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RESEARCH REQUIREMENTS FOR DEVELOPMENT OF REGENERATIVE ENGINES FOR HELICOPTERS

By

Richard D. Semple

Prepared under Contract No. NAS1-13624
By
Boeing Vertol Company
Philadelphia, Pennsylvania

for

NASA

National Aeronautics and
Space Administration

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ABSTRACT

This report documents the basic research and the applied research and technology demonstration requirements to develop a regenerative engine for a civil helicopter. Data is presented which shows the improved specific fuel consumption of the regenerative engine compared to a simple-cycle turboshaft engine, and the further improvement which can be realized at partial-power operating conditions with the use of variable power-turbine stators. The performance improvement and fuel saving are obtained at the expense of increased engine weight, development and production costs, and maintenance costs. Costs and schedules are estimated for the elements of the research and development program. Interaction of the regenerative engine with other technology goals for an advanced civil helicopter is examined, including its impact on engine noise, hover and cruise performance, helicopter empty weight, drive-system efficiency and weight, one-engine-inoperative hover capability, and maintenance and reliability.

FOREWORD

This report was prepared by the Boeing Vertol Company for the National Aeronautics and Space Administration, Langley Research Center, under NASA Contract NAS1-13624. William Snyder was technical monitor for this work. The Boeing Project Manager was Wayne Wiesner.

SUMMARY

The regenerative turboshaft engine uses a heat exchanger to recover much of the heat energy normally lost in the exhaust gases, thereby reducing the amount of fuel required to achieve the desired turbine-inlet temperature. The result is an improvement in the specific fuel consumption (SFC) of the regenerative engine compared to the simple-cycle turboshaft engine.

Previous development efforts have demonstrated the performance potential of regenerators and regenerative engines. In helicopter flight-test programs, performance data for existing engines modified to accommodate a bolt-on recuperator substantiated improvements in fuel requirements and range capability. Performance benefits were accompanied by reductions in engine noise. However, the positive aspects of the regenerative engine must be compared with the negative aspects – increased engine weight, cost, and maintenance requirements – to determine its suitability as a helicopter powerplant.

The following technologies associated with the regenerative engine must be developed to achieve a production engine:

- Integrated regenerator-engine configuration designs
- Regenerator matrix and braze materials technology
- Regenerator producibility techniques
- Variable turbine-stator vanes
- Regenerator bypass-valve concepts
- Turbomachinery cooling concepts

This report presents performance data for a regenerative engine incorporating turbomachinery technologies which will be available in 1985. At a partial-power operating condition corresponding to typical helicopter cruising power, the regenerative engine offers a 22-percent reduction in SFC compared to a simple-cycle engine incorporating existing turbomachinery technologies. Conceptual drawings illustrate integration of the regenerator and engine. Weight trends indicate that the regenerator adds 50 to 60 percent to the weight of a turboshaft engine. A helicopter with an advanced-technology simple-cycle engine would have a lower life-cycle cost, although the difference would be less than 1 percent, but the regenerative-engine-powered helicopter would provide a substantial saving in fuel.

An 8-year program of recommended research to achieve a regenerative engine for flight-test demonstration is presented. The total development expenditure to reach the 60-hour preflight qualification test milestone is estimated to be $73 million for a 3728.5-kw (5,000-shp)

engine, the largest percentage of the development effort to be accomplished in the final 3 years of actual engine development.

The report discusses the interaction of the regenerative engine with other technological goals for an advanced civil helicopter. The regenerator reduces engine noise and improves performance, but has virtually no impact on aircraft empty weight and results in degradation in engine reliability and maintainability. The regenerative engine has no impact on drive-system efficiency and weight. When a regenerator bypass valve is incorporated, one-engine-inoperative capability which is identical to the simple-cycle engine can be provided.

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 INTRODUCTION

Early helicopters were powered by reciprocating engines which, at that time, were nearing the end of their development cycle. The reciprocating engines for helicopters had good fuel economy but were large and heavy. The introduction of the turboshaft engine provided a breakthrough in size and weight, thereby permitting significant progress in both load-carrying capability and speed.

The changeover from reciprocating to turbine engines was not all gain. The reduction in engine weight to about 0.1521 kg/kw (0.25 lb/hp) was accompanied by an increase in specific fuel consumption (SFC) to about 0.6083 kg/kw-hr (1.0 lb/hp-hr). The turbine-engine manufacturers have steadily reduced SFC by improving component efficiencies, by achieving higher pressure ratios, and by increasing turbine-inlet temperatures, but the advantage in fuel consumption is still with the reciprocating engine. Now further improvements in turboshaft-engine technology would result in diminishing improvement in SFC. However, the regenerative engine offers the potential for a 20-percent improvement in design-point SFC compared with an existing-technology turboshaft engine (ref. 1, 2).

The conventional simple-cycle turboshaft engine, with just a single-spool gas generator and a free power turbine, typically dissipates a large proportion of the input fuel energy as exhaust heat. The regenerative turboshaft engine uses a heat exchanger between the engine-exhaust gas and the compressor-exit airflow to recover some of this heat energy normally lost in the exhaust and improve the thermal efficiency of the engine. The heat exchanger preheats the air entering the burner, reduces the amount of fuel required to reach desired turbine-inlet temperatures, and results in a decrease in SFC. Figure 1-1, reproduced from Davis (ref. 3), illustrates the improvement in design-point SFC of the regenerative engine compared to the conventional simple-cycle engine.

The term regenerator usually is applied to the rotating, periodic-flow type of heat exchanger, while the stationary heat exchanger is called a recuperator. In this report, however, regenerator or regenerative are used to describe either concept, and the engines envisioned in this report incorporate a recuperator.

Past development efforts on regenerators and regenerative gas-turbine engines have proven the feasibility of various heat-exchanger concepts (ref. 4, 5). Concurrently, studies of aircraft powered by regenerative engines have shown promise of significant improvement in their performance (ref. 2). In helicopter flight-test programs, regenerative engine-performance data for minimum-modification conversions of existing engines substantiated predicted improvements in fuel requirements and range capability (ref. 1). Reductions in engine-exhaust noise accompanied the performance benefits. These advantages must be compared with increases in engine weight, development and procurement costs, and maintenance requirements to properly assess the merits of the regenerative cycle.

To date, regenerative engines evaluated in static or flight-test programs have been existing engines which were modified to accommodate a bolt-on recuperator. Although they performed satisfactorily and demonstrated the structural integrity of the heat exchanger, the engines were not an optimum design from the standpoint of performance and weight. Analytical and design effort must be expended to achieve integrated regenerative-engine designs which are compact and lightweight.

The design-point SFC of the regenerative engine is lower than that of the simple-cycle engine. Improvement in SFC at partial-power conditions is even more significant than the improvement in design-point performance. The engine operates much of the time at partial power in the helicopter installation, particularly in multiengine helicopters where the powerplant is sized for one-engine-inoperative hover. Although the partial-power SFC characteristic of the regenerative engine is inherently better than the simple-cycle engine, Davis (ref. 3) indicated that the partial-power SFC of the regenerative engine could be further improved – actually the SFC of the engine would be constant down to very low powers – by employing variable stator vanes to modulate the power-turbine flow.

This report includes data to show the improved specific fuel consumption and the increased engine weight of the regenerative engine compared to a simple-cycle turboshaft engine. It defines a research and development program to develop a regenerative engine for a civil helicopter. Interaction of the regenerative engine with other technological goals for an advanced civil helicopter is examined.

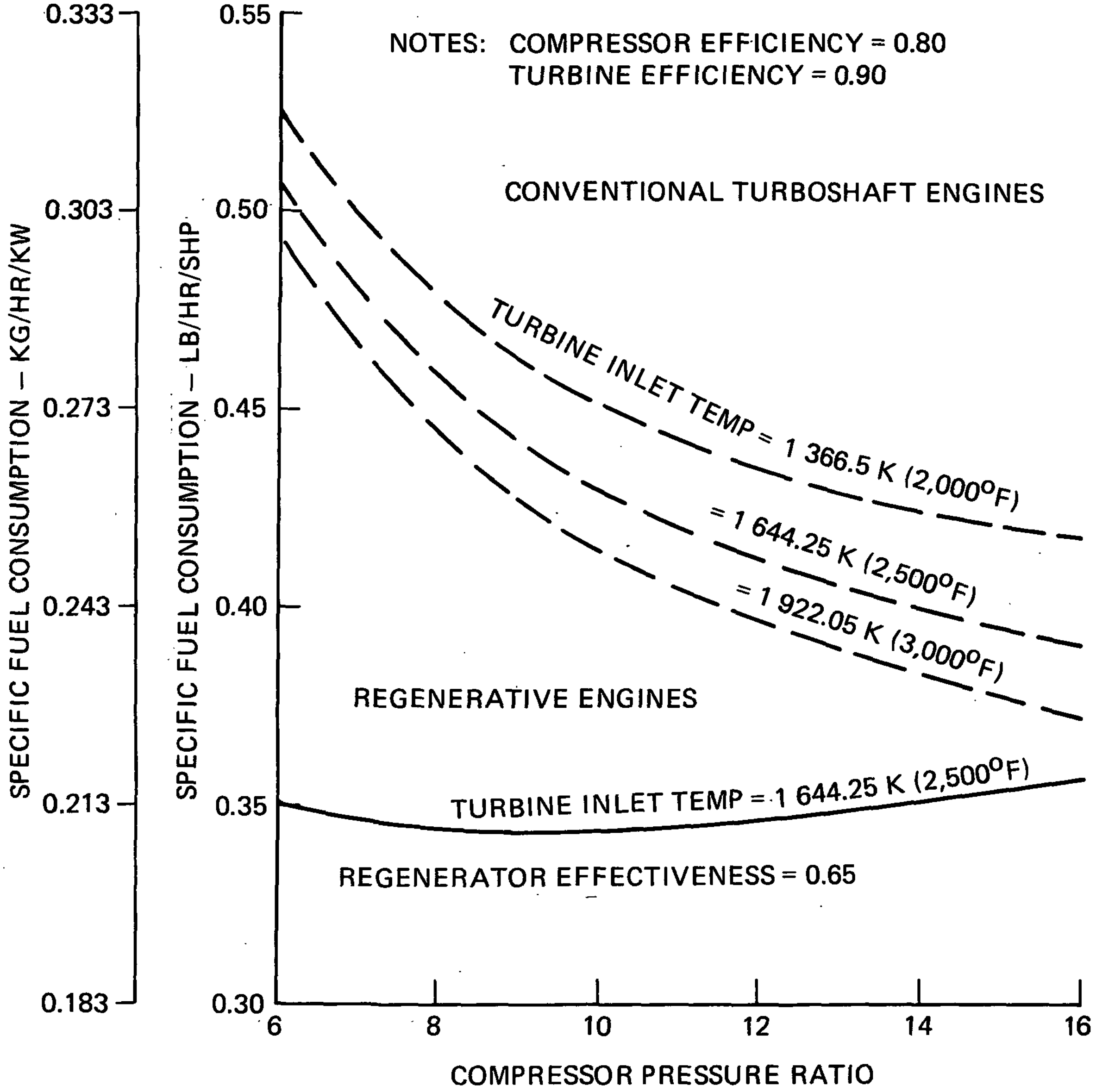

Figure 1–1. Design-point performance of conventional and regenerative engines

2.0 BACKGROUND

Turboshaft-engine technological advances in recent years have been directed primarily toward increases in the principal engine thermodynamic design-point parameters, compressor pressure ratio and turbine-inlet temperature, since component-performance parameters for the compressor, combustor, and turbines are approaching practical limits. Increased design-point compressor pressure ratio results in a reduced SFC. Increased turbine-inlet temperature primarily results in increased shaft horsepower per pound of engine airflow, and consequently reduced airflow and reduced engine weight for a given horsepower requirement. However, increased turbine-inlet temperature also contributes to reduced SFC.

The regenerative turboshaft engine offers a substantial added reduction in SFC, recovering much of the heat energy normally lost in the exhaust gases, transferring the heat to the compressor-discharge flow, and reducing the fuel flow required to achieve a desired turbine-inlet temperature. Figure 1-1 further illustrates that the optimum design point for the regenerative turboshaft engine occurs at a relatively low value of compressor pressure ratio. Compared to the simple-cycle turboshaft engine, then, the regenerative engine has fewer compressor stages and reduced complexity.

A literature search was conducted to determine published technical data related to regenerative engines. A total of 11 publications on the subject are included in the list of references and in a bibliography.

2.1 Previous Research and Development

Development and test programs conducted during the past decade have demonstrated the performance potential of regenerators and regenerative engines.

In a contractual effort for the U.S. Army Aviation Materiel Laboratories, AVCO Lycoming Division designed a recuperator for the T53 turboshaft engine (ref. 4). In the first phase of this program, a multiwave-plate core construction was selected to achieve a compact, lightweight, efficient regenerator. Test cores were fabricated by stamping individual plates and brazing stacked plates in assembly. Effectiveness and pressure loss of the test cores were relatively close to design targets, but leakage problems persisted in the brazed assemblies. Because of the core leakage problems with this construction, a conventional tube-type recuperator was designed and fabricated in another phase of the program. This concept was a two-pass, cross-counterflow core geometry with compressor air making two passes through the tubes and exhaust gas making one pass outside of and perpendicular to these tubes.

Allison Division of General Motors Corporation performed a flight-test program with a regenerative T63 engine in a YOH-6A helicopter (ref. 1). The core geometry of this recuperator was a tubular concept, two-pass cross-counterflow design.

The Boeing Company also undertook a research program to demonstrate the feasibility of achieving a heat-exchanger configuration which would have high thermodynamic performance, low pressure drop, and low weight and volume, and be producible at reasonable cost (ref. 5). The design concept consisted of rectangular modules of small-diameter, thin-walled tubes. The program was discontinued at the request of Boeing because of fundamental problems associated with high production costs for the modules of small-diameter tubes, compounded by intergranular corrosion and oxidation in the thin-walled stainless-steel material. The program identified the need for further basic research in tube size, candidate materials, and manufacturing techniques. Since that time, encouraging results from follow-on programs indicate that solutions to these problems have been found.

AiResearch Manufacturing Division of The Garrett Corporation participated in a 2-year research program to determine the hot-corrosion resistance and rupture strengths of thin-wall tube materials from which economic, lightweight recuperators could be constructed, and to investigate hot-corrosion mechanisms at temperatures below 1088.7 K (1,500°F). Most corrosion investigations have been concerned with gas-turbine-engine materials for use at temperatures above 1088.7 K (1,500°F). However, high-temperature alloys are not necessarily good heat-exchanger core materials and are often extremely expensive, less available, and more difficult to fabricate than lower-strength alloys. The difficulty of fabrication is especially important for small diameter, thin-walled elements of the heat-exchanger core. There is a lack of data on lower-strength alloys resistant to hot corrosion which would be suitable for recuperator concepts.

As a result of the research program conducted by AiResearch, a number of conclusions were reached regarding the suitability of the tested materials for use in recuperators, hot-corrosion effects, test techniques, and the applicability of the test data to recuperator design:

- Suitable alloys for use at metal temperatures up to 1088.7 K (1,500°F) were identified.
- Brazing filler metals with superior hot-corrosion resistance were determined.
- Hot corrosion was demonstrated at metal temperatures between 866.5K (1,100°F) and 1088.7 K (1,500°F).
- The cyclic hot-corrosion test provided the corrosion effects experienced by a recuperator.
- The recuperator test simulated the actual recuperator operating conditions for purposes of comparing candidate materials.

2.2 Technology Gaps – Problem Areas

The foregoing programs have defined the problem areas which remain to be explored and the technologies which must be developed to achieve a production regenerative engine. These are listed below:

- A well-integrated regenerator-engine configuration should be designed, with a compact, lightweight heat-exchanger matrix suitable for helicopter installation.

- Materials technology should be developed to determine satisfactory matrix and braze materials for the recuperator.

- Satisfactory production techniques should be determined for matrix elements and recuperator assemblies, at reasonable production costs.

- Technologies associated with variable engine geometry, both variable turbine-stator vanes and regenerator matrix bypass valve, should be developed, to utilize the performance advantages which these concepts offer.

3.0 REGENERATIVE ENGINE PERFORMANCE GOAL

A goal of 0.213 kg/hr/kw (0.35 lb/hr/shp) for the SFC of the regenerative engine in the 1985 timeframe is dependent upon achieving 1644.25 K (2,500°F) turbine-inlet temperature and the regenerator design-point effectiveness of 0.65. The turbine-inlet temperature is consistent with the trends of cooled-turbine technology. Development of satisfactory combustor and turbine-cooling concepts will minimize technical risk in achieving the temperature goal. Development of regenerator matrix and braze materials technology and regenerator producibility techniques will minimize technical risk in achieving a satisfactory regenerator design and the effectiveness goal.

Basic research requirements and applied research and technological demonstration requirements to realize the regenerative-engine SFC goal are identified in the following paragraphs. In addition, the requirements to develop variable-turbine geometry to improve partial-power SFC and regenerator-bypass geometry for maximum power are considered.

Interactions of the regenerative-engine design with technological goals for engine noise, hover and cruise performance, helicopter empty weight, drive-system efficiency and weight, hover performance with one engine inoperative, and maintenance and reliability are discussed.

4.0 REGENERATIVE ENGINE CONFIGURATIONS

In this section, design-point and off-design performance of a 1985-technology regenerative engine is discussed. Configuration concepts are suggested for the engine and regenerator to achieve the objectives of light weight, compactness, and integration with the engine. Regenerator weight trends are established.

4.1 Design-Point Selection

Improvements in materials and cooling techniques for combustors and turbines permit the trend of increasing turbine-inlet temperature as a function of time, with the attendant benefits of reduced engine weight and improved SFC. Temperature trends in conjunction with *the present state of the art of cooled-turbine technology indicates that 1644.25 K (2,500°F) is a* reasonable estimate for the design-point turbine-inlet temperature of a 1985 production engine.

Figure 1-1 illustrates that the optimum design-point pressure ratio for the regenerative engine is relatively low compared to the state of the art of compressor pressure ratio. The lower pressure ratio results in a higher turbine exhaust-gas temperature entering the recuperator. As a consequence the benefits to be obtained from a recuperator with a selected heat-exchanger effectiveness are greater than the SFC improvement normally produced by higher pressure ratio. A design-point compressor pressure ratio of 10 was selected for the regenerative engine with variable power-turbine geometry, a pressure ratio of 11 for the engine with fixed power-turbine geometry.

The thermodynamic performance of the regenerator is measured by its effectiveness, which is the ratio of the actual temperature increase of the airflow before entering the combustor to the maximum possible temperature increase (airflow heated to the temperature of the turbine exhaust gas). Regenerator effectiveness,

$$\eta_x = \frac{T_{ao} - T_{ai}}{T_{gi} - T_{ai}}$$

where T_{ai} = temperature of the airflow at the compressor exit, ^{o}F

T_{ao} = temperature of the airflow at the regenerator exit, ^{o}F

T_{gi} = temperature of the exhaust gas at the regenerator inlet, ^{o}F

Selection of the design-point regenerator effectiveness involves a tradeoff between recuperator weight and fuel weight saving, and the costs associated with those parameters. To obtain a high effectiveness entails a high regenerator weight, but produces a low SFC. So the result of increasing effectiveness is higher aircraft empty weight, higher airframe cost, but lower fuel weight and cost. Low effectiveness, while producing a lower regenerator weight, increases fuel-tankage requirements, and the result of decreasing effectiveness also is higher aircraft empty weight, higher airframe cost, and in addition higher fuel weight and cost. Previous studies indicate that an effectiveness of 0.65 is nearly optimum from the standpoint of aircraft gross weight, which involves both empty weight and fuel weight, and from the standpoint of life-cycle cost, which involves airframe-associated and fuel costs. A design-point regenerator effectiveness of 0.65 was selected.

4.2 Off-Design Performance

Figure 4-1 compares the performance of regenerative and simple-cycle turboshaft engines at design and off-design conditions. The performance curves for the simple-cycle engines are representative of existing turbomachinery technology and 1985 technology: design-point turbine-inlet temperatures of 1477.6 K (2,200°F) and 1644.25 K (2,500°F). With fixed-turbine geometry (constant effective flow area for both gas-generator and power turbines), the SFC characteristic for the regenerative engine is slightly flatter than that of a simple-cycle turboshaft engine. However, Davis (ref. 3) indicates that variable power-turbine stators, producing a variable power-turbine flow characteristic, result in an SFC characteristic which is almost constant down to very low engine powers. At a typical cruising condition, 60-percent power, the SFC of the regenerative engine with variable power-turbine geometry is 22 percent less than the SFC of the simple-cycle engine incorporating existing technology.

Variable gas-generator turbine geometry has a detrimental effect on SFC in a regenerative engine.

The regenerator introduces pressure losses in the engine which cause a decrease in shaft-horsepower output. For those occasions where peak power is required from the engine, a bypass valve would be needed to direct the flow from the compressor into the combustor, eliminating the air-side regenerator pressure loss, and a valve to direct the exhaust gas out the tailpipe, eliminating the gas-side pressure loss. Peak-power performance without the regenerator pressure losses is indicated also in Figure 4-1.

4.3 Configuration Concepts

McDonald (ref. 6) presents the results of an analytical and design effort which was directed toward achieving integrated regenerative engine designs which were compact and lightweight. The engine concepts employed an annular recuperator wrapped around the turbomachinery, the recuperator acting as the structural backbone of the engine assembly. A typical design is pictured in Figure 4-2.

These concepts were unique in that they were all small engines which featured a centrifugal compressor, radial-inflow combustor, and rear-drive output shaft. However, the integration of the designs to use the recuperator as engine structure and reduce the total weight is equally applicable to larger engines.

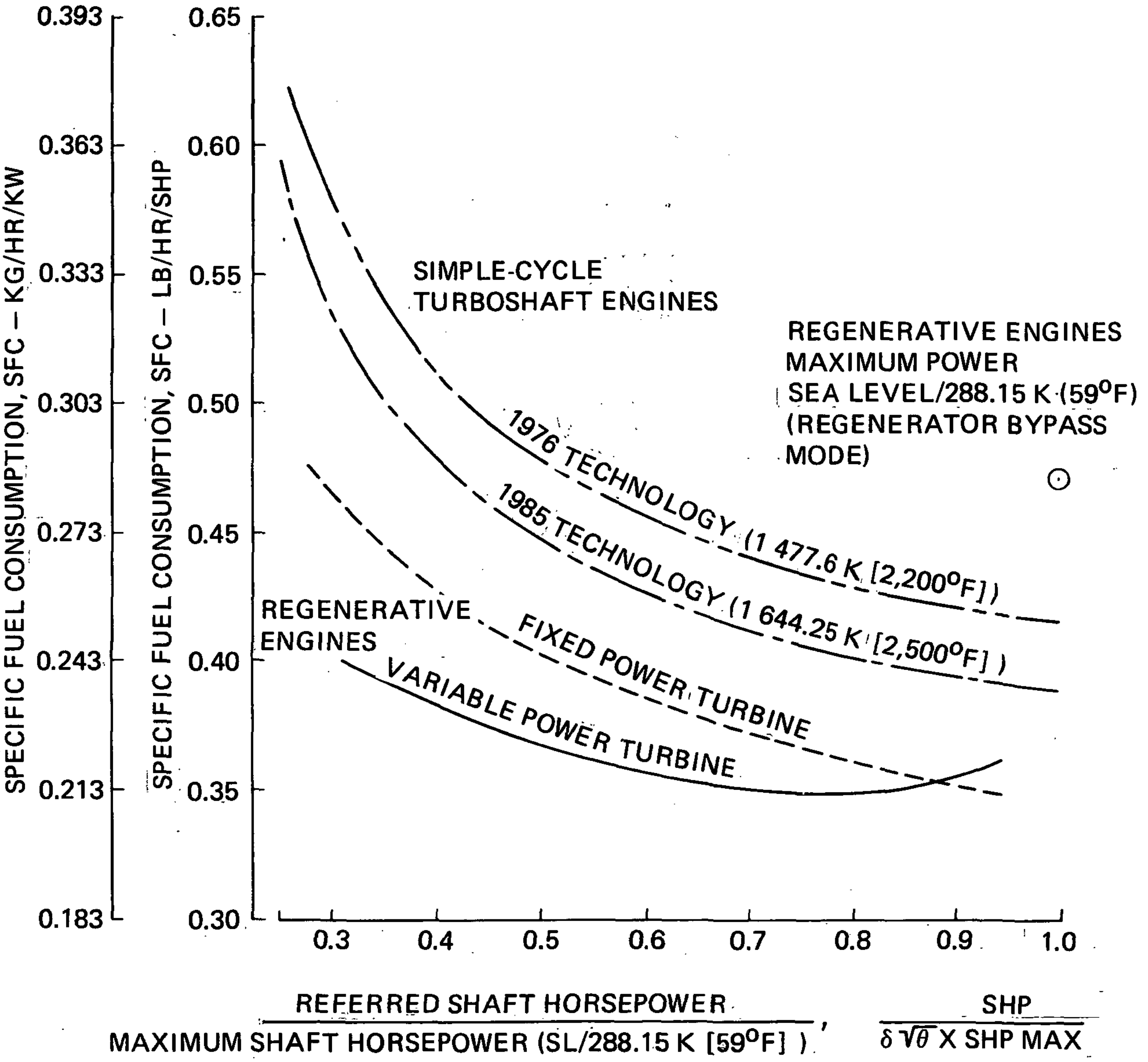

Figure 4–1. Performance of regenerative engines compared with simple-cycle engines

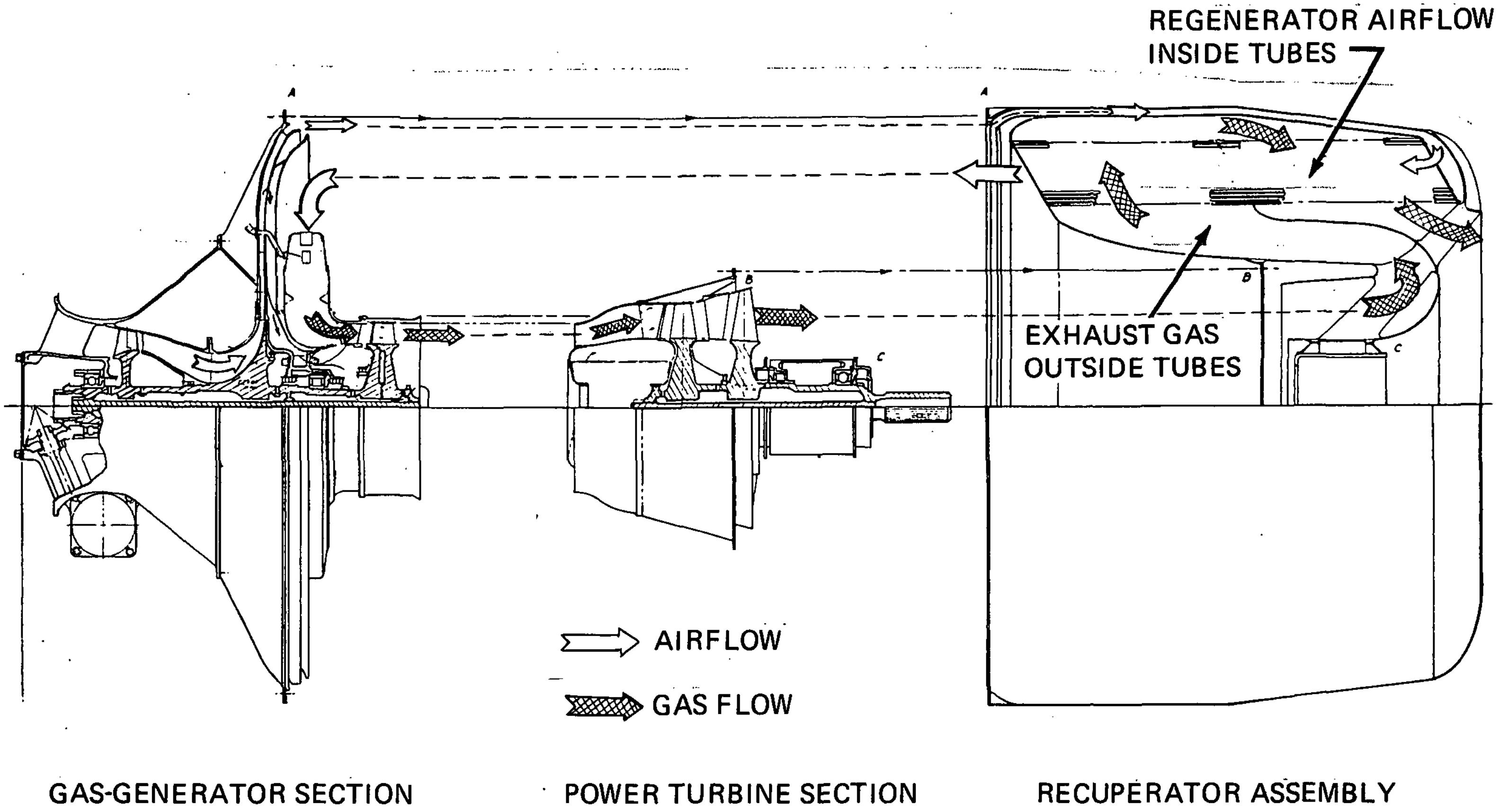

Figure 4–2. Integrated engine-regenerator design concepts

4.4 Regenerator Configurations

Candidate matrices for the recuperator appear to be the tube-in-shell, finned-tube, plate-fin, and dimpled-plate configurations, or design variants of these basic concepts. Producibility will be the major factor in the selection of the recuperator matrix.

4.5 Regenerator Weight Trend

Recuperator weight data from references 2, 3, and 4 were correlated in terms of specific weight (specific weight equals recuperator weight per kilogram per second of engine airflow) and plotted in Figure 4-3. For purposes of comparison, recuperator weights for the parametric engine configurations of reference 6 were included in the correlation (A-1 configuration). Weights for the A-1 parametric recuperators of reference 6 should have been and were reasonably consistent with previous trend data, since the designs included external shells, headers, and hardware usually associated with the heat exchanger.

For the 1985-technology engine basic engine weight, presented in terms of specific weight (per kilogram per second of engine airflow) as in Figure 4-3, is estimated to be 25 to 30 kg/kg/sec (25 to 30 lb/lb/sec), depending on the size of the engine. The regenerator then represents a 50- to 60-percent weight increase for the regenerative engine, compared to the equivalent simple-cycle engine.

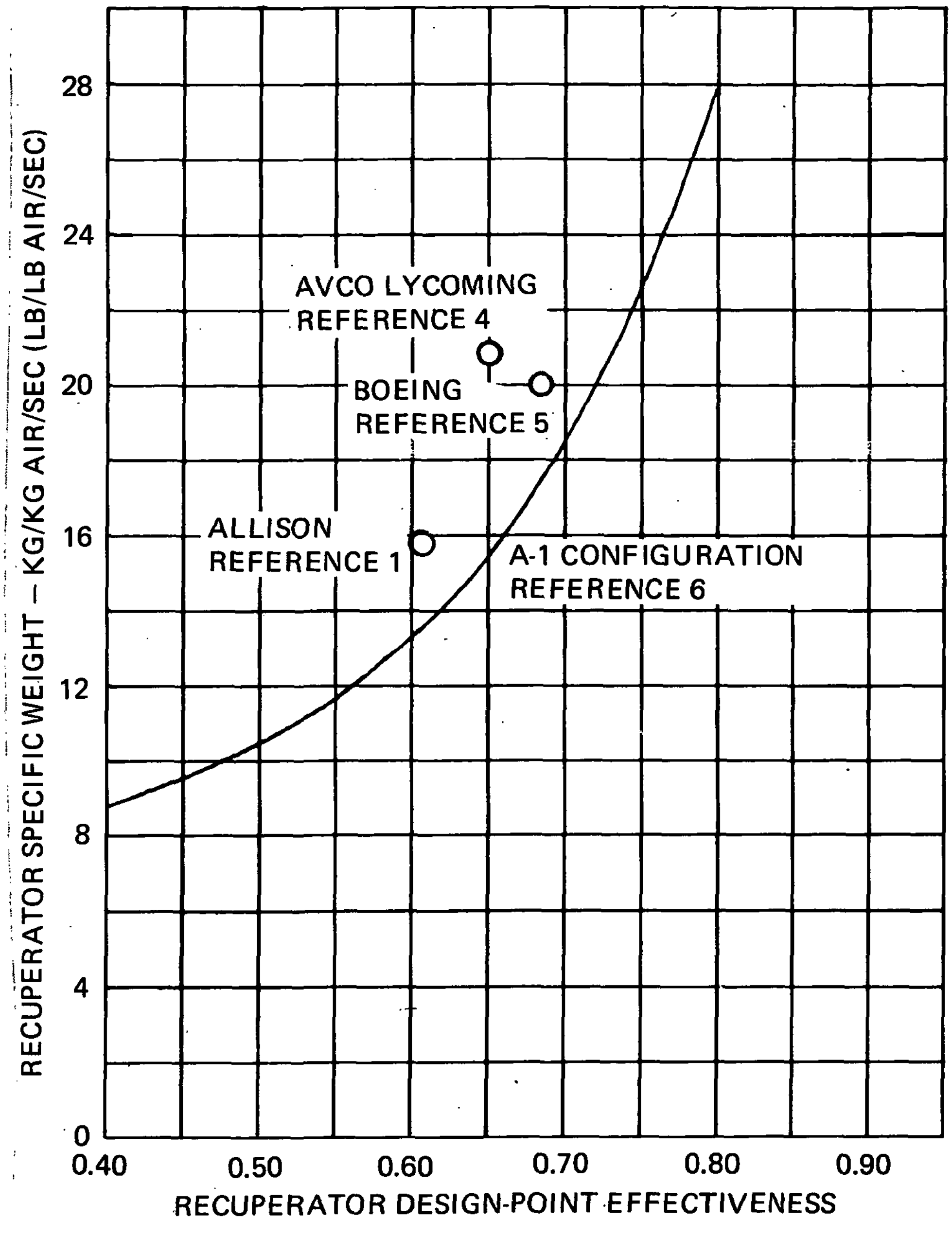

Figure 4–3. Trends of regenerator weight per unit of engine airflow.

5.0 RESEARCH AND DEVELOPMENT REQUIREMENTS

The elements of a research and development program to achieve a regenerative engine for a civil helicopter flight-test demonstration are identified graphically in Figure 5-1.

5.1 Basic Research and Development

The initial element of the basic research and development phase is to evaluate and select candidate design concepts for the engine arrangement, engine-component geometry, and the recuperator.

Of the candidate regenerator design concepts, further evaluation must be devoted to producibility, including the test effort required to select the optimum regenerator configuration from the standpoint of cost, weight, and performance. At the same time, evaluations must be performed to select the regenerator matrix and braze materials.

Basic research and development will be required concurrently to achieve materials and cooling technology applicable to the combustor and gas-generator turbine. The turbine-inlet temperature of 1644.25 K (2,500°F) projected for the 1985 timeframe appears to be consistent with trends of the state of the art for cooled turbines. However, the regenerative engine with variable power-turbine geometry would operate at 1644.25 K (2,500°F) throughout its operating range, not at the highest engine rating only. In accordance with this requirement, the cooled turbomachinery must be designed to operate at the peak temperature for the life of the engine, and not just for a fraction of the engine life.

The time chart incorporated into Figure 5-1 predicts that a 1-year conceptual-design effort is required, followed by 2 years of basic research and development effort in the areas of recuperator producibility and materials and a concurrent cooled-turbomachinery effort.

5.2 Applied Research and Development/Demonstration

The objective of the basic research and development effort is to prepare for a regenerative-engine development program, which Figure 5-1 presents as a phased program. The regenerator, combustor, and gas-generator turbine are identified as high-risk components in such a development program. Consequently, the schedule pictured in Figure 5-1 envisions these components to be the subject of an initial technology-demonstrator type of effort encompassing 2 years. Only after the successful demonstration of these technologies will the engine development be undertaken.

Reference 7 describes the test techniques which would be employed in proving regenerator technology:

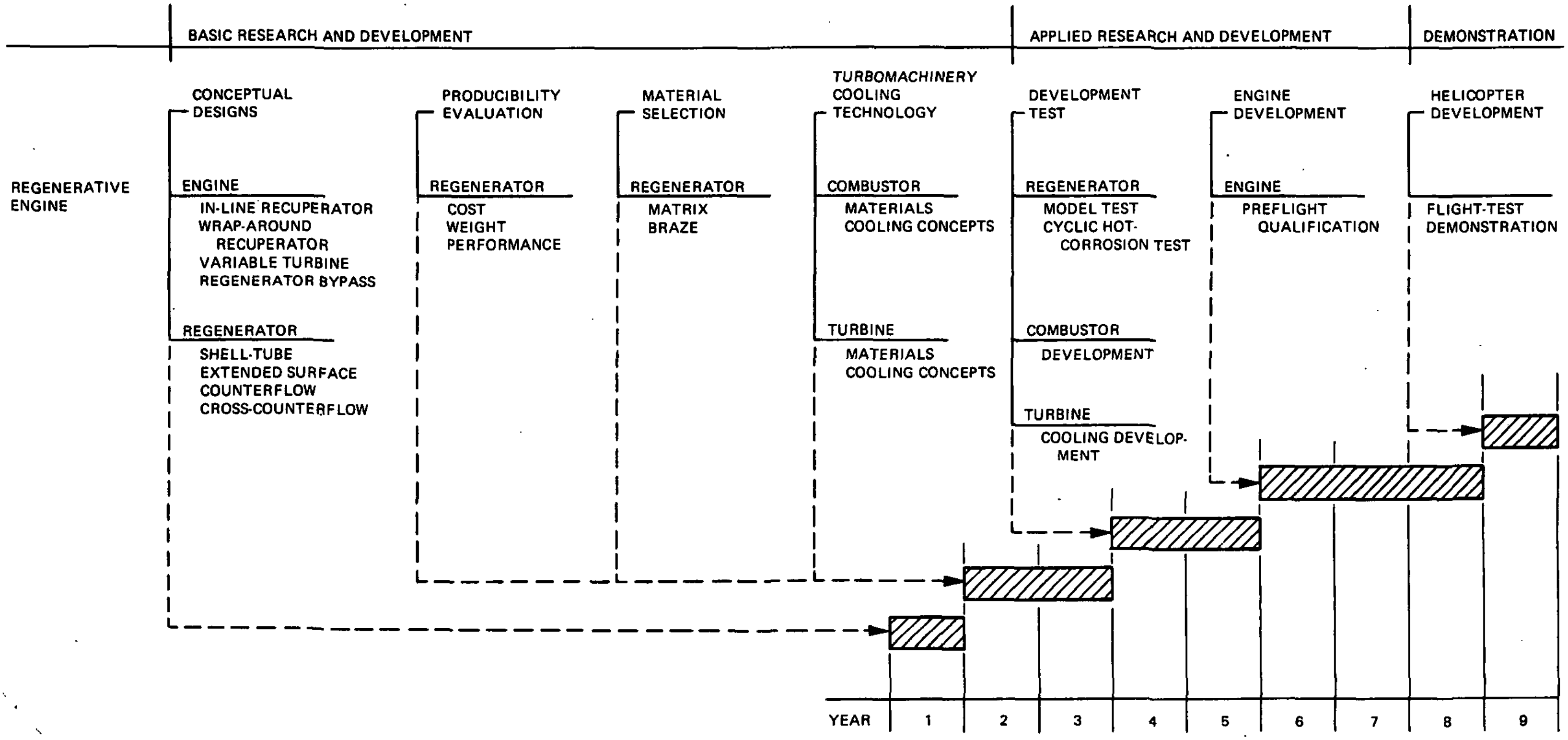

Figure 5–1. Regenerative-engine research and development program

- The cyclic hot-corrosion test
- The recuperator model test.

The former test duplicates the corrosion effects upon the full-scale recuperator and provides actual stress-rupture data. The latter test simulates conditions of temperature, pressure, flow rate, and thermal cycling encountered during the actual operation of the recuperator. Both tests are recommended to provide sufficient information to determine the suitability of materials for use in the recuperator.

For the turbomachinery, quarter-section model tests of the combustor and large-scale model tests of cooled gas-generator turbine blades are suggested to demonstrate the technologies employed in these components.

Successful demonstration of the technologies of the regenerator, combustor, and turbine would initiate the engine-development program, which is estimated to be a 3-year effort culminating in a 60-hour preflight qualification test.

The schedule in Figure 5-1 suggests that 8 years will be required to accomplish the regenerative-engine research and development program, culminating in the flight-test demonstration of the regenerative powerplant in a helicopter. Reference 3 places the cost of the total development programs at $73 million for a 3728.5-kw (5,000-hp) engine. The cumulative expenditure of this development money has been illustrated in Figure 5-2 and is correlated with the planned research and development effort.

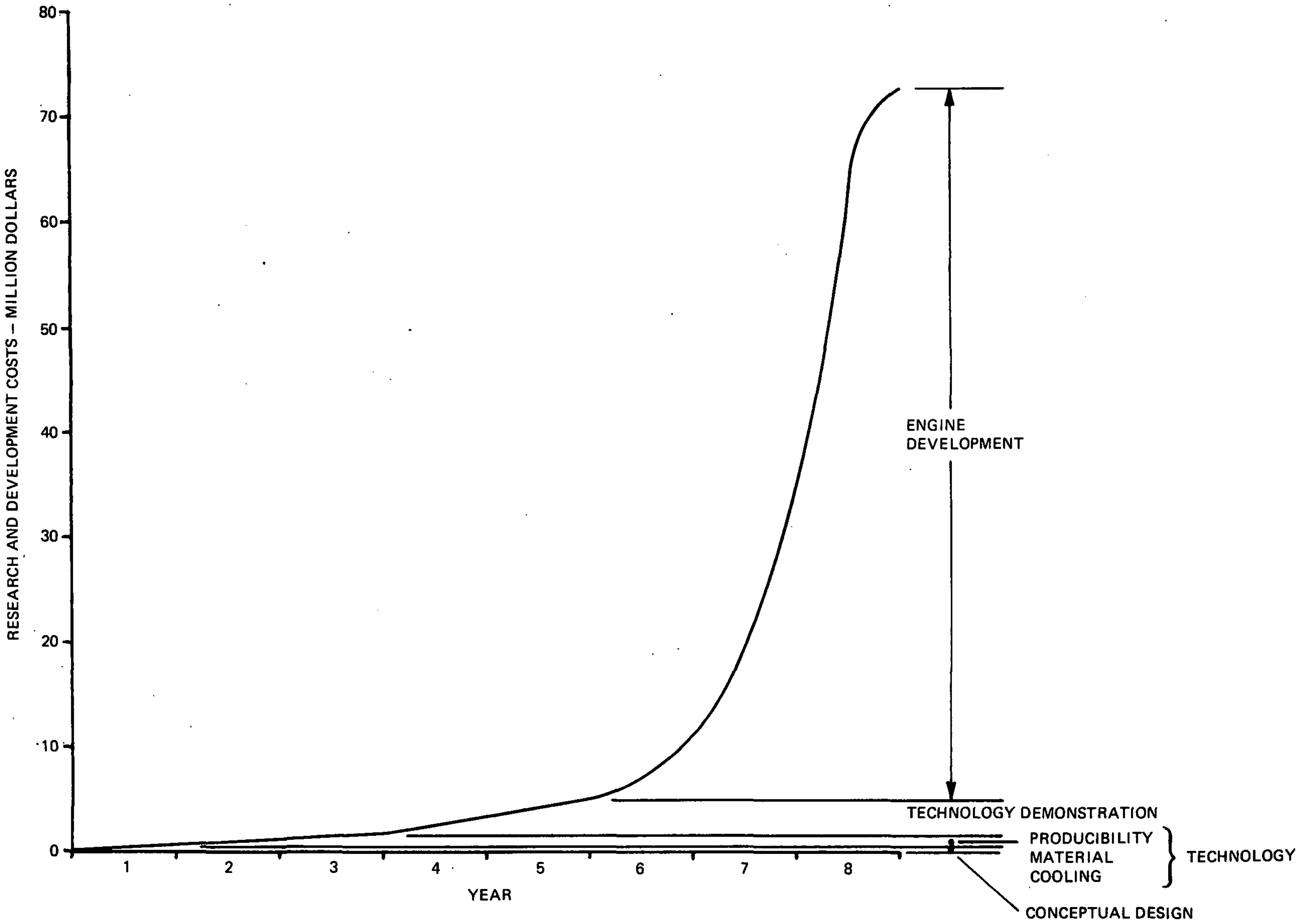

Figure 5–2. Cumulative expenditure of regenerative-engine research and development costs

6.0 TECHNOLOGY AND DESIGN INTERACTIONS

The impact of the regenerative engine on interacting technological areas and systems is discussed in the paragraphs which follow.

6.1 Engine Noise

The overall engine-noise levels result primarily from three factors:

- Inlet Noise: This contribution is a function of the compressor first-stage blades passing through the wakes of the inlet guide vanes.
- Combustor Noise: Combustor noise results from the turbulent flow in the burning process.
- Exhaust Noise: Turbine-blade/stator-vane wake interference and the exhaust velocity contribute to exhaust noise.

Integral regenerator concepts, particularly regenerators which wrap around the turbomachinery, will help to reduce combustor noise. The regenerator also will help to alleviate exhaust noise; this should be true especially of multipass cross-flow concepts, where the exhaust gases will pass repeatedly across the heat-exchanger matrix before exhausting to atmosphere. The effect of the regenerator on inlet noise will be subtle, if there is any interaction. The regenerative engine optimizes at low design-point compressor pressure ratios, which could eliminate the need for variable inlet guide vanes and at the same time eliminate a source of engine-inlet noise.

6.2 Performance

The effect of the regenerative engine on performance in cruise, in terms of reduced fuel consumption, is apparent from the data presented in Figure 4-1. Compared to the simple-cycle turboshaft engine incorporating existing technologies, the regenerative-engine fuel consumption is 22 percent less at a reasonable cruise horsepower condition, 60 percent of maximum power. If the regenerative engine were to incorporate a regenerator with design-point effectiveness greater than 0.65, the improvement in cruise fuel consumption would be even greater. However, previous studies (ref. 2) indicated that increases in regenerator effectiveness resulted in higher engine weight, higher empty weight of the helicopter, and culminated in a higher fleet life-cycle cost.

The effect of the regenerator on hover performance, expressed in terms of power available, could be negated by suitable bypass valves as discussed earlier in the text. Bypass arrangements eliminate the pressure losses in the heat-exchanger matrix and their impact on engine power.

However, the design-point compressor pressure ratio selected for the regenerative engine is relatively low compared to the state of the art of compressor pressure ratio. As indicated in paragraph 2.0, pressure ratio primarily impacts SFC, but it has a secondary effect on shaft horsepower per pound of engine airflow. The lower pressure ratio of the regenerative engine results in a lower maximum power available, even in the regenerator-bypass mode, but the approximate horsepower penalty is only 5 percent.

6.3 Empty Weight

It was estimated that the increase in engine weight with the addition of a regenerator was 50 to 60 percent, but the reduced fuel consumption of the regenerative engine is reflected in lower fuel-cell weight. Reference 3 demonstrated that the two weight changes virtually offset each other, so that the change in the empty weight of the helicopter was very small.

6.4 Drive-System Efficiency and Weight

The regenerative engine should have no impact on the helicopter drive-system efficiency or weight.

6.5 Hover with One Engine Inoperative (OEI)

OEI hover power available should be the greatest possible power from an operative engine. In the regenerator of the regenerative engine, the air-side pressure loss between the compressor exit and the combustor and the gas-side pressure loss at the exit of the power turbine detract from the engine power available. Bypass valves to redirect the air from the compressor into the combustor, bypassing the heat exchanger matrix, and to redirect the exhaust gas away from the heat exchanger and directly out the tailpipe eliminate these pressure losses associated with the regenerator. The bypass valves insure the maximum power available from the engine and permit other techniques to be used to augment power available for OEI situations.

However, the discussion of paragraph 6.2 indicates that the lower design-point pressure ratio of the regenerative engine results in a lower maximum power available, even in the regenerator-bypass mode, although the power penalty is only approximately 5 percent.

6.6 Reliability and Maintainability

The impact of the regenerator on engine reliability and maintainability is directly reflected in the maintenance manhours per flight hour (MMH/FH) tabulations of reference 2. The significant differences in MMH/FH between the regenerative and nonregenerative engines are for replacement and repair of the combustor, turbine-temperature sensor, and power-turbine module, as well as inspection and replacement/repair of the recuperator module itself. The changes in replacement/repair MMH/FH for the combustor, turbine-temperature sensor, and power turbines are to be expected, because in the regenerative engine with integrated recuperator these components are buried inside the heat-exchanger matrix.

The difference in MMH/FH between the regenerative and nonregenerative engines of reference 2 was estimated to have a cost impact of less than 0.5 percent of aircraft-system life-cycle cost.

7.0 IMPACT ON [illegible] OPERATING COSTS

The cost impact of the regenerative engine has been assessed for the following stages of the helicopter-system life:

- Initial Costs
  - Research and development, test, and engineering (RDT&E)
  - Initial investment
- Operations and Maintenance (O&M)

Reference 2 provides cost data to quantify the comparison of regenerative and nonregenerative engines. Of all the cost subheadings under Initial Costs and O&M, only those which show significant cost differences are discussed in the following paragraphs.

The principal reason that RDT&E costs of the regenerative-engine-powered aircraft are larger than those of the helicopter with nonregenerative engines is the development cost of the regenerative engine itself. The reduced design-point compressor pressure ratio of the regenerative engine would result in a simplified compressor design, which would tend to reduce engine-development cost. Despite the effect of this difference in compressor design, it is estimated that development costs for regenerative engines would be 20 percent higher than those for simple-cycle engines. This increase should reflect costs for design, prototype tooling, material, fabrication, assembly, and component testing applicable only to the recuperator, since such costs for other engine components as well as requirements for engine-endurance testing to achieve qualification would be the same for both regenerative and nonregenerative engines. Figure 7-1, which is reproduced from reference 3, indicates this 20-percent cost increase for development through the preflight-qualification endurance test.

Cost differences in the categories under Initial Investment are for flyaway costs – including operational aircraft, maintenance float, and attrition aircraft – and for the attendant spares. Initial-investment costs for the regenerative-engine-powered aircraft are higher due to the higher production costs for the regenerative engines.

In the categories under O&M, the regenerative-engine-powered helicopter maintenance-parts, maintenance-labor, and support-personnel costs would be higher than those for the simple-cycle engine. But the most important cost difference is the reduced fuel cost, which shows the reduction in energy consumption of the regenerative-engine-powered aircraft. Increased maintenance costs are greater than the reduction in fuel costs, so O&M costs are greater for the regenerative-engine-powered helicopter.

A helicopter with an advanced-technology simple-cycle engine would have the lowest life-cycle cost. Higher development and production costs and maintenance requirements for the regenerative engines were too great to be offset by savings in fuel. The differences in life-cycle cost were less than 1 percent.

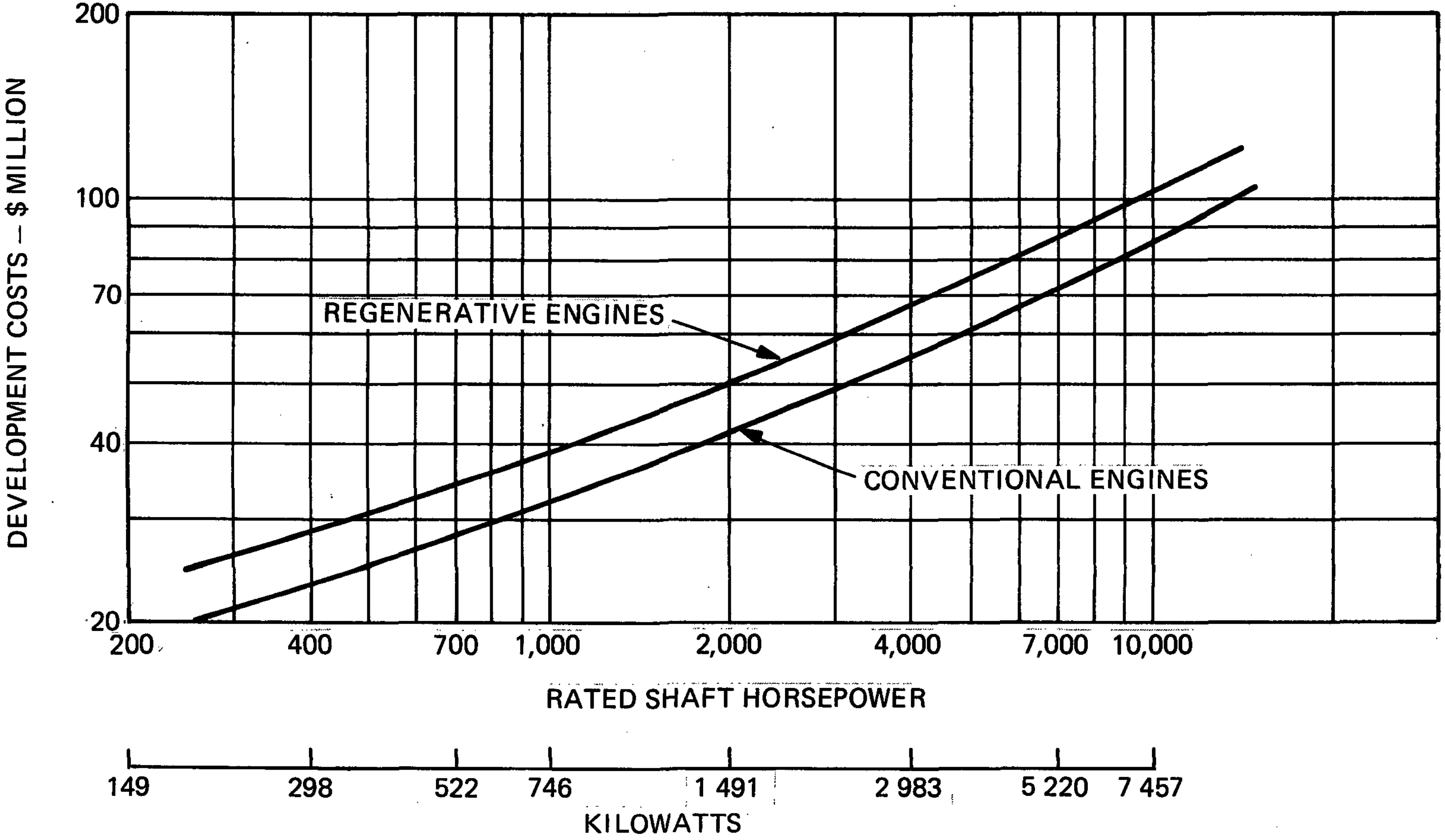

Figure 7—1. Comparison of development costs for regenerative and simple-cycle turboshaft engines

[redacted]

Turboshaft-engine technological advances in recent years have been directed primarily toward increases in design-point compressor pressure ratio and turbine-inlet temperature, to produce a lower SFC. The regenerative turboshaft engine offers a substantial added reduction in SFC, and the optimum design-point compressor pressure ratio of the regenerative engine is much lower than that of the simple-cycle engine. Previous development and test programs have demonstrated the performance potential of regenerators and regenerative engines, and have defined technological gaps and problem areas which remain to be explored to achieve a production regenerative engine. Table 8-1 identifies the positive aspects of the regenerative-engine configuration as well as the negative aspects, many of which correspond to these research and development requirements:

1. The regenerative engine provides a 14-percent reduction in design-point SFC compared to the simple-cycle turboshaft engine incorporating existing technology. However, with variable power-turbine geometry, the SFC of the regenerative engine is essentially constant down to very low-power operating conditions, which are typical of the helicopter in cruise, and provides a 22-percent reduction in fuel consumption.

2. The regenerator results in a reduction in exhaust noise. Integral-regenerator concepts would contribute to a reduction in combustion noise. The lower compressor pressure ratio, obviating the need for inlet guide vanes, would contribute to a reduction in inlet noise.

3. The lower compressor pressure ratio of the regenerative engine minimizes the amount of variable geometry required for transient operation, reducing compressor complexity.

4. A regenerator with 0.65 design-point effectiveness increases engine weight 50 to 60 percent. Higher effectiveness would result in greater fuel weight savings, but also would increase engine weight. The selected value of 0.65 design-point effectiveness is nearly optimum from the standpoint of aircraft takeoff gross weight.

5. The regenerative engine introduces additional costs in the RDT&E, Initial Investment, and Operations and Maintenance phases of the helicopter life cycle. However, the regenerative engine provides a substantial reduction in fuel costs.

6. Increased technical risk is inherent in the development of the regenerative engine and entails a research and development effort to prove the required technologies, which include:

   - Recuperator materials
   - Recuperator producibility
   - Variable power-turbine stators

- Regenerator bypass valves
- Long-life combustor and turbine cooling concepts.

An 8-year program of recommended research to achieve a regenerative engine for flight-test demonstration is summarized in Table 8-2.

TABLE 8–1. POSITIVE AND NEGATIVE ASPECTS OF REGENERATIVE ENGINES

Positive Aspects	Negative Aspects
• Decreased SFC – Design-point performance – Partial-power performance • Decreased Engine Noise • Low Design-Point Compressor Pressure Ratio – Minimum compressor complexity	• Increased Engine Weight • Increased Engine Costs – Initial costs: RDT&E plus initial investment – O&M maintenance costs • Increased Technical Risks – Recuperator materials – Recuperator producibility – Variable power-turbine stators – Regenerator bypass valves – Combustor/turbine cooling requirements

TABLE 8–2. SUMMARY OF RECOMMENDED RESEARCH FOR REGENERATIVE ENGINES

Number	Research Item	Research Recommendation	Priority	Size Applicability	Cost (Million $)	Payoff
1	Integrated regenerator-engine configurations	Yes	Medium	All	0.5	Medium
2	Regenerator matrix/braze materials technology	Yes	High	All	1.5	High
3	Regenerator producibility	Yes	High	All	1.0	High
4	Variable-turbine geometry	Yes	Medium	All	0.5	Medium
5	Regenerator-bypass concepts	Yes	Medium	All	0.5	Medium
6	Turbomachinery cooling concepts	Yes	High	All	1.0	High

[illegible]

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