring section pipe. Inflation of the spheroid to this size is considered to provide the most satisfactory operating results. Over expansion causes excess wear and pressure drop without improving the seal. In the event of wear after long usage, additional fluid may be pumped into the spheroid to restore it to the desired diameter.

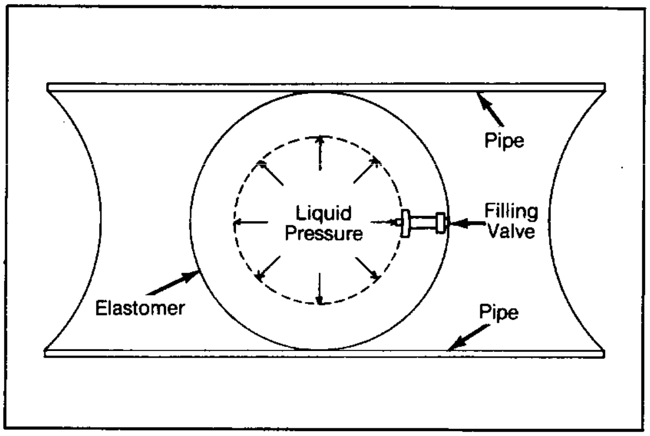

Figure 4 — Cross-Section - Spheroid

3. **Materials**

Spheroids are commonly available in three basic materials:

a. Neoprene - good for low pressure crude oil and anhydrous ammonia service.
b. Nitrile - most commonly used spheroid material. Used for refined petroleum products, such as gasoline, kerosene, fuel oil, and for high pressure crude oils.
c. Urethane - used in applications where abrasion resistance is necessary and for low temperature applications.

A fourth material which spheroids can be made from is Viton. However, Viton spheroids are available only in solid form (non-inflatable) which presents problems in providng a good seal in the measuring section of the prover. Viton spheroids are considered good for use in fluids with high aromatic content since Viton is less likely to swell.

4. **Velocity Limits**

API Standard 2531 "Mechanical Displacement Meter Provers" dated May 28, 1965, makes a general recommendation that spheroid and piston velocities should not exceed 10 and 2.5 feet per second (fps), respectively. However, as a result of economic utilization of materials and space considerations in designing displacement provers, the most common range of spheroid velocities is 3 to 5 fps for Bidirectional Provers and 8 to 9.5 fps for Unidirectional Provers.

In prover design the minimum spheroid velocity, and, therefore, the minimum flow rate, must be considered. This minimum flow rate is primarily a function of the degree of lubricity of the fluid flowing in the prover. If fluid is very dry (non-lubricative) and the spheroid is traveling at a very slow rate (less than 0.5 fps), then there exists a probability that the displacer will move with a jerky motion causing non-repeatable proving. To prevent this, a guideline to follow is to maintain a minimum spheroid velocity of 0.5 fps on non-lubricative fluids. Figure 5 shows the relationship between measuring section pipe size and minimum flow rates based on a spheroid velocity of 0.5 fps.

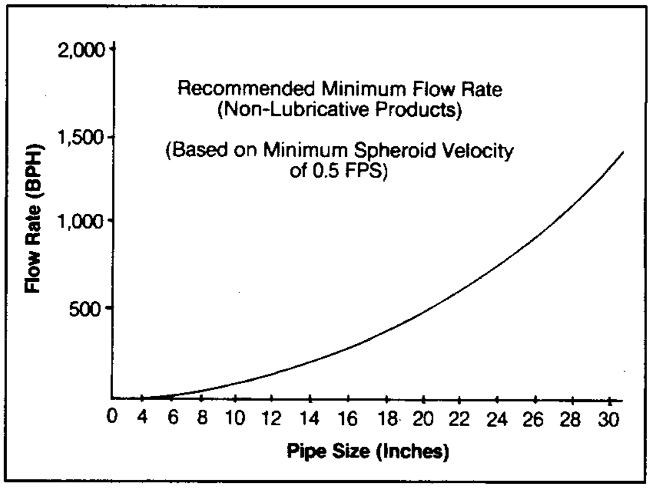

Figure 5

Prover Valves

1. **Requirements**

For an accurate proving run, it is essential that all the fluid passing through the meter also pass through the prover barrel. Hence, it is essential that a positive indication of seal integrity be provided on all critical system valves as liquid must not bypass the prover when the displacer is traveling between detector switches. Diverter valves on Bidirectional Provers and transfer valves on Unidirectional Provers must both be bubble-tight against low pressure differentials since the only pressure drop across the valve is that which is across the displacer plus the piping loss through the prover. This drop seldom exceeds more than a few PSI.

2. **Types**

Unidirectional Prover - This type prover utilizes a transfer valve which must separate the displacer from the flow stream at the downstream end of the prover barrel and launch the displacer into the flow stream upstream of the prover barrel quickly and smoothly. The transfer valve must incorporate a high integrity double block and bleed type seal to prevent passage of liquid during the proving run and must achieve a positive seal before launching the sphere into the prover, thus eliminating the need for pre-run. The valve should also be provided with a hinged closure to permit easy sphere removal. A typical transfer valve is shown in Figure 1.

Bidirectional Prover - This type prover utilizes a four-way diverter valve which reverses the direction of flow within the prover by one simple action. Figure 6 shows a four-way diverter valve with inflatable seals. The seals inflate when the diverter plate is in the proper position and are deflated when the diverter is required to change positions. This eliminates any rubbing, and thus wear, of the seals on the interior of the valve body during rotation of the flow diverter plate.

3. **Actuator and Controls**

Small valves can be operated manually with either handwheel or lever actuators. Large valves require an electric motor or electrohydraulic actuator. Electrohydraulic actuators employ a hydraulic operator on the valve which is supplied with hydraulic pressure from an electric motor and pump unit. As valves increase in size, the actuators and controls become more complex and expensive. The actuators should also have the provision for remote operation since on many systems, the prover operation is controlled from a remote control panel.

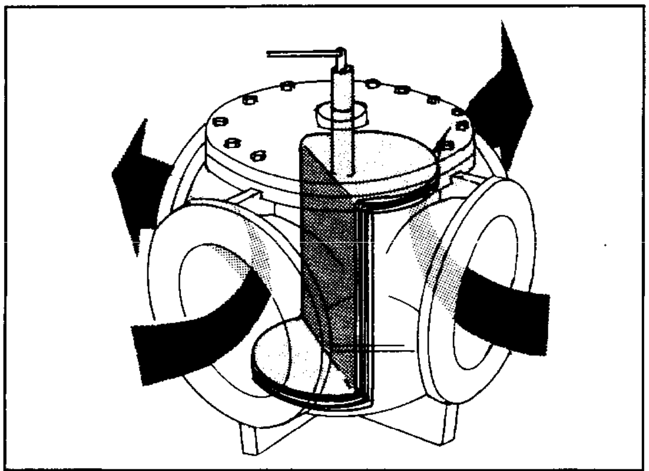

Figure 6 — Four-Way Diverter Valve

4. **Pre-Run**

   Required pre-run can be defined as the distance the spheroid will travel in the measuring section of the prover, for a given flow rate and valve stroking time, prior to sealing of the valve and triggering of the detector switches. As mentioned earlier, pre-run is not critical in a Unidirectional Prover since the block and bleed seal is made prior to launching of the spheroid. However, in a Bidirectional Prover, pre-run must be considered carefully so that the four-way diverter valve is sealed prior to the spheroid contacting the first detector switch. A commonly used formula for calculating pre-run in a Bidirectional Prover is:

   $$\text{Total Pre-run (ft) (Per Side)} = \frac{F \times K}{D^2} \times T$$

   Where: F = Maximum flow rate in BPH

   $K = \text{Constant} = .286 \; \frac{\text{FT - IN}^2}{\text{Sec. - BPH}}$

   D = Inside diameter of measuring section pipe in inches

   T = Valve stroking time (1/2 cycle) in seconds

   Therefore, it can easily be seen that as the flow rate increases, the required pre-run will icnrease unless the measuring section size is increased or the valve stroking time is decreased. Using large size pipe becomes expensive so it is important to keep the valve stroking time to a minimum, especially on portable provers where space limitations exist.

Separator Tees/Launch Chambers

In the design of displacement meter provers, a basic consideration must be the method by which the displacer is decelerated and stopped after a proving run. In Unidirectional Provers, separator tees are used to slow down the spheroid. Sizing of the tee is quite critical to assure dependable separation of the spheroid from the main stream through the entire flow range of the prover.

The Bidirectional Prover design incorporates launching chambers in its design for receiving and launching the spheroid. The launch chambers are normally sized at least 4" larger than the measuring section diameter. The chambers can be horizontal or of some angle up to 90° from the horizontal. However, launch chambers oriented 45° to 90° from the horizontal have the following advantages due to the gravity forces acting on the spheroid:

1. Ensure positive launching of the spheroid at low flow rates when spheroid velocities are very low.
2. Reduce the possibility of spheroid damage due to abrupt stopping at high velocities.

Prover Installation

Displacement provers are furnished most often with pipe-leg supports but can also be partial-skid or full-skid mounted. A full skid is like a partial skid with the addition of beams running the full length of the prover.

Some of the other prover design features required for proper installation and operation of the prover are:

1. Adequate provisions should be made for thermal expansion and contraction, vibration, and reaction to pressure surges.
2. A relief valve installed on the prover to prevent the pressure in the prover from exceeding its design limits due to thermal expansion.
3. Adequate vents and drains for bleeding air completely from the prover prior to proving and for draining fluid from the prover prior to maintenance.
4. Electrical equipment should be designed to conform to applicable codes for safe operation and should be located in a convenient location for operation and maintenance of the prover.
5. Thermometers and pressure gauges should be provided at the prover inlet and outlet so that the average temperature and pressure of the liquid in the prover can be obtained.

Finally, the prover should always be installed downstream of adequate straining or filtering equipment. Most often, the prover is installed downstream of the meter being proved since the meter is being protected by a strainer.

Portable Displacement Prover

Bidirectional Type Displacement Provers, as a result of their compact design, are readily adapted for portable use. A typical truck-mounted prover is shown in Figure 7 and comparative size and cost analysis between stationary and portable Bidirectional Provers can be found in the Appendix. Portable trailer- or truck-mounted provers should include the following equipment for proper operation.

1. Two drains for faster draining piped to the rear of the trailer or truck bed and terminating into double block bleed valves to prevent leakage.
2. Inlet and outlet lines of the four-way diverter valve piped to the rear of the trailer or truck bed. These should terminate into swivel hose connections which allow the hoses to remain attached to the inlet and outlet lines, eliminating the need for the operator to connect and disconnect the hoses each time. Block valves should be furnished directly preceding the swivel connections to minimize spillage when disconnecting the hoses from the meter run.
3. Two flexible hoses should be provided for connecting the prover to the system. Flexible stainless steel braided hoses should be furnished where inlet and outlet lines are 3" and larger for greater operator

safety. On high pressure applications, spring balanced load arms are often used because of the higher maximum allowable working pressures.

4. Hose racks mounted on the trailer or truck bed to provide a method of storing hoses securely while in transit. This prevents damage that would occur if the hoses were not securely fastened and fell off the trailer or truck bed.
5. A sump tank should be provided. All vent connections should be piped into needle valves which can be opened to the sump when bleeding air from the prover. The outlet of the sump tank should be equipped with a valve for easy drainage.
6. Tool boxes are often included on the trailer or truck bed. One tool box will usually contain two (2) cable reels each with 100 feet of cable (one reel for power cable to operate the prover controls and one reel for signal cable connecting the prover counter to the meter pulse transmitters). Prover controls may also be powered by the battery on the truck or towing vehicle.
7. A prover counter is often provided. In many cases the prover counter and controls are mounted inside the truck cab to enable complete operation of the prover out of the weather.
8. A Master Meter may also be provided on the portable prover. The Master Meter would be calibrated by the prover at actual operating conditions. Then the Master Meter would be used to calibrate the Line Meters. The advantages of using a Master are as follows:
   a. The Line Meters can be calibrated over as large a volume as desired to increase resolution and decrease the effect of cyclic Line Meter output.
   b. The Master Meter can be used to calibrate Line Meters with low flow rates at a faster rate than can be done with the prover.
   c. A bank of Line Meters at the same operating conditions can often be calibrated quicker by calibrating the Master Meter once against the prover, than using it to calibrate the several Line Meters.

Conclusion

With the current and projected increases in the cost of liquid petroleum products, the need for their accurate measurements is becoming increasingly important. As a result, displacement provers, being one of the most accurate and efficient methods of meter calibration, are coming into greater use. Therefore, it is important that those involved in liquid petroleum measurement understand the features of a well-designed displacement prover. The manufacturing of displacement provers is very competitive and design "short-cuts" have sometimes been taken to reduce selling price. Unless a buyer or user is fully aware of the importance of various design features, he may unknowingly be sacrificing prover accuracy, reliability, and/or operating convenience or cost for a slightly lower initial purchase price.

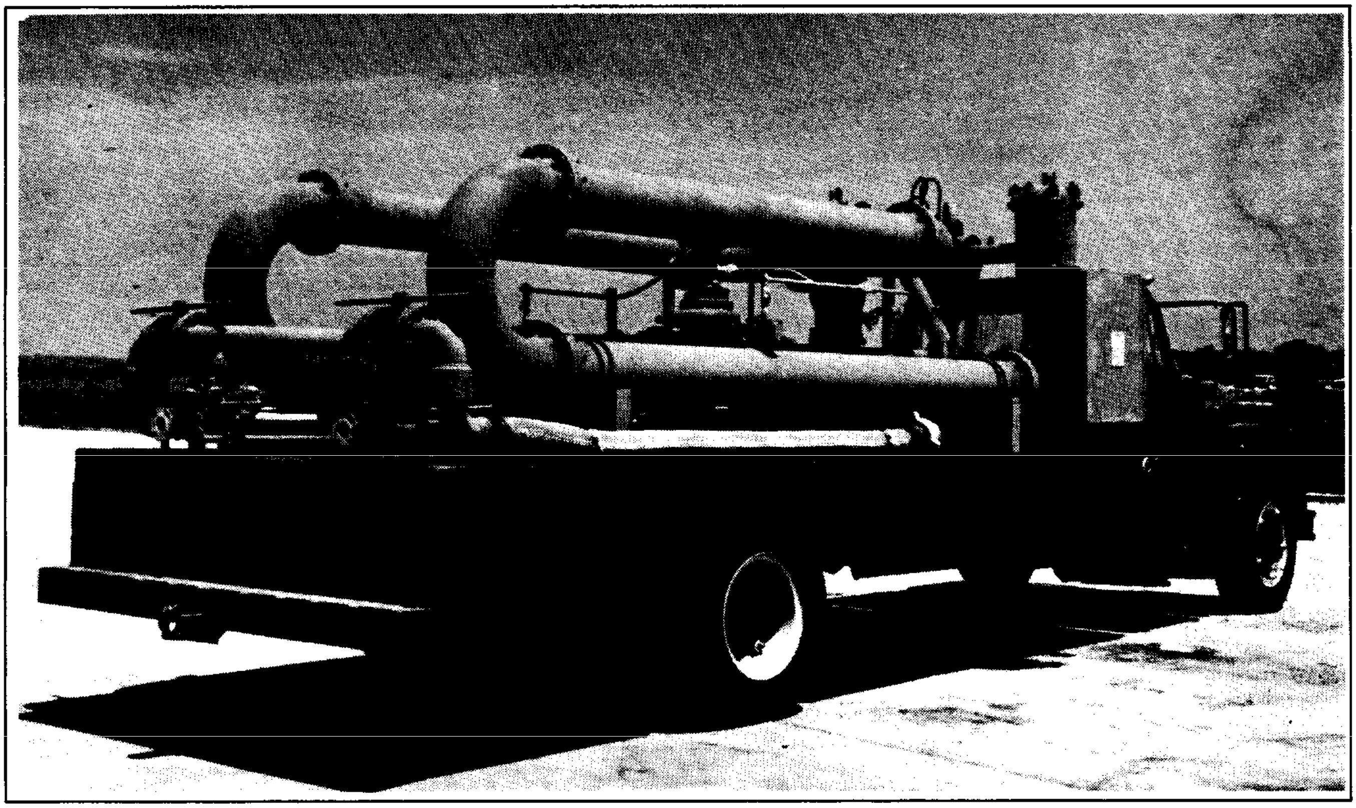

Figure 7 — Truck-Mounted Prover

Appendix

Evaluation of different sizes and types of Bidirectional Displacement Meter Provers with respect to cost and space requirements.

Single vs. Double Loop Stationary Provers

	Single Loop		Double Loop	
Max. Flow Rate (BPH)	**Prover Price**	**Approx. Length**	**Add'l. Price***	**Approx. Length**
600	Base	30 Ft.	+5%	20 Ft.
850	Base	35 Ft.	+8%	21%
1,400	Base	40 Ft.	+8%	20 Ft.
2,300	Base	60 Ft.	+7%	22 Ft.
3,500	Base	55 Ft.	+7%	30 Ft.
4,300	Base	70 Ft.	+6%	40 Ft.
6,000	Base	60 Ft.	+8%	38 Ft.

*Additional price for double loop vs. same size single loop prover.

Single Loop Stationary vs. Double Loop Trailer Mounted Provers

	Single Loop	Double Loop Trailer Mounted Price	
Max. Flow Rate (BPH)	**Stationary Price**	**Without Master Meter**	**With Master Meter**
600	Base	+112%	+132%
850	Base	+112%	+132%
1,400	Base	+115%	+135%
2,300	Base	+116%	+136%
3,500	Base	+117%	+137%

Comparison Summary

It is quite evident from the figures shown that considerable space can be saved by double looping the prover (approximately 1/3 of the overall length) for a minimal cost increase of 5% to 8%. Therefore, double looping the prover should definitely be considered when space is a problem.

The price differential between a stationary prover and a trailer-mounted prover is quite large (112% to 117%) as can be seen in the *Single Loop Stationary vs. Double Loop Trailer Mounted Provers* section. But, if the application involves the proving of several meters at 3 or 4 remote locations, then the price of the trailer-mounted prover becomes very attractive when compared to the price of individual stationary provers at each location. A further point to consider when evaluating the desirability of a portable prover is the fact that it can also be contracted to prove other meters in the general area.

Acknowledgement

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