DETONATION & PRE-IGNITION IN SPARK-IGNITED GAS ENGINES

CAUSE, EFFECT & PREVENTION

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DESIGN COMPANY INC.

PRESENTATION OUTLINE

- **Engine Basics**
  - Normal Combustion
  - LLP = "Location of Peak Pressure"
- **Detonation (or knocking)**
  - Definition of Detonation
  - Causes and Effects of Detonation
- **Pre-Ignition**
  - Definition of Pre-Ignition
  - Causes and Effects of Pre-Ignition
- **Prevention**
  - Mechanical and Control Strategies

Detonation

&

Pre-Ignition

NORMAL COMBUSTION IN SPARK-IGNITED GAS ENGINES

- Burning of a fuel and air mixture charge in the combustion chamber.
- The mixture should burn in a steady, controlled fashion across the chamber, originating at the spark plug and progressing in a three dimensional fashion.
- Comparative to a pebble dropped into a glass smooth pond with the ripples spreading out, the flame front should progress in an orderly fashion.

NORMAL COMBUSTION IN SPARK-IGNITED GAS ENGINES

- The flame-front moves all away across the chamber and quenches (cools) against the liner walls, cylinder head, and piston crown.

- The burn should be complete with no remaining fuel-air mixture.

- The mixture does **not explode;** but burns in an orderly fashion.

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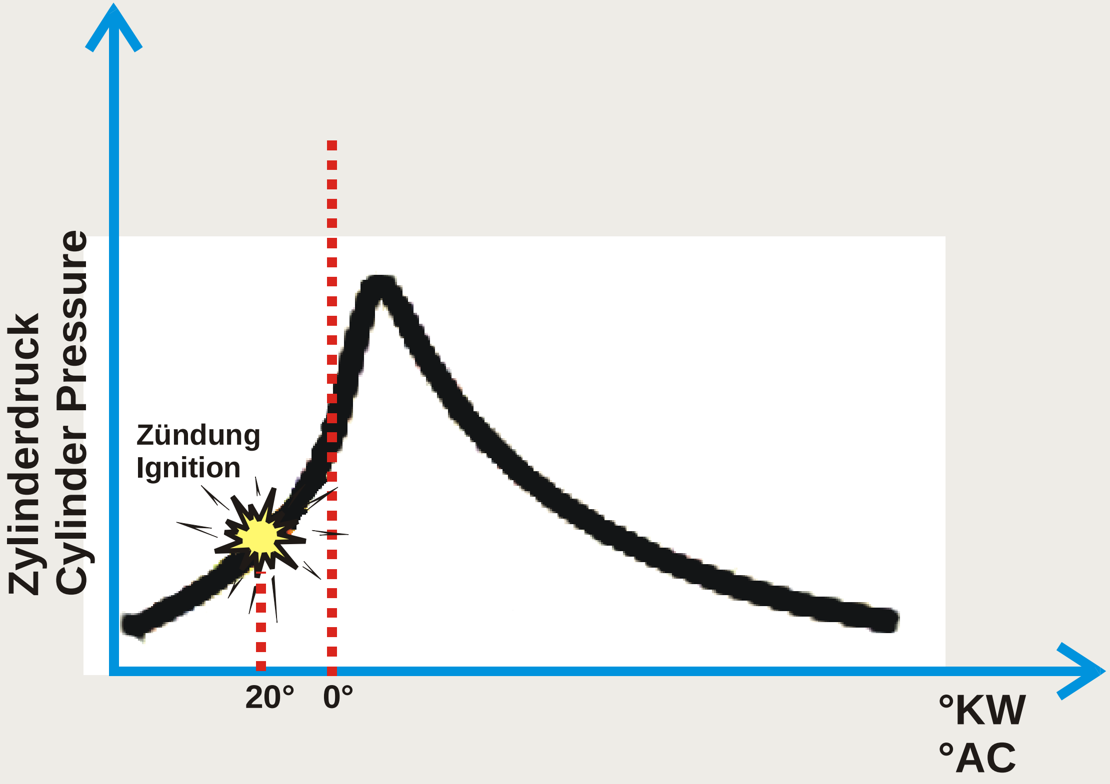
NORMAL COMBUSTION

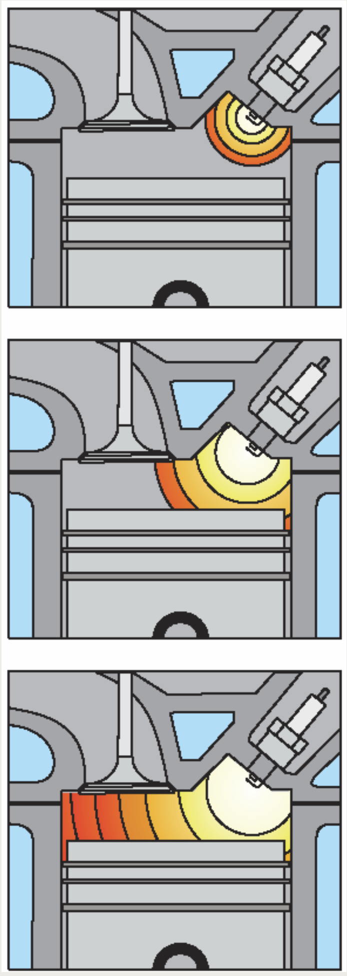
- **LPP = Location of Peak Pressure**
- The combustion is initiated by the spark plug 15-40 crankshaft degrees BTDC; the point of maximum compression.
- This ignition advance time allows time for the combustion process to develop peak pressure at the ideal time for maximum recovery of work from the expanding gases.
- This point is typically 14-18 crankshaft degrees ATDC.

NORMAL COMBUSTION

Ignition pressure : 725 – 1380 psi

Combustion temperatures: 2200 - 2700°F





DETONATION & PRE-IGNITION

- Both Detonation and Pre-Ignition are **abnormal** types of combustion.
- Detonation & Pre-Ignition are somewhat related; but are **two distinctly different phenomenon and induce distinctly different failure modes.**
- Both conditions are not optimum for any engine; they both have the capacity to cause extensive engine damage, lost production, and capital expense.

DEFINITIONS

Detonation: The spontaneous, uncontrolled combustion of the end gas in the chamber, **after** the initial combustion is ignited by the spark plug.

Pre-Ignition: The spontaneous, uncontrolled ignition of the fuel-air mixture, **before** the initial combustion is ignited by the spark plug.

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DETONATION

- Detonation occurs when the air/fuel mixture in the cylinder has been ignited by the spark plug; and the smooth burning flame-front is interrupted by the unburned mixture in the combustion chamber auto-igniting or exploding before the flame front can reach it.

- The resulting shock wave reverberates in the combustion chamber, creating a characteristic metallic “pinging” or “knocking” sound.

- The shock wave is a direct result of the rapid pressure rise.

- Pressures and temperatures increase catastrophically.

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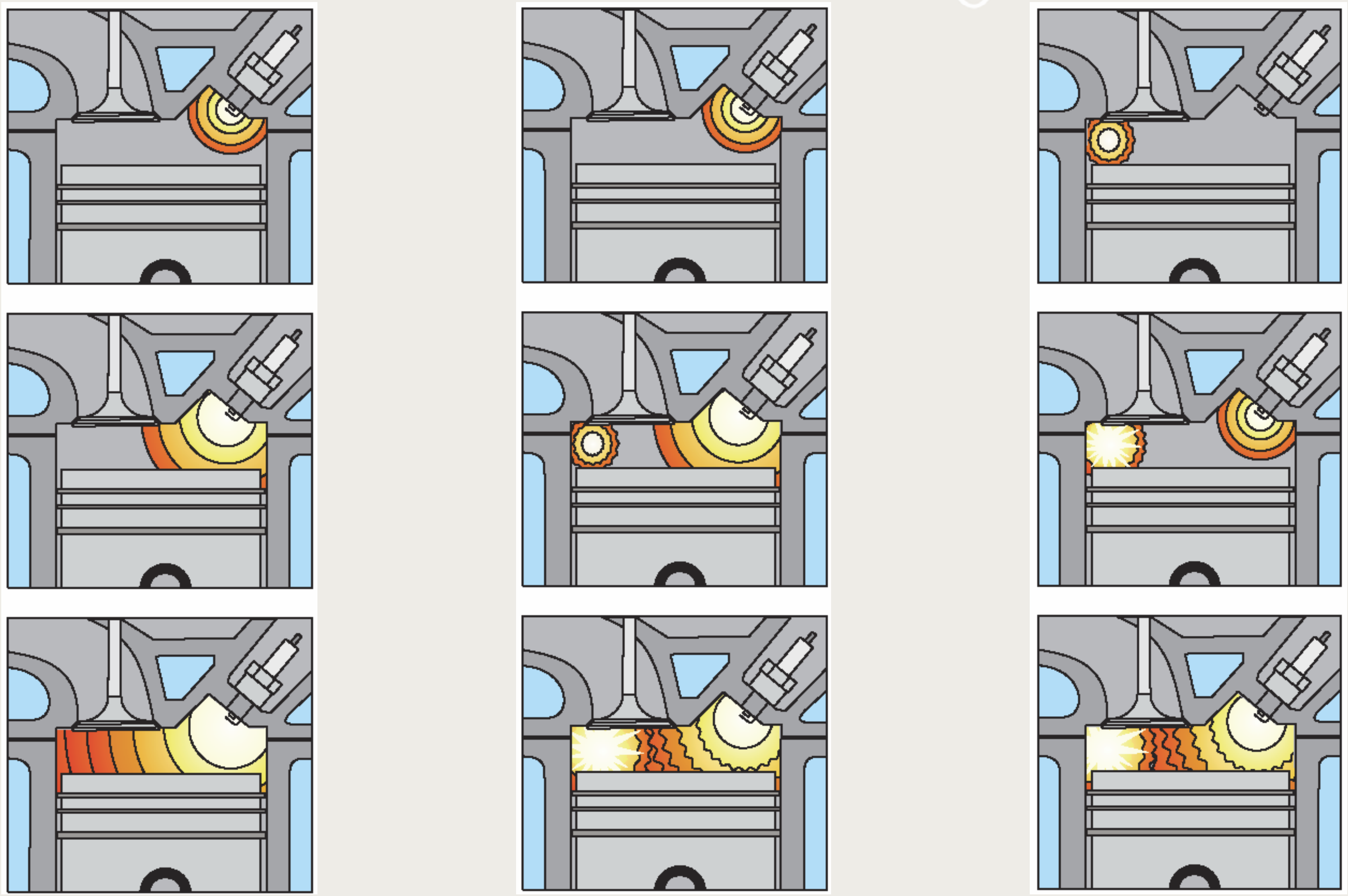
NORMAL COMBUSTION

KNOCKING

PRE-IGNITION



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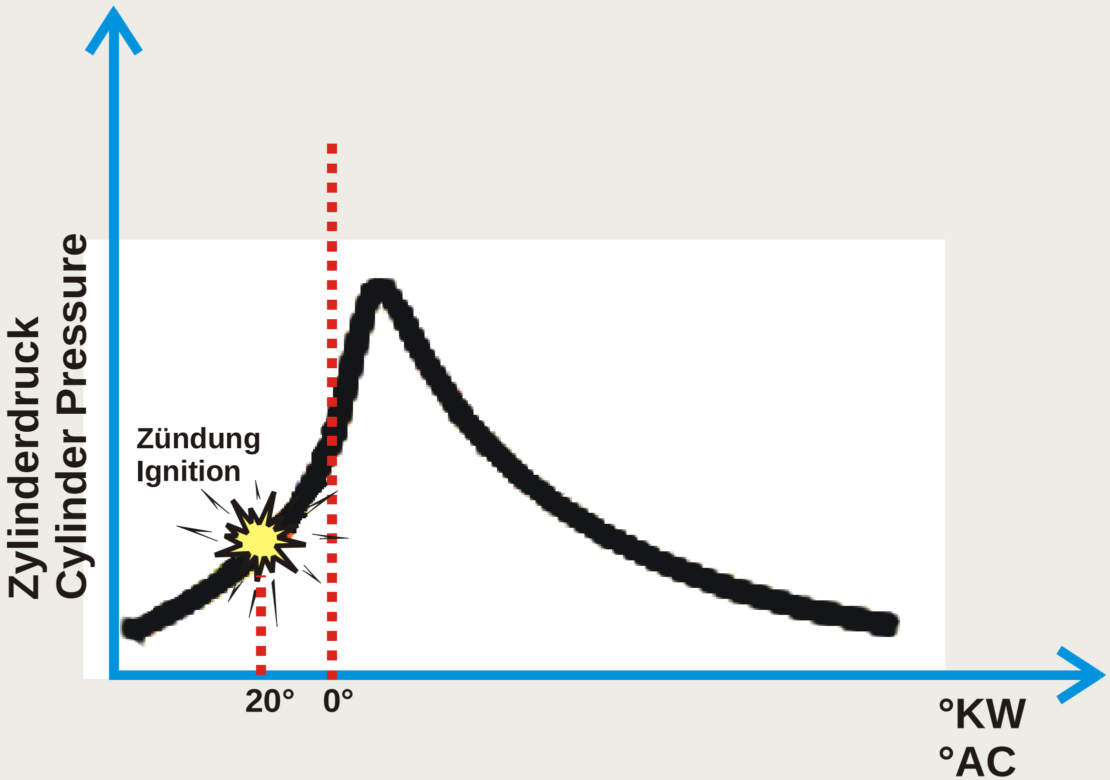

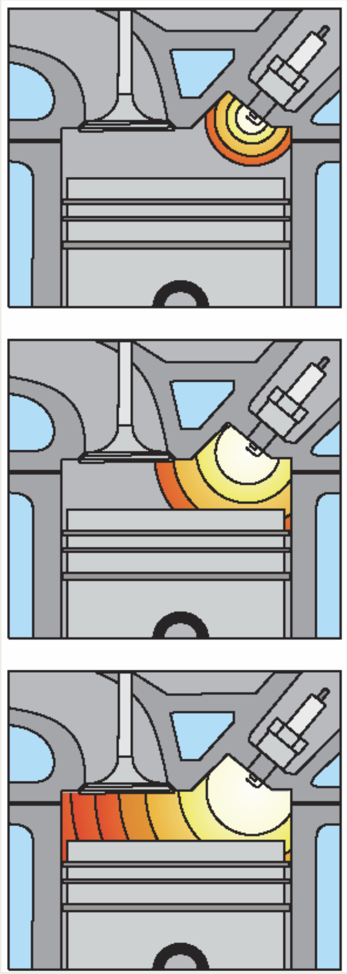

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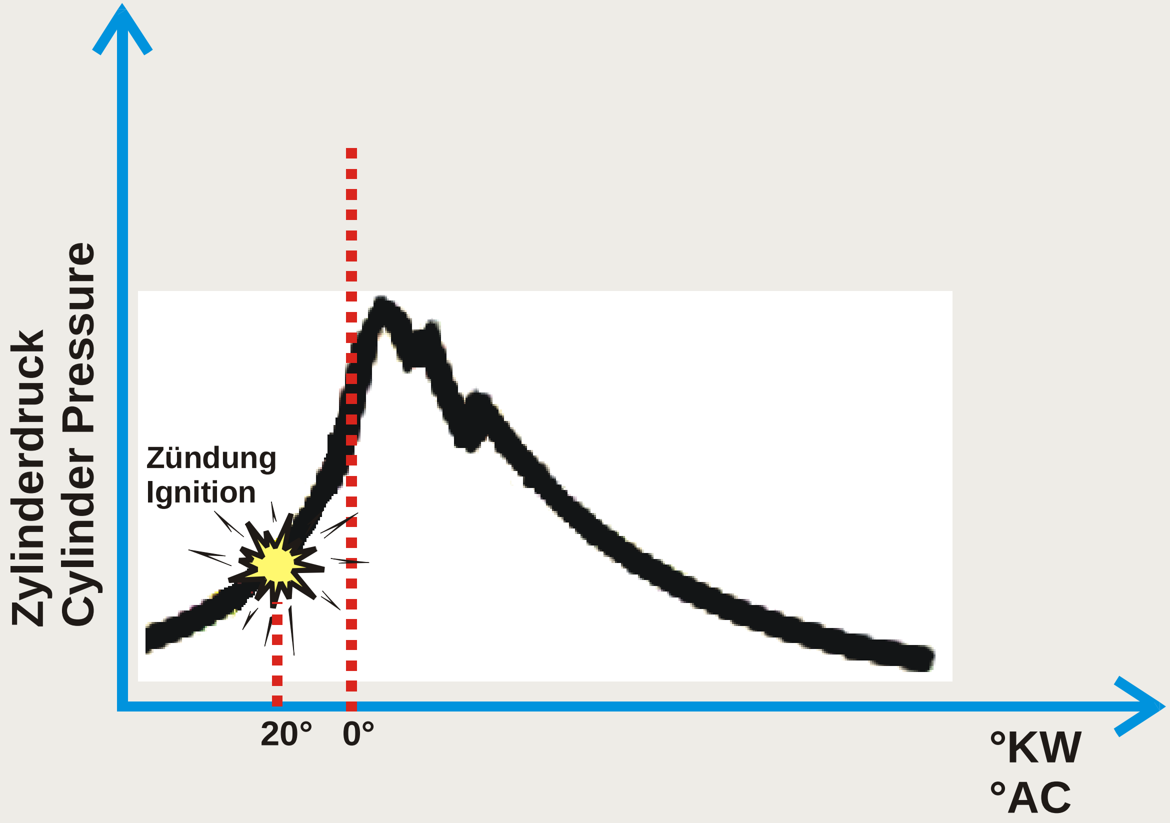
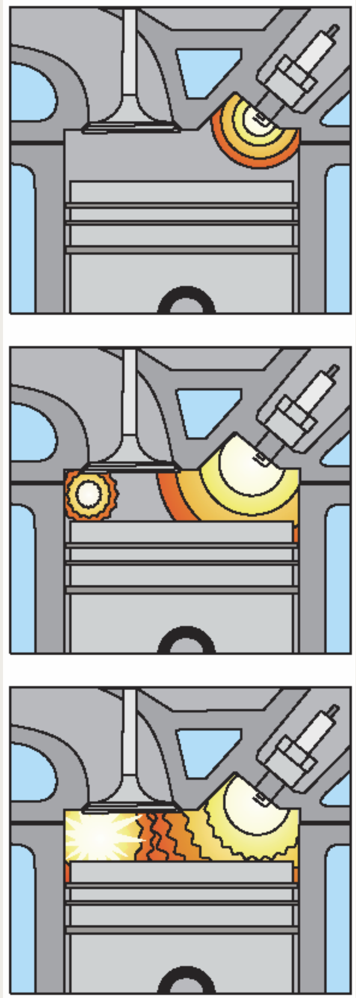
SOFT DETONATION

Ignition pressure: 1740-2320 psi

Combustion temperature: 2730 - 3450 °F





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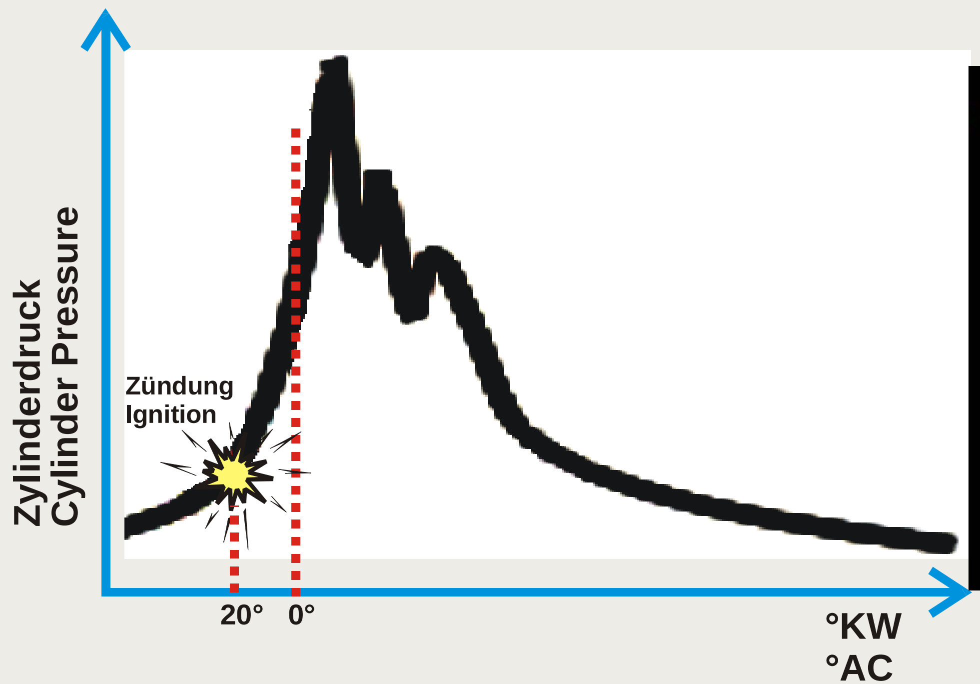
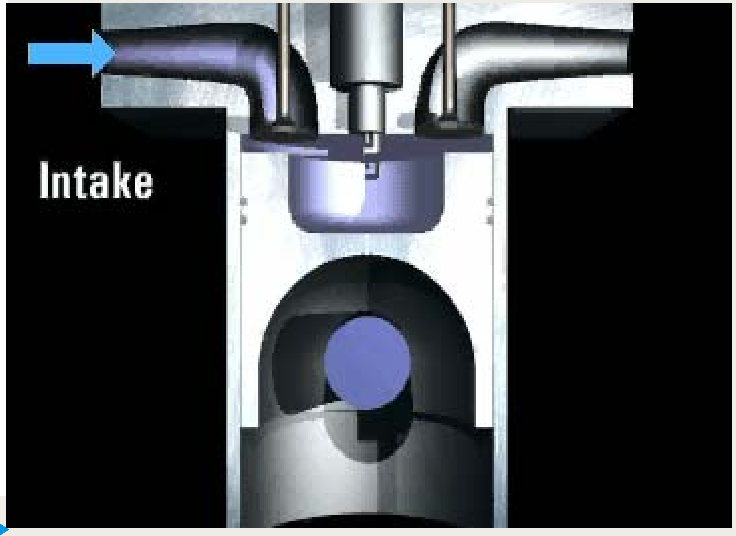
HARD DETONATION

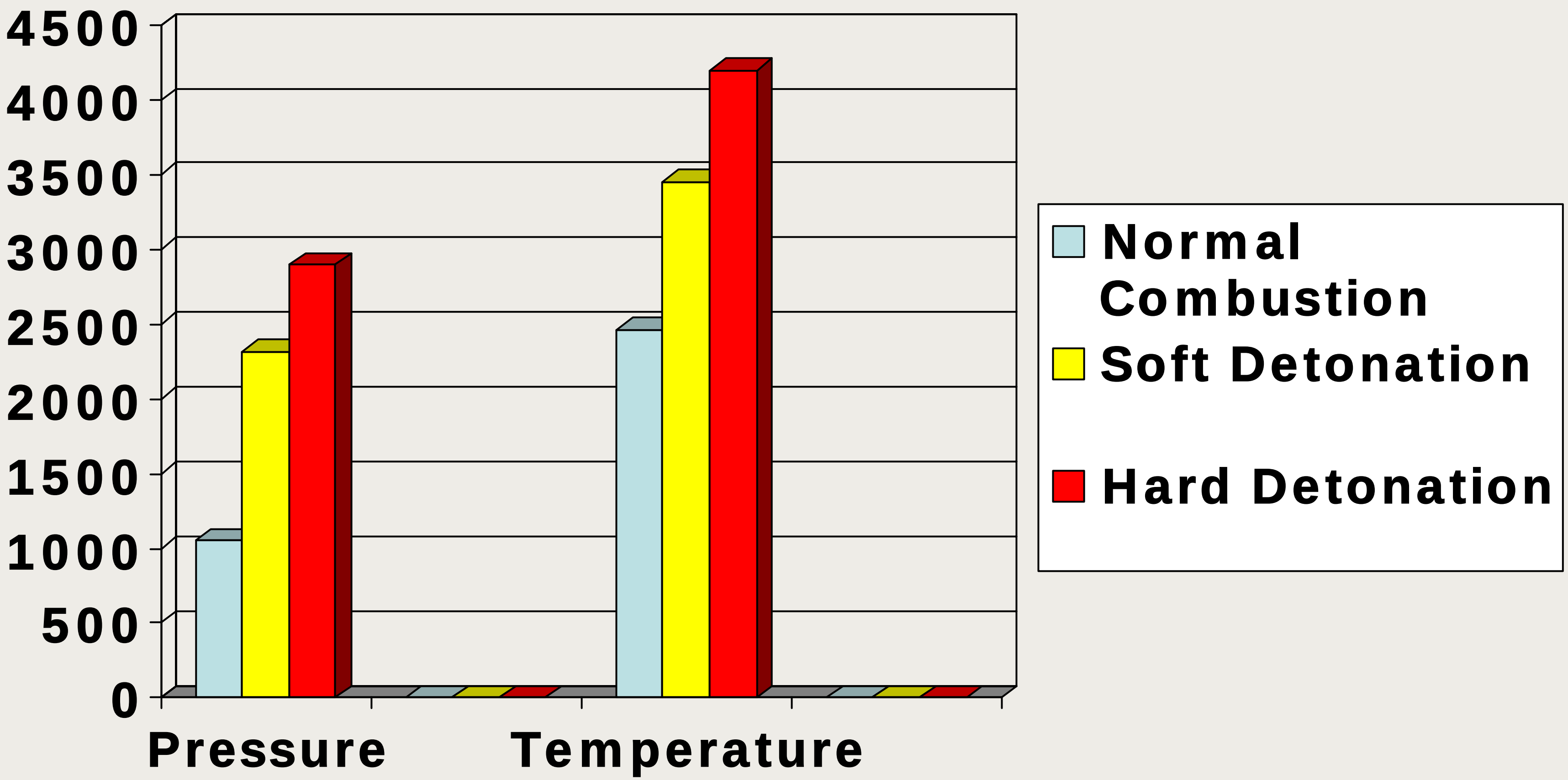
Ignition pressure: 1750 – 2900 psi

Combustion temperatures: 3450-4200 °F





EFFECTS OF DETONATION ON CYLINDER PRESSURE & TEMPERATURES



No OEM Combustion Chamber is designed to handle the types of pressures and temperatures that are caused by detonation.

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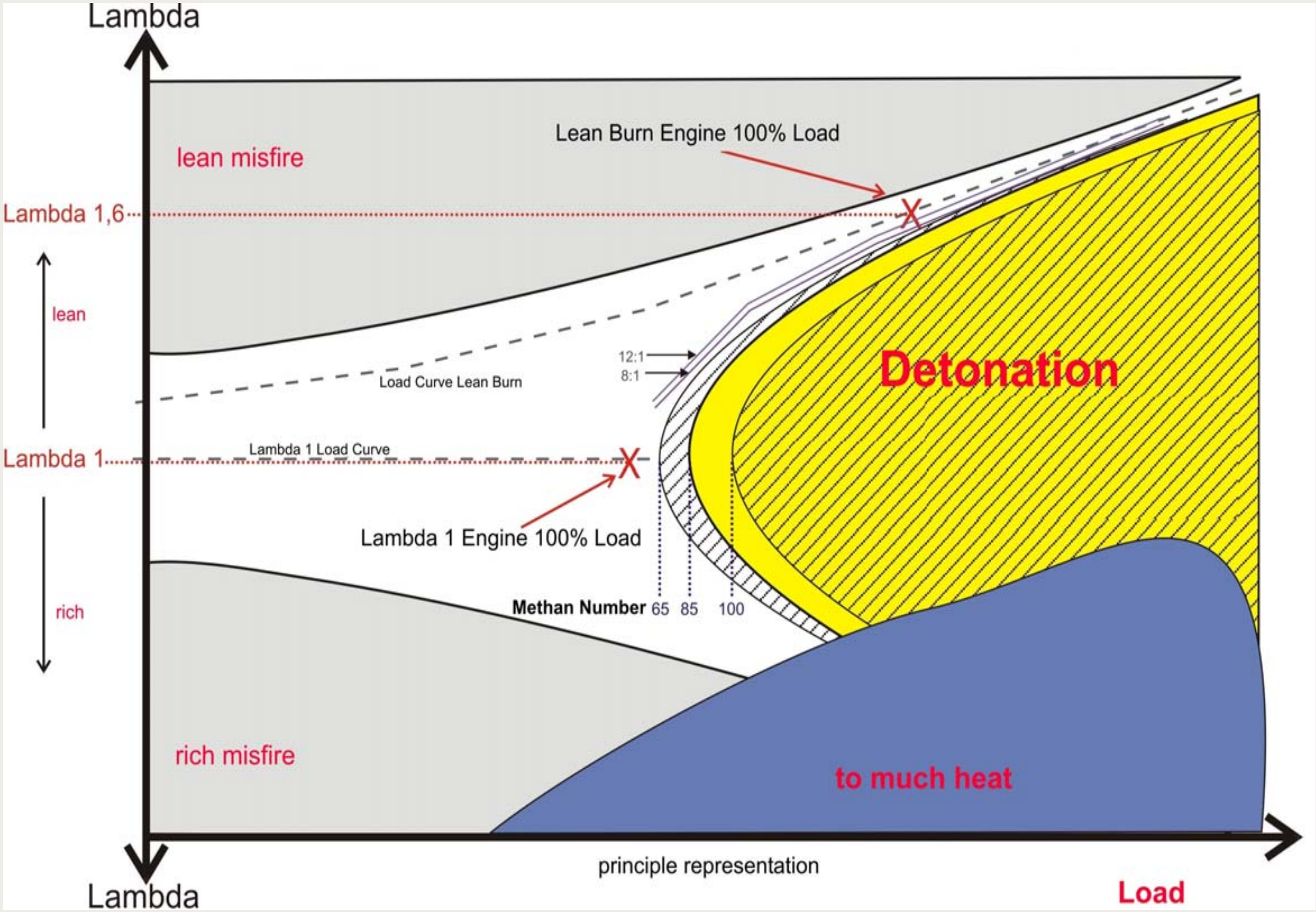
NEGATIVE MECHANICAL EFFECTS OF DETONATION

- **Mechanical Damage**
  - Broken Ring Lands
  - Broken Spark Plug Electrodes
  - Cracked Spark Plug Insulators
  - Fractured Exhaust and/or Intake Valves

- **Abrasion**
  - Pitting of the piston crown.
  - Mechanically erodes or fatigues material out of the piston crown.
- **Overheating**
  - Scuffed piston skirts due to excess heat or high coolant temperatures.

HOUSTON, WE HAVE A PROBLEM

GRAPHICAL REPRESENTATION OF DETONATION & MISFIRE



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GENERAL CAUSES OF DETONATION

- All high output industrial engines are prone to destructive tendencies as a result of:

  - Fuel Composition
  - Incorrect Engine Tuning
  - Over Boost
  - Inadequate Cooling

FUEL COMPOSITION VS. DETONATION

Gas	Formula	Boiling Point (F°)	Autoignition Temperature (F°)
Methane	CH_4	-258.7	1,220
Ethane	C_2H_6	-127.5	968
Propane	C_3H_8	-43.7	914
Butane	C_4H_{10}	31.1	600 (est)
Pentane	C_5H_{12}	96.9	500 (est)
Hexane	C_6H_{14}	155.7	478
Heptane	C_7H_{16}	209.2	433
Octane	C_8H_{18}	258.2	428

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THE PROBLEM

Natural Gas Analysis -Percent by Volume				
	Example A (Field Gas)	Example B (Field Gas)	Example C (Field Gas)	Example D (Dry, Pipeline)
Methane, CH_4	75.23	76.00	89.78	92.20
Ethane C_2H_6	12.56	6.40	4.61	5.50
Propane C_3H_8	7.11	3.50	2.04	0.30
Butane C_4H_{10}	3.38	0.67	0.89	—
Pentane C_5H_{12}	0.69	0.30	0.26	—
Hexane C_6H_{14}	0.40	—	0.21	—
Heptane C_7H_{16}	—	—	—	—
Nitrogen N_2	0.43	12.33	2.13	1.60
Carbon Dioxide CO_2	0.20	0.40	—	0.40
Others	—	0.40	0.08	—
	100.00	100.00	100.00	100.00
HHV (High heat value) Btu/SCF	1,333.00	1,010.00	1,096.00	1,041.00
LHV (Low heat value) Btu/SCF	1,202.00	909.00	986.00	937.00
Methane Number	42.20	66.70	69.00	82.80

Knocking Resistance

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IGNITION TIMING – SHIFTING

Fuel Usage Guide

Derate Factor / Engine Timing vs Methane Number

<30	30	35	40	45	50	55	60	65	70	75	80 to 100
0/--	0/--	0/--	0/--	0/--	0/--	0/--	0/--	.95/16*	1.0/16*	1.0/18	1.0/20

* Denotes Air Fuel Ratio Control required for Maximum Rating(s) Shown.

Fuel Usage Guide

Derate Factor / Engine Timing vs Methane Number

<30	30	35	40	45	50	55	60	65	70	75	80 to 100
0/--	0/--	0/--	0/--	0/--	0/--	0/--	0/--	1.0/18*	1.0/20*	1.0/22	1.0/24

* Denotes Air Fuel Ratio Control required for Maximum Rating(s) Shown.

CATERPILLAR

INCORRECT ENGINE TUNING

- An air-fuel mixture that is too lean
- Incorrect ignition timing set point
- Incorrect heat range of spark plug
- Incorrect lube oil (ie.Too high of an ash content)

INCORRECT ENGINE TUNING

- **Too lean of an air-fuel mixture**

  - The leaner the air-fuel ratio, the more susceptible the engine is to detonation: rich air-fuel ratios resist detonation.

  - Remember, the knocking resistance (or methane number) is a characteristic of the fuel, not the air. The more fuel that is present, the more resistant to knocking.

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INCORRECT IGNITION TIMING SET POINT

- Too much spark advance ignites the burn too soon, so that it increases pressure too greatly and the end gas spontaneously combusts (detonation).

- Retarding the timing will prevent detonation; however operating an engine at a retarded set point continuously, lowers the efficiency and optimum horse power output of the engine.

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INCORRECT HEAT RANGE OF SPARK PLUGS

- A spark plug with a higher heat range may become a source of detonation and/ or pre-ignition.

OVER BOOST

- Controlling the boost pressure in an a turbocharged engine is absolutely critical to prevent detonation.
- The turbo wastegate bleeds off boost pressure in response to rising intake manifold pressure; in order to follow the OEM's recommended air-fuel ratio mixture.
- A malfunctioning wastegate may allow the turbo to deliver too much boost, thereby "leaning" out the air-fuel mixture, and making the engine more susceptible to detonation.

INADEQUATE COOLING – JACKET WATER

- An over heated engine is extremely susceptible to detonation; as it raises the operating temperature of the cylinder liners and heads.

- Over heating can be caused by:
  - Low Coolant Level
  - Loose Jackshaft Belts
  - An undersized cooler; or a cooler placed downwind
  - Fan Pitch
  - Faulty thermostat, or too hot of a thermostat
  - Worn water pump
  - Contaminants in the jacket water(use a coolant filter)

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INADEQUATE COOLING – INTAKE MANIFOLD AIR

- Increased temperature in the intake manifold air may aid in an engine detonating.
- The non-combusted fuel-air mixture “soaks” up heat from any source available; edging the charge ever closer to auto-ignition and detonation.
- Confirm your air selector box is functional.
- On turbocharged engines; the intercooler can only function properly if the coolant is system is operating within design limits.

INCORRECT LUBE OIL

- Incorrect lube oil, and/or an engine running too hot or too cold may cause carbon deposits to accumulate on the cylinder head, piston crown, and intake and exhaust valves.

- This accumulation of carbon deposits can increase compression to a point where detonation occurs.

- Increased compression is also detrimental to piston rings, spark plugs, intake and exhaust valves.

- In addition to increasing compression, carbon deposits also have an insulating effect that slows the transfer of heat away from the combustion chamber and into the head.

PRE-IGNITION

THE SILENT ENGINE KILLER

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DEFINITION OF PRE-IGNITION

Pre-Ignition: The ignition of the fuel/air mixture charge prior to the spark plug firing.

PRE-IGNITION SEQUENCE

The fuel / air mixture enters
the combustion chamber as
the piston reaches BDC for intake.

The piston reverses direction and
starts to compress the charge.

Since the spark plug voltage requirements
to ignite the charge increase with the amount of
compression; almost anything can ignite the charge
at BDC !!!

A glowing spot somewhere in the chamber (over heated
spark plug or carbon ember, etc.) ignites the charge while
the piston is very early in the compression stroke.
This places catastrophic increased load and heat on engine parts through the compression stroke.

AUDIBLE SIGNS OF PRE-IGNITION??

- Unlike detonation, there are no audible sounds associated with pre-ignition; because the pressure build up is slow and gradual; not an instantaneous spike, as with detonation.

PRE-IGNITION vs. MECHANICAL INERTIA

- Pre-Ignition works against the mechanical inertia of the engine; as pre-ignition occurs after BDC; in most engines pre-ignition can affect the engine for approximately 160 degrees of the compression stroke.

- Detonation has only 15-40 degrees to work against the mechanical inertia of the engine, as detonation occurs at or near TDC or ATDC.

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PRE-IGNITION vs. ENGINE ROTATION

- Instead of the fuel igniting at the right instant to give the crankshaft a smooth kick in the right direction, the fuel ignites early causing a momentary backlash as the piston tries to turn the crankshaft in the **wrong direction.**

- This creates catastrophic pressure and temperature spikes; for an extremely long dwell time.

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PRE-IGNITION vs. DETONATION

- <u>Pre- Ignition is much **more hazardous** to a gas engine than detonation</u>; due to the extended time cycles that pre-ignition increases heat and pressure.

GENERAL CAUSES OF PRE-IGNITION

- Carbon deposits
- Incorrect Heat Range of Spark Plugs
- A lean air-fuel mixture
- Inadequate Cooling

INCORRECT ENGINE TUNING

- An air-fuel mixture that is too lean.
- Incorrect heat range of spark plug.
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- Too lean of an air-fuel mixture.

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  - Remember, the knocking resistance (or methane number) is a characteristic of the fuel, not the air. The more fuel that is present, the more resistant to knocking and pre-ignition.

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- Carbon deposits have an insulating effect that slows the transfer of heat away from the combustion chamber and into the head.

- These deposits may create a “glowing ember” in the combustion chamber or on the spark plugs; which makes the engine susceptible to pre-ignition.

OVER BOOST

- Controlling the boost pressure in an a turbocharged engine is absolutely critical to prevent detonation.
- The turbo wastegate controls boost pressure in response to varying levels of intake manifold pressure; in order to follow the OEM's recommended air-fuel ratio mixture.
- A malfunctioning wastegate may allow the turbo to deliver too much boost, thereby "leaning" out the air-fuel mixture, and making the engine more susceptible to detonation.

INADEQUATE COOLING – JACKET WATER

- An over heated engine is extremely susceptible to detonation; as it raises the operating temperature of the cylinder liners and heads.
- Inadequate cooling of the jacket water also is a direct component of high air manifold temperature, and high lube oil temperature (which leads to oxidation of the lube oil and increased carbon deposits in the combustion chamber).
- Over heating can be caused by:
    - Low coolant Level
    - Loose jackshaft belts
    - An undersized cooler; or a cooler placed downwind
    - Fan pitch
    - Faulty thermostat, or too hot of a thermostat
    - Worn water pump
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- On turbocharged engines; the intercooler can only function properly if the coolant is system is operating within design limits.

Detonation can induce Pre-Ignition.

SEQUENCE OF "DETONATION INDUCED PRE-IGNITION"

An Engine Under Heavy Load
Begins to Detonate

Detonation continues for a long period
of time; and the spark plug heats up
because because the pressure spikes
break down the protective layer of gas around the electrode.

The spark plug temperature elevates;
to the point when it becomes a "glow plug"
and induces pre-ignition.

There would have been no danger of pre-ignition;
if detonation had not been present.

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DETONATION & PRE-IGNITION

The Consequences

DetCon KNOCK MONITORING SYSTEM

- Decreased Production
- Lost Revenue
- Engine Damage
- Increased Maintenance Costs
- Decreased Reliability
- Exposure to Penalties

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What can we do?

CONCLUSION

- The BEST way to prevent Pre-Ignition is to prevent Detonation.
- Mechanical adjustments will not guarantee the prevention of Detonation or Pre-ignition.
- The only way to prevent Detonation without de-rating the continuous engine output is with a micro-controller based detonation sensing system.
- Therefore, the best way to prevent Detonation and Pre-Ignition is with a detonation controller.

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KNOCK MONITORING SYSTEM

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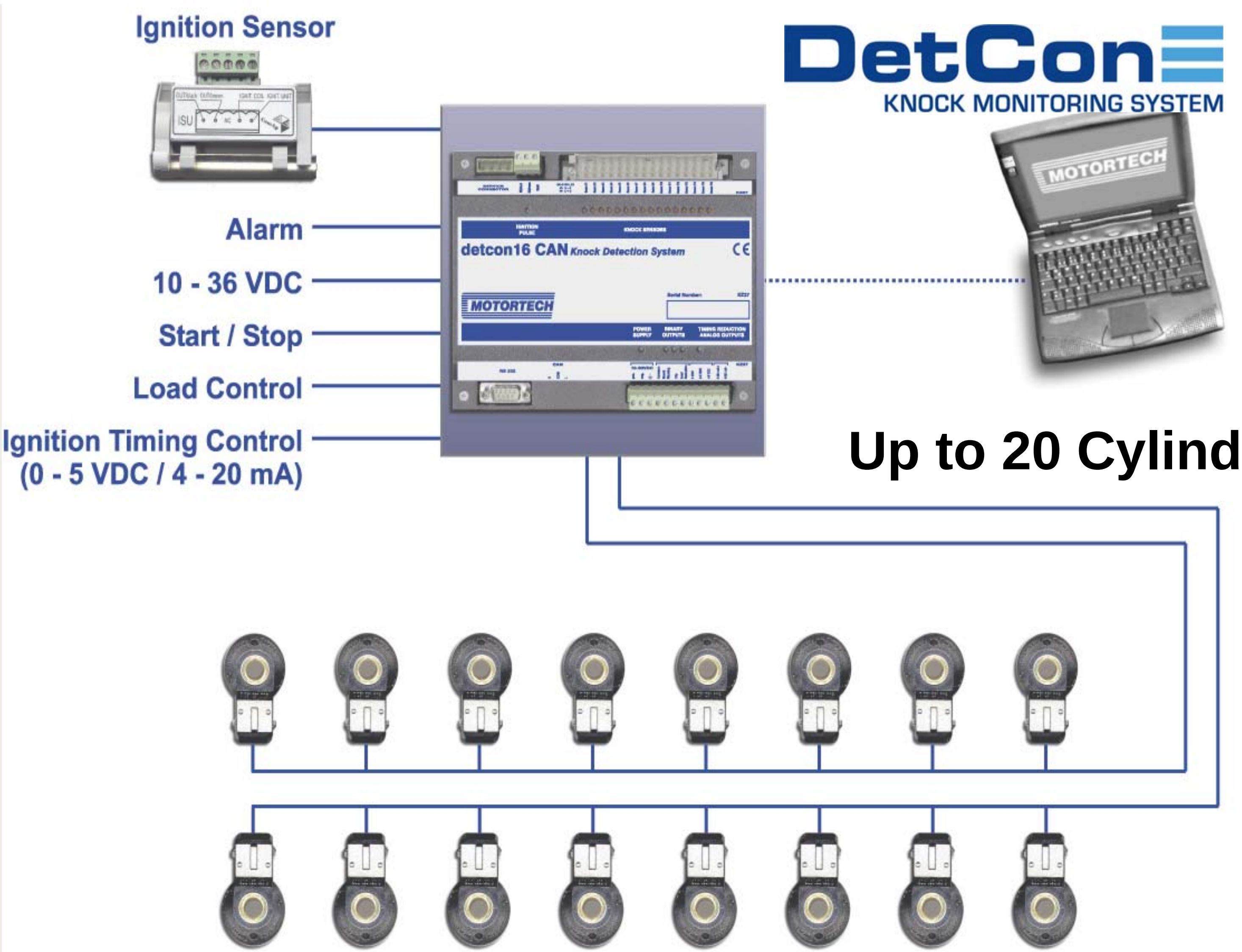
SYSTEM OVERVIEW



Up to 20 Cylinder Input

SYSTEM KIT

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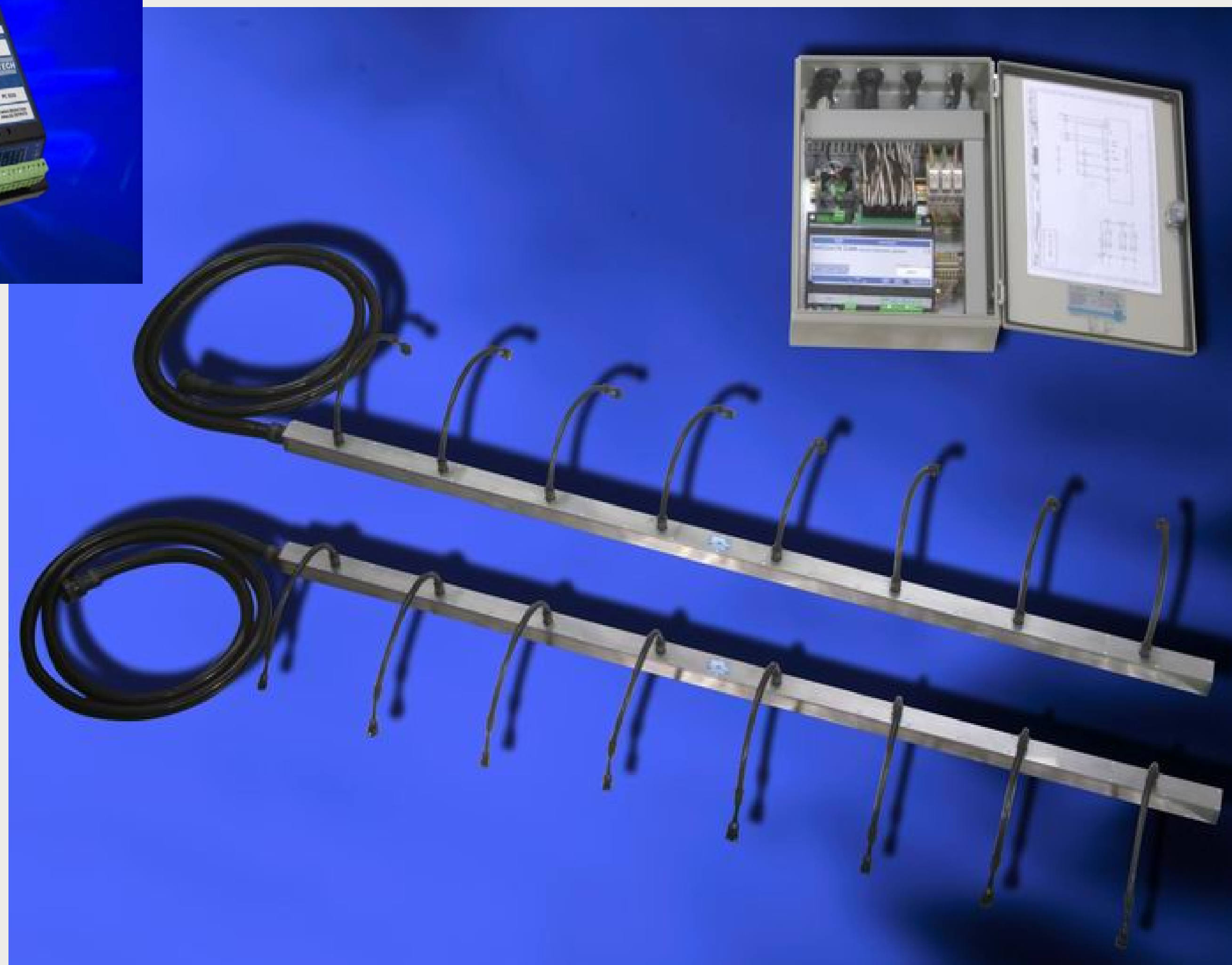
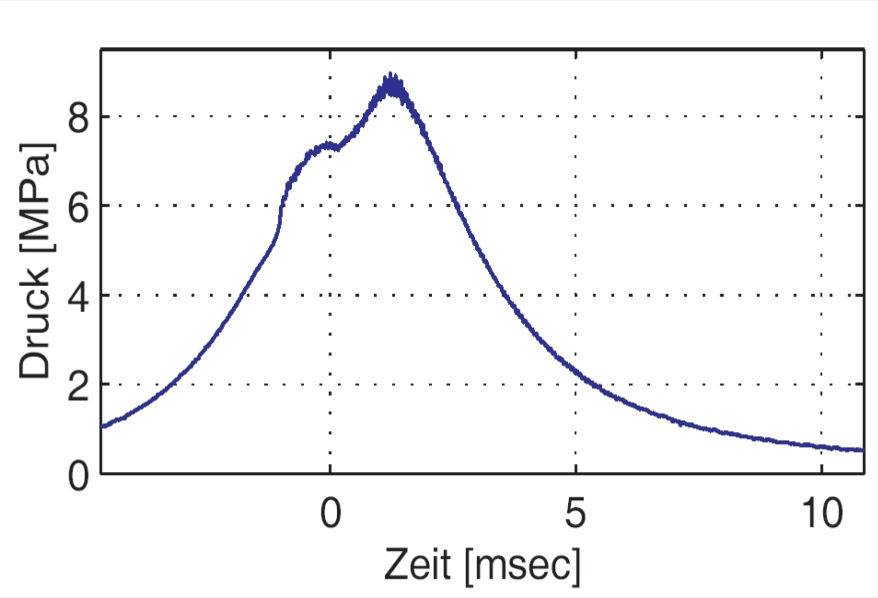
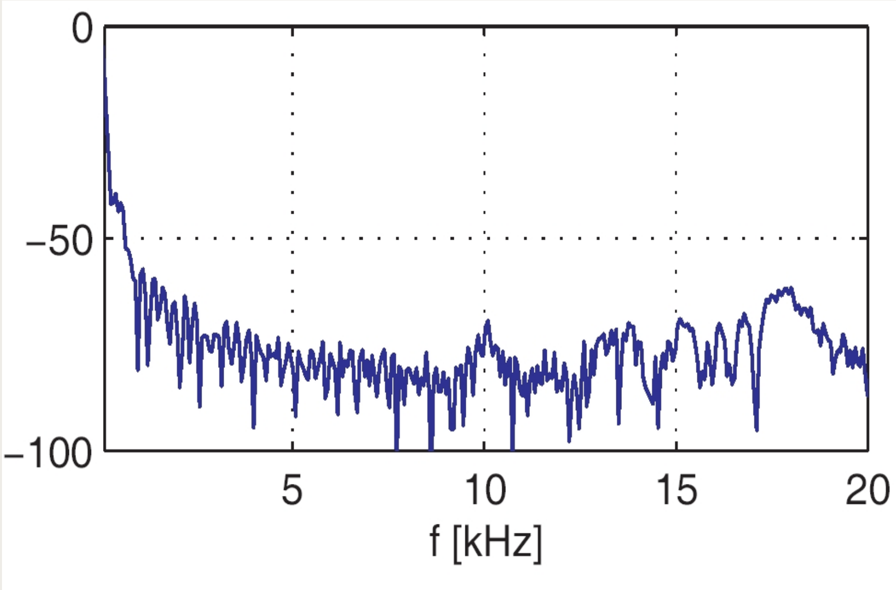
KNOCK MONITORING SYSTEM



DETONATION ANALYSIS

Normal





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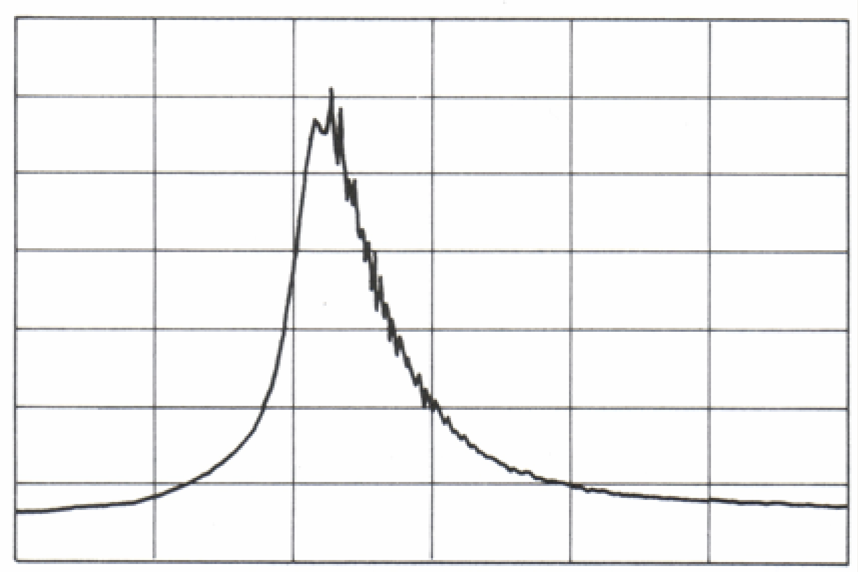
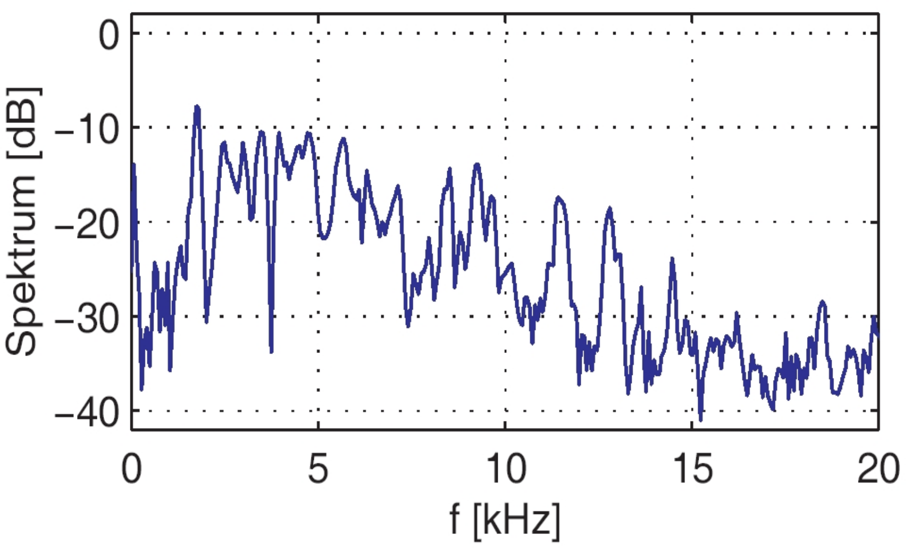
DETONATION ANALYSIS

5-20 kHz

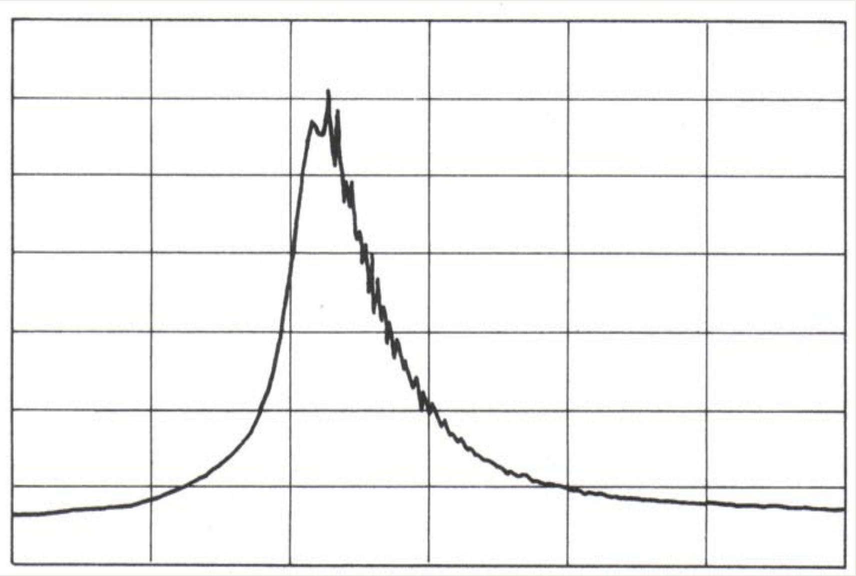
Knocking

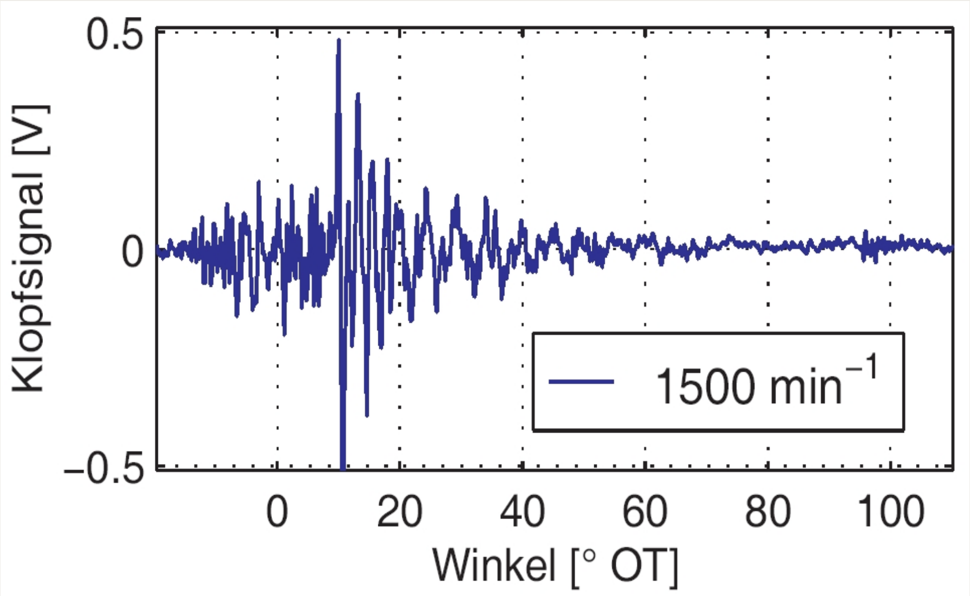




DETONATION ANALYSIS

Knock Sensor Signal





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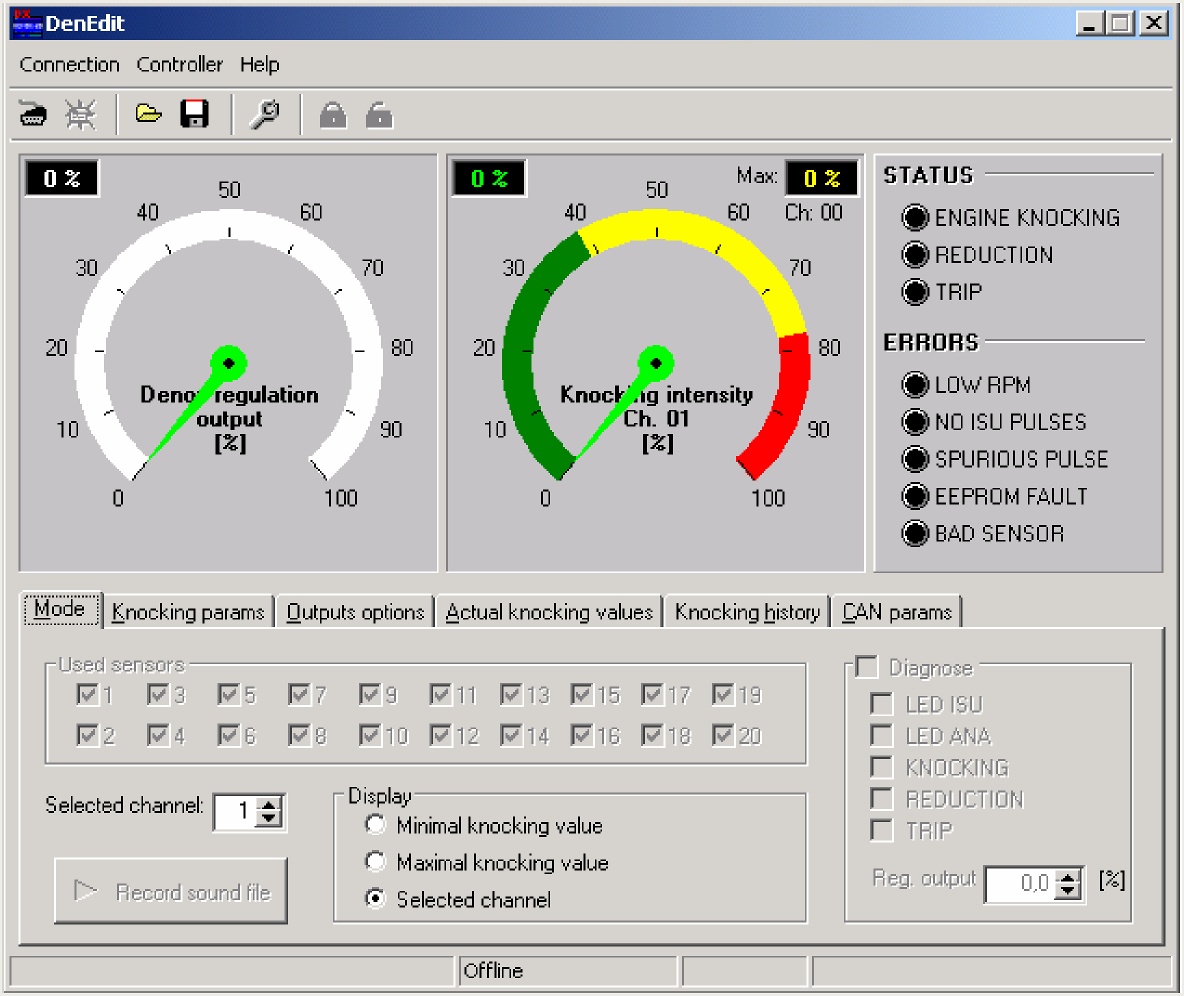
SOFTWARE



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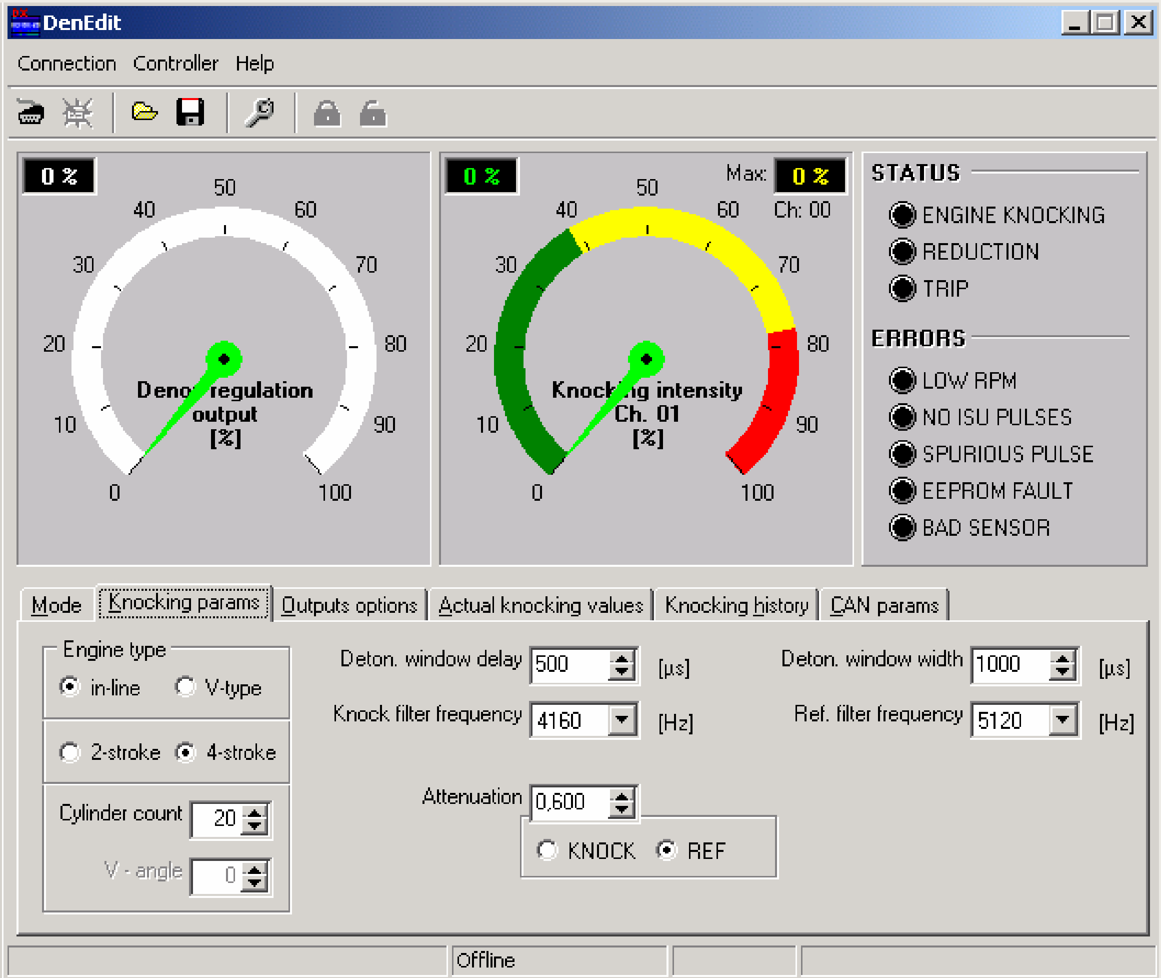

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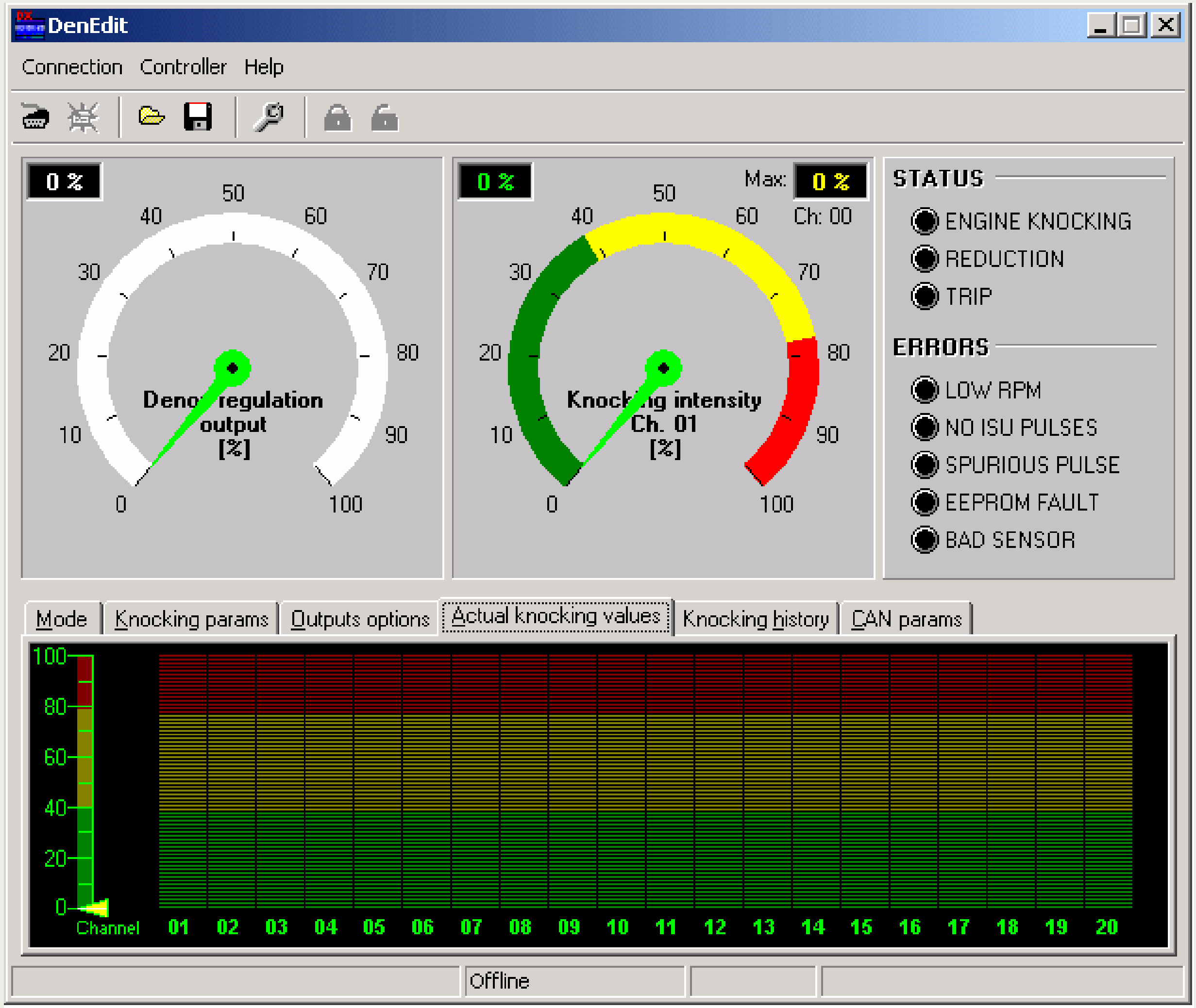

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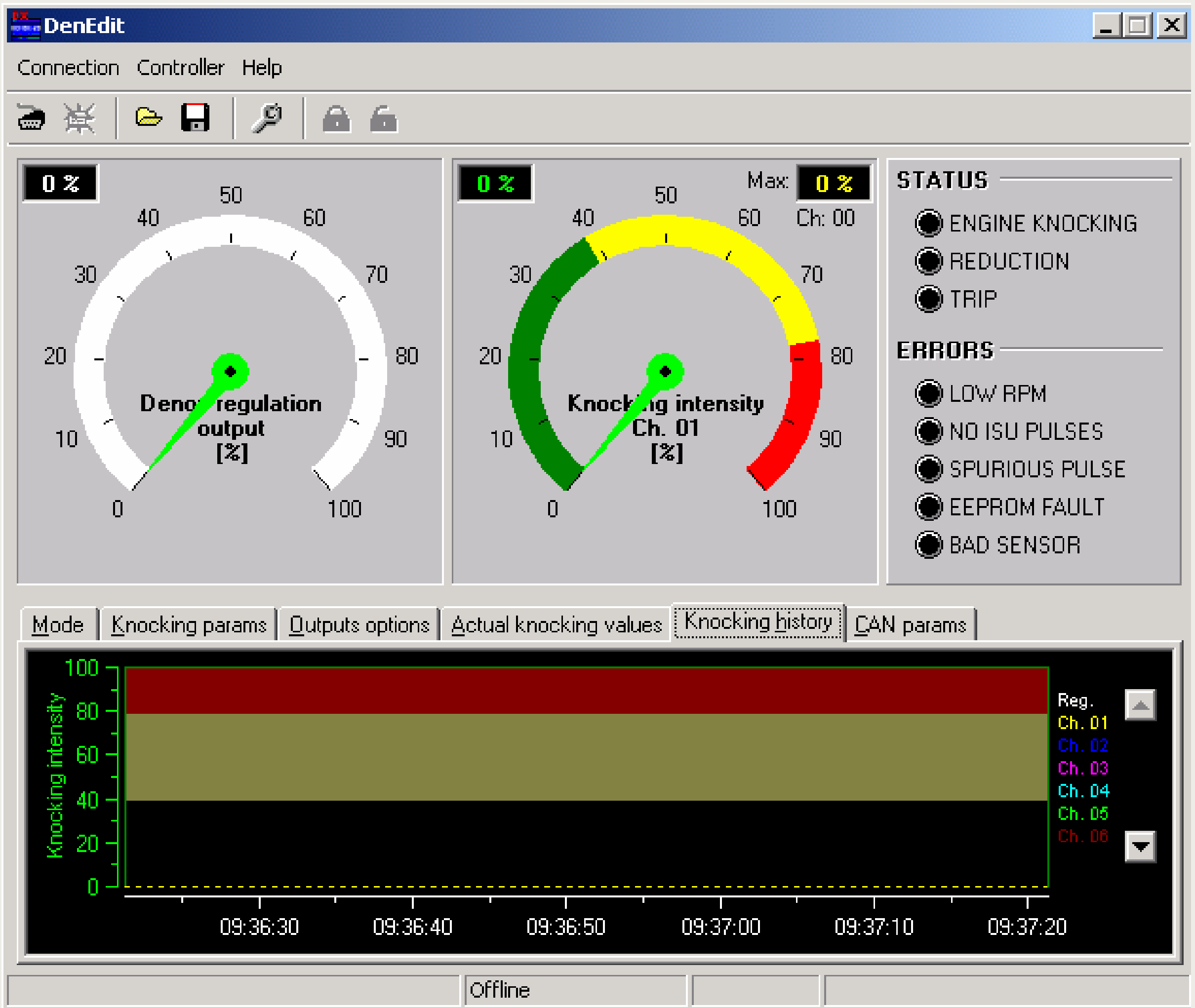

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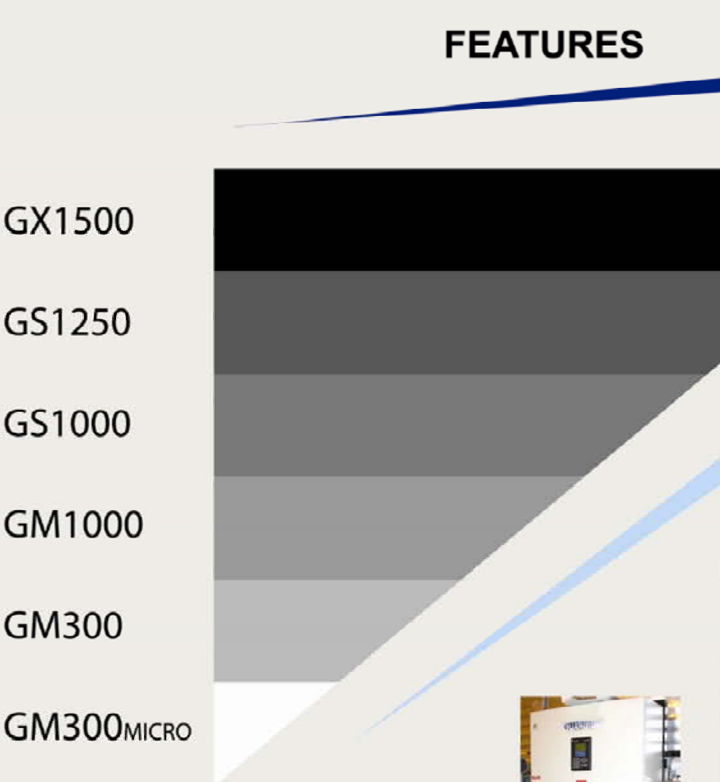
ROTATING EQUIPMENT CONTROL SOLUTIONS

For All Sizes & Applications

GUARDIAN® ROTATING EQUIPMENT CONTROL PANELS



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  - Western USA
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