Ebullient Engine HRSG

Near Term Solution – Low Carbon Future

OVERVIEW

FEB. 1, 2023

PRESENTED BY

BENZ AIR ENGINEERING, CO., INC.

BENZ AIR ENGINEERING

Agenda

- Addressing the Main Impediments to CHP
- Benz Air Solution
- Fabrica Installation
- California's Impending Power Grid Catastrophe – The "Duck Chart"
- Summary
- Benz Air Company Background

Appendix A. Reference Technologies

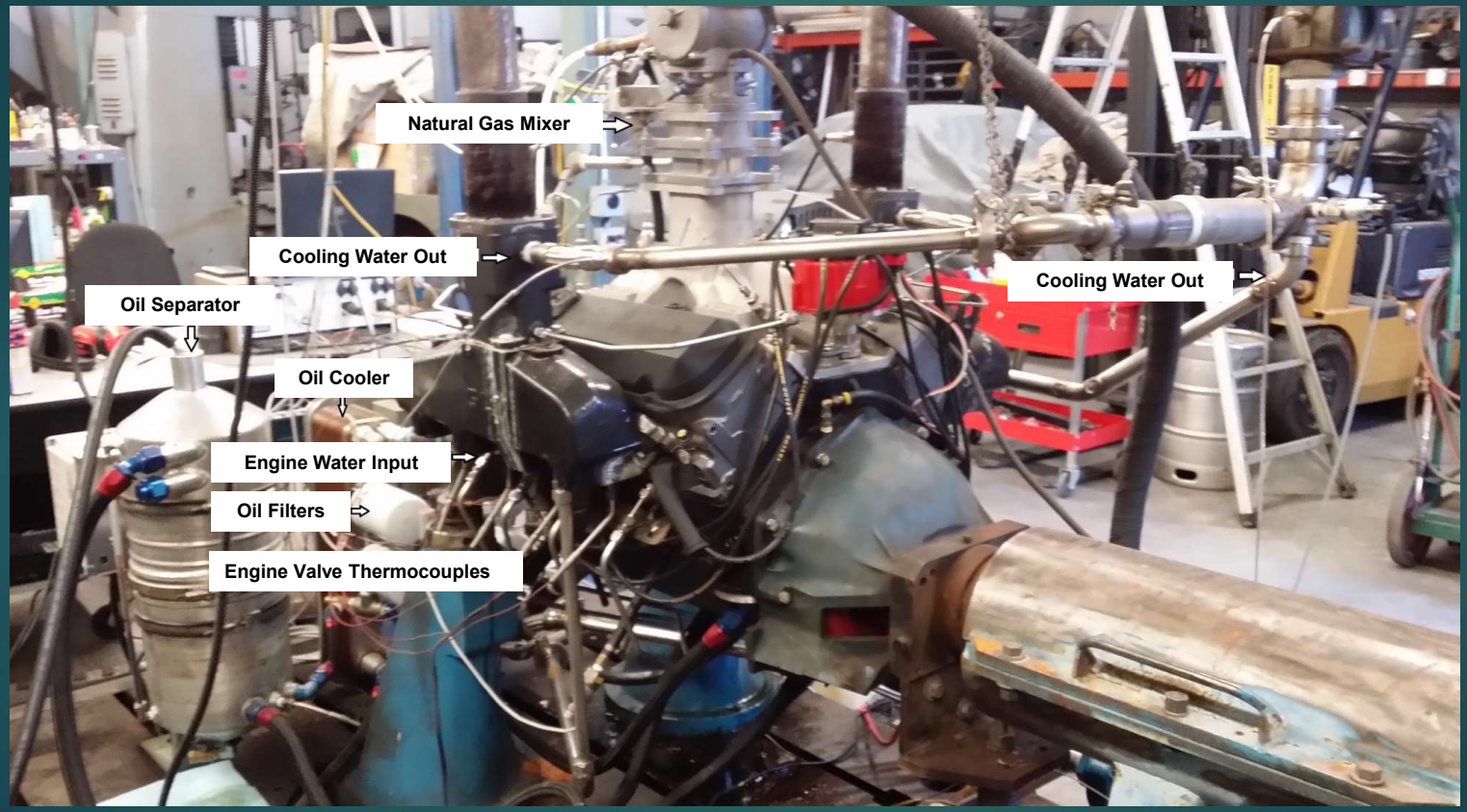
Main Impediments to Small CHP

- Air Permitting
  - Additional point source requiring new air permit
    - New source review including public comment
    - 6 month delay
  - Stringent NOx and CO Requirements
    - 0.07lbNOx/mw-hr or 3.3ppmNOx @ 15%O2
    - Less than 8.8ppmCO@15% O2
- Utility Interconnection
  - Supplemental Review
    - Additional variable cost
    - Minimum of 20 day up to 2 year delay
- Utilization of Waste Heat
  - Heating Has Limited Use
    - Seasonal Variations – Demand Opposite Electrical Demand

Benz Air Advances Address Impediments

- Engine Integrated with an Existing Steam Boiler
  - Engine Exhaust Replaces Boiler Re-circulated Flue Gas
    - NOx and CO reduced in Boiler Combustion
    - Engine Exhaust Heat Recovery Supplements Boiler Fuel
  - No Need for a New Air Permit
    - There is No Additional Emission Point Source
    - So Long as Boiler + Engine Fuel < Boiler Rated Heat Input
- Simplified Interconnection for Fast Track Utility Approval
  - Induction Generator through UL1741 Regenerative VFD
  - 10 day Approval Process Rule 21
  - Variable Generator Output from 30% to 100% Load at Peak Efficiency
- High Value Steam from Ebullient Cooled Engine
  - Supplements DA Steam in Facilities with Steam Processes
    - Additional CHP Credit from Replacing Boiler Steam
  - Use for Cooling in Absorption Systems
  - Nucleate Cooling Allows Higher Continuous Engine Output –
    - Highest Recip Energy Density

Design and Testing Ebullient Engine



Ebullient Cooled Engine Development to Date

454 CID Engine Modified and Tested

- State of the Art Engine Dyno Test Stand
  - 42 thermocouple &16 Analog 14bit in, 16 Analog out, 16 Digital in/out
- 50 Hours Steady State Testing Wide Open Throttle @ Lambda =1
  - 190 kilowatt output @ 11,200 btu/kw-hr HHV heat rate

Average over 50 hours

Cooling Water In		Cooling Water Out			Steam Flow
Temp F	Flow	Temp F	Flow	PSIG	lb/hour
226.9051	12.6937	261.0061	12.6937	21.35	598.4

	Exhaust Temperatures					Exhaust Temperatures		
#8	#6	#4	#2		#7	#5	#3	#1
1333.743	1357.532	1314.466	1367.553	F	1392.359	1341.67	1373.035	1360.469
	Exhaust Valve Temperatures					Exhaust Valve Temperatures		
375.7151	381.7482	379.4726	382.3113	F	393.3092	376.8099	379.074	379.0732

Ebullient Cooled Versus Conventionally Cooled Engine Temperatures

Cylinder Temperature Distribution

	1	2	3	4	5	6	7	8
Exhaust Valve Temp Baseline	362.70	323.09	336.49	334.63	314.44	325.97	323.43	326.35
Exhaust Temps Baseline	1452.55	1447.64	1394.73	1433.48	1390.91	1367.95	1363.19	1437.38
Ebullient Exhaust Temps	1361.10	1380.81	1340.25	1385.03	1420.73	1373.89	1394.96	1385.16
Ebullient Valve Temps	379.98	392.76	387.57	394.38	389.54	389.30	385.39	388.96

Benz Air Steam-Based Polygeneration

- Differentiators from traditional, hot water CHP
  - Generates steam vs, hot water
  - Can also power cooling systems
    - Steam from a 300kw engine can provide 100 tons of cooling
  - Isothermal heat exchange between load and engine

- Benefits from the Benz Air System
  - Increased efficiency of power generation
    - Heat rate less than 4000 btu/kw-hr
  - Reduce electricity cost
  - Reduced NOx emissions

Current 454cid Engine:
Fabrica Installation Santa Ana, California

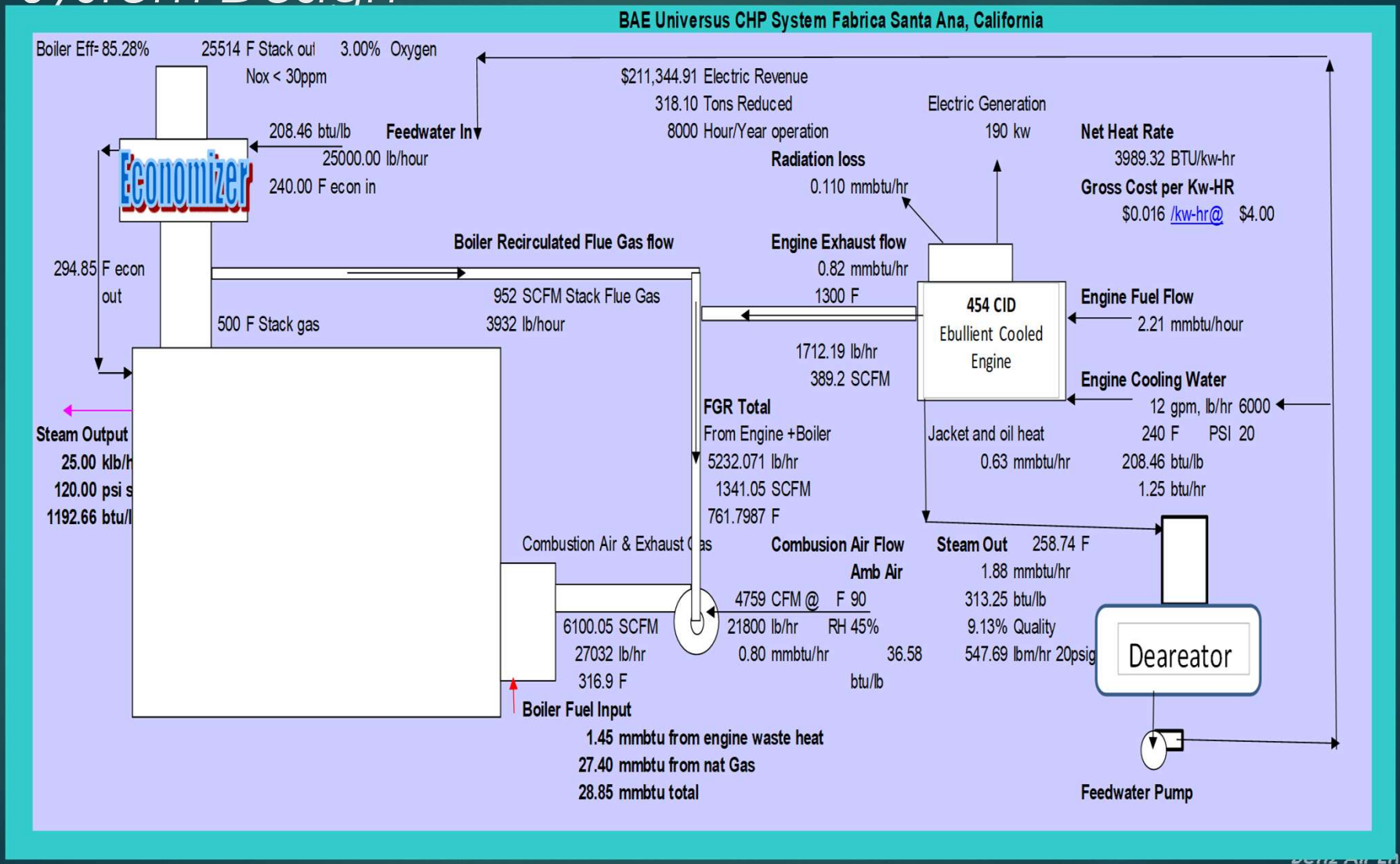
- Current R&D project can be demonstrated as of March, 2014
- Engine integrated into existing boiler plant
  - 25klb/hour boiler
  - 15psig to supplement Deareator Steam
  - Exhaust to replace boiler recirculated flue gas
  - Within Boiler Control Volume – Boiler Already has Air Permit
- Power Generation Grid Friendly
  - UL1741 Certification – Fast Track Installation
  - Regenerative Variable Frequency Drive
    - Power Generated at Peak Efficiency from 30% to 100%
  - Ramp Rate less than 30 seconds 30% 100%

Fabrica Installation Objectives

- Ramp Rate of 30% to 100% power output / 30 sec
- Fast Track Installation
  - UL1741 Regenerative Drive
  - No Net Increase in Boiler Emissions
- Industrial Application – Process Steam
- Variable Output @ Peak Efficiency
- Demonstrate Scalability
  - Determine Optimum Kilowatt Potential per Steam Boiler Capacity
- Demonstrate Long Steam use in an Industrial Facility
  - Practical Applications to Include Cooling, Heating and Industrial Processes

CHP System Design

Fabrica Installation



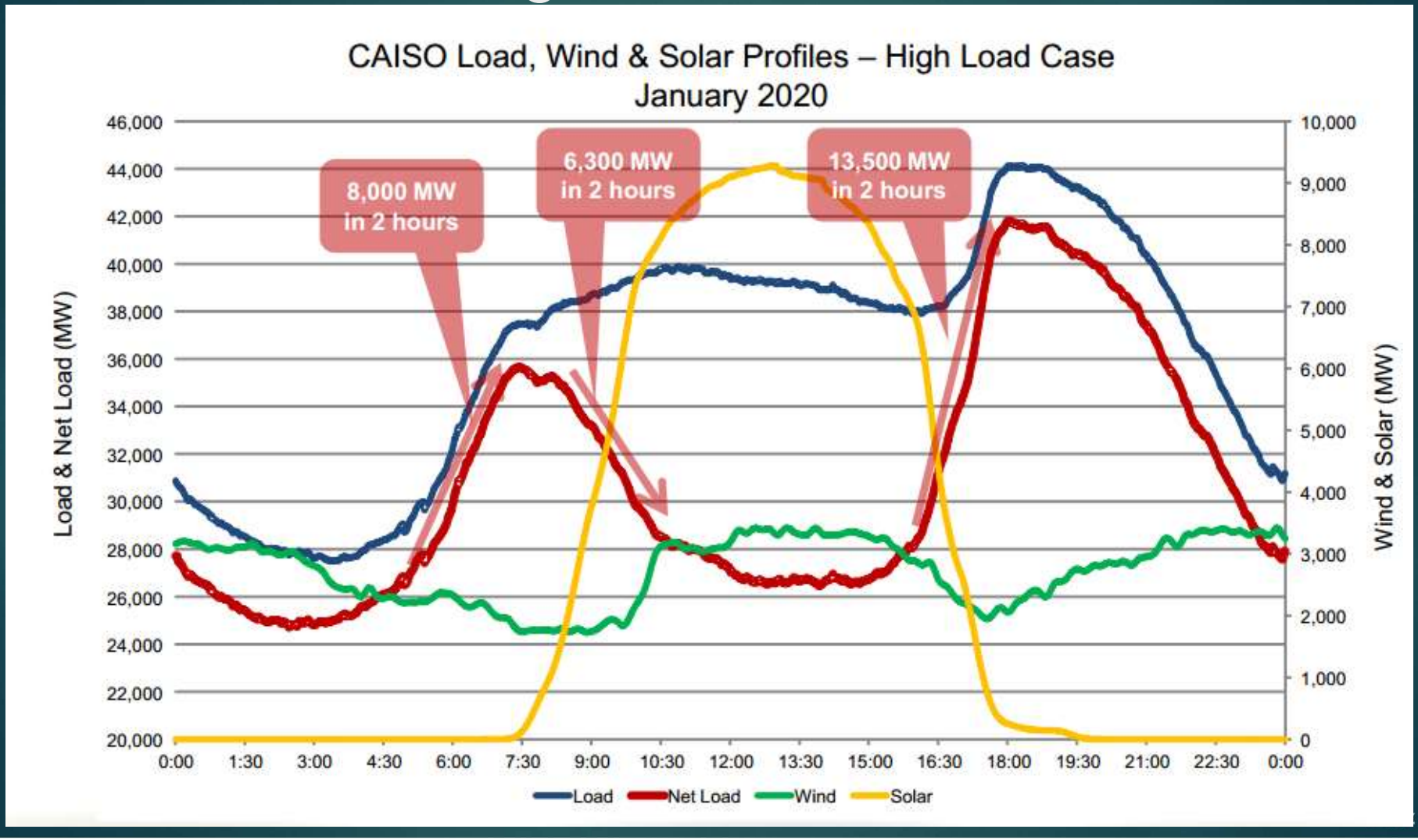
Next Generation 537 CID Engine

- Bigger Bore & Stroke for up to 300Kw
  - Higher Compression Ratio (<12:1)
  - Electric Generating Heat Rate < 10000btu/kw-hr = 34% Electric Generating Efficiency
  - Integral Piston Cooling system
  - Roller Valve components,
  - Same Big Block GM Configuration as 454cid
  - Turbo Charging for higher power and exhaust temperation.
  - Ceramic Coating of Internals to Minimize Heat Loss.
  - Off the shelf availability.
- Development of Micro Stand-Alone Steam Cogeneration Plant
  - Combined Heat and Power Heat Rate < 3990 btu/kw-hr = 86% Net Thermal Efficiency HHV
  - Small Boiler Replacement Alternative for Providing 25psig Steam at up to 2000lb/hour @300kw
  - Ultralow Emission Control - <3ppm NOx and CO
    - Steam Recirculation
    - Digital Air Fuel Ratio Control
  - Switchable from Non Island to Island Standalone Blackstart Capability
  - Packaged Absorption System for 150tons of Cooling
  - Up to 59lbs/hour of CO_2 emission reduction from 8600btu/kw-hr grid heat rate to CHP of 3990btu/kw-hr
    - Up to 215 metric tons of CO_2 reduction over 8000hr year operation.

Early Results at Fabrica

- After 8 months of production, Fabrica is achieving…
  - Electrical cost savings of $20,000/mo (= 40% decrease)
  - Emission reduction of 63lbs NOx
    - 8months, 24hrs/day, 5days/week, 2mmbtu*(0.036lb/mmbtu-0.003lb/mmbtu)
    - Boiler emissions less with engine running than without.

Renewables wreaking Havoc on California's Grid.



Solution to "Duck Chart"

- Battery Storage – A significant cost if available.
- Hydro Storage – Already tapped out.
- Compressed Air – Come on?

- Ebullient Engine HRSG w/Absorbtion Chiller
  - Constant Heat Rate Regardless of Output.
  - Startup and full load within 2 minutes.
- Electrical Chillers, boilers during oversupply
- Ramp up Engine and Absorbtion Chillers during undersupply.

Summary

- Installation and demonstration of engine, exhaust of which replaces industrial boiler recirculated flue gas.
- Setup and installation of the UL1741 drive and testing wide open throttle to determine maximum ramp rate
- Impact of boiler emissions having an engine integrated within the boiler, the control volume including boiler and engine
  - Determining the limits of boiler load to engine output ratio
- Design and specification of turbocharger for increasing power output
  - Effect of head metal temperatures with increased boost at stoichiometric
- Black start and standby generation of induction generators
- Steam driven water chilling
- Steam injection for NOX control
- Local uses of steam for reformation of natural gas
  - Hydrogen production on site
  - Hydrogen injection for NOX emission reduction
  - Hydrogen injection for Power boosting
  - Ammonia production on site

Benz Air Background Information

- Benz Air Engineering (BAE)
- Engine Expertise & History
- Partial Client List
- Contact Information

Benz Air Engineering (BAE)

BAE began providing emission control solutions in the state of California in 1992 at the JW Marriott Desert Springs Resort in Palm Desert, CA.. The company has installed over 200 systems in 20 states, Canada, Europe and Asia.

The company's combustion control products maximize fuel to steam efficiency while reducing NOx emissions to less than state and federal levels. The company combines programming expertise in a variety of PLC and DCS platforms with mechanical engineering providing customers a solution to meeting emission mandates while reducing energy expense and CO2.

BAE offers a total solution to include all aspects of district heating and cooling, cogeneration, and power generation systems. The firm targets utilities, universities, industrial companies and commercial firms that use boilers to generate steam for heating, processing or power transmission.

Products:

- Compu-NOx Control System
  - Commercial and Industrial Sized Boilers to 4000mmbtu/hr
- Boiler Efficiency Upgrades
  - Catamizer – SCR/Economizer
  - Air Preheater
  - Ultra High Turndown
- CHP by Integrating Engines to Industrial Applications
  - Nucleate Cooling

Benz Air Engine Expertise & History

- Association with Alvin Lowi & Associates Since 1980
  - Steam cogen under contract with GRI and Stewart & Stevenson
  - Lowi R&D Diesel–Natural Gas Dual Fuel Gensets. Loma Linda project. Improved particulate-NOX tradeoff.
- Patent Applied for Design of Nucleate Cooled Reciprocating Engine
- Integration of Engine with Existing Steam Boilers
- Developed Working Ebullient Cooled Natural Gas 454 Running WOT
  - Fully instrumented Dyno w 42 thermocouples, 24 analog.
  - Demonstrated more than 100 hours at WOT, head metal temps <370F with exhaust temps >1300F using 260F saturated water coolant.

Benz Air Engineering Partial Client List

- University of Texas, Austin
  - 500 and 150klb/hour Boiler Upgrade
- Enwave Energy Corporation, Toronto
  - SCR, Economizer, Condensing Economizer 8-100klb/hr boilers
- MillerCoors, Milwaukee, WI
  - Milwaukee, Fort Worth Boiler Upgrade
- Del Monte Foods
  - Modesto, Kingsburg CA Boiler Upgrade
- Fabrica, Santa Ana, CA
  - Boiler Upgrade
- Lyondellbasell, Morris, ID
  - Boiler Upgrade
- British Petroleum, Geel, Taipei
  - Boiler Upgrade
- US Navy Anapolis, Bangor
  - Boiler and Water Heater Upgrade
- AES Redondo Beach, CA
  - Rankine Cycle Upgrade
- US Steel, Portside, IL
  - Boiler Upgrade
- Pacific Gas and Electric, San Francisco, CA
  - 22 Projects Verified under the Commercial Industrial Boiler Efficiency Program
  - $12.4 million of Rebates Verified for Central California Food Processing Plant

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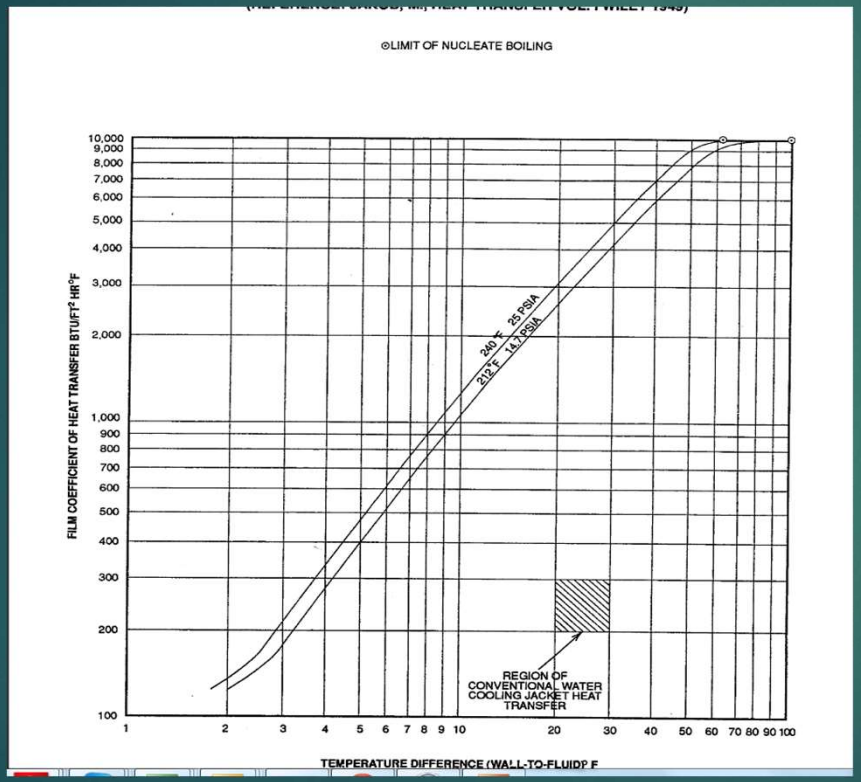
APPENDIX A. REFERENCE TECHNOLOGIES

- Nucleate Boiling Heat Transfer
- Nucleate Heat Transfer Film Coefficient
- Ebullient Cooling Flow Patterns
- Engine Absorption Cooling Example

Nucleate Boiling Heat Transfer 'Nucleate Cooling'

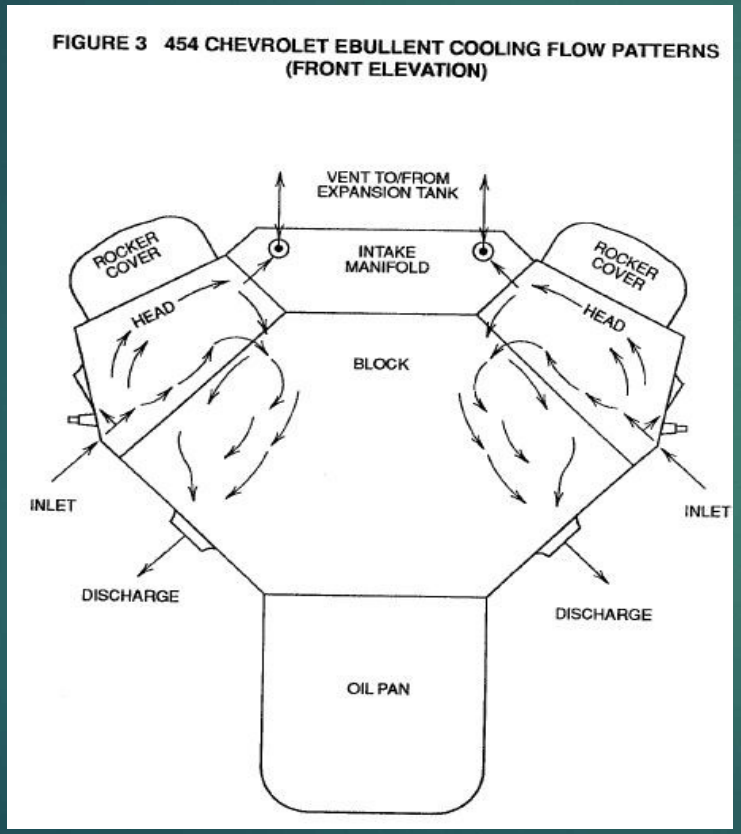
- 25 times the heat transfer rate of water convection
- Cooler Metal Temperatures with Hotter H20
- Uniform Head and Block Temperatures
- High Value Steam
- Low Parasitic Power – 1/10th Coolant Flow of Typical Engine
- Fast Starting
- Higher Margin in Cooling Capacity
  - Typical engine cooling is limited to 180F outlet water.
  - Constant temperature of Nucleate Cooling lacks any Limitation.

Nucleate Heat Transfer Film Coefficient



- Note tremendous difference in heat transfer rate for a given temperature difference between metal and coolant.
- That difference needs to be minimized for durability. – thermal stresses.

Ebullient Cooling Flow Patterns



- Note reversal in direction of coolant circulation, top hot has priority for cooling capacity
- Once through flow

Engine Absorption Cooling Example