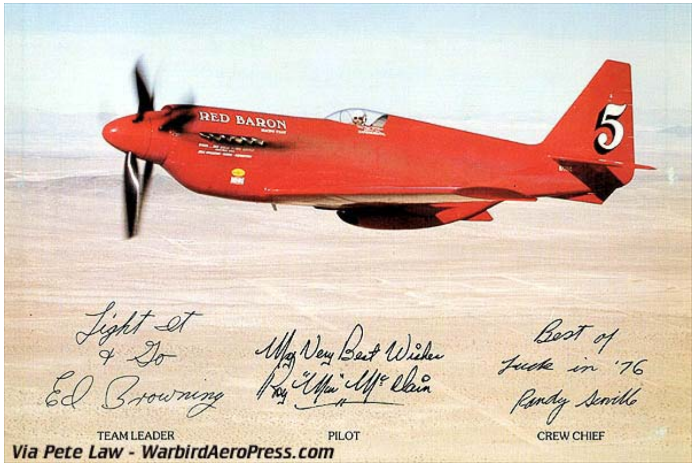
# AIRCRAFT PISTON ENGINE COOLING SYSTEMS

BY PETER LAW



# Peter Law – Who is He and Where Did He Work?

- BSME – Stanford University, 1958. Majored in Thermodynamics
- MSAE – University of Southern California (USC), 1965
- Registered Professional Mechanical Engineer in California & Washington
- Member SAE and AIAA
- Thermodynamics Engineer at Lockheed-Burbank & Palmdale since January 1959; Entire Career of 42.5 years at Lockheed
- Transferred to Lockheed *Skunk Works* in July 1961
- *Skunk Works* Thermodynamics Department Manager from 1980
- Retired from Lockheed July 2001 after 40 years at *Skunk Works*
- Worked on *F-104, A-12, YF-12A, SR-71, M-21, D-21, U-2, F-117A, F-22, JSF(X-35),* and many other Classified Projects
- Did internal and external Heat Transfer and Thermodynamics, Structural Thermal Analysis, Cooling System Design, and Internal Subsystem Thermal Analysis, including hydraulics, fuel, and other systems
- Involved in Piston Engine Aircraft Racing since 1964
- Involved in Unlimited Hydroplane Racing since 1970

# **Peter Law** - *What Does He Do?*

- Involved in Unlimited Racing since 1964
- Started with Darryl Greenamyer, Lockheed A-12 & SR-71 Test Pilot, in 1964 after First Reno Races
- Involved then and since with Bruce Boland
- Boiled ADI Fluid to Cool Oil & Reduce Drag on Darryl's Bearcat Starting at Reno 1965
- Built Water Injection Systems for P-51s & other Aircraft since 1970 through Al DiMauro & Aircraft Carburetor
- Flow Check & Adjust Carburetors for most Unlimited Aircraft Since 1978, when Aircraft Carburetor Terminated
- Design & Build Spray Bars for Oil & Engine Cooling, plus other Engineering since 1970

# **Peter Law** - *What Has He Worked On?*

- **Started with Darryl Greenamyer's Bearcat**
- **Worked with Bruce Boland on several more**
  - Dave Zeuschel P-51 & *Miss America* P-51 in 1,000 Mile Races
  - *Candace* (Cliff Cummins), *Jeannie* (Mac McClain)
  - *Red Baron P-51*, *Merlin & Griffon*
  - *Ciuchetton, Cloud Dancer, Georgia Mae, Ridge Runner*
  - *Dago Red*, Original *Strega, Stiletto, Super Corsair*
  - *Tsunami, Risky Business, Huntress III* & More
  - Help on *Rare Bear, Dreadnought*
- **Unlimited Division Contributions**
  - Rules Committee - Coordinated New Rules 1980
  - Division Secretary-Treasurer for 2 years
  - Division Newsletter for Several Years (with Joanne)
  - Records Keeper & Pilot's Qualification Secretary
  - Unlimited Hydroplane Involvement

# Cooling Required for Large High Power Engines

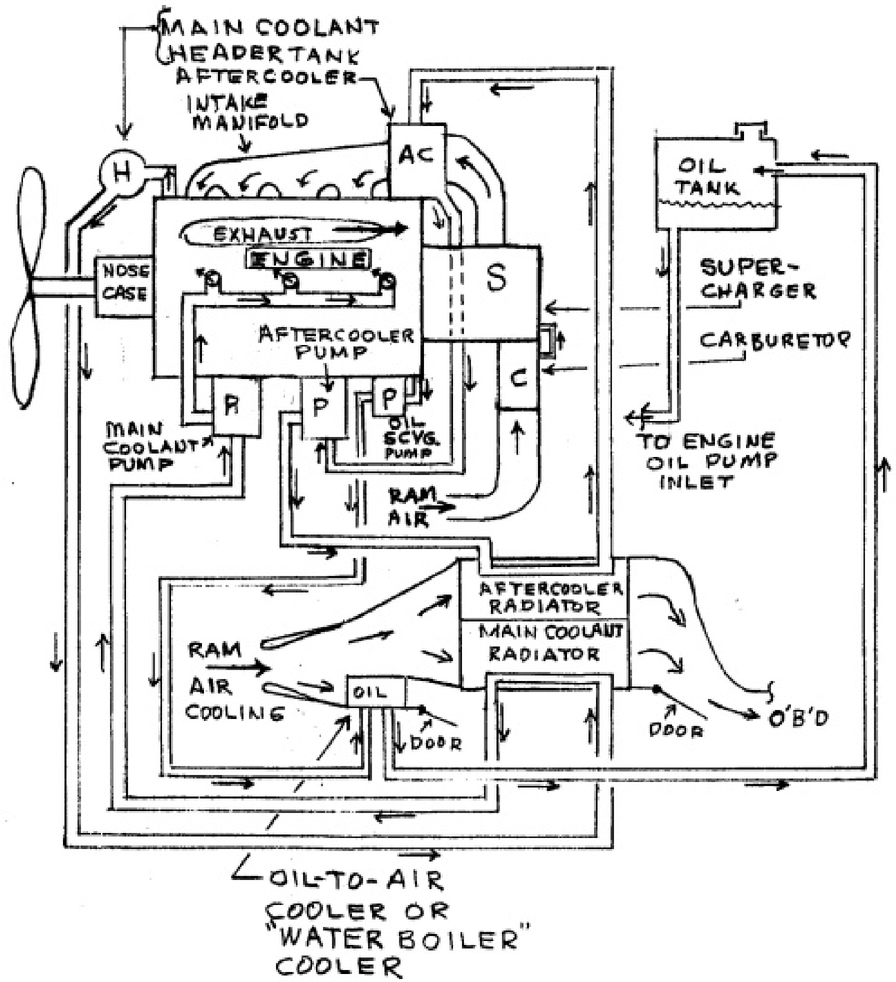
- ENGINES CONSIDERED FOR COOLING METHODS:
  - MERLIN V-1650, ALLISON V-1710, Rolls-Royce GRIFFON
  - P&W R-2800, WRIGHT R-3350, P&W R-4360
- **V-12's:** MERLIN, ALLISON & GRIFFON SIMILAR; **LIQUID-COOLED**
  - CYLINDER HEADS AND BANKS COOLING (Liquid-to-Air)
  - ENGINE LUBRICATING OIL COOLING (Oil-to-Air)
  - ENGINE CHARGE AIR INTER/AFTERCOOLING (Liquid-to-Air)
  - ENGINE CHARGE AIR COOLING FOR HIGH POWER ("ADI")
- **RADIALS:** R-2800, R-3350, R-4360 SIMILAR; **AIR-COOLED**
  - CYLINDER & CYLINDER HEAD COOLING (Air)
  - ENGINE LUBRICATING OIL COOLING (Oil-to-Air)
  - ENGINE SUPPLY AIR INTERCOOLING (None Racing)
  - ENGINE AIR CHARGE COOLING FOR HIGH POWER ("ADI")

# ENGINE COOLING SYSTEM GENERAL SIMPLIFIED SCHEMATICS

(SCHEMATICS ARE SIMPLIFIED FOR CLARITY)

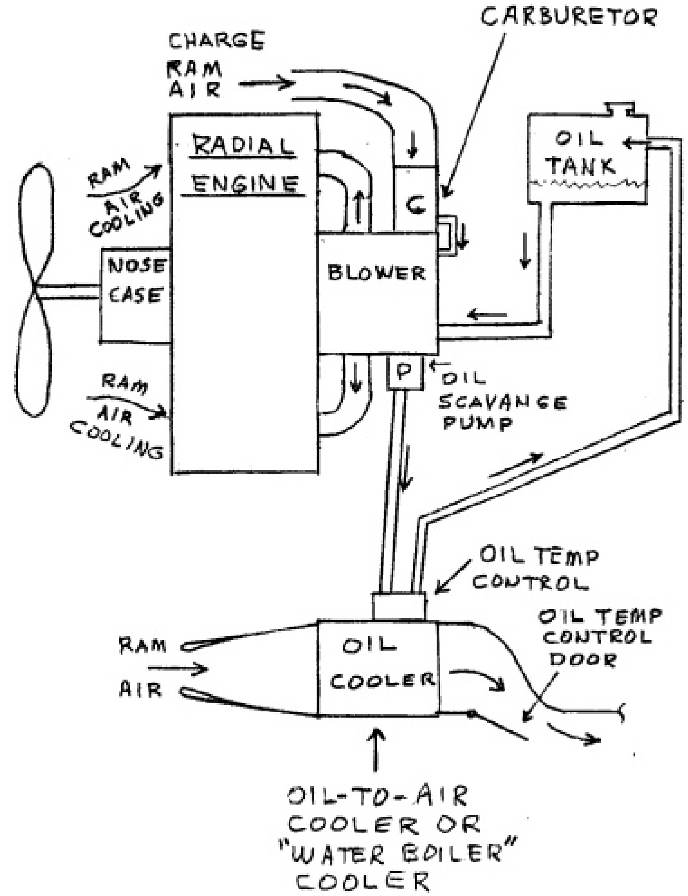
## TYPICAL V-12 CONFIGURATION

(ALLISON IS DOWNDRAFT, NO AFTER COOLED VERSIONS SHOWN)




## TYPICAL RADIAL CONFIGURATION

(NO AFTER COOLED VERSIONS SHOWN)



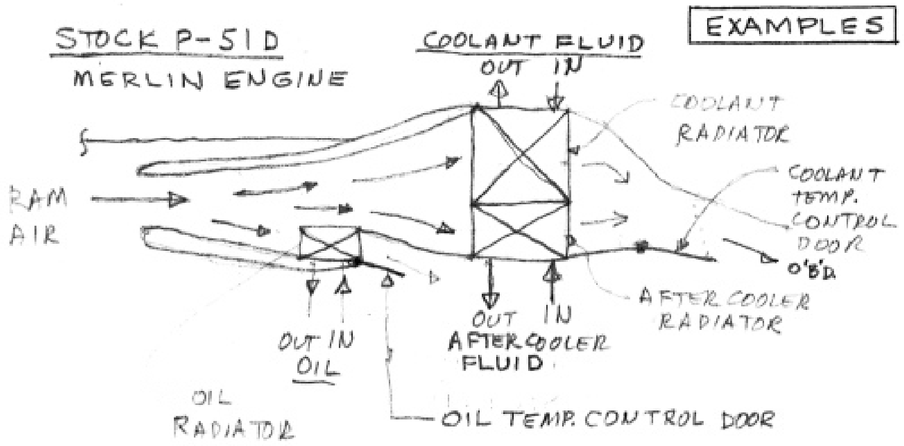
# METHODS FOR COOLING V-12 ENGINES

- V-12's: CYLINDER HEADS AND BANKS: <u>COOLANT CIRCULATES</u>
  - THROUGH AIR HEAT EXCHANGERS (STOCK RADIATORS)
  - THROUGH AIR HEAT EXCHANGERS WITH WATER SPRAYED INTO RADIATOR COOLING AIR (RACERS)
      - CALLED "RADIATOR SPRAY-BAR WATER"
  - THROUGH HEAT EXCHANGERS <u>BOILING</u> "ADI" FLUID*
    - "Anti-Detonation Injection" FLUID: 50% METHANOL AND 50% $H_2O$
      - Used only on *"STILETTO"* and for only one race
- V-12's: ENGINE LUBRICATING SYSTEM: <u>OIL CIRCULATES</u>
  - THROUGH AIR HEAT EXCHANGERS (RADIATORS ON MOST AIRCRAFT)
  - THROUGH AIR HEAT EXCHANGERS WITH WATER SPRAYED INTO COOLING AIR (RACERS)
      - CALLED "RADIATOR SPRAY-BAR WATER"
  - AN OIL-to-LIQUID HEAT EXCHANGER, CIRCULATING LIQUID IS AIR-COOLED (P-51H)
  - HEAT EXCHANGER BOILING "ADI" FLUID* (METHANOL + $H_2O$), HAS BEEN USED BY A FEW RACERS; *"STILETTO"* AND P-63 *"CRAZYHORSE"*

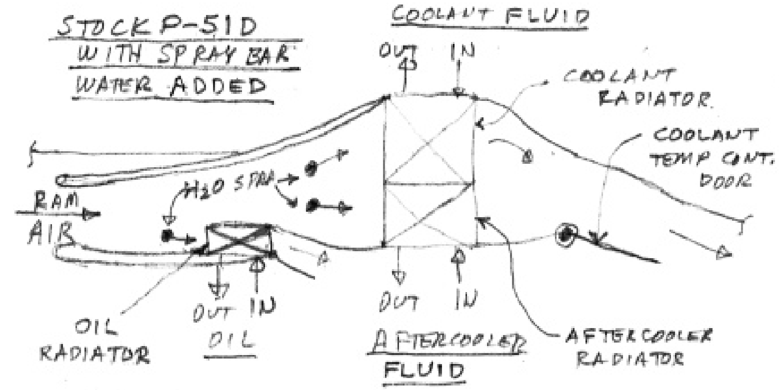
* THESE BOILING COOLERS ARE OFTEN REFERRED TO AS "WATER BOILERS" OR AS "BOIL-OFF" COOLERS

  - (FIRST UTILIZED IN 1965 BY DARRYL GREENAMYER'S F8F BEARCAT *"MISS SMIRNOFF"*, DESIGNED BY PETE LAW)

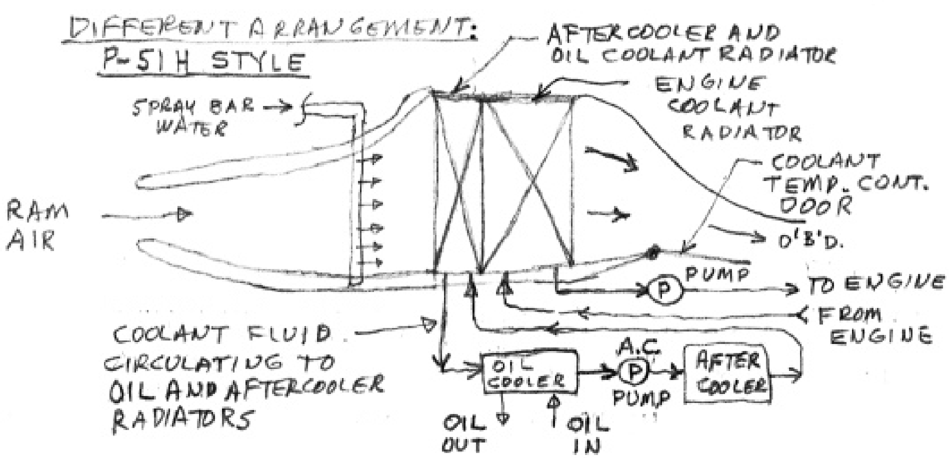
# TYPICAL V-12 ENGINE COOLING SYSTEM EXAMPLES



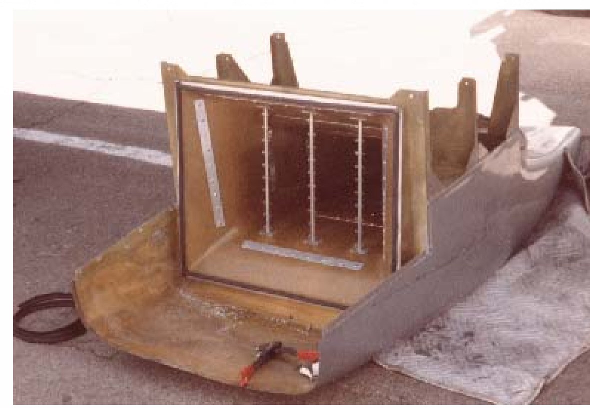

ALLISON COOLING SIMILAR, BUT OIL COOLING IN SEPARATE SCOOP AND NO INTERCOOLER ON MOST ENGINES




GRIFFON POWERED RACERS WERE SET UP IN THE ABOVE CONFIGURATION, AS ARE MOST MID-SPEED P-51 RACERS




THIS WAS ORIGINAL CONFIGURATION FOR MISS CANDACE, DAGO RED, STREGA



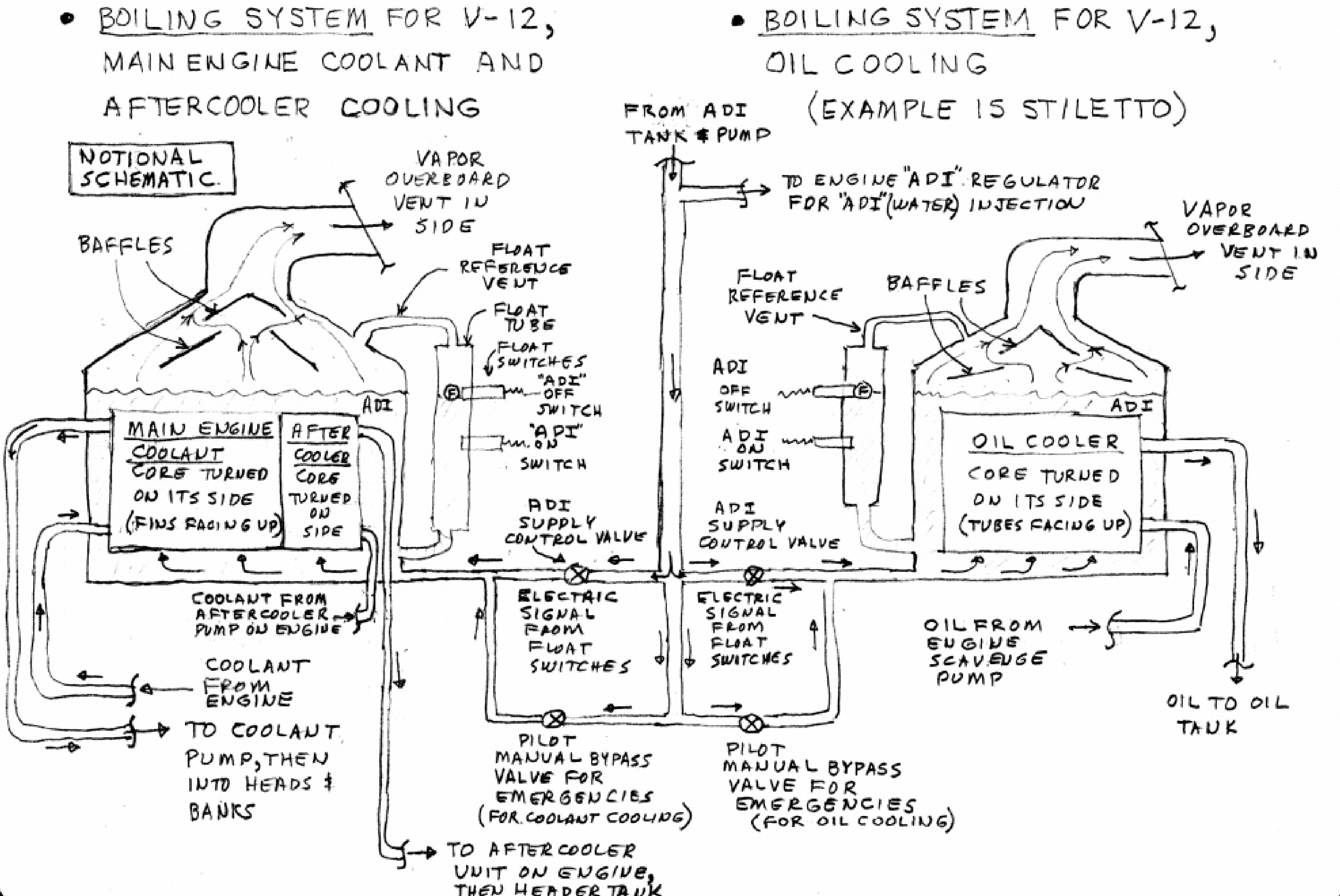
CANDACE, DAGO RED, STREGA

TYPICAL SPRAY BAR INSTALLATION IN COOLANT SCOOP FORWARD OF RADITOR FRONT FACE

# METHODS FOR COOLING V-12 ENGINES (Con't)

- V-12's: COOLING OF SUPERCHARGED ENGINE CHARGE AIR UTILIZING AN AFTERCOOLER HEAT EXCHANGER
  - COOLANT FLUID CIRCULATES THROUGH THE AFTER COOLER AND THEN THROUGH AN AIR HEAT EXCHANGER (RADIATOR) SIMILAR TO MAIN COOLANT RADIATORS
  - THROUGH THE AFTERCOOLER RADIATOR WITH SPRAY BAR WATER ($H_2O$) INTO AFTERCOOLER RADIATOR COOLING AIR (RACERS)
- V-12's: ENGINE AIR CHARGE COOLING FOR HIGH POWER
  - INJECTION OF "WATER" INTO SUPERCHARGER INLET
    - "WATER" IS ACTUALLY "ADI" FLUID, A MIXTURE OF 50% METHANOL & 50% $H_2O$ (BY VOLUME), COOLS CHARGE BY EVAPORATION, SUPPRESSES DETONATION BY REDUCING FLAME SPEED, ALLOWS HIGHER POWER
  - INJECTION OF NITROUS OXIDE INTO SUPERCHARGER INLET
    - GASEOUS $N_2O$ ENTERS SUPERCHARGER AT –127°F (PROVIDES CHARGE COOLING) AND SUPPLYS +36% OF OXYGEN PER POUND OF $N_2O$, SUPPORTS MORE FUEL FOR MORE POWER (10 pounds/min adds 200 bhp)
      - USED IN UNLIMITED HYDROPLANES, AND IN SOME AIRCRAFT, eg *BARDAHL SPECIAL, ROTOFINISH, DAGO RED, STREGA*, DEVELOPED BY DWIGHT THORN

# TYPICAL V-12 ENGINE COOLING SYSTEM (Con't)
# "STILETTO"



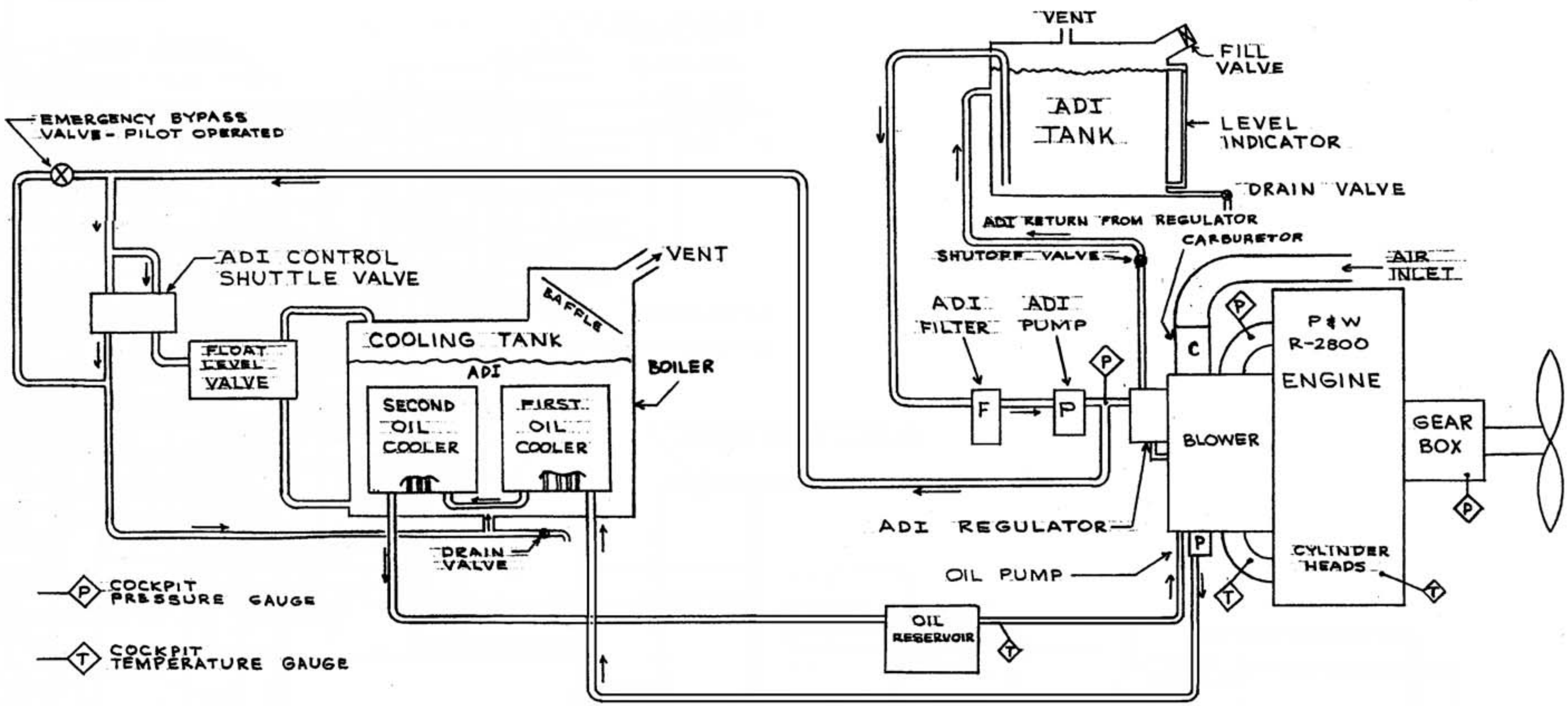
# METHODS FOR COOLING RADIAL ENGINES

- RADIALS:  CYLINDER HEADS AND CYLINDER BARRELS
  - AIR RAMMED THROUGH BAFFLES AROUND CYLINDERS
  - AIR WITH WATER SPRAY RAMMED AROUND CYLINDERS (RACERS)
- RADIALS:  ENGINE LUBRICATING OIL CIRCULATING THROUGH-
  - AIR HEAT EXCHANGERS (RADIATORS – SIMILAR TO V-12's)
  - AIR HEAT EXCHANGERS WITH WATER (H2O) SPRAYED INTO OIL RADIATOR COOLING AIR (RACERS – "SPRAY-BAR WATER")
  - HEAT EXCHANGER BOILING "ADI" FLUID
    - A FEW RADIAL ENGINE RACERS HAVE USED THIS METHOD, INCLUDING *CONQUEST, MR. AWESOME, SEPTEMBER FURY*.  IN PROCESS ARE - GREENAMYER'S *SHOCK WAVE*, MATT JACKSON'S *AMERICAN SPIRIT*
- RADIALS:  ENGINE AIR CHARGE COOLING FOR HIGH POWER
  - INJECTION OF "WATER" (ADI FLUID) INTO SUPERCHARGER INLET – ALL RADIAL RACERS
  - NITROUS OXIDE INJECTION INTO SUPERCHARGER INLET – *RARE BEAR*

*NOTE:   AIR COOLED OIL TEMPERATURES ARE NORMALLY REGULATED BY A CONTROL DOOR ON THE COOLING AIR SIDE, DOWNSTREAM OF THE RADIATOR, SIMILAR TO LIQUID-COOLED ENGINES COOLANT AND OIL RADIATORS*

# OIL COOLING SYSTEM SCHEMATIC

## RACING F8F BEARCAT - *CONQUEST*

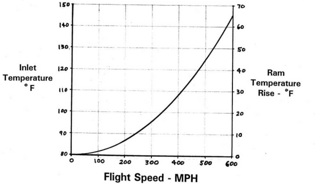



TYPICAL WATER BOILER SYSTEM FOR RADIAL ENGINE APPLICATIONS

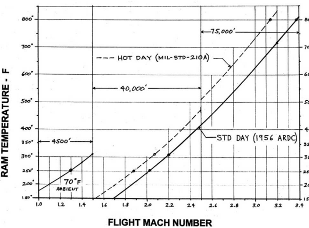
# DISCUSSION OF COOLING REQUIREMENTS

- AVAILABLE HEAT SINKS FOR COOLING
  - RAM AIR IS THE HEAT SINK FOR MOST COOLING
    - AMBIENT AIR TAKEN ONBOARD INCREASES TEMPERATURE AS SPEED INCREASES
    - RAM EFFECT $T_{RAM}{}^{o}F = (T_a{}^{o}F+460)(1+0.2M^2)-460$
    - AMBIENT AIR INCREASES IN PRESSURE AS SPEED INCREASES
    - RAM EFFECT $P_{RAM,\ psia} = P_{a\ psia}\,(1.0 + 0.2M^2)^{3.5}$, "M" is MACH NUMBER
      - RAM INCREASES INLET AIR DENSITY, RESULTS IN HIGHER POWER
  - BOILING OF ADI FOR COOLING REDUCES REQUIREMENT FOR BRINGING AIR INTO AIRCRAFT, REDUCES DRAG, INCREASES SPEED
    - ADI PROPERTIES INCLUDE: BOILING TEMPERATURES, BOILING HEAT ABSORPTION CAPACITY, DENSITY, AND FREEZING TEMPERATURES
- WHAT TEMPERATURE AND PRESSURE VALUES ARE DESIRED?
  - TEMPERATURES
    - LIQUID COOLANT TEMPS FOR V-12's (100 – 115$^{o}$C), OIL TEMPS (80 – 90$^{o}$C)
    - RADIAL CYLINDER HEAD TEMPS (220 – 260$^{o}$C), EXHAUST GAS TEMPS (1200 – 1400$^{o}$F)
    - INDUCTION TEMP or INDUCTION CHARGE TEMPS (80 – 90$^{o}$C)
  - PRESSURES
    - FUEL PRESSURE (25 – 28 psig), OIL PRESSURE (60 – 90 psig)
    - COOLANT PRESSURE (5 – 30 psig), DEPENDANT UPON GLYCOL-WATER MIXTURE
    - ADI PRESSURE (20 – 30 psig), SPRAY-BAR PRESSURE (20 – 30 psig)
    - MANIFOLD PRESSURE (60 – 140 inHgA), NOSE CASE TORQUE PRESSURE (100 – 275 psig)

# Flight Temperatures
## 80°F Ambient



# FLIGHT RAM INLET TEMPERATURES



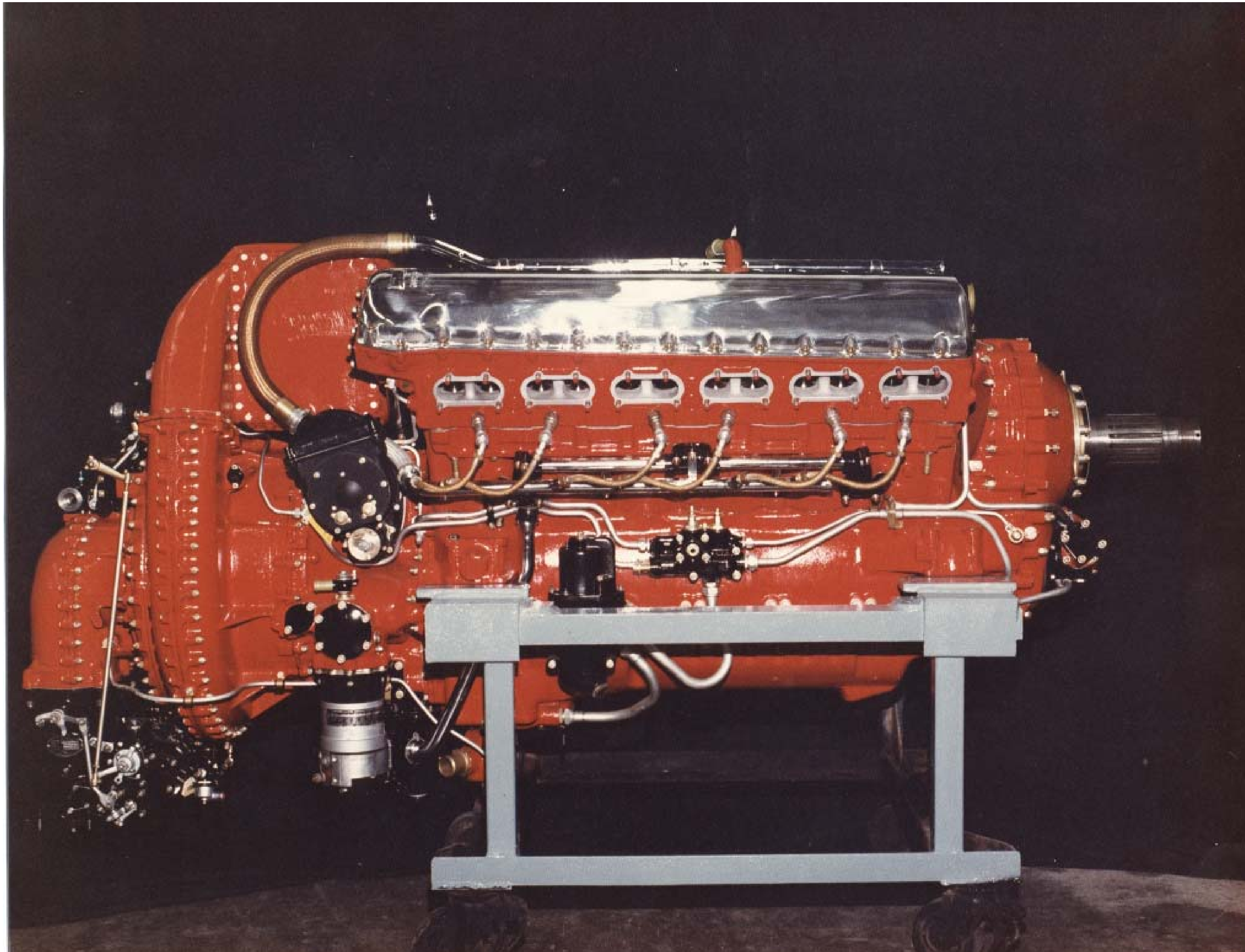
# COOLING LOADS – SPRAY BAR & BOILING SYSTEMS

| Engines | Shaft Output, BHP | Cooling Load, Horsepower | Cooling Load, BTU/min | Spray Water Req'd, GAL/Min, (8080 BTU/GAL) | Boiler ADI Req'd, GAL/Min, (5900 BTU/GAL) | Used By |
|---|---|---|---|---|---|---|
| **Oil Cooling Requirements-Approximate** | | | | | | |
| Merlin | 2800 | 140 ( 5%) | 5,940 | 0.74 | 1.00 | *Stiletto* |
| Griffon | 3200 | 160 ( 5%) | 6,780 | 0.84 | 1.15 | *Red Barron* |
| R-2800 | 3200 | 320 (10%) | 13,570 | 1.68 | 2.30 | *CONQUEST* |
| R-3350 | 3700 | 389 (11%) | 16,500 | 2.04 | 2.80 | *SEPTEMBER FURY* |
| R-4360 | 3800 | 383 (10%) | 16,250 | 2.00 | 2.75 | *SHOCKWAVE* |
| **Coolant Cooling Requirements-Approximate** | | | | | | |
| Merlin | 2800 | 840 (30%) | 35,620 | 4.41 | 5.40 | *Stiletto* |
| Griffon | 3200 | 1120 (35%) | 47,490 | 5.88 | 8.05 | *Red Barron* |
| **Aftercooler Coolant Cooling Requirements-Approximate** | | | | | | |
| Merlin | 2800 | 140 ( 5%) | 5,940 | 0.74 | 1.00 | *Stiletto* |
| Griffon | 3200 | 160 ( 5%) | 6,780 | 0.84 | 1.15 | *Red Barron* |

**Cylinder Head and Barrel Cooling-Radials**

At high power some radials use 2.0 GPM of water spray on cylinders

Examples are: R-4360-63A Powered Racers "*Dreadnought*", "*Super Corsair*", "*Furias*"



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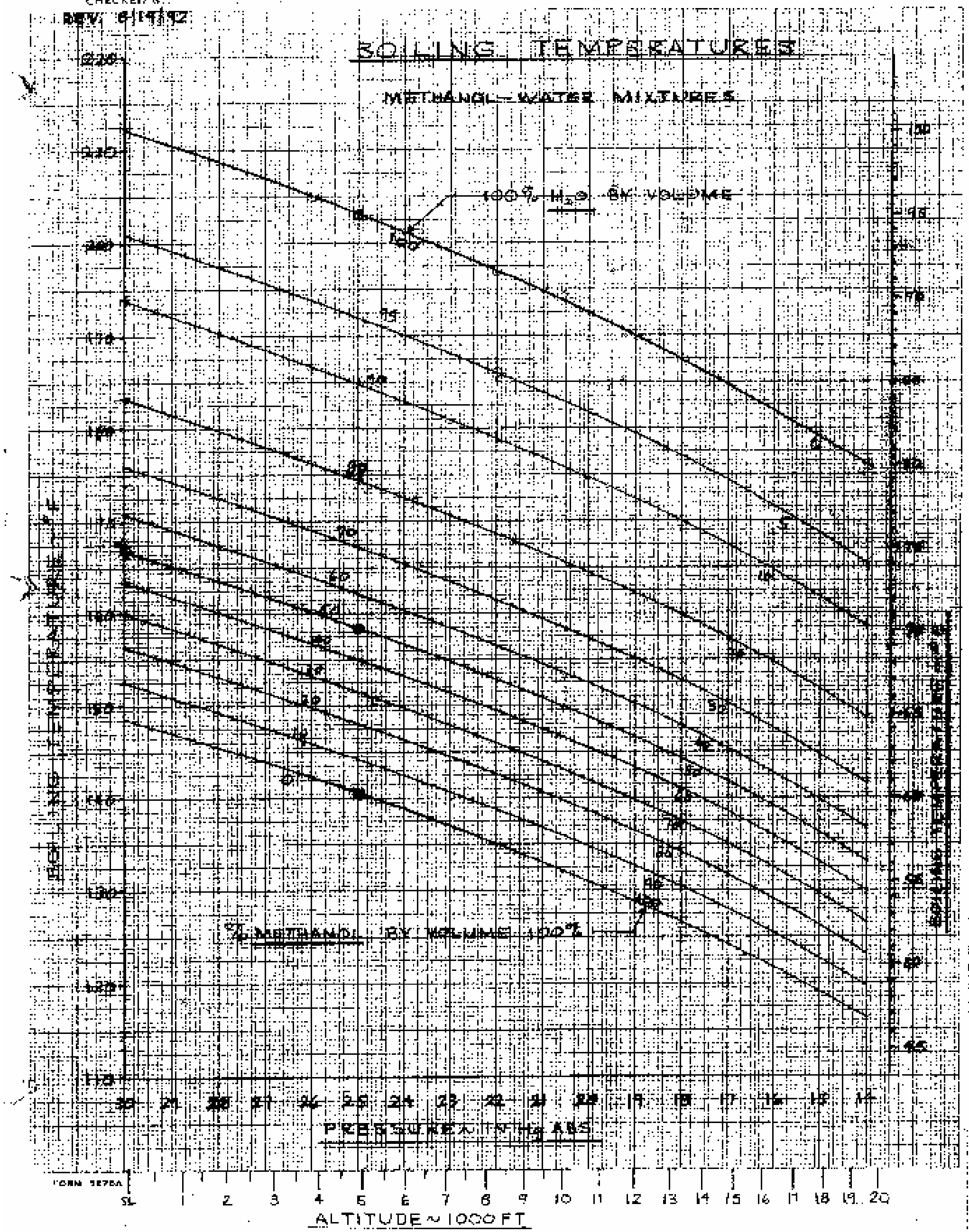

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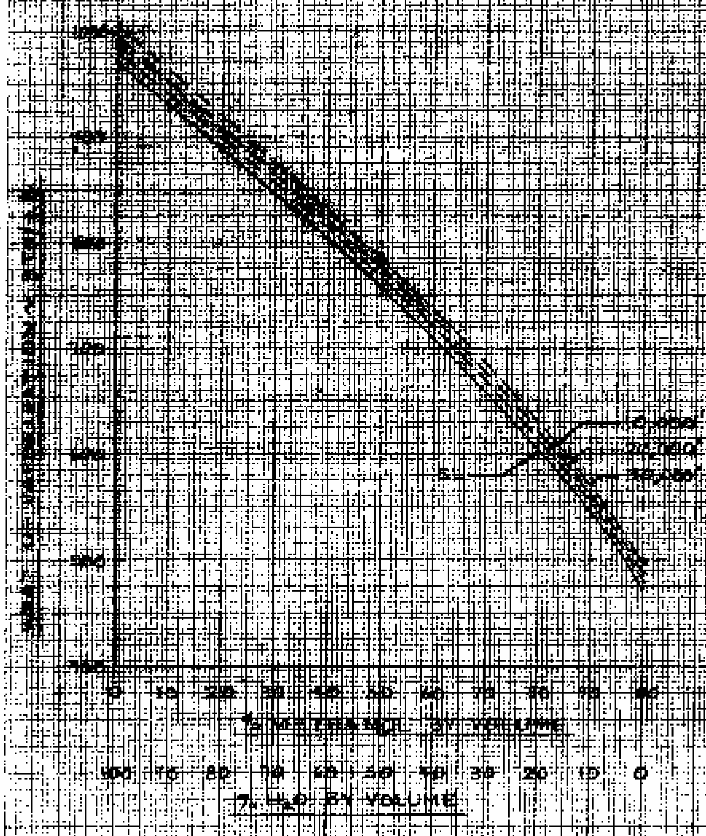
# BOILING HEAT OF VAPORIZATION: METHANOL + $H_2O$

% BY VOLUME



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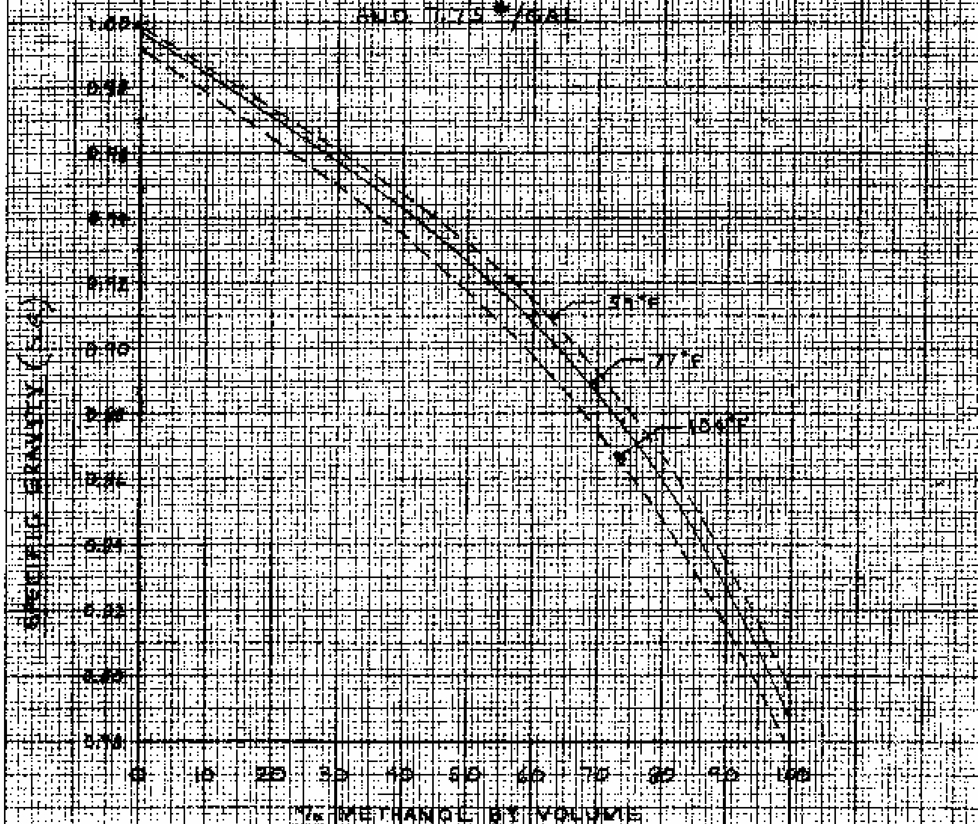
# SPECIFIC GRAVITY OF METHANOL-WATER

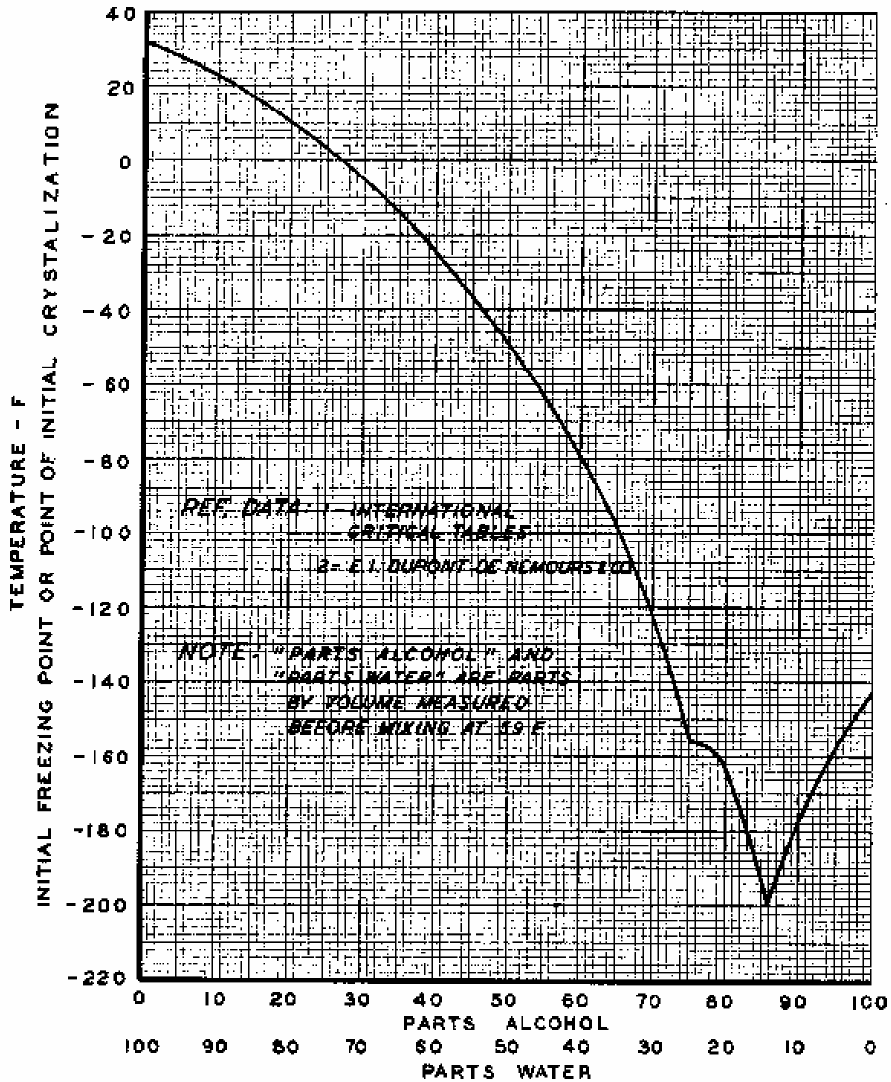
MIXTURE IS BY % OF VOLUME

BASED ON SG=1.000 $H_2O$ @ 4°C

WATER ($H_2O$) IS 62.4#/FT³ @ 57°F, 8.33#/GAL

MULTIPLY SPECIFIC GRAVITY OF MIXTURE BY 62.4#/FT³ OR 8.33#/GAL TO OBTAIN VALUES FOR THE MIXTURE. (FOR 50%-50% BY VOLUME, USE S.G.=0.93 @ 68°F, 50 "AIR" IS 58.0#/FT³ AND 7.75#/GAL






## FREEZING POINTS FOR MIXTURES OF METHYL ALCOHOL AND WATER

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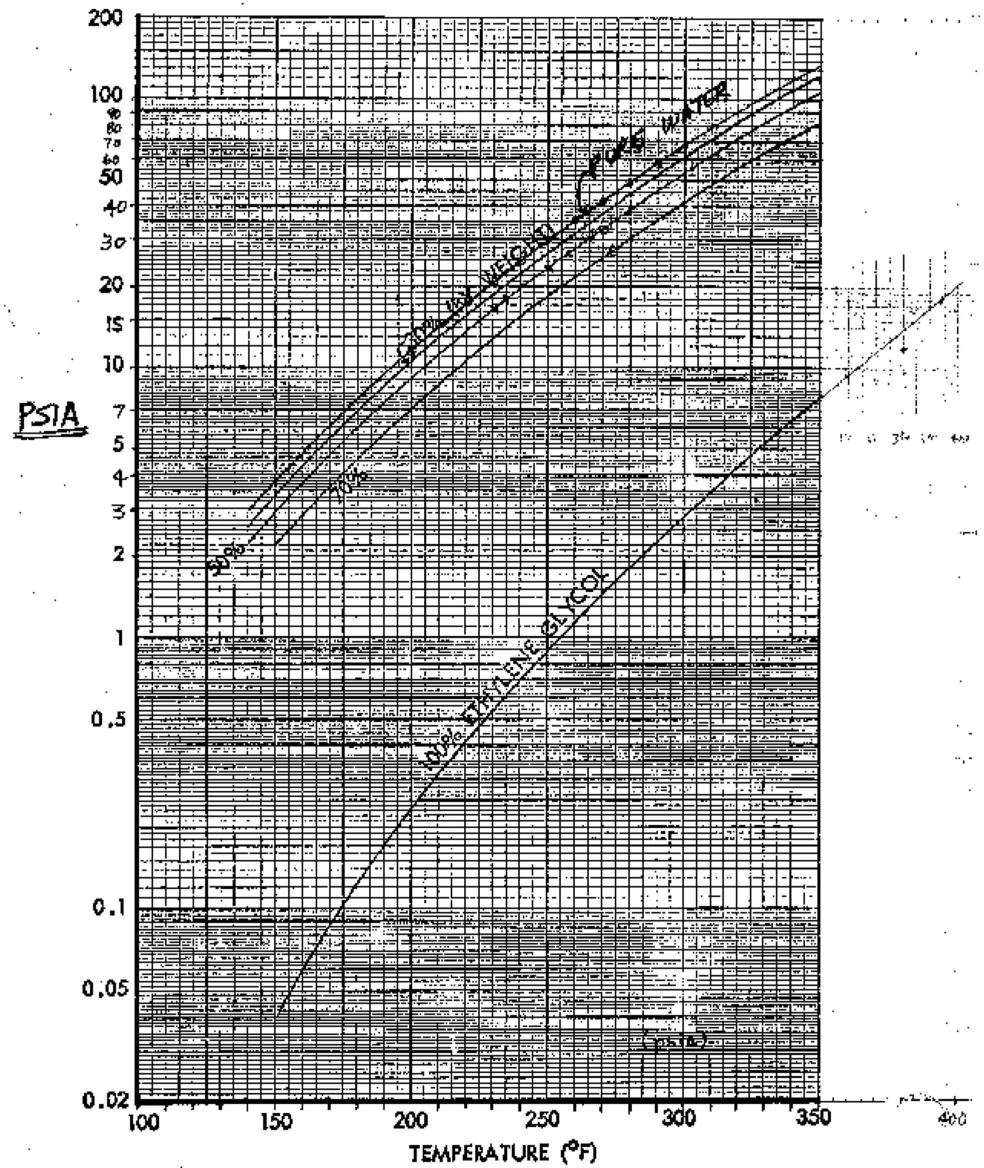
VAPOR PRESSURE OF AQUEOUS ETHYLENE GLYCOL SOLUTIONS

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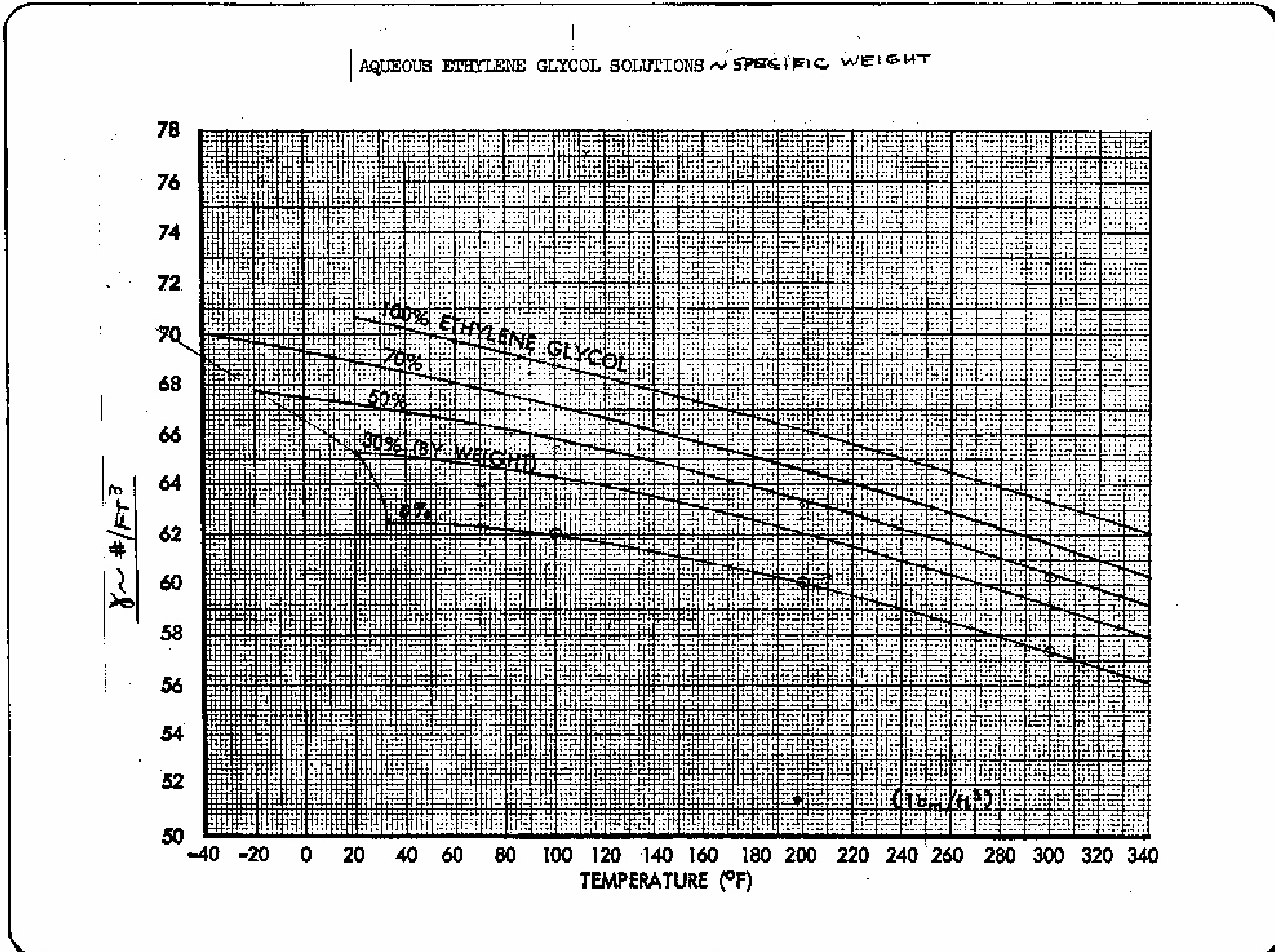


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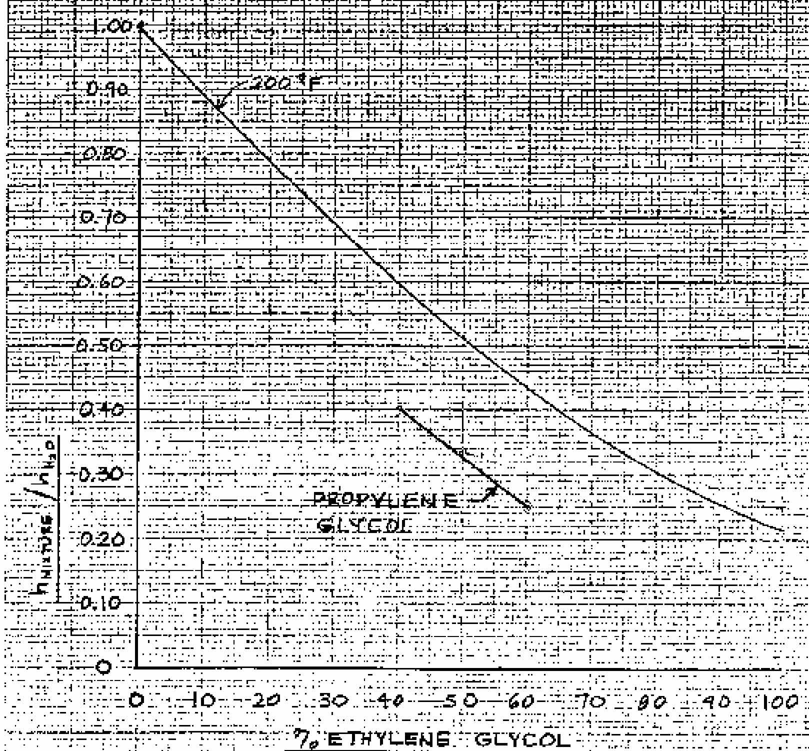
# COMPARISON BETWEEN HEAT TRANSFER OF PURE WATER AND ETHYLENE-GLYCOL-WATER MIXTURES IN HEAT EXCHANGERS AND OVER SURFACES

$$h = f(\rho, C_p, k, \mu)$$

$\rho$ ~ DENSITY
$C_p$ ~ SPECIFIC HEAT
$k$ ~ CONDUCTIVITY
$\mu$ ~ VISCOSITY



# Cooling Systems For Custom Engineered Unlimited Racing Aircraft

Presented on April 21, 1974 by Peter V. Law at an air racing symposium

## I. General Cooling System Information

A. Systems That Require Cooling
   1. Engine coolant: for liquid cooled engines (V-1650, V-1710, automotive)
   2. Engine aftercooling (or intercooling): for after cooled engine (V-1650)
   3. Engine oil: for all engines (including automotive type)

B. Types of Cooling systems
   1. Ram air cooling: direct transfer of heat to ram air (engine coolant and oil radiators)
   2. Intermediate ram air cooling: circulation of an intermediate fluid between ram air and fluid cooled (example is aftercooler and aftercooler radiator)
   3. Surface cooling: surface of aircraft used as heat transfer surface
   4. Boiling: heat is transferred away by boiling of an expendable fluid (water, or alcohol, or ADI)
   5. Auxiliary injection cooling: spray bars (spraying expendable water or ADI into ram air to increase cooling capability)
   6. Engine injection: ADI, or nitrous oxide to cool engine air charge

C. Types of Coolers
   1. Tube-fin radiators: horizontal thin plates, with many vertical tubes (very efficient cooler; moderate cost)
      a) coolant radiators from P-39, P-51, P-63
      b) radiators from cars, trucks, tractors
   2. Bundled-tube radiators: airflow through round tubes, fluid flow across tubes (moderately efficient cooler; moderate cost)
      a) coolant radiators from P-38, P-40
      b) oil radiators from all aircraft (DC-3, DC-4, DC-6, DC-7, Connies, P-38, P-39, P-40, P-51, P-63, etc.)
      c) hydraulic oil radiators from some aircraft (Connie)
   3. Plate-fin heat exchanges: fins on both fluid surfaces (most efficient type of cooler; expensive)
      a) automotive heaters and oil coolers
      b) jet fighters of all types

D. Materials of Coolers
   1. Copper and brass - (most efficient, heavy, expensive)
   2. Aluminum - (efficient, light, expensive)
   3. Stainless steel - (efficient, heavy, expensive)

E. Manufacturers of Coolers
   1. Airesearch, Torrance, California
   2. Harrison, Lockport, New York
   3. Hamilton Standard, Windsor Locks, Connecticut
   4. United Aircraft Products, Dayton, Ohio
   5. Stewart-Warner, Indianapolis, Indiana

6. Liberty Radiator, San Francisco, California
7. Hughes-Treitler, Garden City, New York (new addition)
8. Niagara Development and Manufacturing, Niagara Falls, New York (new addition)

## II. General Design Considerations

A. Design System for a Defined Flight Condition
   1. Speed desired: usually the highest speed sizes the system
   2. Altitude
   3. Ambient temperature
   4. Horsepower output
   5. Duration of high-speed operation

B. Design System for Required Cooling

C. Design System for Minimum Drag
   1. Drag due to taking air on board - drag is lost horsepower
   2. Drag due to being out of streamlined contour
   3. Drag due to weight

D. Design System from Standpoint of:
   1. Being simple
   2. Being practical and reliable
   3. Ease of installation
   4. East of maintenance
   5. Cost: initial and upkeep
   6. Weight and size

## III. Specific Design Analysis

A. Preliminary Design
   1. Choose a speed, altitude, ambient temperature, and flight duration
   2. Choose an engine for horsepower range to obtain speed
   3. Find engine heat rejected to coolant, oil, and aftercooler or intercooler at high speed
   4. Find engine heat rejected at other power settings:
      a) ground idle and taxi
      b) takeoff and climb power
      c) METO power
      d) cruise power
   5. Determine engine fluid temperature limits

B. System Design (for each type of cooling system: coolant, oil, etc.)
   1. Choose an effective type of cooler which requires minimum airflow (tube-fin most reasonable): use existing cooler if possible
   2. Choose coolant fluid compatible with engine fluid temperatures
   3. Size cooler for maximum heat to be removed
   4. Determine cooling air temperature and pressure available for cooling (Note: on an 80°F day at 500 mph, temperature of air available for cooling is 125°F due to ram effect of high speed)

5. Determine airflow necessary for cooling required at various power settings mentioned in A-3 and A-4 above
6. Determine amount of secondary injection fluid (spraybar water, ADI, etc.) required at various power settings
7. Size cooler for power setting near METO power without auxiliary fluid cooling. Check to see if ram air plus auxiliary fluid cooling will work at sustained high power (minimize drag)
   a) keep core of cooler dense (fins and tubes close together)
   b) tube size is important: fluid side heat transfer area must be adequate for proper heat rejection
   c) number of fins important to yield proper airside heat transfer area
   d) fluid flow rates: high enough to transfer rejected heat from engine to coolers (choose adequate pumps)
8. Size air inlet scoop for airflow required near METO power and check that sufficient airflow is available at high speed.
   a) inlet size should be large enough to supply required airflow
   b) size for optimum inlet design parameters (inlet air mass-flow ratio) to reduce drag
   c) inlet lip radius and external air diffusion angle should be optimized to reduce spillage drag
9. Size air exit for minimum back pressure and drag
   a) optimize exit area for minimum back pressure
   b) use adjustable control doors if necessary
   c) keep doors in aerodynamically faired position to reduce drag

C. Component Design
1. Design components to meet system requirements
2. Design tanks to hold expendable fluids (water, ADI, etc.) with an adequate reserve
3. Design reservoirs and venting system to be compatible with maximum speed operation
4. Select pumps that operate far from the cavitation region for temperatures expected at the pump inlet (Choose fluids whose boiling points are well above temperature expected, unless expendable fluid boiling is design criteria)

D. Instrumentation
1. Install adequate instruments for both flight test and normal flight
   a) use inflight cameras for recording if possible
   b) use radio communication for relay of data
2. Record enough temperatures and pressures to know systems are functioning as expected
3. Keep accurate flight records as to time, place, altitude, ambient temperatures, equipment configurations, speeds, and other data useful for reference. Keep track of initial and final fuel and other fluid quantities

The procedures outlined in this presentation can be used to design other systems in the aircraft.