TABLE I. - ADVANCED AUTOMOTIVE GAS TURBINE CONCEPTS

| Detroit Diesel Allison - Pontiac | Ford - AiResearch | Chrysler - Williams Research |
|---|---|---|
| Two shaft with power transfer | Single shaft | Single shaft |
| Centrifugal compressor with variable inlet guide vanes (VIGV) | Centrifugal compressor with VIGV and variable diffuser | Centrifugal compressor with VIGV |
| Premixed-prevaporized, varible-geometry ceramic combustor | Premixed-prevaporized, varible-geometry ceramic combustor | Premixed-prevaporized or catalytic ceramic combustor |
| Ceramic rotating regenerator | Ceramic rotating regenerator | Dual ceramic rotating regenerators |
| Ceramic radial turbines | Ceramic radial turbine | Ceramic radial turbine |

TABLE II. - COMBUSTOR OPERATING PARAMETERS

| | Overall fuel-air ratio range | | Flow parameter, $w \sqrt{T}/P^a$ | | Pressure drop, $\%(\Delta P/P)$ | |
|---|---|---|---|---|---|---|
| | Maximum | Minimum | Maximum | Minimum | Maximum | Minimum |
| Current turbines - no variable-geometry combustor | | | | | | |
| Upgraded engine | 0.01 | 0.003 | 0.67 | None | 2 | None |
| CATE (1406 K) | .013 | .003 | 1.7 | None | —— | None |
| Advanced turbines - variable-geometry combustor | | | | | | |
| AiResearch | 0.014 | 0.003 | 0.40 | 0.33 | 3 | None |
| Detroit Diesel | .014 | .003 | .38 | .19 | 2.5 | 1.7 |
| Stirling engines - no variable-geometry combustor | | | | | | |
| Ford (with exhaust gas recirculation) | 0.55 | None | 0.82 | 0.12 | 5 | 0.06 |
| P-40 (with combustor gas recirculation) | .55 | 0.04 | —— | —— | 5 | .06 |

[a] Where w is weight flow in kg/sec; T is temperature, and P is pressure.

TABLE III. - REPRESENTATIVE COMBUSTOR OPERATING LIMITS

| | |
|---|---|
| Flame temperature, K: | |
| Maximum $NO_x$ limit | 1920 |
| Minimum CO/HC limit | 1310 |
| Primary-zone, lean-stability-limit fuel-air ratio | ~0.020 |

## TABLE IV. - ASTM D2880-78 TRACE-METAL LIMITS FOR FUEL ENTERING TURBINE COMBUSTORS

[From ref. 24.]

| ASTM fuel designation | Vanadium | Sodium plus potassium | Calcium | Lead |
|---|---|---|---|---|
| | Trace-metal limits (maximum), ppm by weight | | | |
| 0-GT | 0.5 | 0.5 | 0.5 | 0.5 |
| 1-GT | ↓ | ↓ | ↓ | ↓ |
| 2-GT | ↓ | ↓ | ↓ | ↓ |
| 3-GT | ↓ | ↓ | ↓ | ↓ |
| 4-GT | (a) | (a) | (a) | (a) |

[a]Consult turbine manufacturers.

## TABLE V. - TEXACO REFINERY STUDY

[From ref. 34. Refinery charging 100 000 barrels per calendar day of crude oil, maximum transportation fuel production.]

| | Case | | | |
|---|---|---|---|---|
| | A (base case) | B (Research octane number, 91; motor octane number, 83) | C (maximum diesel) | D (maximum, 100°-650° F) |
| | Yield, barrels per calendar day | | | |
| Refinery fuel: | | | | |
| Fuel gas | 1 461 | 1 649 | 1 172 | 975 |
| Propane and propylene | 191 | 2 420 | 88 | ——— |
| No. 6 fuel oil | 4 526 | 3 568 | 4 150 | 4 005 |
| Fluid-coking coke (400 lb/barrel) | 1 575 | 1 652 | 1 094 | 1 041 |
| Subtotal | 7 753 | 9 289 | 6 504 | 6 021 |
| Transport fuels: | | | | |
| Premium gasoline | 20 910 | ——— | 18 389 | ——— |
| Regular gasoline | 33 944 | ——— | 29 853 | ——— |
| Lead-free gasoline | ——— | 52 759 | ——— | ——— |
| Diesel fuel | 10 131 | 10 131 | 17 349 | 10 131 |
| 100°-650° F end-point fuel | ——— | ——— | ——— | 56 609 |
| Subtotal | 64 985 | 62 890 | 65 591 | 66 740 |
| Protected products: | | | | |
| Aviation jet fuel | 9 100 | 9 100 | 9 100 | 9 100 |
| Home heating oil | 13 651 | 13 651 | 13 651 | 13 651 |
| Petrochemicals and special naphthas | 3 400 | 3 400 | 3 400 | 3 400 |
| Lubrication oils and wax | 1 800 | 1 800 | 1 800 | 1 800 |
| Asphalt and road oils | 3 300 | 3 300 | 3 300 | 3 300 |
| Subtotal | 31 251 | 31 251 | 31 251 | 31 251 |
| Other fuels (coke, liquefied petroleum gas, and #4, #5, #6 fuel oils) | 8 392 | 8 561 | 8 378 | 8 388 |
| Total | 112 381 | 111 991 | 111 724 | 112 400 |

[redacted]

TABLE VI. - REFINERY YIELD

[From ref. 34.]

| Case | Transportation fuels output, barrels/day | Energy required at refinery, Btu/barrel |
|---|---|---|
| A | 64 985 | 502 000 |
| B | 62 890 | 575 000 |
| C | 65 591 | 433 000 |
| D | 66 740 | 376 000 |

TABLE VII. - COMPARISON OF PETROLEUM AND SYNTHETIC CRUDE OIL CHARACTERISTICS

[From ref. 36.]

| | Distillation yields | | | | | | | | | Gravity, °API |
|---|---|---|---|---|---|---|---|---|---|---|
| | Gasoline, C5-400° F, vol % | Kerosene, 400°-525° F, vol % | Heating oil, 525°-650° F, vol % | Fuel oil, 650°-975° F, vol % | Residuum 975° F+, vol % | Sulfur, wt % | Hydrogen, wt % | Oxygen, wt % | Nitrogen, wt % | |
| East Texas crude | 40 | 14 | 12 | 20 | 14 | 0.33 | 14 | --- | 0.09 | 38 |
| H-Coal syncrude | 37 | 26 | 17 | 20 | -- | .19 | 10.9 | 0.6 | .1 | 23 |
| SRC-1 | 10 | --- | 12 | 6 | 72 | .4 | 6.6 | 3.5 | 1.8 | -6 |

TABLE VIII. - ELEMENTAL ANALYSIS OF DRY SHALE OILS

[From ref. 41.]

| Shale | Carbon | Hydrogen | Nitrogen | Sulfur | Oxygen[a] | Carbon-hydrogen ratio |
|---|---|---|---|---|---|---|
| | Elemental analysis, wt % | | | | | |
| Lean Colorado | 84.1 | 12.1 | 1.56 | 0.37 | 1.67 | 6.95 |
| Average Colorado | 84.3 | 11.8 | 2.00 | .66 | 1.24 | 7.14 |
| Rich Colorado | 84.2 | 12.0 | 1.76 | .83 | 1.21 | 7.02 |
| Utah | 84.7 | 12.0 | 2.09 | .62 | .59 | 7.06 |
| Antrim (Michigan) | 83.8 | 10.6 | .74 | 1.83 | 3.03 | 7.91 |
| Moroccan | 80.7 | 10.8 | 1.45 | 7.11 | [b]-0.06 | 7.32 |

[a] Determined by difference.
[b] High values for one or more of the other determinations.

TABLE IX. - PROPERTIES OF DISTILLATES FROM PARAHO SHALE OIL

[From ref. 37.]

| Property | Naptha | | | | Middle distillation | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Kerosene | | | | | | Heavy oils | | | |
| | Temperature, K | | | | | | | | | | | |
| | 347-367 | 378-411 | 411-444 | 444-467 | 467-522 | 522-544 | 544-588 | 588-617 | 617-644 | 644-672 | 672-700 | 700-722 |
| Cumulative middle distillates, vol % | 0,66 | 1.61 | 2.62 | 3,65 | 8.07 | 14.10 | 20.92 | 28.27 | 34.52 | 41.68 | 50.36 | 61.33 |
| Crude, vol % | 0,97 | 0.93 | 1.09 | 0.97 | 7,87 | 4.20 | 9.43 | 5.28 | 7.22 | 7.10 | 10,25 | 11.70 |
| Cumulative crude, vol % | 1.14 | 2.07 | 3.16 | 4.13 | 12.00 | 16.20 | 25.63 | 30.91 | 38.13 | 45.23 | 55.48 | 67.18 |
| Gravity, °API | 35.6 | 38.0 | 38.1 | 34.9 | 31.7 | 28.9 | 27.4 | 23.6 | 22.2 | 19.7 | 19.0 | 17.7 |
| Specific gravity at 60° F | 0.8468 | 0.8348 | 0.8343 | 0.8504 | 0.8670 | 0.8822 | 0.8905 | 0.9123 | 0.9206 | 0.9358 | 0.9402 | 0.9484 |
| ASTM D-86 distillation, °F: | | | | | | | | | | | | |
| Initial boiling point | 175 | 200 | 180 | 330 | 398 | 462 | 522 | 562 | 608 | 561 | 556 | 554 |
| 10 Percent | 196 | 235 | 293 | 348 | 412 | 477 | 530 | 589 | 640 | 694 | 769 | 809 |
| 30 Percent | 206 | 256 | 315 | 352 | 420 | 482 | 540 | 595 | 642 | 707 | 782 | 822 |
| 70 Percent | 218 | 273 | 322 | 356 | 426 | 487 | 546 | 601 | 646 | 716 | 785 | 828 |
| 80 Percent | 236 | 288 | 330 | 360 | 436 | 491 | 551 | 605 | 650 | 722 | 791 | 835 |
| 90 Percent | 270 | 306 | 340 | 370 | 452 | 499 | 564 | 616 | 664 | 728 | 799 | 841 |
| Final boiling point | 296 | 324 | 364 | 388 | 472 | 517 | 580 | 628 | 688 | 734 | 806 | 849 |
| Amount recovered, percent | 96.0 | 97.0 | 97.0 | 96.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 95.0 | 98.0 | 98.0 |
| Amount residual, percent | 4.0 | 3.0 | 3.0 | 4.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 5.0 | 2.0 | 2.0 |
| Vanadium content, ppm | ------ | ------ | ------ | ------ | ------ | ------ | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Nickel content, ppm | ------ | ------ | ------ | ------ | ------ | ------ | 0.04 | 0.04 | 0.03 | 0.04 | 0.19 | 0.24 |
| Iron content, ppm | ------ | ------ | ------ | ------ | ------ | ------ | 2.7 | 2.7 | 0.71 | 1.3 | 9.7 | 21.0 |
| Viscosity at 100° F, cS | ------ | ------ | ------ | ------ | ------ | ------ | 6.07 | 11.09 | 23.03 | 41.2 | 110 | 360 |
| Viscosity at 100° F, SUS | ------ | ------ | ------ | ------ | ------ | ------ | 45.8 | 62.7 | 110.9 | 192.2 | 510 | 1668 |
| Viscosity at 210° F, cS | ------ | ------ | ------ | ------ | ------ | ------ | 1.67 | 2.38 | 3.42 | 4.88 | 6.50 | 7.37 |
| Viscosity at 210° F, SUS | ------ | ------ | ------ | ------ | ------ | ------ | ------ | 34.1 | 37.6 | 42.3 | 47.5 | 50.3 |
| Total sulfur content, wt % | 1.93 | 1.67 | 1.45 | 1.15 | 0.96 | 0.91 | 0.75 | 0.78 | 0.73 | 0.72 | 0.64 | 0.55 |
| Mercaptan sulfur content, ppm | 140 | 10 | 100 | 20 | 60 | 40 | 60 | 30 | 19 | 36 | 52 | 68 |
| Total nitrogen content, wt % | 0.10 | 0.57 | 1.24 | 1.62 | 1.15 | 1.46 | 1.71 | 1.80 | 2.00 | 2.25 | 2.14 | 1.89 |
| Paraffin content, wt % | ------ | ------ | ------ | ------ | 3.04 | 33.4 | 36.3 | 31.2 | 33.8 | 26.8 | 24.1 | 19.7 |
| Naphthlene content, wt % | ------ | ------ | ------ | ------ | 16.6 | 18.6 | 19.7 | 20.8 | 15.2 | 16.2 | 27.9 | 37.3 |
| Aromatics content, wt % | ------ | ------ | ------ | ------ | 34.0 | 29.0 | 28.0 | 31.0 | 33.0 | 35.0 | 32.0 | 28.0 |
| Olefins content, wt % | ------ | ------ | ------ | ------ | 19.0 | 19.0 | 16.0 | 17.0 | 18.0 | 22.0 | 16.0 | 15.0 |

TABLE X. - PROPERTIES OF DISTILLATES FROM OCCIDENTAL SHALE OIL

[From ref. 37.]

| Property | Naphtha | | | Middle distillation | | | | | | | | Whole crude |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Kerosene | | | | Gas oils | | | | | |
| | Boiling range, °F | | | | | | | | | | | |
| | IBP-250 | 250-300 | 300-400 | 400-510 | 510-590 | 590-650 | 650-730 | 750-850 | 850-950 | 950-1050 | 1050+ residual | |
| Yield, vol % | ----- | 1.0 | 3.7 | 12.3 | 16.0 | 12.8 | 20.8 | 17.6 | 8.5 | 2.8 | 4.5 | 100 |
| Cumulative yield, vol % | ----- | 1.0 | 4.7 | 17.0 | 33.0 | 45.8 | 66.6 | 84.2 | 92.7 | 95.5 | 100.0 | 100 |
| Specific gravity | ----- | 0.814 | 0.821 | 0.848 | 0.876 | 0.885 | 0.911 | 0.920 | 0.939 | 0.980 | 1.059 | 0.904 |
| Sulfur content, wt % | ----- | 0.430 | 0.714 | 0.555 | 0.670 | 0.561 | 0.531 | 0.400 | 0.503 | 0.893 | 1.32 | 0.64 |
| Concentrated carbon content, wt % | ----- | ----- | ----- | ----- | ----- | ----- | 0.01 | 0.11 | 1.43 | 6.29 | 27.2 | ----- |
| Nitrogen content, wt % | ----- | ----- | ----- | 0.458 | 0.640 | 1.327 | 1.598 | 1.532 | 1.605 | 1.776 | 1.98 | 1.30 |
| Aniline point, °C | ----- | ----- | 29 | 42 | 46 | 51 | 53 | 62 | 58 | 46 | ----- | ----- |

TABLE XI. - STABILIZERS FOR METHANOL-GASOLINE BLENDS AT 70° F

[From ref. 37.]

| Blend composition | Stabilizer | Amount of stabilizer in blend, percent | Water added to haze point, percent |
|---|---|---|---|
| 10 Percent methanol in 37 percent aromatic gasoline | None | — | 0.17 |
| | sec-Butanol | 1 | .22 |
| | sec-Butanol | 3 | .35 |
| | Ethanol | 10 | .80 |
| | Methyl benzoate | 10 | .29 |
| | Dimethylphthalate | 10 | .35 |
| 20 Percent methanol in 28 percent aromatic gasoline | None | — | 0.24 |
| | Isopropanol | 5 | .62 |
| | n-Butanol | 5 | .79 |
| | Isobutanol | 5 | .91 |
| 17 Percent methanol in 37 percent aromatic gasoline | None | — | 0.3 |
| | tert-Butanol | 3 | .5 |
| | Methyl acetate | 3 | .5 |
| | Dimethoxyethane | 3 | .6 |
| | Tetramethylurea | 3 | .6 |

## TABLE XII. – WATER SENSITIVITY OF METHANOL-GASOLINE BLENDS

[From ref. 37.]

| Blend in gasoline | Aromatics content, percent | Water added to haze point, vol % | Temperature, °F |
|---|---|---|---|
| 10 Percent methanol | | | |
| Chevron U | 19 | 0.025 | 37 |
| | | .10 | 70 |
| Chevron S | 37 | .08 | 37 |
| | | .15 | 70 |
| Texaco G | 26 | .13 | Room |
| Texaco M | 32 | .16 | Room |
| 20 Percent methanol | | | |
| Chevron S | 37 | 0.1 | 37 |
| | | .3 | 70 |
| Texaco G | 26 | .23 | Room |
| Texaco M | 32 | .26 | Room |
| 30 Percent methanol | | | |
| Chevron S | 37 | 0.23 | 37 |
| | | .50 | 70 |
| Texaco G | 26 | .35 | Room |
| Texaco M | 32 | .38 | Room |

## TABLE XIII. – POTENTIAL ELECTRIC AND HYDROGEN-FUELED VEHICLES BASED ON EXISTING TECHNOLOGY

| Fuel storage | Storage fuel weight, lb | Equipment weight, lb | Vehicle test weight, lb | Range, miles |
|---|---|---|---|---|
| Advanced lead-acid battery | 1500 | — | 3975 | 52.9 |
| Fe-Ti hydride | 435 | 110 | 3010 | [a]50 |
| | 669 | 167 | 3330 | [b]52.9 |
| | 1736 | 436 | 4800 | [c]200 |
| Methanol reforming | 69 | 282 | 2805 | [d]50 |
| | 275 | 312 | 3055 | [c]200 |
| MCH-toluene | 321 | 330 | 3125 | [d]50 |
| | 965 | 400 | 3910 | [c]200 |
| Hydrogen liquid | 33 | 220 | 2710 | [c]200 |

[a] Nominal; equivalent to 5 gallons of gasoline plus a one-third increase in thermal efficiency.

[b] Based on same run time over driving cycle plus 2.65 kg $H_2$/hr.

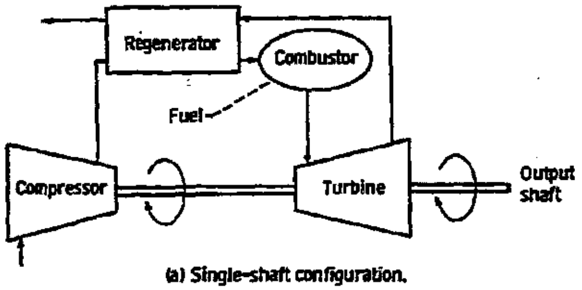
[c] Equivalent to 20 gallons of gasoline plus one-third increase in thermal efficiency.

[d] Equivalent gasoline not stated.

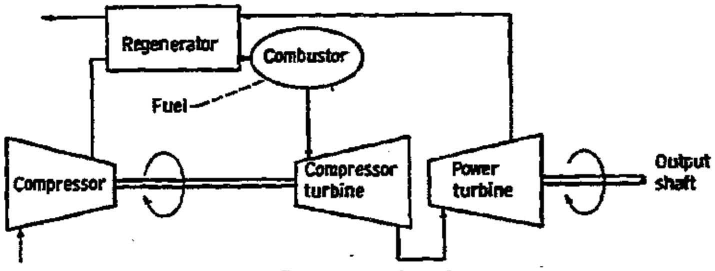
TABLE XIV. - PRELIMINARY FUEL REQUIREMENTS FOR AUTOMOTIVE GAS TURBINE AND STIRLING ENGINES

| Property | Allowable range |
|---|---|
| Viscosity at ambient temperature, cS | <10 |
| Boiling range, °C | ≤400 |
| Allowable hydrogen-carbon content | (a) |
| Aromatic content | (a) |
| Nitrogen content,[a] wt % | <0.08 |
| Ash content, wt % | <0.01 |
| Gum content, mg/milliliter | <7 |
| Sulfur content,[c] wt % | 0.5 |
| Mercaptan content,[c] wt % | 0.003 |
| Vanadium content,[c] ppm by wt | 0.5 |
| Sodium and potassium content,[c] ppm by wt | 0.5 |
| Lead content,[c] ppm by wt | 0.5 |

[a] To be determined.
[b] Depends on combustor type, vehicle fuel economy, and emissions regulations.
[c] For all-metal engines; content for ceramic components to be determined, but will be greatly increased.



(a) Single-shaft configuration.



(b) Two-shaft configuration.

Figure 1. - Engine configurations for automotive gas turbines.

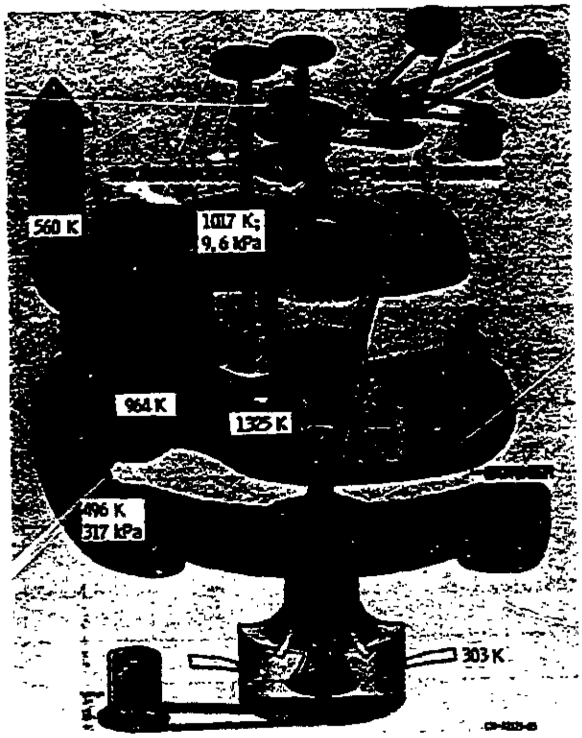


Figure 2. - Cutaway drawing of Chrysler upgraded engine.

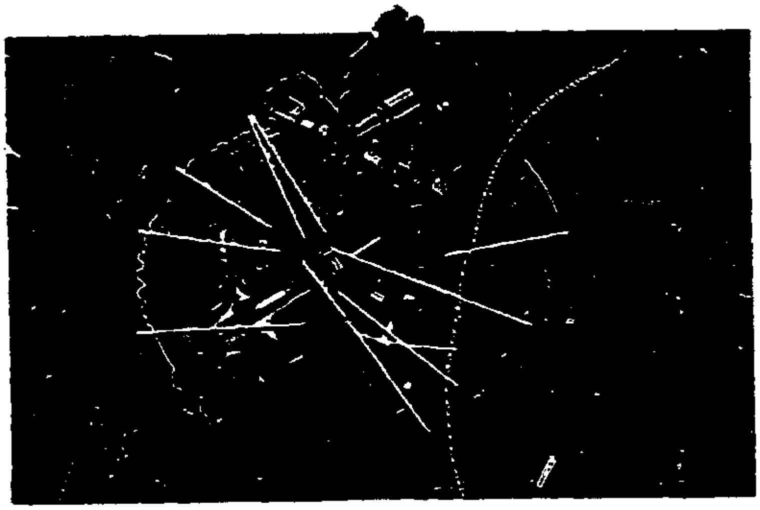


Figure 3. - Ceramic components used in Detroit Diesel Allison CATE program engine tests. (GT 404/505-4 engine; from ref. 3.)

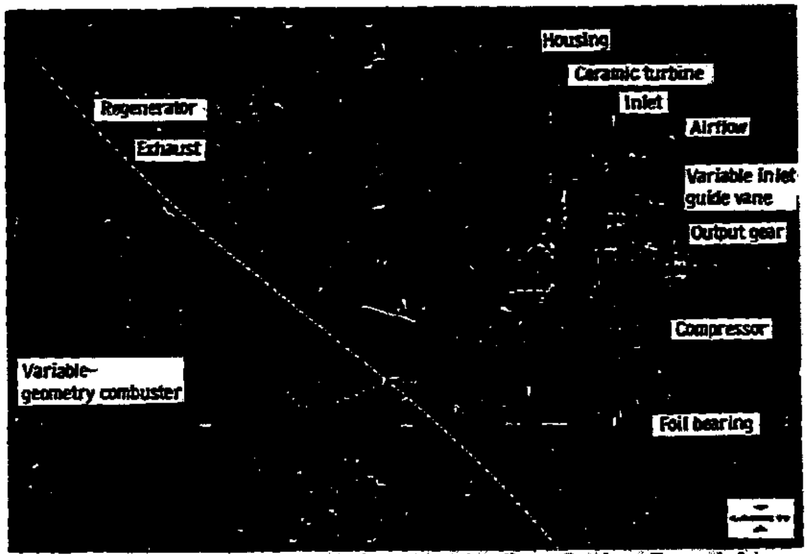


Figure 4. - Cutaway drawing of Ford-AiResearch automotive gas turbine. (From ref. 4.)

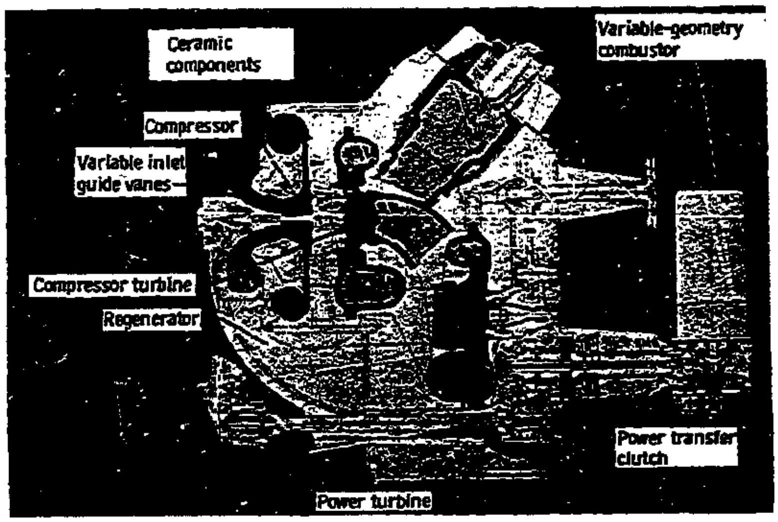


Figure 5. - Cutaway drawing of Detroit Diesel Allison automotive gas turbine. (From ref. 5.)

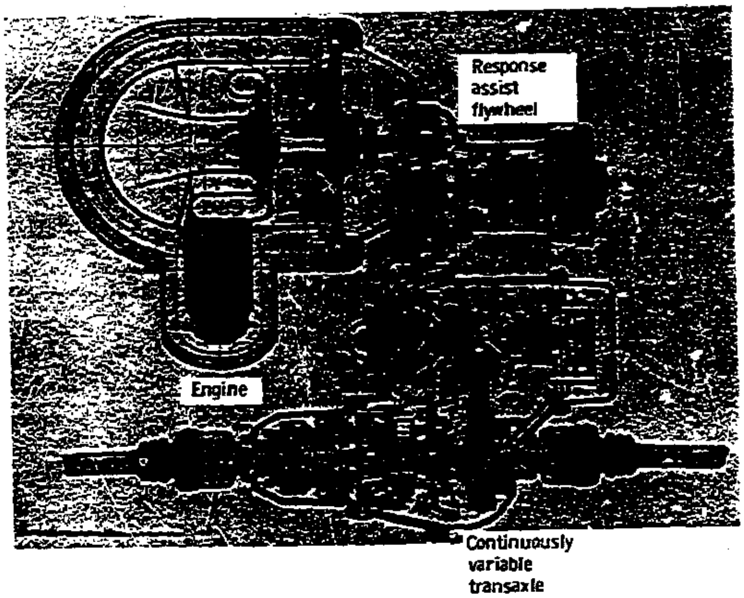
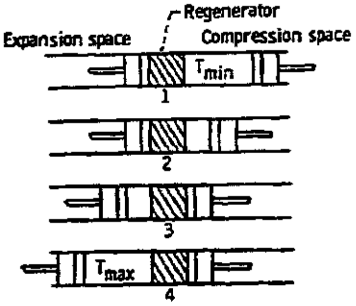
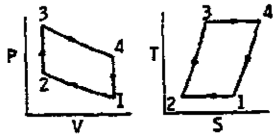


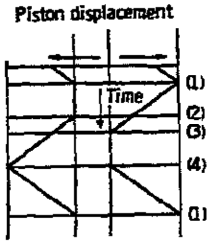
Figure 6. - Cutaway drawing of Chrysler automotive gas turbine.



(a) Piston arrangement and terminal points of cycle.



(c) Pressure-volume and temperature-entropy diagrams.



(b) Time-displacement diagram.

| Process | Description |
|---|---|
| 1-2 | Isothermal compression; heat transfer from working fluid at $T_{min}$ to external dump |
| 2-3 | Constant volume; heat transfer to working fluid from regenerative matrix |
| 3-4 | Isothermal expansion; heat transfer to working fluid at $T_{max}$ from an external source |
| 4-1 | Constant volume; heat transfer from working fluid to regenerative matrix |

Figure 7. - The Stirling cycle. (From ref. 7.)

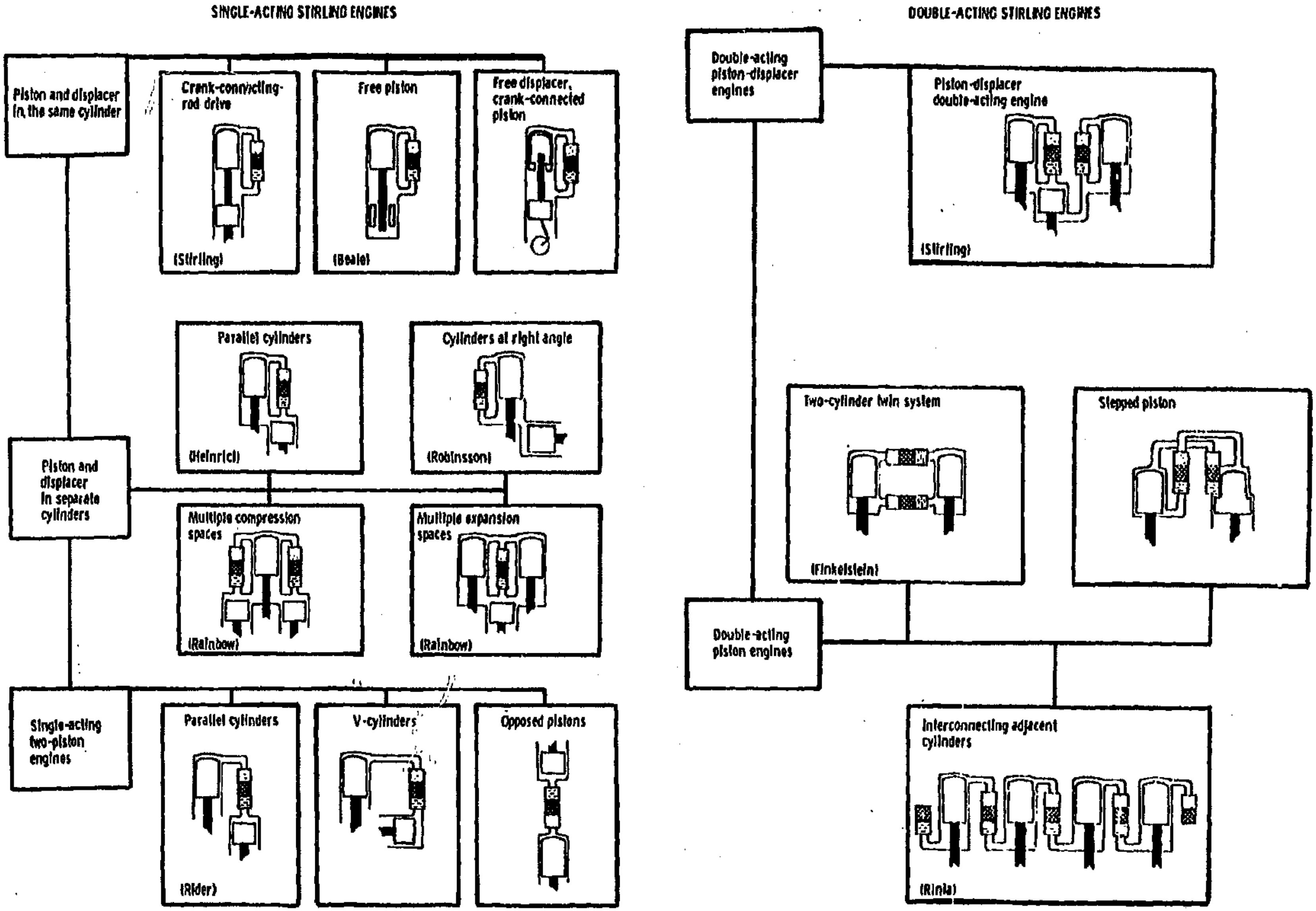
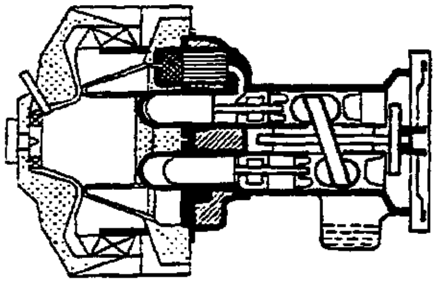
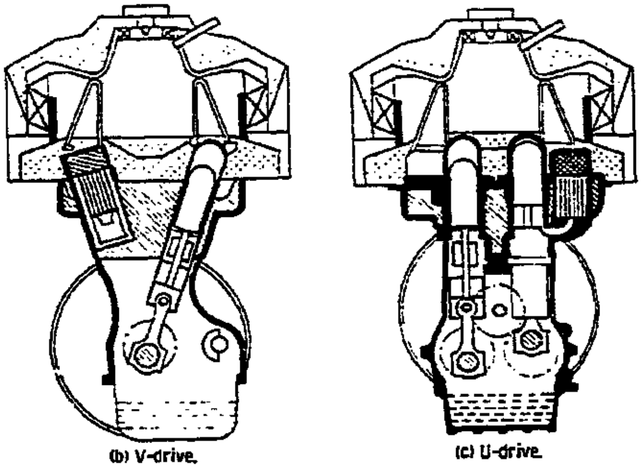


Figure 8. - Stirling engine cycle configurations. (From ref. 8.)



(a) Swashplate drive.



(b) V-drive.

(c) U-drive.

Figure 9. - Stirling engine mechanical arrangements.

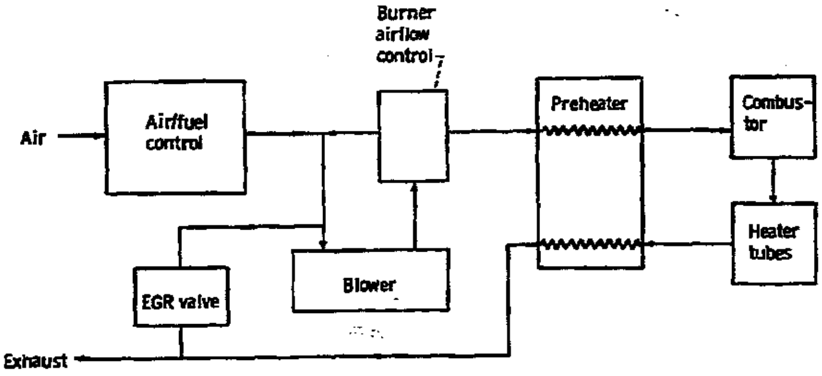


Figure 10. - Schematic of exhaust gas recirculation system.

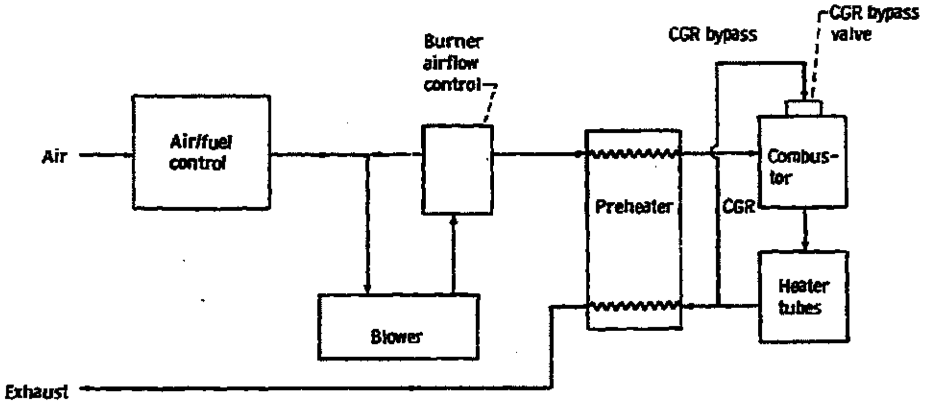


Figure 11. - Schematic of combustion gas recirculation system.

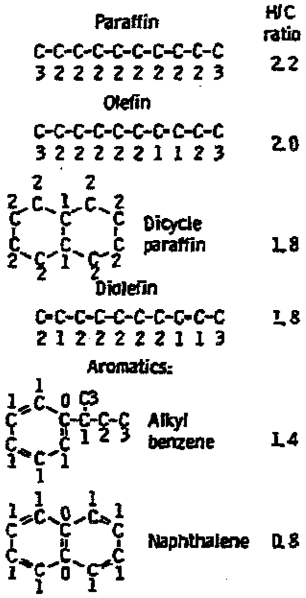


Figure 12. - Liquid hydrocarbons atomic H/C ratio for different structures containing 10 carbon atoms. (From ref. 29.)

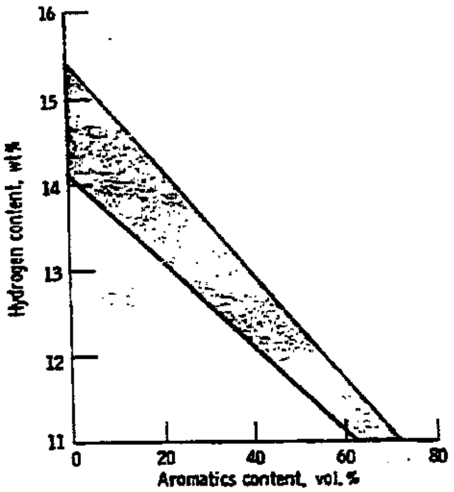


Figure 13. - Variation of hydrogen content with aromatics content. (From ref. 19.)

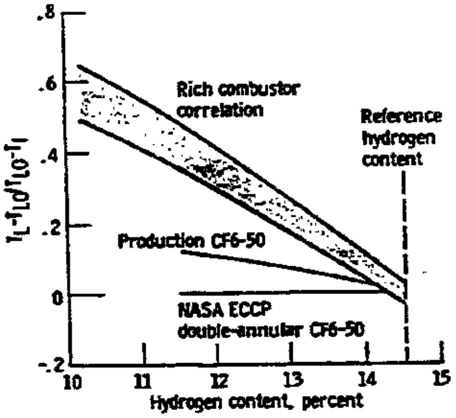


Figure 14. - Variation in maximum combustor liner temperatures with hydrogen content of fuel, where $T_L$ is maximum combustor liner temperature, $T_{LO}$ is maximum combustor liner temperature for a fuel with reference hydrogen content (14.5 percent), and $T_I$ is combustor inlet temperature. (From ref. 16.)

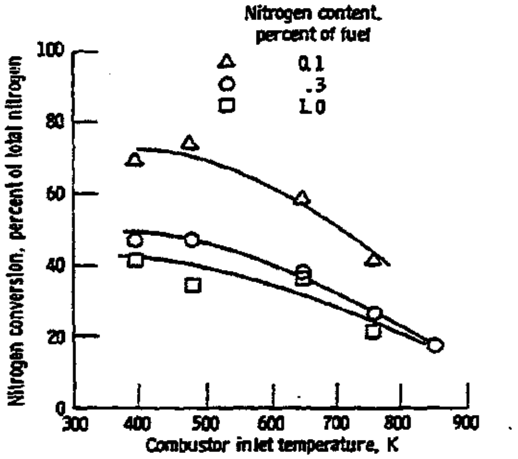


Figure 15. - Fuel-bound nitrogen conversion to $NO_x$ in an aircraft gas turbine combustor. (From ref. 18.)

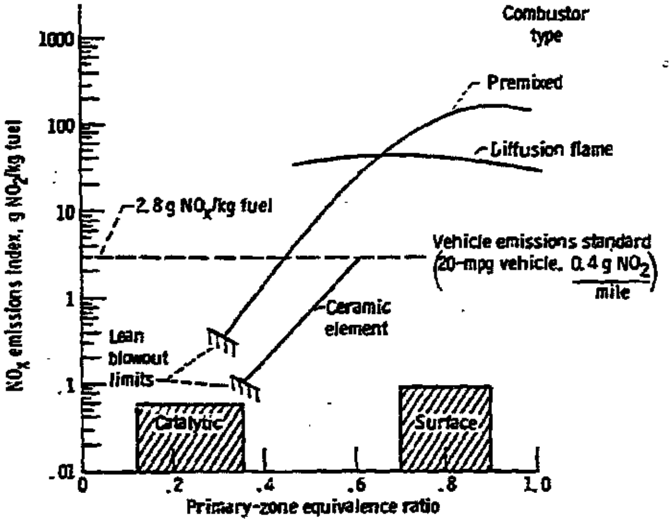


Figure 16. - Variation of $NO_x$ emissions index with combustor type. Combustor inlet temperature, 978 K (1300° F); petroleum distillate fuel. (From ref. 23.)

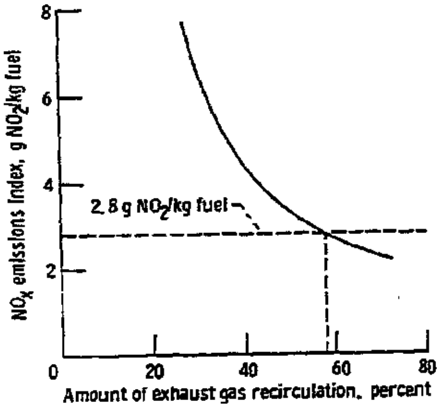


Figure 17. - Variation of $NO_x$ emissions index with amount of exhaust gas recirculation. P-40 no. 1 acceptance test: equivalence ratio, ~0.8; fuel flow, 0.7 to 3.8 g/sec.

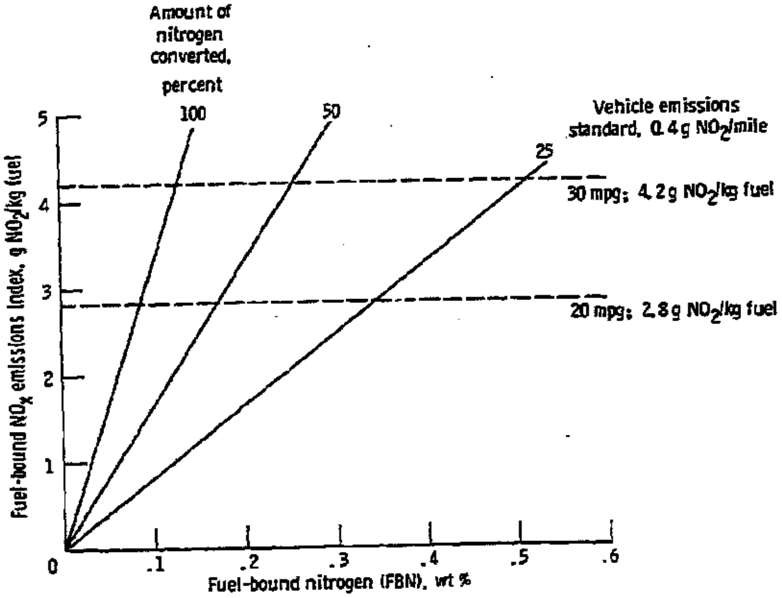


Figure 18. - Influence of fuel-bound nitrogen conversion rates on $NO_x$ emissions (no thermal $NO_x$). Emissions index, 32.85 x FBN x conversion.

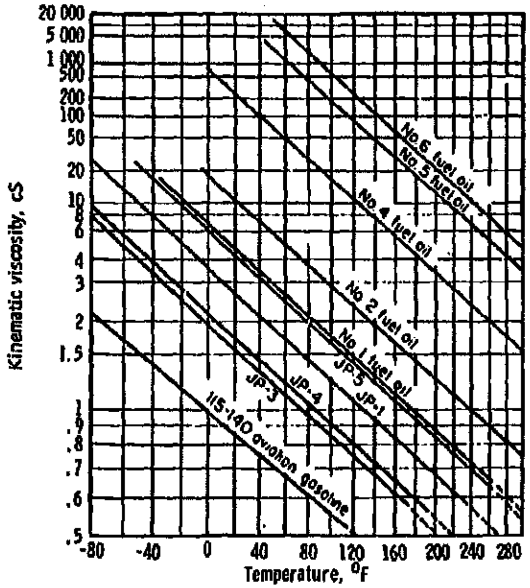


Figure 19. - Relation of viscosity to temperature for typical fuels. (From ref. 15.)

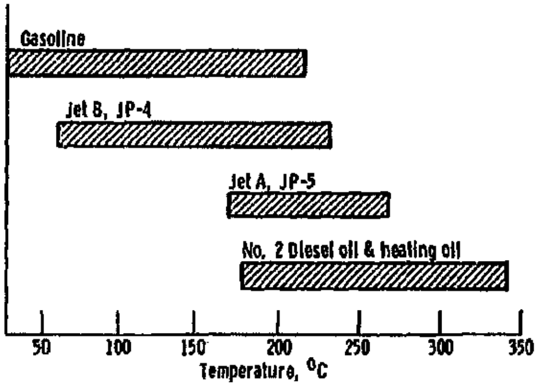


Figure 20. - Boiling range of various petroleum products. (From ref. 19.)

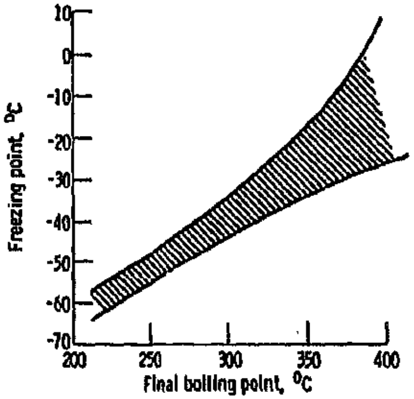


Figure 21. - Typical fuel blend freezing points. (From ref. 19.)

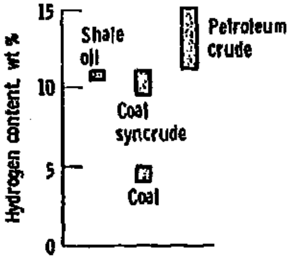


Figure 22. - Hydrogen content of alternative sources of jet fuel. (From ref. 19.)

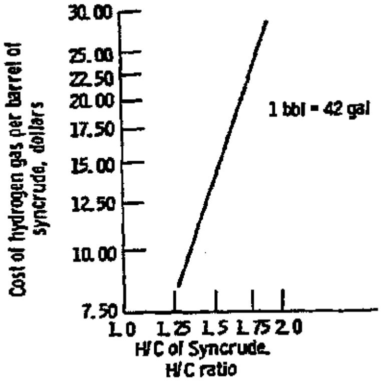


Figure 23. - Estimate of cost of hydrogen required to achieve a specific syncrude H/C ratio - starting from coal H/C of 0.75. Hydrogen gas cost (1980), $2/1000 ft$^3$; coal cost (1982), $20/ton.

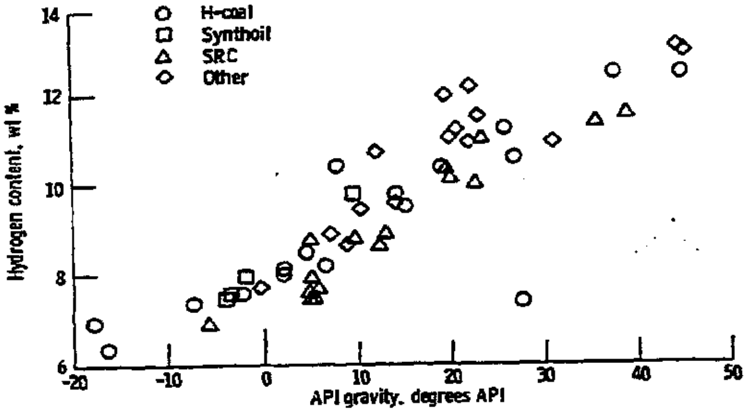


Figure 24. - Variation of hydrogen content of coal-derived fuels with API gravity. (From ref. 38.)

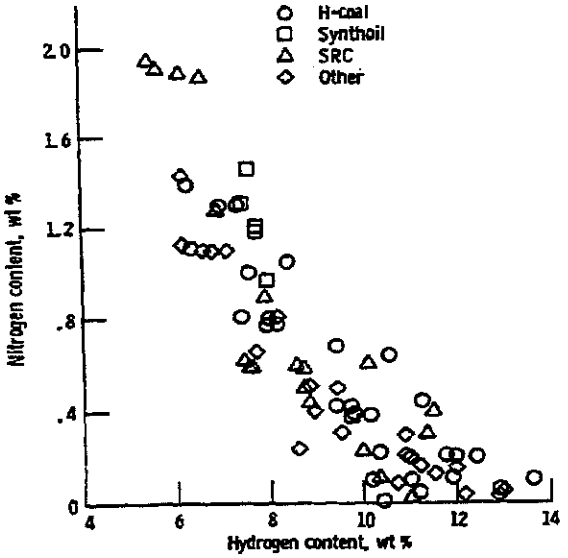


Figure 25. - Relation of fuel-bound nitrogen and hydrogen contents for coal-derived fuels. (From ref. 38.)

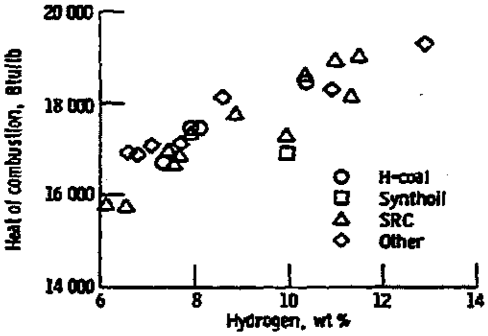


Figure 26. - Variation of heat of combustion of coal-derived fuels for varying hydrogen content. (From ref. 27.)

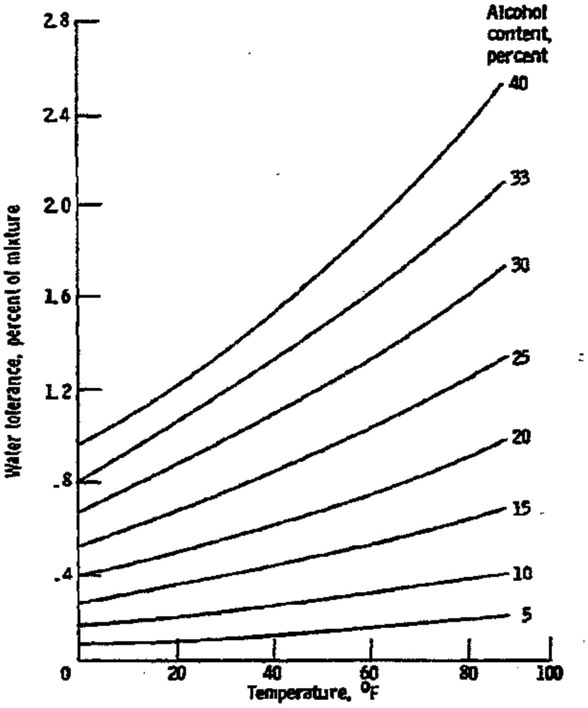


Figure 27. - Water tolerance of ethanol-gasoline blends. (From ref. 37.)