NASA TM-86901

NASA-TM-86901 19850005383

DOE/NASA/50194-41
NASA TM-86901

Overview of Waste Heat Utilization Systems

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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Vehicle and Engine R&D

Prepared for
Twenty-Second Automotive Technology Development Contractors' Coordination Meeting sponsored by the U S Department of Energy
Dearborn, Michigan, October 29-November 1, 1984

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Available from
National Technical Information Service
U S Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes[1]
Printed copy A02
Microfiche copy A01

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Washington, D.C. 20545
Under Interagency Agreement DE-AI01-80CS50194

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N85-13692#

E-2379

ABSTRACT

The heavy truck diesel engine rejects a significant fraction of its fuel energy in the form of waste heat. Historically, the Department of Energy has supported technology efforts for utilization of the diesel exhaust heat. Specifically, the Turbocompound and the Organic Rankine Cycle System (ORCS) have demonstrated that meaningful improvements in highway fuel economy can be realized through waste heat utilization. For heat recovery from the high temperature exhaust of future "adiabatic" diesel engines, the DOE/NASA are investigating a variety of alternatives based on the Rankine, Brayton, and Stirling power cycles. Initial screening results indicate that systems of this type offer a fuel savings advantage over the turbocompound system. Capital and maintenance cost projections, however, indicate that the alternative power cycles are not competitive on an economic payback basis. Plans call for continued analysis in an attempt to identify a cost effective configuration with adequate fuel savings potential.

OBJECTIVES OF THE PROGRAM

FUEL SAVINGS - The objectives of the waste heat utilization program have remained essentially constant throughout approximately a decade of activity. The primary objective, as with other DOE sponsored activities, is fuel savings. A specific goal of 15 percent improvement in engine rated specific fuel consumption (s.f.c) was established early in the program. Naturally the desire is to see this goal translated into a like improvement in highway fuel economy.

ACCEPTANCE - System acceptance is a second objective, established out of a recognition that the degree of acceptance and use controls the magnitude of total fuel savings. The specific goal is to limit the systems incremental hardware costs such that fuel savings provide economic payback in a period of 2 to 3 years ownership. Early payback of the initial capital outlay allows for an attractive net gain during the balance of the ownership period.

BARRIER REMOVAL - The final, and also a continuing objective, has been to identify any technology barriers associated with specific waste heat system configurations. A technology barrier is defined as a technological problem of such magnitude that it would prevent industry from proceeding with final development of an otherwise attractive system. The Governments' role would be to conduct a technology program appropriate to the removal of such items as barriers.

BACKGROUND

The background era of waste to heat utilization systems spans the decade of 1974-1984. In that time period, the heat recovery efforts were addressing the water-cooled diesel engines with exhaust gas temperatures in the range of 700 to 900 °F. The approach included system buildup, truck installation, and on-highway fuel economy testing. There were two waste heat systems investigated; the turbocompound system and the organic Rankine cycle system.

TURBOCOMPOUND - The turbocompound system was developed by Cummins Engine Company and later subjected to on-highway testing (1)* and advanced development (2) under DOE sponsorship. The turbocompound system involves a low pressure power turbine downstream of the turbocharger turbine and connected through a gear train to the diesel output shaft. The program results indicated a 6 percent highway fuel economy improvement attributable to the advanced development version of the turbocompound.

*Numbers in parentheses designate references at end of paper.

ORGANIC RANKINE CYCLE SYSTEM (ORCS) - The ORCS was a DOE funded development originating out of the Rankine Cycle Automotive Engine program of the early 1970's. The development contractor was Thermo Electron Corporation. The cycle (organic) working fluid was a mixture of trifluoroethanol and water with a peak operating temperature of 550 °F. A single-stage axial flow turbine was used as the prime mover in the system (3). The ORCS was installed in a Mack truck for on-highway testing which subsequently demonstrated a 12 percent fuel economy advantage over a similar truck without waste heat utilization.

Rankine Heat Exchanger Fouling - A prominent feature in the ORCS configuration is the heat recovery heat exchanger (HRHX). The HRHX design used was a shell and finned-tube type with fin spacing of approximately 10-fins/in. A problem which soon became apparent was that of HRHX fouling by the diesel exhaust gasses. The fouling degrades overall system performance in two ways:

(1) increased backpressure on the diesel
(2) reduced heat transfer to the ORCS working fluid

Dynamometer test cell results indicated that the gas side heat transfer coefficient degrades by as much as 50 percent during a 50 hr test series.

The HRHX fouling problem was considered to be a technology barrier as defined previously under the program objectives. The approach to removal of the barrier was two pronged:

(1) Conceptual design study of a fluidized-bed system as an alternative HRHX
(2) Experimental evaluation of various cleaning techniques in the existing finned-tube HRHX

The fluidized-bed design involves bare tubes immersed in the bed. The constant agitation of the bed material is expected to produce high heat transfer coefficients; as well as a cleaning action that eliminates any concern for fouling of the bare tube surfaces. Unfortunately, the conceptual design study results indicated that size, weight, and cost factors associated with the fluidized-bed seriously reduce the concepts attractiveness for truck applications.

The experimental evaluation of cleaning techniques for the existing finned-tube HRHX fortunately identified two techniques that appear acceptable for control of the fouling problem in that unit

(1) Water wash with a built-in spray bar
(2) High temperature "self-cleaning"

The water wash is accomplished with tap water introduced at a standard hose connection on the HRHX body and connecting to a circular spray bar mounted inside at the top of the HRHX tube bundle. The water wash is completed in approximately 30 min at any truck stop location.

The self-cleaning approach is perhaps more attractive than the water wash because self-cleaning can be accomplished on-highway. The technique involves the temporary shut-down of the Rankine working fluid loop such that the HRHX metal temperature approaches that of the diesel exhaust gas. At the elevated temperatures the accumulated soot dries and flakes off to be carried away in the gas stream. A testing program indicated that a 20 min self-cleaning each day will maintain the HRHX in a clean condition. In practical applications, the self-cleaning technique may be limited to steam (water) Rankine systems since fluid residue may remain in the tubes during the cleaning cycle and the temperatures involved exceed those normally associated with organic fluid stability.

CURRENT PROGRAM

The current program was formulated in 1982. It addresses the "adiabatic" engine of the future, an engine anticipated to have exhaust gas temperatures in excess of 1100 °F. The program is formulated on the assumption that industry accepts and is pursuing on its own the turbocompound system for use with advanced engines. The Government role is to screen the waste heat power cycle alternatives with the objective of identifying economically acceptable systems that offer a fuel savings advantage over the turbocompound system.

SCREENING MATRIX - Figure 1 illustrates the alternative power cycle screening matrix which addresses the Rankine, Brayton, and Stirling cycles. The blocks below the cycle designations represent individual conceptual design studies. As indicated on the figure, the Stirling cycle study is currently underway and scheduled for completion in 1985. The prime contractor is Cummins Engine Company with Mechanical Technology, Inc. and Adiabatics, Inc. as subcontractors.

Completed Studies - The four blocks under the Rankine and Brayton cycle headings in Fig. 1 represent studies that have been completed. In the Rankine cycle area, the Steam Rankine study was completed by Foster-Miller Associates, Inc. The final configuration was a 1000 °F/1000 psia steam system using a two-cylinder piston expander operating at diesel engine speed (4). The RC-1 Organic Rankine study was completed by Thermo-Electron Corp. The RC-1 organic fluid is a mixture pentafluorobenzene and hexafluorobenzene. The final system configuration involved 750 °F/800 psia working fluid conditions with expansion in a single stage, axial flow turbine (5).

Under the Brayton cycle heading, the AGT Adaptation block refers to a study completed at NASA Lewis Research Center involving a minimum cost adaptation of the automotive Advanced Gas Turbine (AGT) hardware for use as a waste heat recovery system. The concept involves use of the AGT (6) rotating regenerator as the HRHX. The motivation was one of minimum hardware cost on the assumption that AGT components might be the subject of high rate production for passenger car use.

The Clean Sheet Brayton block refers to a study completed by United Technologies Research Center of a Brayton system optimized for the waste heat utilization application. The resulting configuration used a plate-fin HRHX design with a turbomachinery arrangement that included two compressor wheels with intercooling between stages (7).

RANKINE/BRAYTON COMPARITIVE REVIEW - The individual studies in the power cycle alternative screening matrix (Fig. 1) have been, or are being completed to a common set of ground rules assigned by NASA Lewis Research Center. In an attempt to further insure comparability among individual systems, NASA has conducted a comparative reivew of results from the completed Rankine and Brayton studies.

Common Diesel Core - A major feature in the common ground rules is the definition of the diesel core which is the source of exhaust gas heat intended for recovery and utilization by the alternative power cycles under consideration. Figure 2 illustrates one of several "adiabatic" diesel core options included in the ground rules. This core is a turbocharged diesel with aftercooling omitted as a concession to the waste heat cycles' desire for higher operating temperature. The 1240 °F exhaust gas stream represents 288 recoverable horsepower if cooled to the 300 °F level in an appropriate power recovery cycle.

Engine Performance Gain - Figure 3 illustrates the net horsepower recovered by each of the candidate alternative power cycles when applied to the exhaust gas stream from the common diesel core. Note that the specific fuel consumption (s.f.c.) improvement shown in Fig. 3 is based not on the s.f.c. of the core diesel, but rather against the s.f.c of a competing turbocompound aftercooled diesel engine. Comparison of the steam and organic Rankine systems' results in Fig. 3 should be tempered with the knowledge that the organic systems' apparent performance advantage is attributable to a significantly larger HRHX; the cost implications of which will be discussed later.

Fuel Dollars Saved - The dollar value of the fuel saved through the s.f.c. improvement is a major factor impacting the economic payback time. For purposes of this study, fuel dollar savings were calculated on the basis of several assumptions:

(1) Truck miles per gallon (mpg) performance will improve in proportion to the change in engine rated s.f.c.

(2) The future truck is a fuel saver configuration with full aerodynamic treatment (cab and trailer), single wide radial tires, and electronic cruise controls.

(3) Such a truck would average 9.2 mpg if equipped with an "adiabatic" turbocompound diesel.

(4) The truck runs 100 000 miles each year and is fueled at an average diesel fuel price of $1.22/gal.

On the basis of these assumptions it was determined that the 7.5 percent s.f.c. improvement shown in Fig. 3 for the steam Rankine system over the competing turbocompound diesel equated to approximately $1000/yr in reduced fuel expense.

Maintenance expenses - The money saved each year due to reduced fuel expense, unfortunately, will be partially offset by the maintenance expense associated with the alternative power cycle system. Annual maintenance costs for each of the alternative power cycles were estimated on the basis of a 7-yr "owner protection" contract that covers virtually all maintenance including overhaul as required. Costs were assigned to each alternative power cycle system according to major subsystems content as illustrated in Fig. 4.

Capital Costs - Major subsystem content was again used as a guideline in compiling the capital cost estimates illustrated in Fig. 5. As noted earlier, the assumed passenger car use of the AGT gives that system the benefit of high rate production for capital cost estimating purposes. The relatively high price shown in Fig. 5 for the clean sheet Brayton system is attributable primarily to the expensive turbomachinery package for relatively low power output. The larger size (surface area) and resulting higher price of the HRHX is the primary reason for the Organic Rankine system price estimate exceeding that of the Steam Rankine.

Payback Results - The fuel savings, maintenance costs, and capital costs need to be combined in the appropriate manner to calculate payback time. For this study, the cost estimates were first subjected to a minor scaling adjustment to a 350 hp common size (core plus heat recovery). The comparison was then made to a competing turbocompound - aftercooled diesel of the same size. An additional assumption was made that all systems will retain a 15 percent salvage value after the 7-yr (700 000 mile) life. The payback equation thus becomes

$$\frac{0.85\ (\Delta\ \text{capital})}{\Delta\ \text{fuel} - \Delta\ \text{maintenance}} = \text{payback years}$$

The payback results are illustrated graphically in Fig. 6 as a function of fuel price. Unfortunately, the results indicate that at the reference fuel price the alternative power cycle systems do not meet the payback target. The target would be realized for the Rankine systems if the often discussed $2/gal fuel price became a reality, but only if that fuel price change were not accompanied by a general inflation affecting the system hardware prices. Note in Fig. 6 that the lower capital cost of the Steam Rankine system now "pays off" in terms of payback time. Also, the Clean Sheet Brayton and AGT systems appear not be competitive with the Rankine at any fuel price.

Figure 7 illustrates a second set of payback results, similar to those of Fig. 6 except that now the core diesel is a turbocompound (nonaftercooled) diesel. The hardware arrangement involves the alternative power cycle(s) operating downstream of the turbocompound power turbine. Surprisingly, the difference to the alternative power cycle is a mere 100 °F lower gas temperature than that available from the turbocharged diesel core. The payback results (Fig. 7) show significant improvement but still fail to meet the established payback target.

Conclusions - A major conclusion drawn from the power cycle comparative review is that 8 to 10 percent fuel economy improvement over a turbocompound diesel is possible with an appropriate alternative power cycle system. For this application, the Rankine cycle is superior to the Brayton both in terms of fuel economy improvement and economic payback. The use of a Rankine cycle in combination with turbocompounding appears interesting as a means to provide the maximum fuel economy and economic payback.

The design complexity and resulting high cost of the Rankine cycle systems evaluated are considered to constitute a technology barrier. A 25 to 50 percent reduction in cycle capital cost is needed to produce acceptable economic payback at current fuel price levels.

FUTURE PLANS

The future plans, for the near term at least, are analytical rather than hardware oriented. A study is currently underway at Argonne National Laboratory for modeling and analysis of the Rankine cycle systems in an attempt to further define optimum designs from a combined performance and cost viewpoint. The completed Rankine cycle model will be utilized at NASA Lewis Research Center in conjunction with an appropriate Diesel model and vehicle mission simulation model to continue the optimization process.

Also underway is the Stirling cycle study identified in Fig. 1 as the last item to be completed in the alternative power cycle screening matrix. This study, to be completed by Cummins Engine Company during 1985, will include an engine manufacturing and vehicle integration review of the completed Rankine and Brayton designs.

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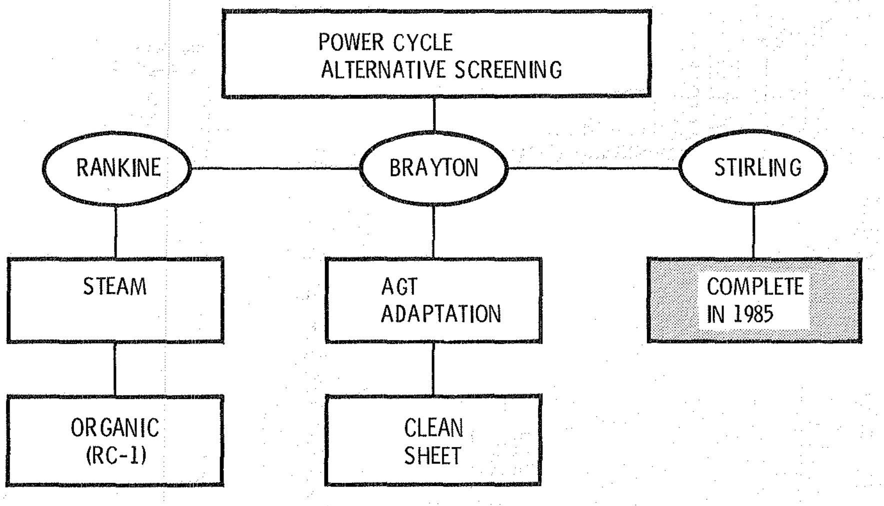

Figure 1. - Alternative power cycle screening matrix.

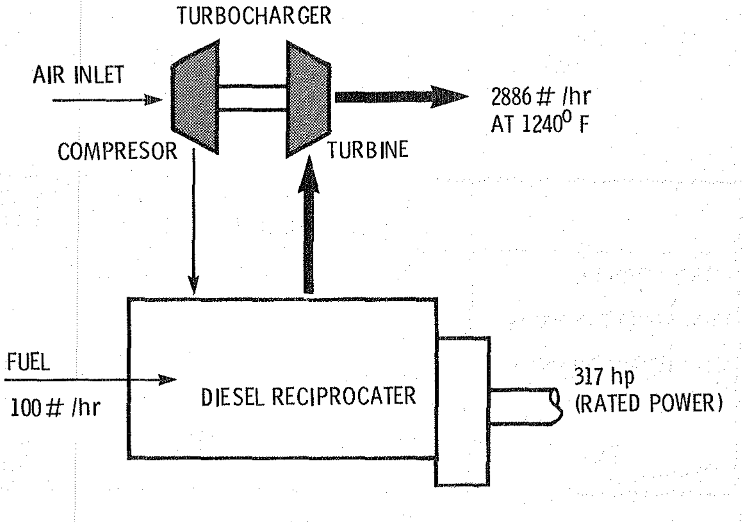

Figure 2. - Common diesel core.

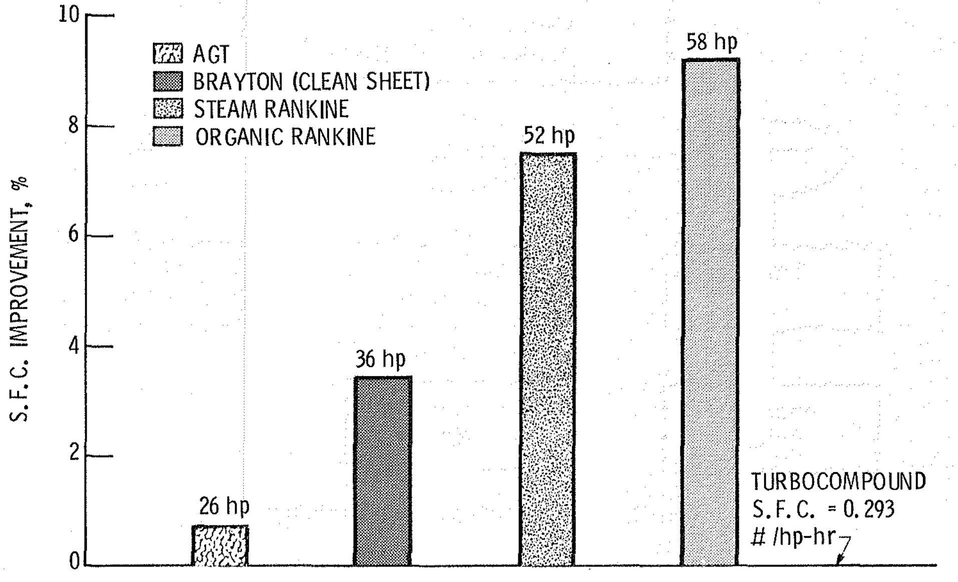

Figure 3. - Horsepower recovery and resulting S.F.C. improvement.

	AGT (26 hp)	BRAYTON (36 hp)	STEAM (52 hp)	ORGANIC (58 hp)
PRIME MOVER	X	X	X	X
HEAT RECOVERY HX	X	X	X	X
HEAT REJECTION HX		X	X	X
CONTROLS AND FLUIDS			X	X
$/hp	31	24	29	28

Figure 4. - Annual maintenance cost estimates.

	AGT* (26 hp)	BRAYTON (36 hp)	STEAM (52 hp)	ORGANIC (58 hp)
PRIME MOVER	X	X	X	X
HEAT RECOVERY HX	X	X	X	X
HEAT REJECTION HX		X	X	X
CONTROLS AND FLUIDS			X	X
$/hp	118	179	117	144

*HIGH RATE PRODUCTION

Figure 5. - Capital cost estimates.

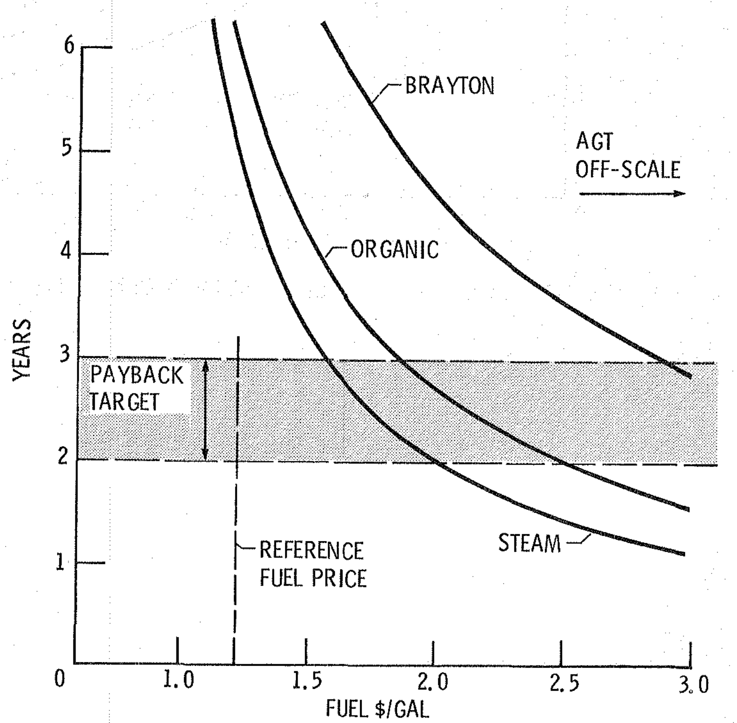

Figure 6. - Payback results using turbocharged diesel core.

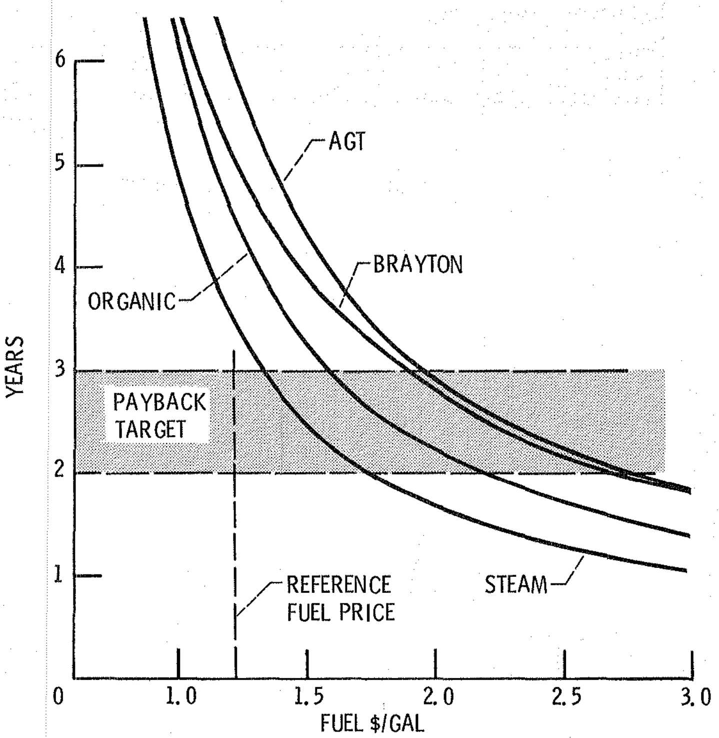

Figure 7. - Payback results using turbocompound diesel core.

1. Report No	2. Government Accession No	3. Recipient's Catalog No
NASA TM-86901		

4. Title and Subtitle

Overview of Waste Heat Utilization Systems

5. Report Date

6. Performing Organization Code

778-34-12

7. Author(s)

M. Murray Bailey

8. Performing Organization Report No

E-2379

10. Work Unit No

9. Performing Organization Name and Address

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No

13. Type of Report and Period Covered

Technical Memorandum

12. Sponsoring Agency Name and Address

U.S. Department of Energy
Office of Vehicle and Engine R&D
Washington, D.C. 20545

14. Sponsoring Agency ~~Code~~ Report No.

DOE/NASA/50194-41

15. Supplementary Notes

Prepared under Interagency Agreement DE-AI01-80CS50194. Prepared for Twenty-Second Automotive Technology Development Contractors' Coordination Meeting sponsored by the U.S. Department of Energy, Dearborn, Michigan, October 29-November 2, 1984.

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Diesel technology; Waste heat utilization; Brayton cycle; Rankine cycle	Unclassified - unlimited STAR Category 85 DOE Category UC-96

19. Security Classif (of this report)	20. Security Classif (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified		A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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