Machine Condition Monitoring

and

Fault Diagnostics

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Course Overview

- Introduction to Machine Condition Monitoring and Condition Based Maintenance
- Basics of Mechanical Vibrations
- Vibration Transducers
- Vibration Signal Measurement and Display
- Machine Vibration Standards and Acceptance Limits (Condition Monitoring)
- Vibration Signal Frequency Analysis (FFT)

Course Overview

- Machinery Vibration Testing and Trouble Shooting
- Fault Diagnostics Based on Forcing Functions
- Fault Diagnostics Based on Specific Machine Components
- Fault Diagnostics Based on Specific Machine Types
- Automatic Diagnostic Techniques
- Non-Vibration Based Machine Condition Monitoring and Fault Diagnosis Methods

Current Topic

- Machinery Vibration Testing and Trouble Shooting
- Fault Diagnostics Based on Forcing Functions
- Fault Diagnostics Based on Specific Machine Components
- Fault Diagnostics Based on Specific Machine Types
- Automatic Diagnostic Techniques
- Non-Vibration Based Machine Condition Monitoring and Fault Diagnosis Methods

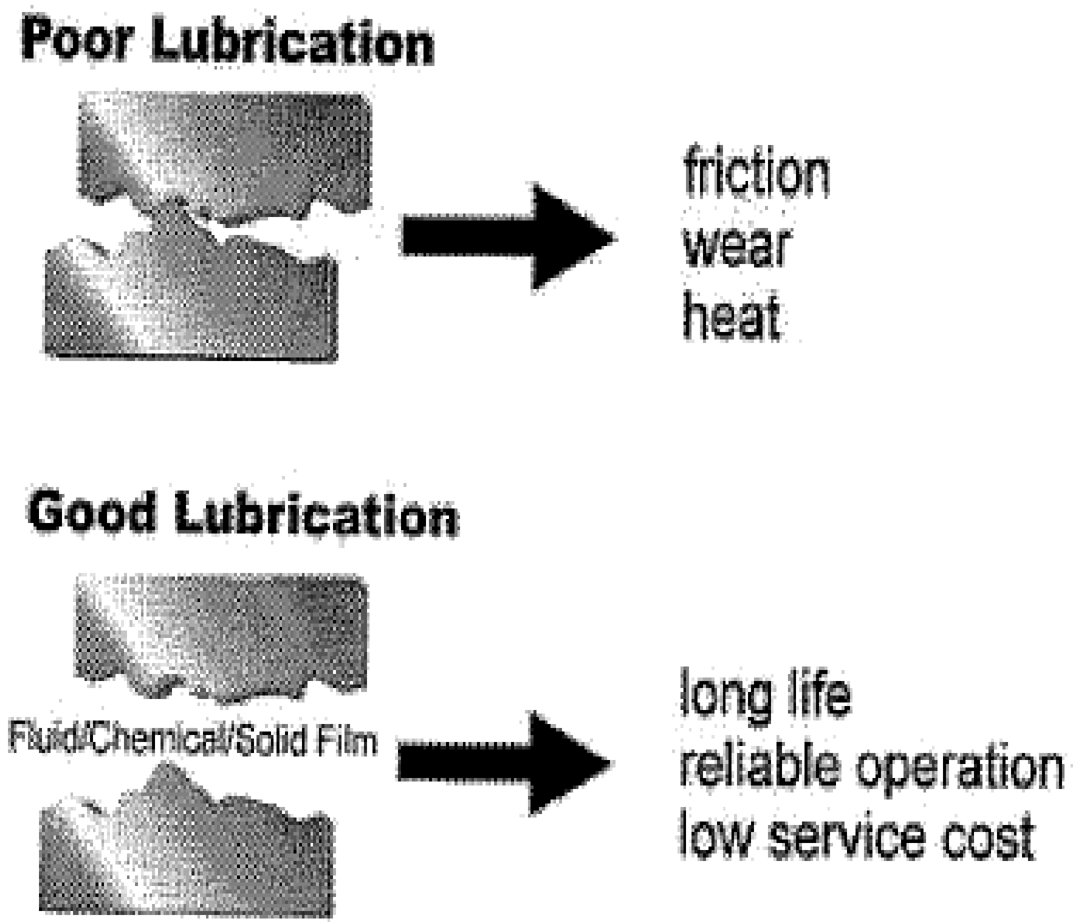
Oil Quality Analysis

Lubrication Fundamentals

Benefits

- Friction and wear reduction (separates parts moving relative to one another)
- Heat control
- Contamination control
- Reduce chemical attach
- Transfer of energy (hydraulic systems)

Lubrication Fundamentals



Lubrication Fundamentals

Base Stock Considerations

- Base stock properties largely determine the lubricant performance
- Most base oils are mineral oils (refined from crude oil)
- Fractional distillation sorts hydrocarbon molecules by size and type
- Other refining – solvent extraction, hydrogen processing, acid refining, clay refining, solvent de-waxing

Key Physical Properties of New Base Oils

Property	Why Important	How Determined	ASTM No.
Viscosity	Defines base oil viscous grade	Gravity flow capilary viscometer	D-445
Viscosity Index	Defines viscosity-temperature relationship	Viscosity variance between 40°C and 100°C (indexed)	D-2270
Specific Gravity	Defines density of oil relative to water	Hydrometer	D-1298
Flash Point	Defines high-temp volatility and flammability properties	Flash point tester (temp at which flash surface flame is achieved)	D-92/D-93
Pour Point	Defines low-temp oil fluidity behaviour	Gravity flow in test jar	D-97/IP-15

Typical Base Oil Properties

Property	ASTM Method	Paraffinic Oil	Naphthenic Oil	Aromatic Oil
Viscosity @ 40°C	D-445	40	40	36
Viscosity @ 100°C	D-445	6.2	5	4
Viscosity Index	D-2270	100	0	-185
Specific Gravity	D-287	0.8628	0.9194	0.9826
Flash Point °C	D-92	229	174	160
Pour Point °C	D-97	-15	-30	-24
% Paraffinic	D-3238	66%	45%	23%
% Naphthenic	D-3238	32%	41%	36%
% Aromatic	D-3238	2%	14%	41%

Mineral versus Synthetic Oils

Potential Benefits of using Synthetic Base Oil

- Increased oxidative life
- Improved lubricity
- Fire resistance
- Better thermal resistance
- Extended drain intervals

Synthetic Base Oil - Polyalphaolins, Synthetic esters (diesters, polyolesters, alklylated napthlenes, alkyklated benzenes, polyglycols etc.)

Mineral versus Synthetic Oils

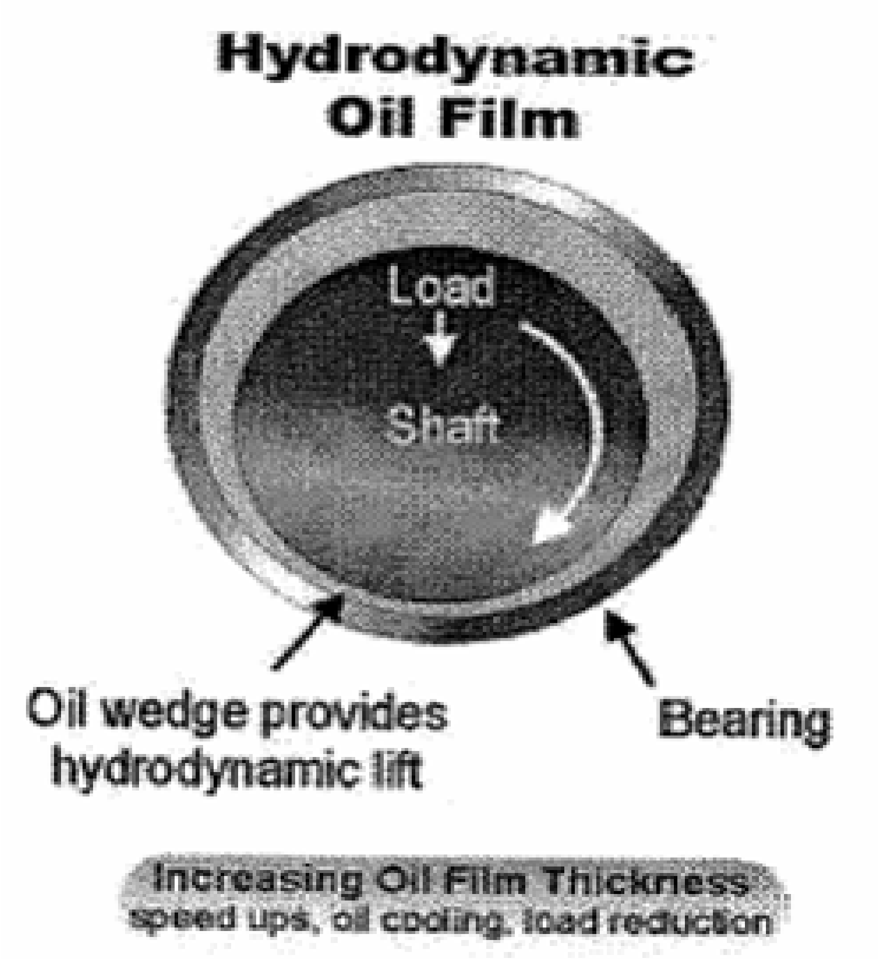
Potential Limiting Factors of using Synthetic Base Oil

- High purchase cost
- Seal or coating incompatibility
- Potential toxicity
- High disposal cost
- Possible incompatibility with mineral oil

Lubrication Fundamentals

Hydrostatic Lubrication

- Used when surface-to-surface contact is likely due to high loads or contamination
- Also called “thin-film lubrication”
- A “wedge” of lubricating oil is created hydrodynamically
- Depends on machines speed, load, interacting surface shape, and oil viscosity
- Not available at start-up and coast-down


Hydrodynamic
Oil Film
Load
Shaft
Oil wedge provides
hydrodynamic lift
Bearing
Increasing Oil Film Thickness
speed ups, oil cooling, load reduction

Lubrication Fundamentals

Elasto-Hydrodynamic Lubrication

- Takes place in rolling element bearings and between gears
- Small contact area creates high local pressure
- Liquid oil may change into a solid state temporarily, then change back to liquid state after pressure is removed

Lubrication Fundamentals

Boundary Lubrication

- Only the lubricant “sticking” to the surface of the machine components acts to separate moving parts
- Occurs when component surface roughness is high, there are frequent stops and starts, shock loading conditions, high static loads, or low speeds
- Additives and/or solid lubricants may help

Lubrication Fundamentals

Additives and Their Functions

- Enhance existing base oil properties
- Suppress undesirable base oil properties
- Impart new properties to base oils

Additives and Their Functions

Antioxidants/Oxidation Inhibitors

- Reduce oil reaction with oxygen at high temps
- Reduce aeration (air mixed into oil)
- Reduce temperature (oxidation rate doubles with every 10° C increase in temp)
- Reduce water in oil
- Reduce metal catalysts (copper, lead, iron)

Additives and Their Functions

Oxidation Causes

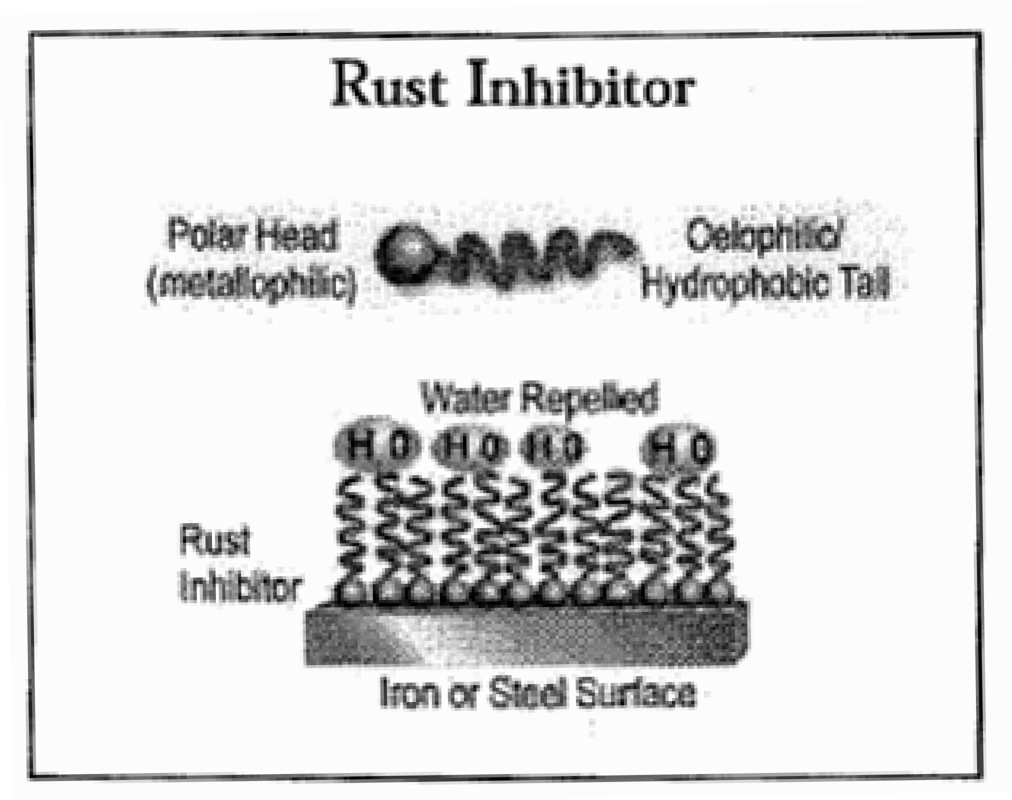
- Increased viscosity
- Increased acidity
- Increased specific gravity
- Darkened colour
- Varnished component surfaces
- Sludge accumulation

These effects cannot be stopped – only delayed

Additives and Their Functions

Rust Inhibitors

- Additives form a barrier to protect steel (iron) from water



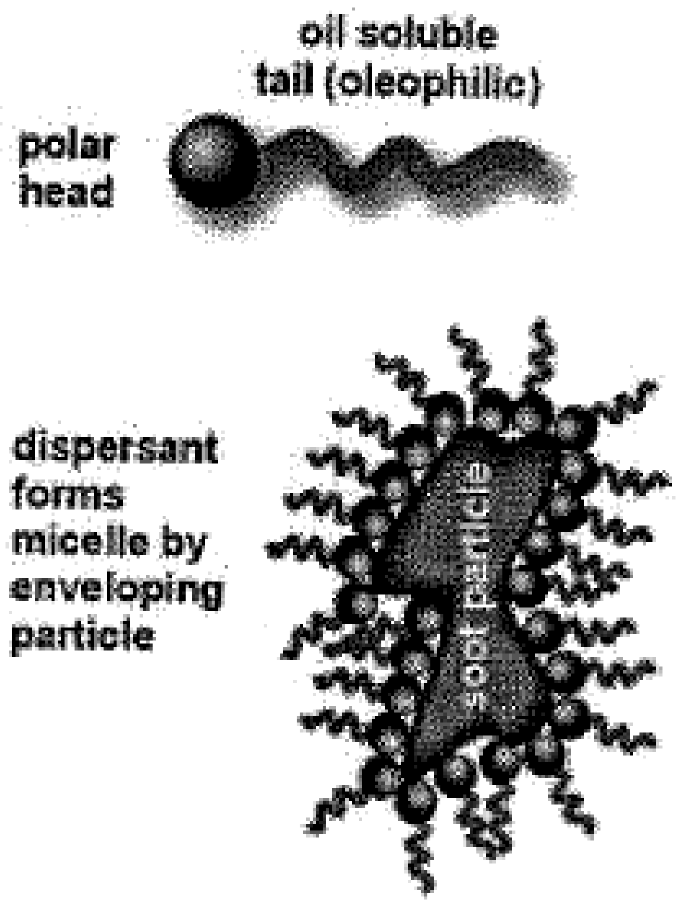
Additives and Their Functions

Dispersants and Detergents

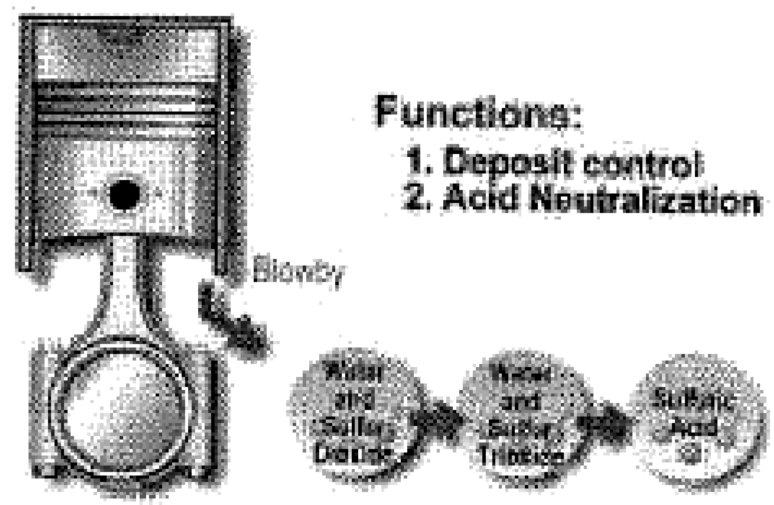
- Dispersants envelop sludge and soot particles to stop them from joining together into larger particles that would degrade lubricant
- Detergents cleanse high temperature surfaces (pistons, rings, valves, etc.)

Additives and Their Functions

Dispersants



Detergents



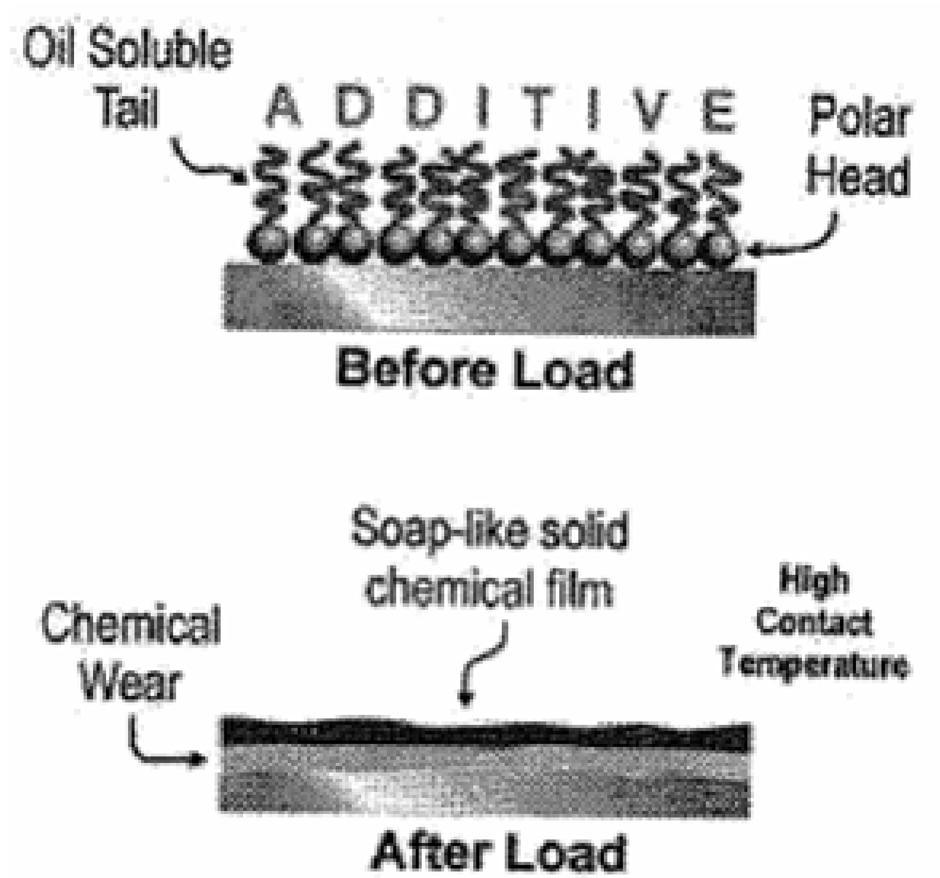
Additives and Their Functions

Anti-Wear and Extreme Pressure Additives

- Also called “anti-scuff” additives
- Under high pressure these additives react with component surfaces to form soap-like oxide films that enhance lubricity at the boundary contact between surfaces

Additives and Their Functions

Anti-Wear and Extreme Pressure Additives



Oil Quality Analysis

Oil Quality Parameters

- viscosity
- acidity
- flashpoint
- dilution (fuel leakage into oil)
- IR spectroscopy (dissolved metals)
- UV spectroscopy (dissolved metals)
- total solids
- water

Oil Quality Analysis

What is being analyzed?	Fluid Properties (Physical and Chemical)	Contamination	Wear Debris
Particle Count	-	++	+
Moisture Analysis	-	++	-
Viscosity Analysis	++	+	-
Wear Debris Density	-	-	++
Analytical Ferrography	-	+	++
TAN/TBN	++	+	+
FTIR	++	+	-
Patch Test (filtergram)	-	++	+
Flash Point	+	++	-
Elemental Analysis	++	+	++
	Proactive	**Proactive**	**Predictive**

- **TAN – Total Acid Number**
- **TBN – Total Base Number**
- **FTIR – Fourier Transform Infrared Spectroscopy**

++ Appropriate
+ Acceptable
- Inappropriate

Oil Quality Analysis

Table 4.1 General test suite

Test	*Unit*	*Method*	*Hydraulic*	*Gearbox*	*Slewing bearing*	*Engine*
Appearance	–	Visual	✓	✓	✓	✓
Colour	–	Visual	✓	✓	✓	✓
KV@40	mm^2/s	IP71	✓	✓		✓
Flash point	°C	IP303				✓
Water	% (v/v)	IP74	✓	✓	✓	✓
Insolubles	% (m/m)	ASTM D893	✓	✓		✓
TBN	mgKOH/g	IP276				✓
TAN	mgKOH/g	IP177	✓	✓		
SAN	mgKOH/g	IP177	✓	✓		
Particle size	–	ISO 4406	✓			
Ferrography	–	Qualitative	✓	✓	✓	✓
PQ INDEX	–	–		✓		✓
Elements*	mg/kg	ICP	✓	✓	✓	✓

*__Wear elements__ – iron, aluminium, chromium, copper, lead, nickel, tin. **Contaminant elements** – sodium, silicon, aluminium, magnesium. **Fuel elements** – vanadium. **Additive elements** – phosphorus, zinc, calcium, magnesium.

Oil Quality Analysis

Water in Oil

- Dissolved water – amount depends on oil base stock, additives, contaminant load and temperature
- Emulsified – small globules that remain suspended
- Free water – settles to tank/sump bottom

Water in Oil

Where Water Enters System

- Atmospheric – free water from working environment (rain, sprays, coolant) enters through seals, vents, hatches or new oil
- Condensation – with frequent starts and stops (temp increases and decreases) water can dissolve in oil and then condense out
- Coolant leakage

Water in Oil

Water Contamination – Effect on Oil

- Reacts with additives to form precipitates and aggressive chemical by-products
- Acts as catalyst to oxidation
- Micro-organisims can live in water and feed on oil (decompose to form acids) and cause filter clogging

Water in Oil

Water Contamination – Effect on Machine

- Interferes with lubrication by weakening the strength of the oil film
- Rusts iron/steel
- Increases the corrosive effect of acids

Water in Oil

Controlling Water Contamination

- Settling tanks – quiet areas where water can settle out of oil (heating is sometimes applied to encourage separation)
- Centrifugal separators – accelerates settling process
- Vacuum distillation – lower pressure lower water boiling temperature, water is separated from oil without damaging oil with high temps
- Polymeric filters – impregnated with a super absorbent polymer

Water in Oil

On-line Impedance-type Moisture Sensor

Calcium Hydride Test Kit

Sievers 900 Laboratory TOC Analyzer and 900 Autosampler

Water in Oil

On-line Headspace Moisture Sensor

Single-channel Infrared Moisture Sensor

Desiccant Air Breathers

Oil Quality Analysis

Fuel in Oil

- Occurs primarily in crankcase applications
- Fuel dilutes oil during engine operation
- Caused by delayed oil changes, improper operation, and malfunction

Fuel in Oil

Where Fuel Enters System – Piston Blowby

- Blowby is due to incomplete or ineffective combustion
- Excessive idling
- Lugging
- Defective fuel injection spray pattern
- Improper fuel/air ratio

Fuel in Oil

Fuel Contamination – Effect on Oil

- Premature oxidation – fuel oxidizes easily
- Loss of viscosity – thinning
- Additive dilution
- Sulfur build-up – increases risk of corrosion

Fuel in Oil

Fuel Contamination – Effect on Machine

- Increases wear – viscosity loss and additive dilution
- Increased corrosion – sulfuric acid
- Risk of fire and explosion

Fuel in Oil

Controlling Fuel Contamination

- Fuel contamination must be stopped at its source
- Once contaminated the oil must be replaced

Oil Quality Analysis

Soot in Oil

- Natural by-product of combustion
- Poor combustion leads to soot accumulation

Soot in Oil

Where Soot Enters System – Piston Blowby

- Soot in blowby is caused by:
- Low compression – poor combustion
- High fuel/air ratio
- Cold air temperatures
- Lugging
- Excessive idling

Soot in Oil

Soot Contamination – Effect on Oil

- Dispersant additives loose effectiveness
- Anti-wear additives loose effectiveness
- Increased viscosity

Soot in Oil

Soot Contamination – Effect on Machine

- Filter plugging
- Increased abrasive wear
- Deposits of sludge – flow blockage

Soot in Oil

Controlling Soot Contamination

- Fuel combustion and general operation must be well maintained
- Low flow and “slip-stream” filters and centrifuges can help remove soot from oil

Oil Quality Analysis

Glycol in Oil

- Particularly common in crankcase applications, but may contaminate any system that is using a glycol/water mix for cooling

Glycol in Oil

Where Glycol Enters System

- Defective seals
- Cavitation and erosion of components
- Corrosion
- Damaged cooler core

Glycol in Oil

Glycol Contamination – Effect on Oil

- Forms gels and emulsions
- Increases viscosity
- Increases oxidation
- Forms acids
- Forms “oil balls” (glycol droplets collect oil into balls)

Glycol in Oil

Glycol Contamination – Effect on Machine

- Increased wear – reduces lubricating quality of oil due to increased viscosity
- Increased corrosion – glycol creates acids
- Filter failure – glycol clogs filters

Glycol in Oil

Controlling Glycol Contamination

- Glycol cannot be effectively removed from oil
- Contamination must be controlled at the ingestion point

Oil Sampling

Methods (general)

- Drain Port Sampling
- Drain Port Vacuum Sampling
- Drain Line Tap Sampling
- Portable Off-Line Sampling
- Dedicated Off-Line Sampling
- Probe-On Vacuum Sampling
- Drop Tube Vacuum Sampling

Oil Sampling

Methods - Pressurized Line Sampling

- Low Pressure Tap Sampling
- Portable Tap Sampling
- Low Pressure Ball Valve Sampling
- High Pressure Sampling

Oil Sampling

General Tips

- Poor samples lead to poor decisions based on oil analysis
- Oil properties unaffected by sample location include: viscosity, pH (neutralization number), oxidation, sulfation, nitration, additive levels
- Oil properties affected by sample location include: particle count, moisture level, wear particle levels

Oil Sampling

General Guidelines for Drawing Samples

- Sample while operating under normal operating and environmental conditions
- Sample from zones of active circulation
- Sample upstream of filters and downstream of components
- Use sampling hardware that minimizes interference with operations and allows samples to be drawn from the same place each time

Oil Sampling

General Guidelines for Drawing Samples

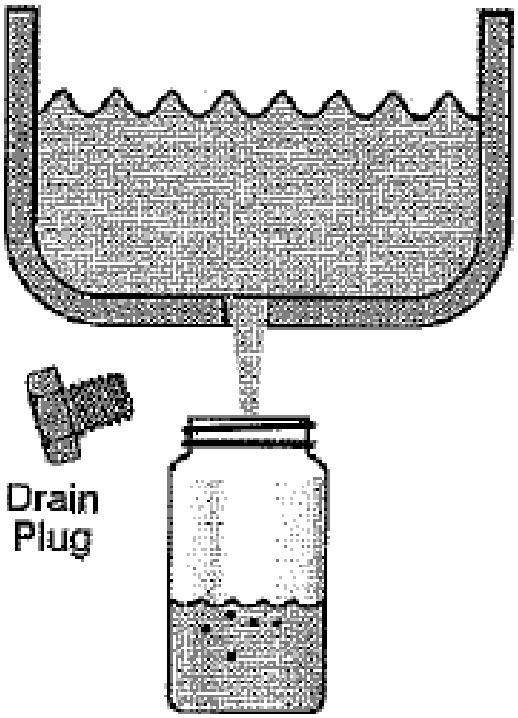
- Flush sample ports thoroughly before collecting sample
- Use clean bottles and tubing
- Sample at the proper frequency
- Record the sampling hours
- Analyze the oil immediately
- Educate staff about the importance of high-quality oil samples
- Train staff on effective sampling procedures

Oil Sampling

General Safety Considerations

- Conform to all safety requirements of the plant
- Check oil temperature prior to sampling (if above 120°F (50°C) use proper protective gloves and clothing)
- Wear protective eyewear
- Wear latex gloves to protect hands
- Wash any skin that comes into contact with oil with a high quality industrial cleaner and plenty of water
- Seek medical attention if oil gets into the eyes or is ingested

Drain Port Sampling



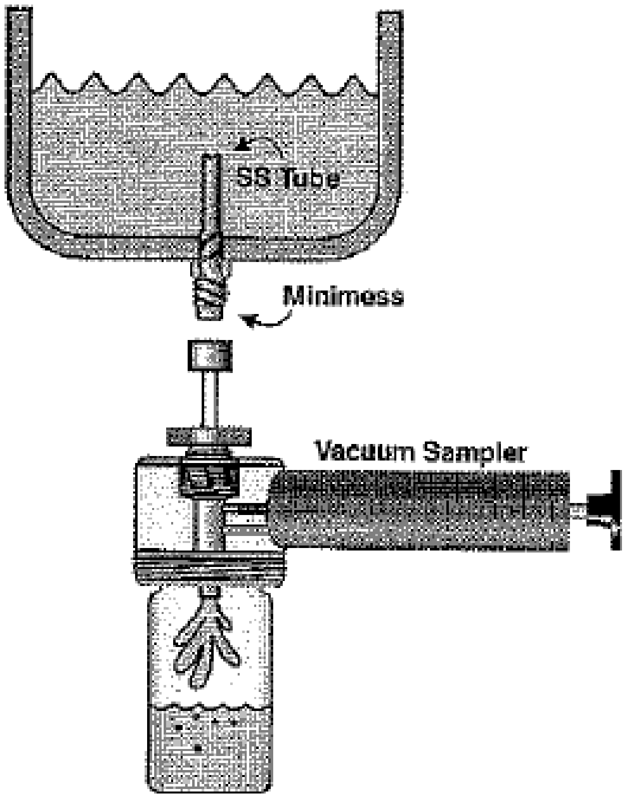
Lub System or Machine Type	Drain Port Sampling
Bath-Lub Plain Bearings	Less Desirable
Ring Lub Plain Bearings	Less Desirable
Inverted Bottle Bath Oiler	Less Desirable
Vented Bottle Bath Oiler	N/A
Splash Lub Gearing	Less Desirable
Circulating System – Dry Sump	Less Desirable
Circulating System – Wet Sump	Less Desirable
Hydraulic System	Less Desirable
Screw Compressor	Less Desirable
Large Circulating System	Less Desirable
Crankcase Lub	Less Desirable

Drain Port Sampling

- As this sample is typically taken from the bottom of the tank, there is a high possibility of obtaining a high particle count due to sedimentation

Drain Port Vacuum Sampling

- Sample is taken from a permanent sampling fixture
- Example – “Minimess”
- Sample can be taken from a strategic location to avoid unrepresentative amounts of water or debris
- No need to remove drain plug vent or fill port

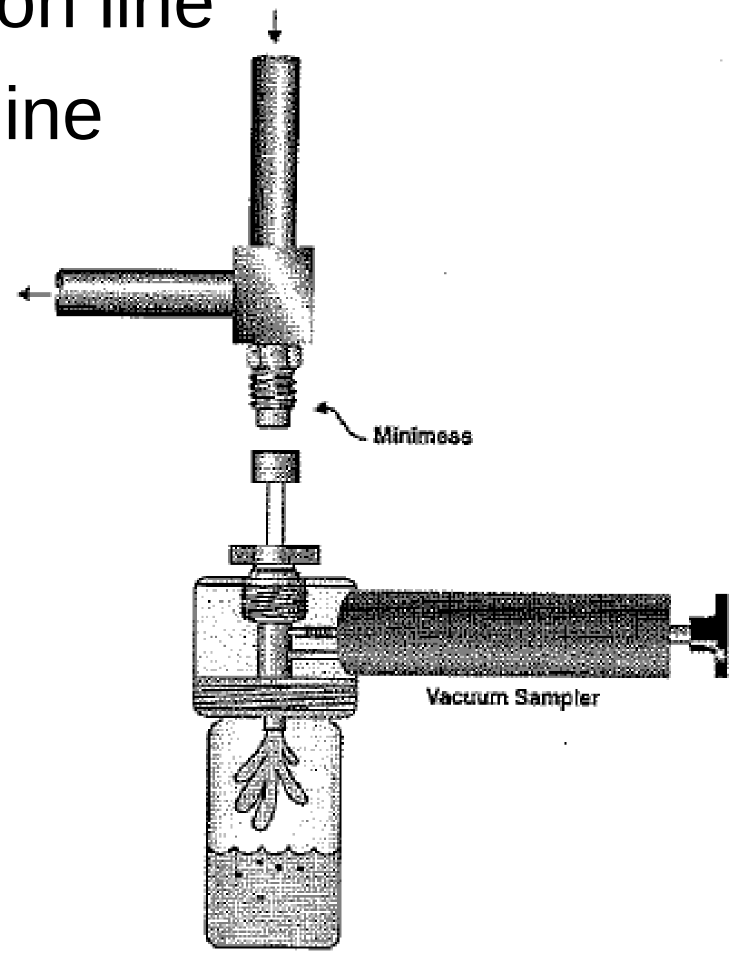


Drain Port Vacuum Sampling

Lubrication System or Machine Type	Drain Port Vacuum Sampling
Bath Lubricated Plain Bearings	Best
Ring Lubricated Plain Bearings	Best
Inverted Bottle Bath Oiler	Best
Vented Bottle Bath Oiler	N/A
Splash Lubricated Gearing	Best
Circulating System – Dry Sump	Less Desirable
Circulating System – Wet Sump	Best
Hydraulic System	Less Desirable
Screw Compressor	Good
Large Circulating System	Less Desirable
Crankcase Lubrication	Good

Drain Line Vacuum Sampling

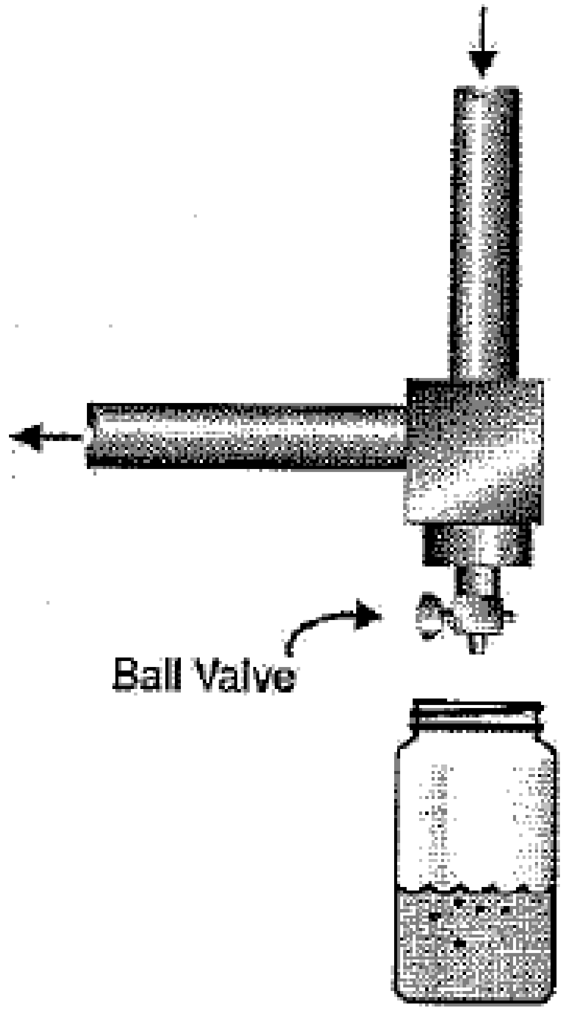
- Sample comes from a common line
- Good representation of machine overall condition



Drain Line Vacuum Sampling

Lubrication System or Machine Type	Drain Line Vacuum Sampling
Bath Lubricated Plain Bearings	N/A
Ring Lubricated Plain Bearings	N/A
Inverted Bottle Bath Oiler	N/A
Vented Bottle Bath Oiler	Best
Splash Lubricated Gearing	N/A
Circulating System – Dry Sump	Best
Circulating System – Wet Sump	N/A
Hydraulic System	Best
Screw Compressor	N/A
Large Circulating System	Best
Crankcase Lubrication	N/A

Drain Line Tap Sampling

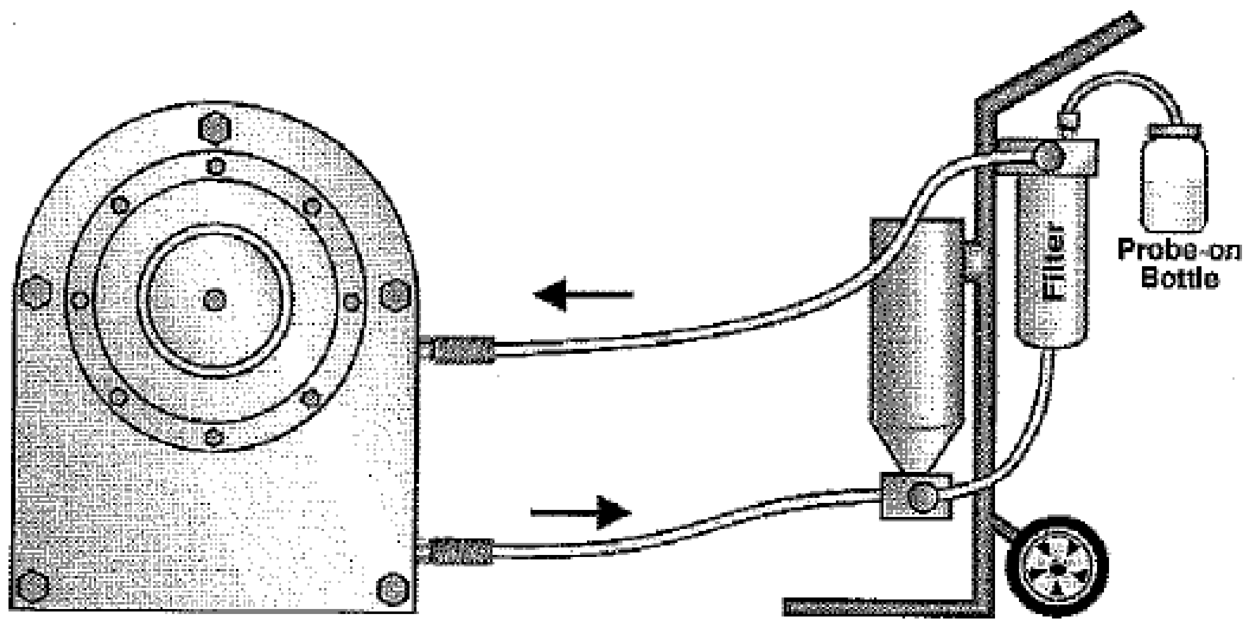


Drain Line Tap Sampling

Lubrication System or Machine Type	Drain Line Tap Sampling
Bath Lubricated Plain Bearings	N/A
Ring Lubricated Plain Bearings	N/A
Inverted Bottle Bath Oiler	N/A
Vented Bottle Bath Oiler	Best
Splash Lubricated Gearing	N/A
Circulating System – Dry Sump	Best
Circulating System – Wet Sump	N/A
Hydraulic System	Best
Screw Compressor	N/A
Large Circulating System	Best
Crankcase Lubrication	N/A

Portable Off-Line Sampling

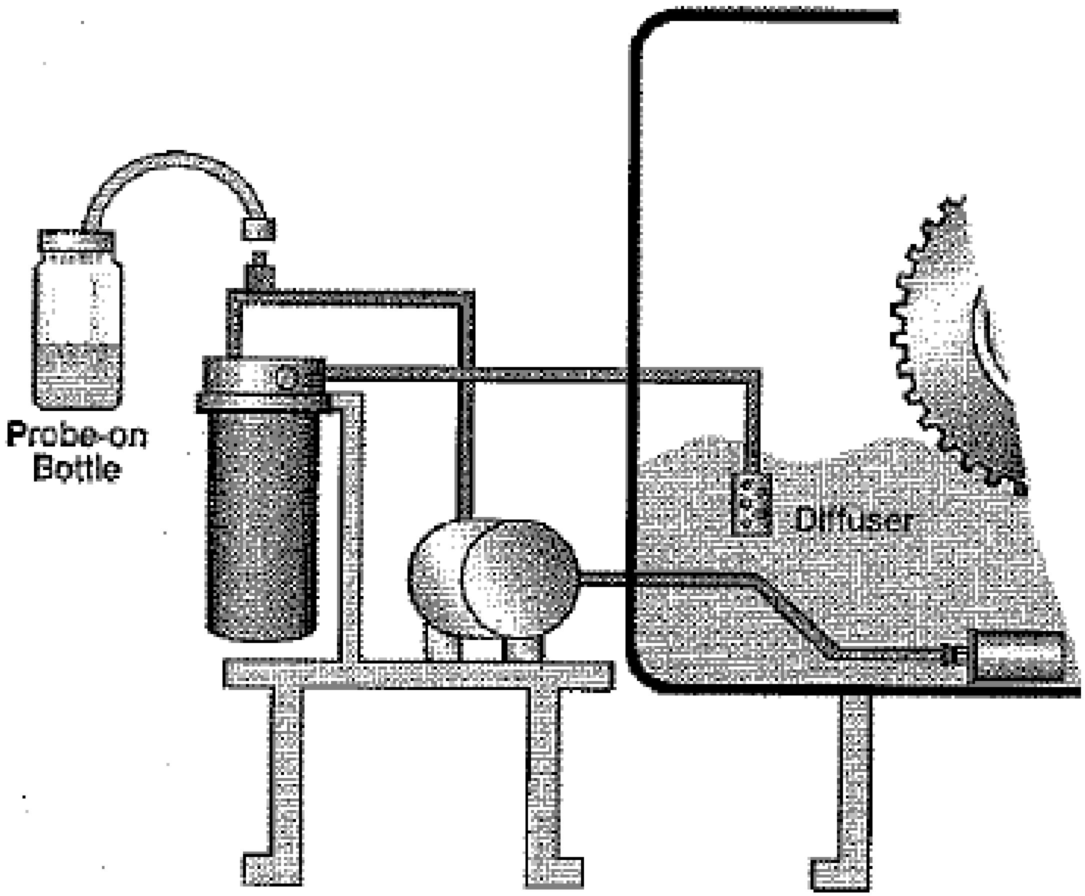
- Good for machines without return line sampling (gearboxes, engines, wet-sump lub systems)
- After sample is taken the oil remaining in the machine can be filtered or conditioned by portable apparatus



Portable Off-Line Sampling

Lubrication System or Machine Type	Portable Off-Line Sampling
Bath Lubricated Plain Bearings	N/A
Ring Lubricated Plain Bearings	N/A
Inverted Bottle Bath Oiler	N/A
Vented Bottle Bath Oiler	N/A
Splash Lubricated Gearing	Good
Circulating System – Dry Sump	Less Desirable
Circulating System – Wet Sump	Good
Hydraulic System	Less Desirable
Screw Compressor	N/A
Large Circulating System	Less Desirable
Crankcase Lubrication	N/A

Dedicated Off-Line Sampling

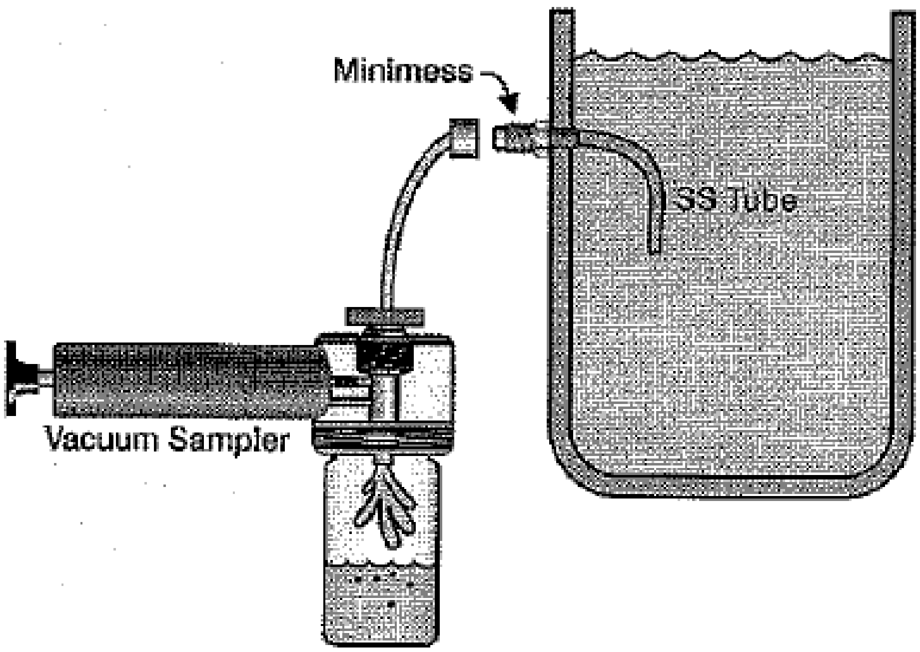


Dedicated Off-Line Sampling

Lubrication System or Machine Type	Dedicated Off-Line Sampling
Bath Lubricated Plain Bearings	N/A
Ring Lubricated Plain Bearings	N/A
Inverted Bottle Bath Oiler	N/A
Vented Bottle Bath Oiler	N/A
Splash Lubricated Gearing	Best
Circulating System – Dry Sump	Less Desirable
Circulating System – Wet Sump	Best
Hydraulic System	Less Desirable
Screw Compressor	N/A
Large Circulating System	Less Desirable
Crankcase Lubrication	N/A

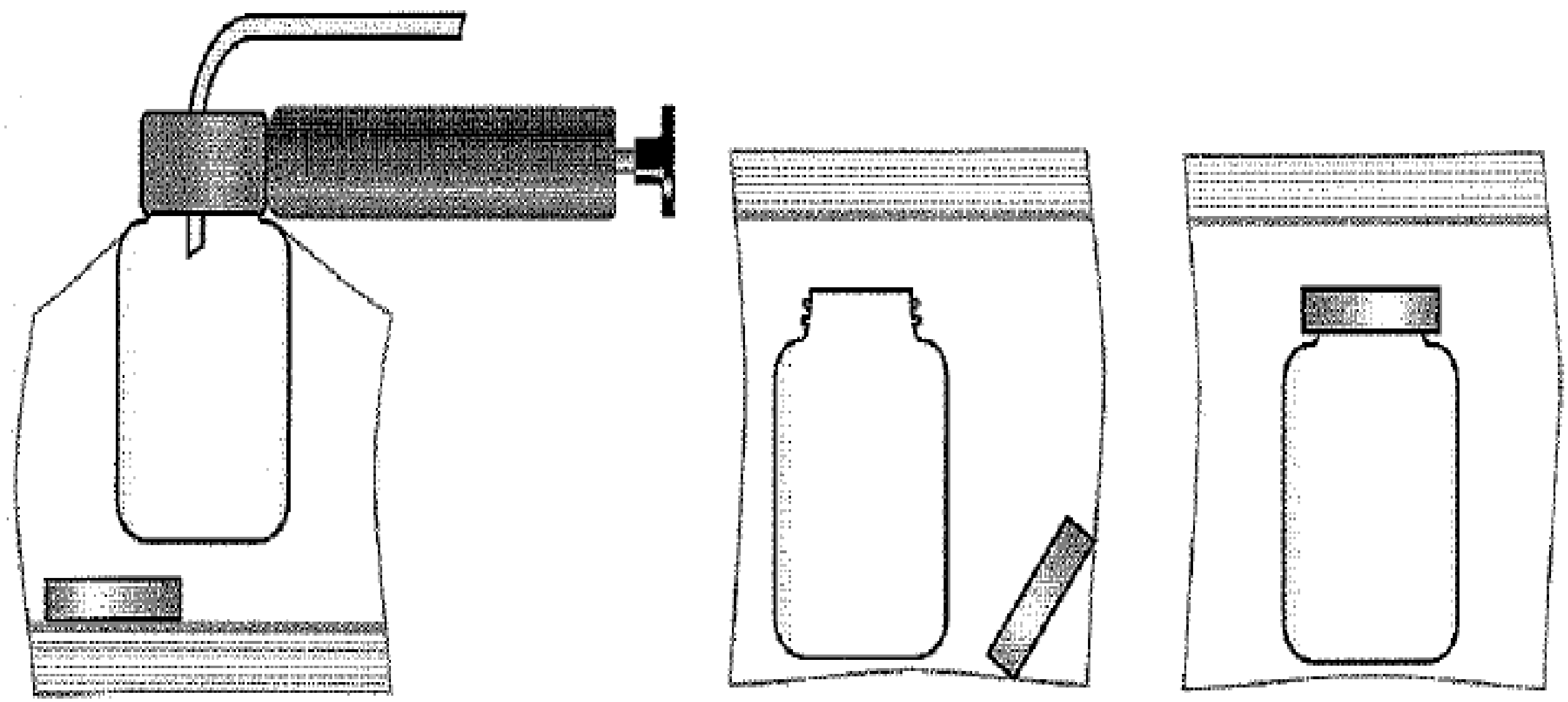
Probe-On Vacuum Sampling

- Requires permanent sampling port
- Good for sampling tanks, sumps and static containers
- Sample taken from strategic location
- No need to remove/re plug or vent



Probe-On Vacuum Sampling

- Requires sampling with sample bottle inside a plastic bag to reduce risk of contamination

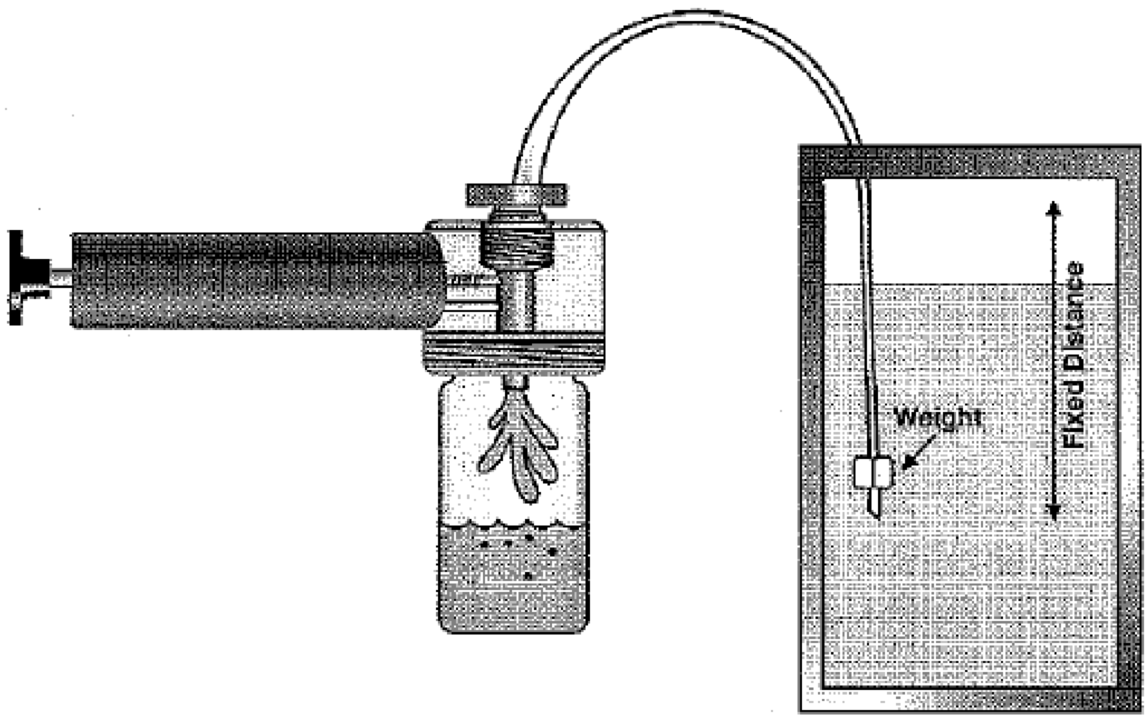


Probe-On Vacuum Sampling

Lubrication System or Machine Type	Probe-On Vacuum Sampling
Bath Lubricated Plain Bearings	Best
Ring Lubricated Plain Bearings	Best
Inverted Bottle Bath Oiler	Best
Vented Bottle Bath Oiler	N/A
Splash Lubricated Gearing	Best
Circulating System – Dry Sump	Less Desirable
Circulating System – Wet Sump	Best
Hydraulic System	Less Desirable
Screw Compressor	Good
Large Circulating System	Less Desirable
Crankcase Lubrication	Good

Drop-Tube Vacuum Sampling

- Common method for sampling tanks and sumps
- Access to tank from fill port
- No permanently installed hardware needed



Drop-Tube Vacuum Sampling

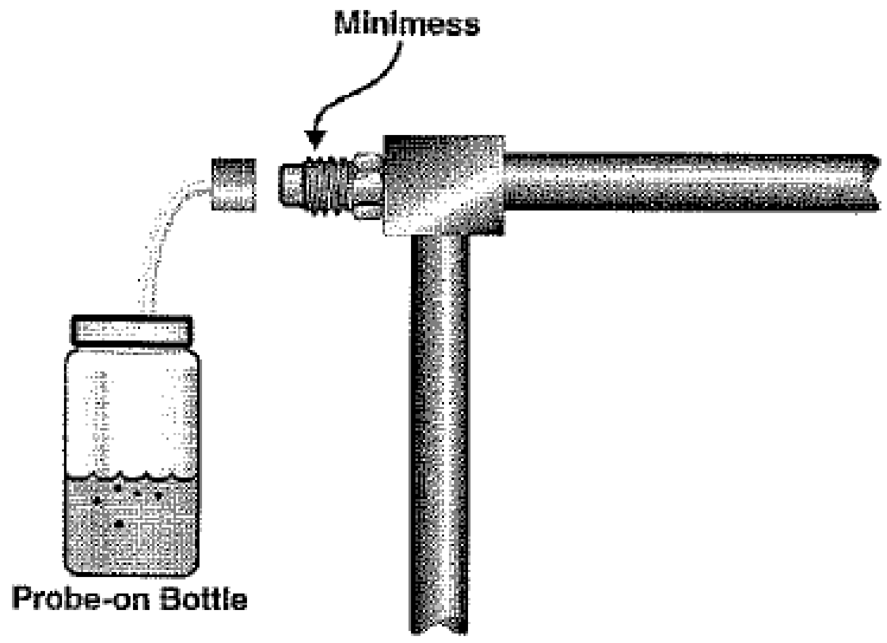
Lubrication System or Machine Type	Drop-Tube Vacuum Sampling
Bath Lubricated Plain Bearings	Avoid
Ring Lubricated Plain Bearings	Avoid
Inverted Bottle Bath Oiler	Avoid
Vented Bottle Bath Oiler	Less Desirable
Splash Lubricated Gearing	Avoid
Circulating System – Dry Sump	Less Desirable
Circulating System – Wet Sump	Less Desirable
Hydraulic System	Less Desirable
Screw Compressor	N/A
Large Circulating System	Less Desirable
Crankcase Lubrication	Less Desirable

Pressurized Line Sampling – Low Pressure Tap Sampling

- Can be used to detect contamination from breather vents and new oil addition
- Good for detecting wear generated by the oil pump
- For systems without pressure-side, in-line filters, this method can help assess the cleanliness of the oil being fed to the machine components
- Provides background for comparing return line samples

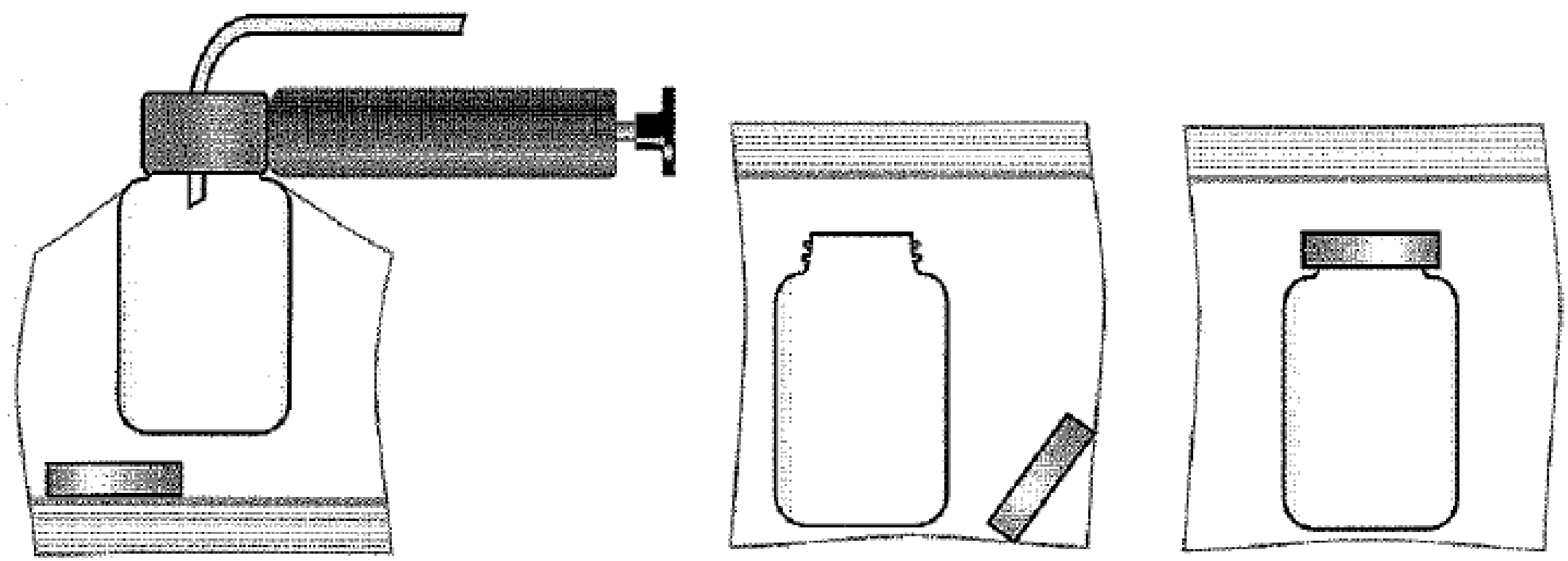
Pressurized Line Sampling – Low Pressure Tap Sampling

- For systems with in-line filters this provides a background for comparing filter performance
- Good for wet-sump circulating systems that do not allow drain line sampling



Pressurized Line Sampling – Low Pressure Tap Sampling

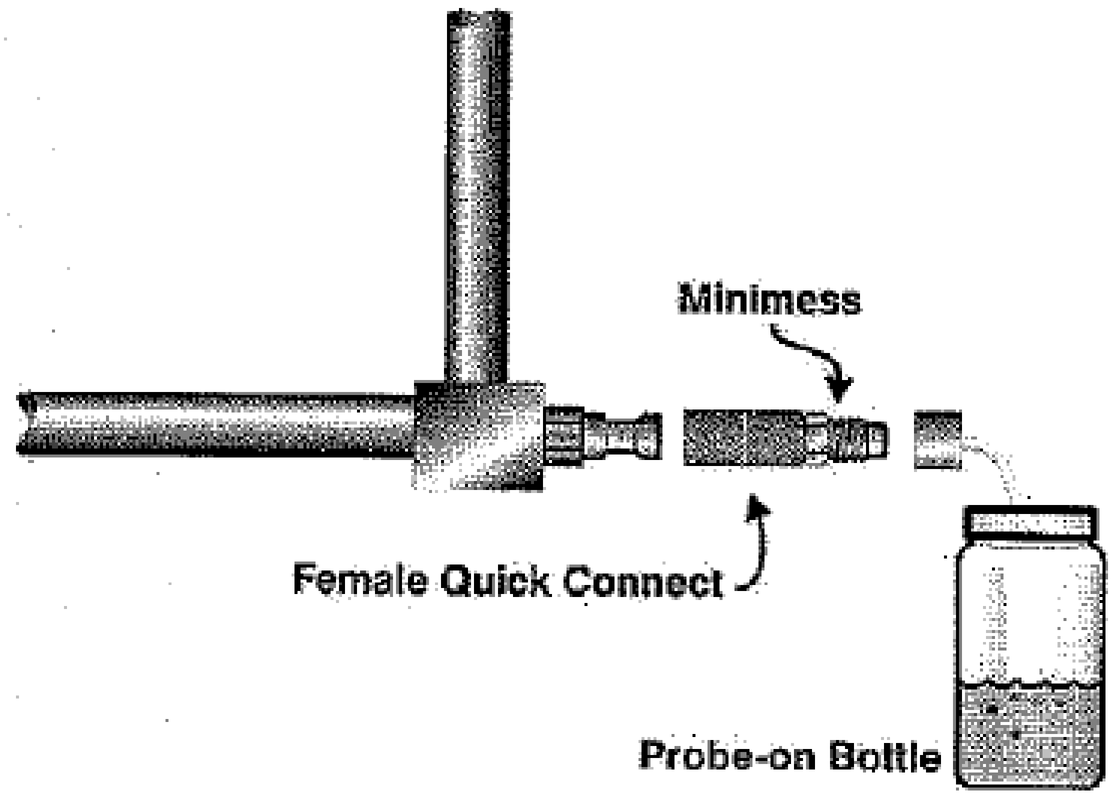
- Requires sampling with sample bottle inside a plastic bag to reduce risk of contamination



Pressurized Line Sampling – Low Pressure Tap Sampling

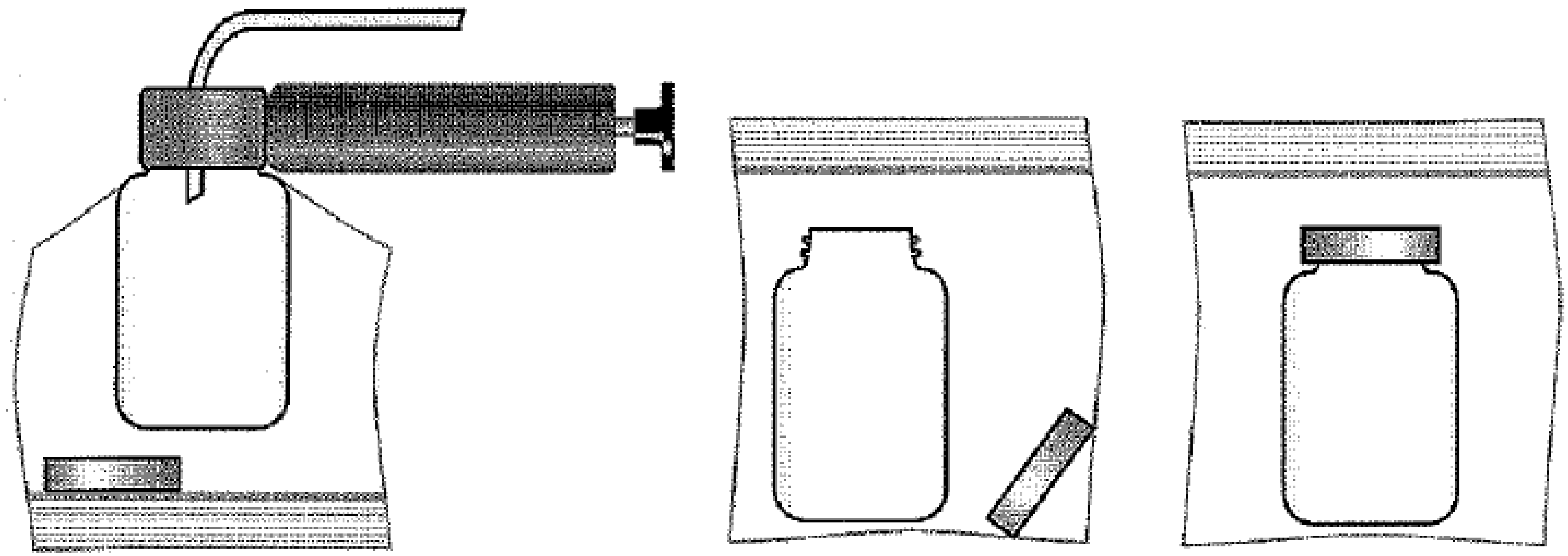
Lubrication System or Machine Type	Pressurized Line Sampling
Bath Lubricated Plain Bearings	N/A
Ring Lubricated Plain Bearings	N/A
Inverted Bottle Bath Oiler	N/A
Vented Bottle Bath Oiler	N/A
Splash Lubricated Gearing	Best
Circulating System – Dry Sump	Less Desirable
Circulating System – Wet Sump	N/A
Hydraulic System	Less Desirable
Screw Compressor	Avoid
Large Circulating System	Less Desirable
Crankcase Lubrication	Avoid

Pressurized Line Sampling – Portable Tap Sampling



Pressurized Line Sampling – Portable Tap Sampling

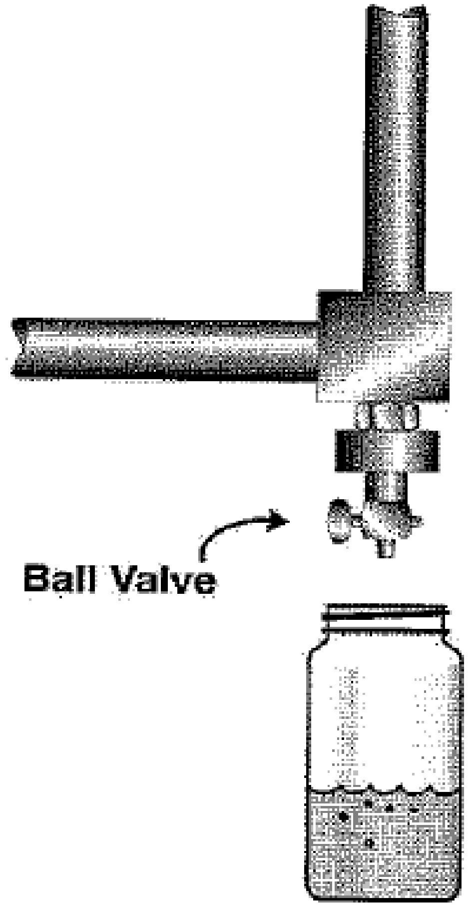
- Requires sampling with sample bottle inside a plastic bag to reduce risk of contamination



Pressurized Line Sampling – Portable Tap Sampling

Lubrication System or Machine Type	Pressurized Line Sampling
Bath Lubricated Plain Bearings	N/A
Ring Lubricated Plain Bearings	N/A
Inverted Bottle Bath Oiler	N/A
Vented Bottle Bath Oiler	N/A
Splash Lubricated Gearing	N/A
Circulating System – Dry Sump	Less Desirable
Circulating System – Wet Sump	Best
Hydraulic System	Best
Screw Compressor	Best
Large Circulating System	Best
Crankcase Lubrication	Best

Pressurized Line Sampling – Low Pressure Ball Valve Sampling

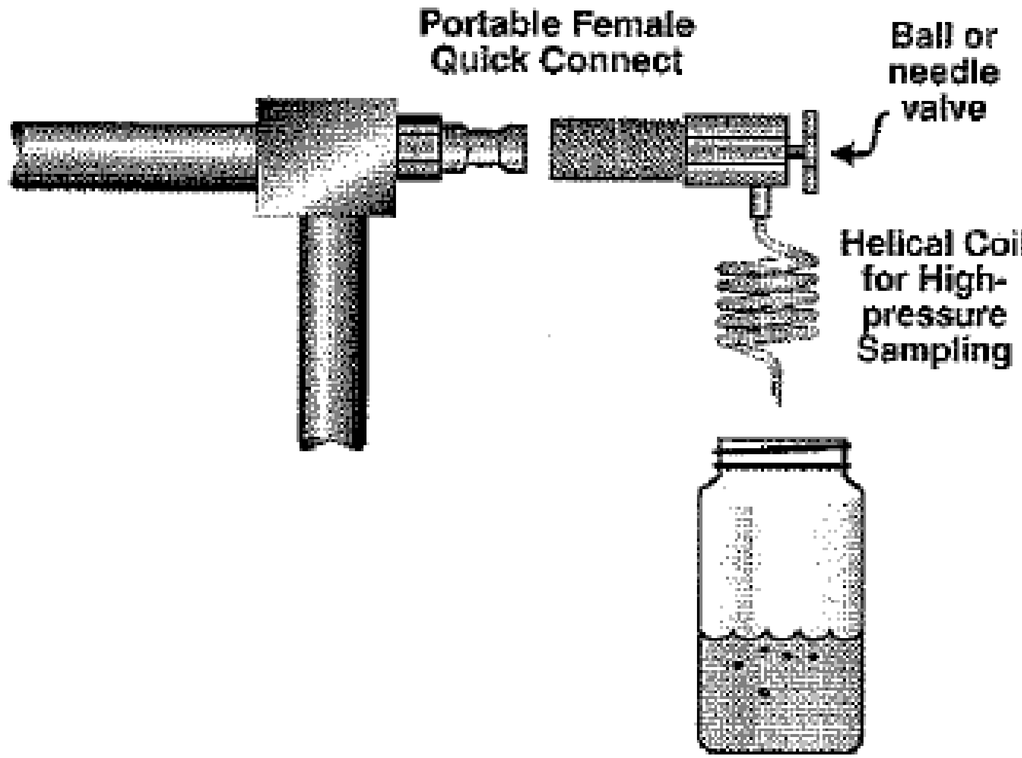


Pressurized Line Sampling – Low Pressure Ball Valve Sampling

Lubrication System or Machine Type	Pressurized Line Sampling
Bath Lubricated Plain Bearings	N/A
Ring Lubricated Plain Bearings	N/A
Inverted Bottle Bath Oiler	N/A
Vented Bottle Bath Oiler	N/A
Splash Lubricated Gearing	N/A
Circulating System – Dry Sump	Less Desirable
Circulating System – Wet Sump	Best
Hydraulic System	Best
Screw Compressor	Best
Large Circulating System	Best
Crankcase Lubrication	Best

Pressurized Line Sampling – High Pressure Sampling

Confirm that the helical coil's length relative to its internal diameter is sufficient to reduce the pressure to below 300 PSI for the system's operating pressure and the fluid viscosity at the operating temperature



Pressurized Line Sampling – High Pressure Sampling

Lubrication System or Machine Type	Pressurized Line Sampling
Bath Lubricated Plain Bearings	N/A
Ring Lubricated Plain Bearings	N/A
Inverted Bottle Bath Oiler	N/A
Vented Bottle Bath Oiler	N/A
Splash Lubricated Gearing	N/A
Circulating System – Dry Sump	Less Desirable
Circulating System – Wet Sump	Best
Hydraulic System	Best
Screw Compressor	Best
Large Circulating System	Less Desirable
Crankcase Lubrication	Best

Sources of Error in Data

- Samples taken under cold (machine not running) conditions
- Drain port sampling
- Variable sampling methods and locations
- Contaminated sampling hardware
- Insufficient dead space flushing
- Sampling just after an oil change
- Cross contamination between two oil samples
- Delays in sending samples to the testing lab

Recommended Oil Sampling Frequencies

Machine Type	Hours
Diesel Engines – off highway	150
Transmissions, differentials, final drives	300
Hydraulics – mobile equipment	200
Gas turbines – industrial	500
Steam turbines	500
Air/gas compressors	500
Chillers	500
Gear boxes – high speed/duty	300
Gear boxes – low speed/duty	1000
Bearings – journal and rolling element	500
Aviation reciprocating engines	25-50
Aviation gas turbines	100
Aviation gear boxes	100-200
Aviation hydraulics	100-200

Information to be Supplied with Oil Sample

- Machine I.D.
- Sample point
- Date sampled
- Running conditions
- Hour meter reading (machine usage)
- Last oil change
- Last addition of oil (and amount)
- Last major service, repair or overhaul
- Last filter change
- Operator reported machine/oil abnormalities
- Requested test on oil sample