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OPTIMUM WORKING FLUIDS FOR AUTOMOTIVE RANKINE ENGINES

VOLUME I - EXECUTIVE SUMMARY

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Water Programs
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Advanced Automotive Power Systems Development Division
Ann Arbor, Michigan 48105

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INTRODUCTION

This is the final report of a research program performed by Monsanto Research Corporation for the Environmental Protection Agency, Advanced Automotive Power Systems Development Division (AAPSDD) under Contract 68-04-0030. The objective of the work was to determine the best working fluids for Rankine cycle automotive power plants.

The Rankine Engine has been identified by EPA as a potential alternative to the internal combustion engine for the automotive application in the event the internal combustion engine cannot satisfy the 1975/76 Federal Emission Standards. Development work has been proceeding on the Rankine engine, as well as other alternative power plants, under the direction of AAPSDD since initiation of the Clean Air Act Amendments of 1970.

In a Rankine cycle power plant, the working fluid, which is repeatedly vaporized, expanded and recondensed, plays a key role in determining the competitiveness of this system. The thermodynamic, chemical and physical properties of the fluid have a strong influence on the power plant efficiency, materials of construction, component weight and size, the degree of hazard, if any, and to some extent the power plant cost. Therefore, to make certain that the Rankine engine could be evaluated at its greatest potential, this study program was initiated to search out the best fluids currently available for the automotive Rankine engine application.

To accomplish this objective, specific guidelines were established for the fluid screening process. These guidelines, contained within the contract work statement, covered all significant fluid characteristics: availability, compatibility, thermal stability, cycle efficiency, cold start ability, applicability in principal engine types, owner cost, toxicity, flammability and environmental hazard. Quantitative targets set for these characteristics were intended to approximate the upper limit of what could be achieved with presently known materials and current technology. The results indeed reveal that the criteria were well chosen, as only two possible fluids from over 100 candidates survived the screening process, and these did not totally satisfy all of the stated requirements. In reviewing the results it should be kept in mind that less stringent or different selection criteria could very well have led to the selection of different candidates.

The volume of reportable material resulting from this program has dictated the physical subdivision of the detailed technical matter into three separate volumes (II through IV) with this Volume I serving as an executive introduction and summary.

SUMMARY

A translation of system and working fluid contractual goals into fluid screening criteria was the first step toward meeting contract objectives. Contractual goals are listed in Table 1, while the derived screening criteria are given in Table 2. A detailed discussion of the derivation of the criteria is given in Volume II. It may be noted that the screening criteria are mainly of the go/no-go variety useful in the early elimination of unsuitable materials. Additional requirements on cost, hazards, compatibility and system operability were treated on an ad hoc basis involving only a few of the more promising candidate fluids.

On the basis of predicted thermal stability and melting/boiling points, 112 candidate fluid constituents were identified and, where possible, procured. Included in the candidate list (Table 3) for comparison are several organic fluids previously used or suggested as Rankine working fluids. Except for water, all identified candidates are organic chemicals. Although inorganic candidates were sought and a list of 32 possibilities was similarly compiled, none was judged to be compatible with low-cost metals at the 712°F minimum peak fluid temperature needed to meet cycle efficiency requirements.

Binary and ternary mixtures of several of the 112 constituent candidates were also identified with the expectation that such mixtures offer wider latitude in matching diverse fluid requirements.

Identified fluids were next subjected to screening tests under the first five criteria. Criteria 1 through 3 required mainly literature work. A special steel ampoule thermal exposure test was employed to screen fluids for 720°F thermal stability under Criterion 4. Criterion 5, designed to distinguish between fluids requiring "reasonable" and "too-much" regeneration, drew on published thermophysical properties or, when these data were not available, on recognized property prediction procedures to compute the I-factors.

Candidate screening results under Criteria 1 through 5 are summarized in Table 3. Here it is seen that the majority of initial candidates failed to survive 200 hours at 712°F in the Criterion 4 steel ampoule test. The few which did are listed in Table 4 with their corresponding capsule survival times, I-factors (at normal boiling points), and Criterion 3 (normal boiling point) results. Brackets in the I-Factor column delineate the fluids satisfactory per se (innermost bracket) from those suitable only as components of a mixed (or complex) working fluid (outermost bracket) and from those satisfactory as neither, all based upon the tolerable regenerator size, Criterion 5.

Table 1. PROPULSION SYSTEM AND WORKING FLUID GOALS

Propulsion System Characteristic	Goal[1]
Type Expander	1-stage recip. and 1-stage turbine
Approx. Net[2] Full Power	145[3] HP
Max. Weight	1600 lb
Max. Volume	35 cu ft
Regenerator Size	Nil or small
Min. WF[6] Condensing Temp.	220°F
Max. Low Ambient Temp.	-40°F
Min. High Ambient Temp.	125°F
Max. Starting Time (idle at -20°F.	25 sec
Max. Starting Time (65% power) @ 60°F.	45 sec
Average Annual Usage	350 hr
Life Expectancy	3500 hr

Working Fluid Characteristic	Goal[4]
Presently available?	Yes
Min. Carnot Cycle Efficiency	42%
Min. Ideal Cycle Efficiency	30%
Max. Cost[5] to Owner, 5 yr. period	$100
Compatible with Low Cost Materials?	Yes
Compatible Lubricant Needed?	Yes - recip. Maybe - turbine
Health Hazard	Nil
Fire and Explosion Hazard	Nil
Environmental Hazard	Nil

NOTES:

1. Prime sources: 1971 Vehicle Design Goals (EPA) as amplified in consultation with EPA
2. Gross expander shaft less feed pump shaft
3. Sundstrand calculation based on performance requirements of 1971 Vehicle Design Goals (EPA)
4. Prime source: contract work statement
5. Initial factory fill plus materials only for any subsequent refills
6. "Working Fluid"

Table 2. WORKING FLUID SCREENING CRITERIA

1. Fluid component(s) known and available at reasonable cost.
2. Flow point[1] below:
   a) 20°C (68°F) for mixture component
   b) -29°C (-20°F) for final working fluid
3. Normal boiling point 65 to 120°C (150 to 250°F)
4. Stable in mild steel ampoule test for at least 200 hours at 720°F.
5. I-Factor[2] (at normal dew point) between:
   a) 0.65 and ∞ for mixture component
   b) 0.75 and 1.5 for final working fluid
6. Reference ideal cycle efficiency at least 30% ($UAk \leq \infty$)
7. Equivalent real cycle efficiency - report only - (UAk = 125 Btu/HP-hr-F)
8. Isentropic expansion enthalpy drop no greater than 200 Btu lb (turbine expander only, equivalent real cycle)
9. Isentropic expansion density ratio no greater than 25 (reciprocating expander only, equivalent real cycle).

NOTES:

1. Lowest temperature at which fluid will freely flow (melting point in case of pure compound).
2. Parameter related to slope of saturated vapor curve on T-S diagram (1 = vertical)

Table 3. SUMMARY OF SCREENING TEST RESULTS, CRITERIA 1 to 5

Defined Organic Component		Result,* Criterion No.				
FSN	Name	1	2	3	4	5
1	benzotrifluoride	0	0	0	X	X
2	o-bromobenzotrifluoride				3	
3	m-bromobenzotrifluoride	0	0	X	X	
4	p-bromobenzotrifluoride	0	0	X	X	
5	2-bromo-1,4-difluorobenzene	0	0	X	6	
6	o-bromofluorobenzene	0	0	X	X	
7	m-bromofluorobenzene	0	0	X	X	
8	bromopentafluorobenzene	0	0	X	X	X
9	p-bromofluorobenzene	0	0	X	X	
10	p-bromophenyl trifluoromethyl ether	0	0	X	X	
11	o-chlorobenzotrifluoride	0	0	X	X	
12	p-chlorobenzotrifluoride	0	0	X	X	
13	m-chlorobenzotrifluoride	0	0	X	X	X
14	o-chlorofluorobenzene	0	0	X	X	0
15	m-chlorofluorobenzene	0	0	X	X	0
16	p-chlorofluorobenzene	0	0	X	X	0
17	chloropentafluorobenzene	0	0	0	X	X
18	1,2-dichlorohexafluorocyclobutane	0	0	X	X	X
19	2,3-dichlorooctafluorobutane				18	
20	1,2-dichlorooctafluorocyclohexene-1				20	
21	1,2-dichlorotetrafluorocyclobutene-1	0	0	0	X	
22	o-difluorobenzene	0	0	0	0	0
23	p-difluorobenzene	0	0	0	0	0
24	m-difluorobenzene	0	0	0	0	0
25	2,4-difluorotoluene	0	0	0	0	X
26	2,5-difluorotoluene	0	0	0	0	X
27	2,6-dimethylfluorobenzene	0	0	X	0	X
28	2,3-dimethylfluorobenzene	0	0	X	0	X
29	3,4-dimethylfluorobenzene	X				
30	1,3-di(trifluoromethyl)benzene	0	0	0	0	X
31	1,4-di(trifluoromethyl)benzene	0	0	0	X	X

0 means pass
X means fail
42 means failed by implication by FSN-42

Table 3. SUMMARY OF SCREENING TEST RESULTS, CRITERIA 1 to 5 (Cont'd.)

Defined Organic Component		Result,* Criterion No.				
FSN	Name	1	2	3	4	5
32	o-fluoroanisole	0	0	X	X	X
33	m-fluoroanisole	0	0	X	X	X
34	p-fluoroanisole	0	0	X	X	
35	fluorobenzene	0	0	0	0	0
36	p-fluorobenzotrifluoride				37	
37	m-fluorobenzotrifluoride	0	0	0	X	X
38	o-fluorobenzotrifluoride	0	0	0	X	X
39	fluoroether No. 3	X				
40	2-fluoro-3-methylpyridine				42	
41	p-fluorophenyl trifluoromethyl ether	0	0	0		X
42	2-fluoropyridine	0	0	X	X	
43	o-fluorotoluene	0	0	0	X	X
44	p-fluorotoluene	0	0	0	X	X
45	m-fluorotoluene	0	0	0	X	X
46	hexafluorobenzene	0	0	0	0	0
47	methylpentafluorobenzene	0	0	0	X	X
48	octafluorotoluene	0	0	0	0	X
49	pentafluorobenzene	0	0	0	0	0
50	pentafluoropropanol-1	0	0	0	X	
51	perfluoro(methylcyclohexane)	0	0	0	0	X
52	perfluoroalkane-70	0	0	0	X	X
53	perfluorotributylamine	0	0	X	X	X
54	perfluoro-n-hexane	0	0	X		
55	perfluoro-2-butyltetrahydrofuran	0	0	0	X	X
56	perfluoro(dimethylcyclohexanes)	0	0	0	0	X
57	phenyltrifluoromethyl ether	0	0	0	X	X
58	phenyltrifluoromethyl sulfide	0	0	X	X	
59	1,2,4,5-tetrafluorobenzene	0	0	0	0	0
60	1,2,3,5-tetrafluorobenzene	0	0	0	0	0
61	1,2,3,4-tetrafluorobenzene	X				
62	2,3,5,6-tetrafluorotoluene	0	0	X	X	X

0 means pass
X means fail
42 means failed by implication by FSN-42

Table 3. SUMMARY OF SCREENING TEST RESULTS, CRITERIA 1 to 5 (Cont'd.)

Defined Organic Component		Result,* Criterion No.				
FSN	Name	1	2	3	4	5
63	trifluoroacetophenone	0	0	X	X	
64	1,2,4-trifluorobenzene	0	0	0	0	0
65	1,3,5-trifluorobenzene	0	0	0	0	0
66	2,2,2-trifluoroethanol	0	0	0	X	
67	tris(trifluoromethyl)-s-triazine	0	0	0	0	X
68	resorcinol bis(trifluoromethyl) ether	X				
69	3-chloropyridine	0	0	X	X	0
70	3-methylpyridine	0	0	X	0	0
71	pyrazine	0	X	0		0
72	pyrimidine	0	X			
73	toluene	0	0	0	0	0
74	methanol	0	0	0	X	0
75	1-propanol	0	0	0	X	0
76	benzene	0	0	0	0	0
77	monochlorobenzene	0	0	X	X	0
78	pyridine	0	0	0	0	0
79	tetrachloroethylene	0	0	X	X	0
80	trichloroethylene	0	0	0	X	
81	trichloroethane				80	
82	2,2,3,3-tetrafluoropropanol	0	0	0	X	0
83	perfluorosuccinic anhydride	X				
84	perfluoroglutaric anhydride	0	0	0	X	X
85	undecafluoropropoxy-2-propanol-1	X				
86	2,4,6-trifluoropyrimidine	0	0	0	X	0
87	hexafluoroacetone trihydrate	Corrosive				
88	hexamethyldisilazane	0	0	X	X	X
89	perfluoroether P-ID (Allied)	0	0	X	0	X
90	water	0	0	0	0	0
91	acetic acid	0	0	0	X	X
92	morpholine	0	0	X	X	0
93	ethanol	0	0	0	X	

0 means pass
X means fail
42 means failed by implication by FSN-42

Table 3. SUMMARY OF SCREENING TEST RESULTS, CRITERIA 1 to 5 (Cont'd.)

Defined Organic Component		Result,* Criterion No.				
FSN	Name	1	2	3	4	5
94	neopentanol	0	X	0	X	X
95	ethylene glycol monomethyl ether	0	0	X	X	0
96	anisole	0	0	X	X	
97	thiazole	X				
98	N-methylmorpholine	0	0	0	X	X
99	thiophene	0	0	0	X	0
100	1,1,1,2,4,4,4-heptafluoro-2,3,3-trichlorobutane	0	0	0	X	
101	perfluoroheptene-1	0	0	0	X	
102	2,3,5,6-tetrafluorophenol	0	X	X		
103	pentafluorophenol	0	X	X		
104	N-nonafluorobutyloctafluoromorpholine	0	0	0	X	
105	2-methylpyridine	0	0	X	0	X
106	4-methylpyridine	0	0	X	0	0
107	pentafluoropyridine	0	0	0	0	0
108	2-chlorothiophene	0	0	X	X	
109	2,6-dimethylpyridine	0	0	X	0	0
110	2-methylpyrazine	0	0	X	X	
111	hexamethyldisiloxane	0	0	0	0	X
112	trimethyl borate	0	0	0	X	
Defined Mixtures						
MFSN	Components					
1	FSN-73 and FSN-78	0	0	0		
2	FSN-74 and FSN-90	0	0	0	X	X
3	FSN-90 and FSN-93	0	0	0	X	0
4	FSN-78 and FSN-91	0	0	0	X	X
5	FSN-75, FSN-76 and FSN-90	0	0	0	X	
6	FSN-76, FSN-90 and FSN-93	0	0	0	X	
7	FSN-73 and FSN-75	0	0	0	X	
8	FSN-75 and FSN-76	0	0	0	X	

0 means pass
X means fail
42 means failed by implication by FSN-42

Table 3. SUMMARY OF SCREENING TEST RESULTS, CRITERIA 1 to 5 (Cont'd.)

Defined Mixtures		Result,* Criterion No.				
MFSN	Components	1	2	3	4	5
9	FSN-73 and FSN-74	0	0	0	X	
10	FSN-74 and FSN-76	0	0	0	X	
11	FSN-75 and FSN-90	0	0	0	X	0
12	FSN-74, FSN-78 and FSN-90	0	0	0	X	
13	FSN-73 and FSN-76	0	0	0	0	0
14	FSN-71 and FSN-90	0	X	X	X	
15	FSN-78 and FSN-90	0	0	0	0	0
16	FSN-23 and FSN-78	0	0	0	X	
17	FSN-30 and FSN-78	0				X
18	FSN-61 and FSN-78	0	0	0	X	
19	FSN-23 and FSN-96	0	0	0	X	X
20	FSN-66 and FSN-90 ("Fluorinol")	0	0	0	X	
21	FSN-70 and FSN-90	0	0	0	0	0
22	FSN-71 and FSN-90	0	X		X	
23	FSN-90 and FSN-105	0	0	0	0	0
24	FSN-90 and FSN-106	0	0	0	0	0
25	FSN-90 and FSN-109	0	0	X	0	
26	FSN-90 and FSN-110	0	0	0	X	
27	FSN-46 and FSN-107	0	0	0	0	0
28	FSN-46 and FSN-49	0	0	0	0	0
29	FSN-70, FSN-90 and FSN-105	0	0	0	0	0
30	FSN-90, FSN-105 and FSN-106	0	0	0	0	0
31	FSN-70, FSN-90 and FSN-106	0	0	0	0	0

0 means pass
X means fail
42 means failed by implication by FSN-42

Table 4. THERMALLY STABLE COMPONENTS AND I-FACTORS

FSN	Name	Stable Hrs. at 720°F	NBPt I-Factor	Result* Crit.3
56	perfluoro(dimethylcyclohexanes)	>336	0.27	0
89	perfluoroether P-ID (Allied)	>336	0.28	X
111	hexamethyldisiloxane	312	0.35	0
67	tris(trifluoromethyl)-s-triazine	>312	0.36	0
51	perfluoro(methylcyclohexane)	>336	0.40	0
30	1,3-di(trifluoromethyl)benzene	>336	0.42	0
28	2,3-dimethylfluorobenzene	>288	0.50	X
27	2,6-dimethylfluorobenzene	>336	0.50	X
48	octafluorotoluene	>336	0.55	0
105	2-methylpyridine	>288	0.56	X
25	2,4-difluorotoluene	>336	0.60	0
26	2,5-difluorotoluene	>336	0.60	0
73	toluene	>336	0.66	0
46	hexafluorobenzene	>336	0.68	0
49	pentafluorobenzene	>336	0.71	0
59	1,2,4,5-tetrafluorobenzene	>336	0.74	0
60	1,2,3,5-tetrafluorobenzene	>336	0.75	0
107	pentafluoropyridine	>336	0.75	0
109	2,6-dimethylpyridine	>288	0.75	X
64	1,2,4-trifluorobenzene	>336	0.76	0
65	1,3,5-trifluorobenzene	>336	0.76	0
35	fluorobenzene	>336	0.77	0
22	o-difluorobenzene	>336	0.78	0
23	p-difluorobenzene	>336	0.79	0
24	m-difluorobenzene	>336	0.81	0
70	3-methylpyridine	288	0.82	X
106	4-methylpyridine	240	0.82	X
78	pyridine	>336	0.87	0
76	benzene	>336	0.89	0
90	water	-	2.81	0

* 0 = pass, X = fail

Chemicals in the lower part of Table 4, i.e. the primary automotive candidates, all fall in several chemical categories with the characteristics shown in Table 5.

Table 5. ADVANCED FLUID COMPONENT CLASSIFICATIONS

I. Aromatics (benzene, toluene, pyridine and methylpyridines)

- A. inexpensive (articles of present commerce)
- B. flammable
- C. water solubility
  1. Benzene, toluene - insoluble
  2. Pyridines - soluble in all proportions
- D. recognized toxicity

II. Polyfluorinated aromatics (fluorinated benzene, toluene, pyridine and methylpyridines)

- A. inherently expensive, several in limited production
- B. Flammability
  1. fluorobenzene, difluorobenzenes, trifluorobenzenes - flammable in normal air (by flash point test)
  2. tetra-, penta-, hexa-fluorobenzenes, pentafluoropyridine, octafluorotoluene - nonflammable in normal air (by flash point test)
- C. water insoluble
- D. toxicity not well established, thought to be of same order as parent aromatics

III. Water

Of the simple fluids within the innermost I-factor bracket in Table 4, not all meet the Criterion 2 requirement for final working fluids (flow point below -29°C). Those which do are listed in Table 6 with their melting points (same as flow point) and an indication of flammability in normal air.

Table 6. SIMPLE FLUID CONDIDATES

FSN		Melting Pt. (°C)	Flam. Test*
60	1,2,3,5-tetrafluorobenzene	-48	0
107	pentafluoropyridine	-44	0
64	1,2,4-trifluorobenzene	-32	X
35	fluorobenzene	-42	X
22	o-difluorobenzene	-34	X
24	m-difluorobenzene	-78	X
78	pyridine	-42	X

*flashpoint in normal air; 0 = pass, X = fail

When a requirement for non-flammability is added to Criteria 1 to 5, then, the only simple candidates to emerge are:

1,2,3,5-tetrafluorobenzene, and pentafluoropyridine

While test amounts of these materials are available, their prices are so high as to suggest that even high-volume production would not lower them enough to meet owner cost requirements of $100/5 yr supply. This added impetus to a search for mixed (or complex) fluids to take advantage not only of the wider choice of physical parameters so afforded, but also of the possibility of lowering the cost below that of the most expensive component. Water is an especially attractive component of such a mixture since it can be expected to reduce flammability and toxicity as well as cost.

Some 31 mixtures were defined at various stages of the search (Table 3). Most of these were eliminated from consideration when they failed the Criterion 4 test, or were found to contain components which had failed. Two more (MFSN's 1 and 13) are quite flammable and were eliminated on that basis. The remaining group is constituted as in Table 7.

Table 7. COMPLEX FLUID CANDIDATES

1. hexafluorobenzene with
   a. pentafluorobenzene (MFSN-28)
   b. pentafluoropyridine (MFSN-27)
2. water with
   a. pyridine (MFSN-15)
   b. 2-methylpyridine (MFSN-23)
   c. 3-methylpyridine (MFSN-21)
   d. 4-methylpyridine (MFSN-24)
   e. binary combinations of b, c and d (MFSN-29, 30, 31)

Each of the three methylpyridines violates either the I-factor or boiling point criterion. Retention of these as candidate components is justified primarily on the grounds that they are the only water-soluble organics (other than pyridine itself) found to have reasonable thermal stability.

Predictive computer routines were used to enable cycle evaluations of the advanced candidates of Tables 5, 6 and 7. Their functions are listed in Table 8.

These routines were used extensively to analyze the behavior of advanced candidates in the "Reference Ideal Cycle", defined as follows:

> Reference Ideal Cycle - An ideal Rankine cycle (clockwise rectangle on a pressure-entropy diagram) operating between a top (bulk fluid) temperature of 712°F and a bottom temperature of 220°F (saturated liquid at condenser outlet) and with the peak fluid pressure chosen as the lesser of:
>
> a. that just preventing expansion penetration into the 2-phase region;
> b. 1000 psia

Table 8. COMPUTER ROUTINES EMPLOYED

1. Estimation of pure compound
   a. critical constants (P, T, V)
   b. perfect vapor heat capacity coefficients
   c. vapor pressures
   d. liquid densities
   e. enthalpies of vaporization
2. Calculation of liquid activity coefficients from vapor pressure data on particular complex fluids.
3. Calculation of vapor phase properties by a special generalization of the Redlich-Kwong equation of state to cover complex as well as simple vapor mixtures.
4. Prediction of principle PVT/thermodynamic functions of either simple or complex fluids, using as input, data found in the literature, or generated as in 1 to 3 above, and having as an option (when treating simple fluids) the use of the Hirschfelder, Buehler, McGee and Sutton formulation.
5. Calculation of specified ideal or real Rankine cycles (only with the Hirschfelder et al. formulation).
6. Plotting of temperature-entropy diagrams for any fluid processed in 4.

Reference ideal cycles calculated for many of the Table 5-7 candidates are compiled in Table 9. The first column is a test of Criterion 6, which requires an ideal cycle efficiency of at least 30% at any level of regenerator effectiveness. All straight organic fluids pass, whereas the pyridine-water mixtures fail. While water itself appears disqualified, it is capable of higher efficiencies by raising its upper operating temperature.

Other entries in the table demonstrate compliance with certain interim (non-criterion) goals; namely,

1. condenser pressure from 5 to 50 psia

2. ideal expansion density ratio less than about 40 (to serve in a single expansion reciprocator)

3. ideal expansion enthalpy drop less than about 200 Btu/pound (to serve in a single-stage impulse turbine)

4. I-factor in the approximate range of 0.65 to ∞ components) or 0.75 to 1.5 (final fluids)

The ideal Rankine cycle with a fully effective regenerator is only of limited applicability in evaluating working fluids, especially as concerns cycle efficiency. A 100% effective regenerator is by definition infinite in size. Since the space available for an automotive regenerator is severely restricted in the engine compartment, and since the cycle efficiency is highly sensitive to extent of regeneration (as well as to expander efficiency), a more realistic "Equivalent Real Cycle" was defined as follows:

> Equivalent Real Cycle - A real Rankine cycle which matches the Reference Ideal Cycle at the two extreme corners (expander and pump inlets), has engine and pump efficiencies of 75% each, has pressure losses in the regenerator, vapor generator and condenser representative of those predicted by system contractors (in January 1972), and has an adiabatic pump and expander. The "size" of the regenerator may be limited by restricting its $q/\Delta t$ (log mean) ratio (or equivalently its UAk product) to a "reasonable value".

Equivalent Real Cycle calculations employing many of the same simple fluids recorded in Table 9 are compiled in Table 10. Comparison of the entries with the reciprocating/turbine suitability Criteria 8 and 9 reveals all fluoroaromatics and benzene suitable for either engine type and all aromatics but benzene suited only for turbine use.

Table 9. SUMMARY OF REFERENCE IDEAL CYCLE CALCULATIONS ON THERMALLY STABLE CANDIDATES

	Ideal Cycle Effic.%*	Condenser Pressure (psia)	Expansion Density Ratio	Expansion Enthalpy Drop (Btu/lb)	I-Factor at 220°F
Aromatics					
Benzene	31.8	29.4	40.3	81.3	0.85
Toluene	31.7	12.3	145.9	79.3	0.75
Pyridine	31.5	10.5	145.1	93.9	0.98
3-Methylpyridine	32.4	4.2	338.1	97.3	0.89
Fluoro Aromatics					
Fluorobenzene	31.9	25.9	46.6	70.1	0.65
m-Difluorobenzene	31.6	28.5	43.7	56.9	0.70
p-Difluorobenzene	31.7	23.6	54.6	59.1	0.71
1,2,3,5-Tetrafluoro-benzene	30.6	28.2	42.4	43.0	0.76
1,2,4,5-Tetrafluoro-benzene	30.8	22.8	54.7	44.8	0.77
Pentafluorobenzene	30.3	26.6	45.2	35.3	0.68
Octafluorotoluene	30.2	14.9	86.9	29.7	0.55
Pentafluoropyridine	30.3	28.2	41.6	38.2	0.75
Hexafluorobenzene	31.4	30.5	40.3	35.2	0.54
Water	20.5	17.3	5.8	226.0	3.34
Pyridine/Water Solutions**					
40% Pyridine	27.4	21.3	36.3	154.9	1.66
60% Pyridine	28.3	19.6	47.1	125.9	1.33
30% 2-Methylpyridine	27.9	22.8	33.8	160.8	1.48
60% 2-Methylpyridine	27.9	21.6	49.4	107.3	0.89
30% 3-Methylpyridine	27.3	19.3	39.1	167.1	1.75
60% 3-Methylpyridine	27.7	15.9	65.4	112.3	1.21
30% 4-Methylpyridine	27.6	18.9	40.1	165.5	1.73
60% 4-Methylpyridine	28.6	14.3	76.4	114.8	1.20

* Full regeneration on all simple fluids: full regeneration or regeneration only to the dew line, whichever occurs first, on all solutions.

** Concentrations shown are mol percents.

Table 10. SUMMARY OF EQUIVALENT REAL CYCLE CALCULATIONS ON SIMPLE THERMALLY STABLE FLUIDS

	Real Cycle Effic.(%[1])	Expansion Density Ratio[2]	Expansion Enthalpy Drop,(Btu/lb)
Aromatics			
benzene	22.8	15.1	57.4
toluene	22.7	46.4	56.5
pyridine	23.7	43.5	67.3
3-methylpyridine	24.8	83.6	70.2
Fluoro Aromatics			
fluorobenzene	22.1	17.0	49.5
m-difluorobenzene	21.9	16.2	40.2
p-difluorobenzene	22.3	19.5	41.8
1,2,3,5-tetrafluorobenzene	21.2	15.7	30.4
pentafluoropyridine	20.9	15.4	27.0
hexafluorobenzene	20.7	15.2	24.8

Notes: 1. Regenerator $Q/\Delta T(\text{log mean}) = UAk = 125$ Btu/HP-hr-°F

2. Isentropic, from engine inlet to exhaust enthalpy

3. Condenser pressures and 220°F I-factors same as in Table 9

A searching examination of the complex fluid candidates listed in Table 7 was carried out to further limit the number of final candidates. This included experimental studies of flammability, toxicity and freeze (flow) point, in addition to the development of criteria data discussed above.

The first choice was obvious. Of the nonflammable fluids, only the highly fluorinated benzenes stand a reasonable chance of approaching the cost goal in large-scale production. Hexafluorobenzene is too high melting to be used alone, but mixtures with tri-, tetra- and pentafluorobenzenes possess the requisite low flow points. Such mixtures actually result from the fluorination of benzene, so processing economies could be expected. As a particular model representing this class, the first final Rankine candidate fluid, designated RC-1, was fixed as follows:

RC-1

Constituent	Mol Wt	Concentration Mol %	Concentration Wt %
pentafluorobenzene	168.1	60.0	57.5
hexafluorobenzene	186.1	40.0	42.5

The only obvious way to avoid using the expensive fluoro compounds and still secure some measure of fire hazard protection is to employ an organic-water solution. Only the pyridines, with their water solubility, permit this approach. Mixtures involving two or more of the three methylpyridines and pyridine itself, all contemplated in this category, offer some advantage in processing economics because of the simultaneous production of all four in practice. In consideration of freeze (flow) point depression, cycle utility, and flash/fire points, it appeared that a mixture of 2-methylpyridine in water was the best binary choice, so as the second final candidate the representative model defined as follows was chosen:

RC-2

Constituent	Mol Wt	Concentration Mol %	Concentration Wt %
water	18.0	65.0	26.4
2-methylpyridine	93.1	35.0	73.6

Thorough experimental and computational characterization of the two final candidates followed their definition. Physical property measurements included flow points, vapor pressures, liquid densities, specific heats, viscosities and thermal conductivities. Selected values appear in Table 11. Computations using these and pure component literature data then provided such derived properties as vapor viscosities and thermal conductivities, ideal vapor heat capacity coefficients, and liquid activity coefficients.

Thermodynamic tables and T-S diagrams were next prepared, and the two principal Rankine cycles were calculated, as summarized in Table 12. It is significant to compare the cycle efficiencies of the two fluids. While RC-2 fails the 30% ideal cycle efficiency stricture, it actually shows a slightly higher real cycle efficiency than does RC-1. The main reason is that the fixed "size" regenerator is more effective in recovering the lesser superheat of the RC-1 fluid. This supports the original use of the I-factor screening criterion.

Application-oriented test work was also undertaken to further explore candidate utility. Included were stability-compatibility tests in dynamic pumping loops and steel ampoules, animal acute toxicity experiments, flammability tests, lubrication studies, and manufacturing cost estimations. Highlights are listed in Table 13.

Fluid RC-2 was found to be incompatible with SAE 4130 steel boiler tubing at 720°F. Failure of the steel to passivate was evidenced by formation of hydrogen gas and magnetic iron oxide. An attempt to prepassivate the steel with water/steam reduced, but did not stop, the water-iron reaction.

An idea of the inhalation toxicity hazards of the two final candidates was garnered from comparisons of the rat LC_{50} results with (a) expected inhalation doses in a hypothetical "worst case" Rankine automobile accident involving driver entrapment and fluid release, and (b) known inhalation accidents involving common volatile fluids. The inhalation hazards of both candidates are considered comparable to those of gasoline. Products of flame decomposition of each fluid were identified.

Attempts to find lubricants with all characteristics desired in the reciprocating engine application were largely unsuccessful. Desired characteristics were (a) stable, compatible, and a liquid at 712°F; (b) incompletely soluble in the working fluid at ambient temperature; and (c) solidification point (in suspension in working fluid) below -20°F. All lubricant candidates known to be stable above 700°F were completely miscible in RC-1 and most were highly soluble in RC-2. A number of highly silylated benzenes were synthesized which had minimal solubility in RC-2 and thermal stability comparable to the RC-2. These compounds suffered from inherent expense and too-high solidification points.

Table 11. SELECTED PROPERTIES OF FINAL CANDIDATES

Property	Final Candidate RC-1	RC-2
Average molecular weight	175.3	44.3
Flow point, °F	-44	-40
Normal boiling point, °F	172	200
Condensing pressure @ 220°F, psia	30	21
Heat of vaporization @ NBPt, Btu/lb	79.1	378
I-Factor at 220°F	0.72	1.38
Liquid density at 77°F, g/ml	1.549	0.985
Specific heat at 77°F, Btu/lb	0.290	0.668

Table 12. FINAL CANDIDATE CYCLE CALCULATION SUMMARY

Final Candidate:	RC-1		RC-2	
Cycle[1]:	Ideal	Real	Ideal	Real
Cycle Efficiency	30.0	21.0	28.8	22.2
Per 100 Net Cycle HP				
Fluid rate, lb/hr	7470	11500	1760	2520
Eng. exhaust, cfm	259	340	233	310
Pump rate, gpm	12.2	18.8	3.93	5.66
Pump HP	7.34	16.8	2.43	5.04
Heat flows, kBtu/hr				
Vapor gen., kBtu/hr	848	1220	883	1150
Regen., kBtu/hr	391	692	64.8	213
Conden., kBtu/hr	409	950	629	890
Engine, % Effic.[2]	100	75	100	75
Pressure ratio	36.6	29.8	43.6	35.4
Density ratio	44.6	37.9	35.6	32.9
Isentropic[3]	44.6	15.4	35.6	12.1
Exhaust quality, %	176	190	108	118
Enthalpy drop, Btu/lb	36.6	25.8	149	106
Pump, % Effic.[2]	100	75	100	75
Pressure ratio	36.6	42.1	43.6	50.1
Regenerator, % Effect.	95.3	91.8	100	98.4
UAK, Btu/HP-hr-°F	12.0	12.5[2]	∞	12.5[2]
Log mean temp. diff., °F	32.6	55.6	0	23.0

Notes: 1. "Reference ideal" and "equivalent real" as defined earlier

2. Input specified

3. From engine inlet condition to exhaust enthalpy

Table 13. PERFORMANCE PARAMETERS OF FINAL CANDIDATES

	Candidate RC-1	Candidate RC-2
Stability, Compatibility		
1000-hour dynamic loop test	Pass	Fail
Failure mode	-	Decomposition
Toxic Hazards		
Inhalation 4-hr rat LC_{50}, ppm	16,000	8,000[1]
30-min rat LC_{50}, ppm	40,000[2]	-
Oral, rat, LD_{50}, mg/kg	12,000	810[1]
Dermal, rabbit, LD_{50}, mg/kg	>8,000	250[1]
Irritation score		
Rabbit skin (8 max.)	3	5.6[1]
Rabbit eye (110 max.)	10	71[1]
Flammability		
Flash point, modified COC, °F	None	130
Fire point, modified COC, °F	None	145
Auto ignition temp., °F	None	1,060
Hot compartment ignition rating (benzene=14)	0	8
Cost (to owner, 5 yr supply), est.$	112	<100

Notes:
1. Experiments conducted with a 40/60 mol % mixture of 2-methylpyridine/water
2. Experiment conducted with a 50/50 mol % mixture of penta-/hexafluorobenzene by Imperial Smelting Corporation

A low cost synthetic fluid - biphenyl/terphenyl eutectic - was evaluated as a miscible lubricant in friction-wear experiments involving cast iron rubbing against various typical mating materials. This material has promise as a miscible lubricant in either RC-1 or RC-2. No petroleum-based lubricants can be expected to survive the high temperatures demanded in this application.

Fairly detailed economic studies were carried out to project the ultimate cost to the driving public of the RC-1 fluid. Present manufacturing techniques are not suited to high volume low-cost production. A considerable technological investment would be necessary to bring the cost to the level indicated in Table 13. The RC-2 fluid is inherently cheaper and is currently abundant.

Ancillary experimental studies were carried out to probe the ultimate thermal stability of "Fluorinol 85" with and without added refrigeration oil. The upper temperature limit of these fluids was placed near 650°F. Another study of a class of semi-organic heat stable fluids called "carboranes" revealed a flammability deficiency.

The two final candidate fluids were subjected to a Rankine Cycle Engine Optimization Analysis where the size, weight, and efficiency of an engine for each of these fluids was determined. Fluid RC-1 was used to optimize an engine with a turbine expander and fluid RC-2 was used to optimize an engine with a reciprocating expander. An optimum automotive engine was determined by using a criterion that weighed engine size and weight against engine overall efficien (miles per gallon) over a time-weighted average of five operating load points representing country, suburban, and city driving conditions.

The Sundstrand Rankine Cycle Design Optimization Program used is a comprehensive analytical design procedure in which detailed design point and off-design calculations are made, and components meeting cycle requirements are calculated. In the design procedure a design point cycle is first calculated, from which engine components are designed. The performance of the system using these components is then evaluated by means of off-design cycle calculations. The overall system and its performance is then evaluated against an optimizing criterion, the results of which are used to vary the inputs to the design point cycle analysis. A new design point cycle is then calculated, components designed, and off-design performance evaluated. This procedure is repeated until an optimum system, based on the optimizing criterion, is found.

The first step in defining an optimum engine is to define the load points for which the engine is to be optimized, and to define the parameters of the optimizing criterion. For the purposes of this study only steady state load points were to be used, and the optimizing criterion was a trade-off between system efficiency and system weight. The optimizing criterion was based on the fact that high-efficiency systems tend to be high-weight systems, and reduced-weight systems result in lower efficiencies. As system weight is directly related to system volume, system size is also being optimized by this criteria.

The load points used in the analysis consisted of one design point load and four off-design load conditions. These load points were derived from the Federal driving cycle and EPA's prototype vehicle performance specification.

The load points selected were:

		Speed	Power	% Time
Design Point	maximum power acceleration	70 mph	108 HP	0.5
Off-design 1	steady speed	60 mph	32 HP	16.5
Off-design 2	steady speed	30 mph	8.4 HP	33.0
Off-design 3	acceleration	25.1 mph	9.92 HP	28.0
Off-design 4	acceleration	1.74 mph	1.143 HP	22.0

The power is the power output from the transmission to the drive shaft, the engine power required being determined by the mechanical losses, accessory requirements and the cycle calculations. These load points were also used to calculate the fuel load required for a 200 mile range.

The optimizing criterion was constructed using miles-per-gallon as representative of engine efficiency, weighed against system weight in pounds. In the optimizing process a weighting factor was varied to place more emphasis on system efficiency or system weight to see how this affected the system configuration. The optimum conditions found in each calculation are listed in Tables 14 and 15.

The turbine engine was optimized as a supercritical engine assuming a turbine inlet temperature of 712°F (required for a 200°F condenser in order to meet the EPA specifications of 42% carnot cycle efficiency), and a 425 psia turbine inlet pressure. This pressure was selected to keep pump work to a minimum since the fluid properties did not indicate any significant benefit in increased adiabatic head or reduced regenerator size by going to a higher pressure. The turbine tip speed was limited to 1200 ft/sec to allow economical materials, and the condenser assumed was the AiResearch design for the EPA Thermo Electron engine.

Table 14. PRINCIPAL RESULTS OF ENGINE OPTIMIZATION CALCULATIONS

Engine Type Working Fluid Weighting Factor, Effic. (Vs Weight)	Turb. RC-1 0.5	Turb. RC-1 0.97	Recip. RC-2 0.5
Overall Miles/Gallon	13.33	13.81	18.89*
Weights, Pounds			
Expander and Gear Box	146	178	225
Condenser and Fan	173	172	142
Regenerator	195	234	36
Burner and Vapor Generator	380	368	281
Transmission and Drive Train	355	355	355
All Other Components and Fuel	322	319	322
Total System	1571	1626	1361
Volumes, Cubic Feet			
Expander and Gear Box	0.23	0.28	2.25
Condenser and Fan	7.55	7.71	5.56
Regenerator	4.13	5.01	0.82
Burner and Vapor Generator	9.58	8.83	9.79
Transmission	1.50	1.50	1.50
Unoccupied Space	15.31	15.57	13.3
Total System	38.3	38.9	33.2

* Based on 3% of stroke clearance volume and square wave operation of valves porting 20% of piston area

Table 15. OPTIMIZED DESIGN POINT PARAMETERS

Engine Type Working Fluid Weighting Factor, Effic. (Vs Weight)	Turb. RC-1 0.5	Turb. RC-1 0.97	Recip. RC-2 0.5
Condensing Temperature, °F	179	179	242
Regenerator Press. Drop/Press. In, %	1.27	1.27	1.43
Regenerator Effectiveness, %	93	95	87
Condenser Effectiveness, %	81	81	80
Condenser Air Power, kW	5.48	4.93	5.0
Expander Speed			
Tip Speed, ft/sec	677	677	-
Pitch Diam., in.	4.96	6.00	-
RPM (3 in. stroke)	-	-	1900
Admission			
Arc/Total Circum., %	77.1	100.	-
Intake Angle, Degrees	-	-	54
Flue Gas Press. Split (Vap. Gen/ Total) %	80.4	89.4	72.6

The optimization analysis for the turbine engine was performed over six values of the optimization weighting factor (which can vary from 0 to 1; the higher the value, the greater the emphasis on high efficiency). The result of this analysis showed that there was no appreciable variation in the weight of the engine or in miles per gallon over the range of the weighting factor. It was also seen that there was little variation in the design point condenser temperature, which varied from 179°F to 200°F. It appeared from an analysis of the results that this situation was the result of the restriction of condenser size to one fitting the frontal region of a normal engine compartment. The size restriction on the condenser so severely restricts the condenser size for the power level required that essentially the same size condenser results with all values of the optimization weighting factor. As a result, the condenser influence on the rest of the power system is such that there is very little variation in the optimum engine weight and efficiency throughout the range of the optimizing weighting factor.

The reciprocating engine was analyzed as a subcritical engine using RC-2. The design assumed an expander inlet temperature of 712°F and a 700 psia inlet pressure for the same reasons as in the turbine engine, and to keep cylinder bore diameter a reasonable size for an automotive engine. The reciprocator was a single acting, single expansion engine whose speed was limited to 2000 rpm to keep valve train forces within reasonable limits. The condenser core was that of the AiResearch design developed for the Thermo Electron engine.

As can be seen by the miles per gallon, the reciprocating engine shows very encouraging results. However, it must be taken into consideration that the simplified reciprocator model used assumed a three percent of stroke clearance volume and "square wave" valve operation that had flow areas equal to one-fifth the piston area. These rather optimistic assumptions result in low valve losses and high volumetric efficiency which may be difficult to attain in an actual engine. The result of these assumptions is a high efficiency expander which results in the high miles per gallon figures. It should be borne in mind when comparing these figures to that of the turbine, that the turbine expander model used was a well developed turbine analysis that gave realistic results based on current state-of-the-art technology.

CONCLUSIONS

1. No organic or aqueous organic fluids were found to completely satisfy all the requirements established in the contract for Rankine cycle automotive power plant working fluids.

2. Fluid RC-1 comes nearest to satisfying the automotive organic working fluid requirements and goals set by AAPSDD. It meets all of the established performance criteria for both turbine and reciprocating engines, including efficiencies, temperature, pressure and density limitations, and regenerator size. Additionally, it is considered fire-safe and unlikely to cause serious injury on accidental human exposure (subject to verification in extended toxicity testing recommended as a follow on). The fluid is quite stable at temperatures to at least 720°F in low-cost system materials, and it is expected to last for at least the 5-year span of initial vehicle ownership. It possesses a distinct advantage over water in not freezing at temperatures down to -40°F. A low-cost, soluble lubricant is available if needed. The main contractual deficiency of the fluid is its projected cost of no less than $112/over its expected five year life, as compared to a $100 contract limit. To arrive at the $112 cost it was necessary to assume (a) successful advancement of the state of fluorination technology beyond that now practiced, and (b) the existence of a 50 million pound per year benzene fluorination plant. Current prices of the higher fluorinated benzenes are many times the projected price.

   Turning to cycle practicality, the comparatively high flow rate (Table 12) of the RC-1 fluid per net cycle horsepower (related to its higher molecular weight) may be considered a disadvantage despite the lack of a contractual limit. All in all, this fluid is worthy of further development.

3. Fluid RC-2 is a back-up candidate for automotive use, either in a turbine or reciprocating engine. It satisfies all performance criteria except the 30% minimum ideal cycle efficiency. Even so, the fluid is capable of high efficiency usage in a real cycle with a compact regenerator. Although the fluid is flammable, it is less so than common fuels. In burning it releases considerably less energy on account of its water content, and its products of combustion are not hazardous to humans. The fluid itself is unlikely to cause serious injury. It is marginally stable at 720°F in steel. SAE 4130 steel is not a compatible material for boiler tube construction with RC-2. The fluid acts chemically to corrode this steel, forming Fe_3O_4 and hydrogen. A more suitable steel alloy needs to be found before this fluid can be considered a contender with RC-1. Assuming a satisfactory steel were found, the RC-2 fluid would cost the vehicle owner about $100 in the first five years of vehicle life. This presumes three system refills. Traditional lubricants cannot be used with this fluid above 700°F, but low cost synthetics offer promise when mutual solubility is permissible. Synthetic silane lubricants may be considered if immiscibility is mandatory, but further development is needed. Fluidity above -40°F is another feature of importance. The prime ingredient of the fluid is commercially available at

low cost now, but in lesser quantity than would be commanded by a million cars-per-year market. RC-2 is worthy of further development only in the unlikely event that candidate RC-1 must be abandoned.

4. Many organic fluids possess the state and thermodynamic properties needed to attain engine performance goals.

5. Very few fluids possess the requisite thermochemical stability in steel at 712°F (and higher). Those that do fall in these categories:

   Aromatics

   Fluoroaromatics

   Aromatic tertiary amines

   Perfluoroaliphatics

   Water

6. Flammability eliminates the aromatics from contention, and places the aromatic tertiary amines in a contingency category. Since the aromatic tertiary amines (or pyridines) are quite flammable and water soluble, their safe usage in automobiles is contingent upon a suitable reduction in flammability effected by mixing with water.

7. An excessive demand for regenerator space to maintain tolerable cycle efficiency rules out the perfluoroaliphatics. This is clearly shown by the I-factor criterion and the supporting cycle calculations.

8. Additional restrictions on vapor pressure, melting point (or "flow" point), cost, and toxicity further narrow the choice to

   mixed fluorobenzenes and

   aqueous pyridines,

   from which categories the final candidates RC-1 and 2 were chosen.

9. The search rationale adopted at the outset was basically sound, although some adjustments were necessary. Particularly valuable features were:

   a. an efficient thermal stability screening program

   b. development and effective use of the I-factor concept for thermodynamic screening - including confirmation via I-factor - efficiency correlations

   c. maximal use of computation throughout, but especially in these areas:

prediction of thermodynamics of non-ideal/ ideal mixtures

I-factor and physical property predictions

ideal and real cycle calculations

d. the concept of progressive advancement of candidates, exposing each to increasingly rigorous examination.

10. As shown by the optimization studies, both the RC-1 and RC-2 final candidate fluids are appropriate fluids for automotive-size engines and are conducive to good efficiencies for automotive application.

RECOMMENDATIONS

Relative to fluid RC-1, it is recommended that

1. it be considered an acceptable organic fluid for a prototype engine development program.

2. static thermochemical stability tests be performed to learn how far above 720°F the fluid might be driven

3. providing prototype experience is favorable, the fluid be subjected to a carefully planned set of exposure tests in the areas of

   chronic inhalation

   chronic dermal contact

   environmental fate

   as necessary to qualify the fluid for widespread use

4. encouragement be given to prospective manufacturers to develop the necessary low-cost processes for large scale production.

Relative to fluid RC-2 and assuming abandonment of RC-1, it is recommended that:

5. additional work be undertaken to find a suitable steel and/or steel passivation technique to avoid the iron-water reaction at high temperature

6. if appropriate, additional synthesis work be done to finalize an immiscible silane lubricant

7. a fire hazard simulation be performed - preferably involving a mock-up burner-vapor generator and a simulated high pressure fluid leak

8. the first three recommendations under RC-1 be followed

9. additional engine optimization studies be carried out using computer models of components which more closely represent that for automotive type advanced state-of-the-art designs. These models would give a better description of component weight, size, effectiveness, and efficiency.

10. further engine optimization studies be performed that optimize more parameters than were done for this program. A more detailed optimizing criteria would also be beneficial in determining an optimum engine.

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16. ABSTRACT

The objective was to determine the best working fluids for Rankine cycle automotive power plants. This study program was initiated to search out the best fluids currently available for the automotive Rankine engine application. Specific guidelines were established for the fluid screening process. These guidelines covered all significant fluid characteristics: availability, compatibility, thermal stability, cycle efficiency cold start ability, applicability in principal engine types, owner cost, toxicity, flammability and environmental hazard. This Volume I serves as an executive introduction and summary. The best Rankine candidate fluid, designated RC-1, was fixed as follows: pentafluorobenzene 60 Mol%, hexaflurorbenzene 40 Mol%. The best binary choice, RC-2 was fixed as follows: water 65 Mol%, 2-methylpyridine 35Mol%. Fluid RC-1 was used to optimize an engine with a turbine expander and fluid RC-2 was used to optimize an engine with a reciprocating expander. The optimization studies indicate that both the RC-1 and RC-2 final candidate fluids are appropriate fluids for automotive-size engines and are conducive to good efficiencies for autonotive application. Additional conclusions and recommendations are given. The results of the study are summarized and presented in fifteen tables.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Working Fluid	13 B
Rankine cycle	Mixed Fluorobenzenes	21 G
Engines	Aqueous Pyridines	21 E
Design		14 B
Turbines		7 C
Reciprocating Engines		

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