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Rotorcraft Convertible Engines for the 1990's

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ROTORCRAFT CONVERTIBLE ENGINES FOR THE 1990'S

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ABSTRACT

Two rotorcraft studies sponsored by NASA were executed by General Electric and Detroit Diesel Allison. The goal was to identify attractive techniques for implementing convertible powerplants for the ABC, Folded Tilt Rotor, and X-wing type high-speed, high-L/D rotorcraft; to determine the DOC and fuel savings benefits achieved thereby; and to define research required to bring these powerplants into existence by the 1990's. These studies are reviewed herein and the different methods of approach are pointed out as well as the key findings. Fan/shaft engines using variable inlet guide vanes or torque converters, and turboprop powerplants appear attractive. Savings in DOC and fuel consumption of over 15 percent are predicted in some cases as a result of convertible engine use rather than using separate engines for the thrust and the shaft functions. Areas of required research are fan performance (including noise), integrated engine/rotorcraft control, torque converters, turbine design, airflow for rotorcraft torque control, bleed for lift flow, and transmissions and clutches.

THE ROLE OF HIGH SPEED ROTORCRAFT

The high-speed, high-L/D rotorcraft combines the vertical flight capability of the helicopter with the high-speed cruise capability of a fixed-wing aircraft. This type of aircraft offers two major advantages, a reduction in fuel use and a shorter trip time when compared to helicopter performance at relatively long ranges. Figure 1, based upon information in ref. 1-3, presents the trends of fuel consumption per passenger mile as a function of range for helicopters, high-speed rotorcraft of which there are prototypes flying today, proposed more advanced high-speed rotorcraft, and conventional takeoff, fixed-wing turboprop transports.

The helicopter band compares favorably with that of the turboprop at a range of 50 nautical miles. At this range or lower, the fuel required for ground maneuvers, including takeoff and landing, more than offset the better L/D and propulsion system weight fraction offered by the turboprop. As the range increases, the turboprop's three to one L/D advantage has a great effect on fuel use, and the helicopter fuel consumption becomes nearly four times that of the turboprop. Figure 2 shows that in addition to the fuel penalty the limited speed of the helicopter, 150 kns. compared to perhaps 350 kns., would make a one hour 350 N.M. trip last 2 1/2 hours. The rotorcraft being tested today have double the L/D of the helicopter during cruise. The fuel consumption of these aircraft is represented by the middle band. The fuel use for these aircraft is far better than that of the helicopter for ranges in excess of 200 nautical miles. Further, the flight duration for the 350 nautical mile flight is only about 20 minutes greater for the rotorcraft than for the turboprop.

The lower band, representing more advanced rotorcraft with L/D values above 10 at cruise, indicates that in the neighborhood of a 400 N.M. range these rotorcraft are close to the turboprop in fuel use and fly at the same speed. With this type of rotorcraft the penalty for vertical capability in terms of fuel and flight duration would be quite modest.

There are many possible uses for high speed rotorcraft aircraft. For example, they are ideally suited for the supply of distant offshore oil rigs and for the supplying of remote military units in rough terrain (figure 3).

THE PROPULSION REQUIREMENT

There are four high-speed, high-L/D rotorcraft that are of current interest: the Advancing Blade Concept (ABC), the Tilt Rotor, the X-wing which is of interest to the U.S. Navy, and the Fold Tilt Rotor (FTR) (figure 4). The ABC concept (figure 5) utilizes counter-rotating rotors and auxiliary thrust for high speed operation. As the aircraft accelerates beyond 150 kns., the rotational speed of the rotors is decreased and the auxiliary thrust is utilized. The Tilt Rotor (figure 6) is a winged vehicle whose rotors tilt 90 degrees as the aircraft converts from vertical flight to horizontal flight. The X-wing (figure 7) is one of the more advanced, higher-speed, higher-L/D concepts. Here there is a single rotor for lift and a separate thrust capability for high-speed flight. At a speed above 150 kns., possibly as high as 250 kns., the rotor is brought to a full stop and then acts as a wing at higher speeds. To satisfy the lift requirement with a small weight penalty, additional lift is obtained by blowing air through orifices in the rotor blades. The auxiliary thrusters provide all the propulsion during high-speed flight. The FTR (figure 8) carries the tilt rotor another step. With the rotors positioned in the vertical plane after achieving horizontal flight, they are stopped, indexed, and folded. Auxiliary thrust devices then supply all propulsion requirements during high-speed flight.

THE CONVERTIBLE POWERPLANT CONCEPT

The ABC, FTR, and the X-wing all require a thrust system for high speed flight (figure 4). This thrust could be supplied by separate turbofan or turboprop engines. However, since the rotor requires little or no power during cruise, one set of engines can be envisioned that supply power to the rotor during vertical flight and also supply power to the forward propulsor during cruise flight. This dual role is known as the convertible powerplant concept.

NASA recently sponsored two studies to define possible convertible powerplant configurations for ABC, FTR, and X-wing craft, and to define the required research and technology work to bring such systems into existence. It was a search for those technologies required to make the future rotorcraft better in the propulsion area rather than an attempt to compare different types of rotorcraft or to define specific missions for such aircraft.

General Electric examined the ABC and the X-wing with Boeing Vertol providing airframe support, and Detroit Diesel Allison examined the ABC and the FTR with Sikorsky and Bell Textron respectively providing airframe support.

Figure 9 presents schematically the powerplant alternatives examined in the initial screening. Both the variable inlet guide vane (VIGV) engine and the fluid coupling engine use a fixed pitch fan. In the VIGV concept the inlet guide vanes are open during high speed cruise operation. They are closed during periods of helicopter type operation, blocking the bypass flow but allowing core flow to be maintained. The rotor is clutched into the engine which then operates as a turboshaft engine.

In the fluid coupling concept, the coupling mechanism accelerates and then locks the fan to the engine during high speed cruise. The torque converter is then drained of fluid to avoid power losses and the resulting heat build up. During vertical operations, the fan is decoupled. The rotor is then engaged by means of a clutch or fluid couplings, and turboshaft operation is achieved.

In the variable-pitch fan and propeller systems the fan or propeller is set at an unloaded condition during shaft operation.

The remaining two systems use separate turbines for fan and shaft operation. Power is delivered to the fan or rotor as desired by using valves to divert gas flow to the proper turbine.

GROUNDRULES

The groundrules for the study are presented in Tables I and II. These groundrules represent estimated, typical civilian usage. The one engine inoperative (OEI) requirement was based upon the assumption that safety requirements for civilian, passenger, high-speed rotorcraft would become more stringent with time. This OEI requirement is to insure complete land back capability of a fully loaded rotorcraft with one engine out at maximum power at sea level on a hot day. In general, the turbine inlet temperature was about 300°R higher at the maximum than at cruise. The number of hours of annual utilization was chosen based upon the premise that by the 1990's the passenger demand would be sufficient to result in commercial airline type operation.

The civil mission scenarios, including the passenger capacities of the aircraft of 48 and 30 for GE and DDA respectively were chosen by the airframers based upon their marketing experience and judgement. In actuality the civil rotorcraft market is not large on a dollar basis when compared, for example, with the fixed-wing, commercial transport market (ref. 4), and most rotorcraft are designed for both commercial and military use (ref 5). If such commonality is required, the payload capacities and thus the size of such rotorcraft might be somewhat different from those chosen for this study. Since, however, this was only a search for engine technology, the only criterion needed was that the powerplants be in the proper size range so that the technologies would be applicable to whatever propulsion systems are eventually chosen. To prevent possible confusion, a special point should be made regarding the X-wing concept. DARPA has recently defined in great detail a specific military X-wing which is being designed under groundrules totally different from those of these studies. The DARPA X-wing is similar only in concept to the hypothetical civil X-wing used in the work described in this report.

The separate-engine baseline vehicles are defined in figure 10. The ABC separate-engine baseline rotorcraft for GE is powered by turbofans for forward thrust. The DDA ABC utilizes turboprops for this auxiliary forward thrust. The X-wing and the FTR baseline rotorcraft both use turbofan engines for the required auxiliary thrust.

POWERPLANT SCREENING

The screening of the convertible powerplant types was executed in two stages. In the initial screening, one engine system was chosen as a convertible powerplant baseline for each aircraft type. Then other engine conceptions were evaluated against the baselines using a preliminary screening method.

The chief criteria used by GE were fuel use and cost obtained by utilizing mission sensitivities from the separate engine configurations. Several judgemental factors concerning matters such as complexity and reliability were also addressed. The DDA chief criterion was SFC with similar judgemental factors also being included.

The surviving engine concepts from the initial screening were then subjected to more detailed mission evaluation in which they were hypothetically installed on an aircraft. Missions studies were then performed.

The initial screenings for the ABC ranked the candidates as shown in Table III with the prop/shaft convertible powerplant achieving the highest score. The preferred choice is essentially the same in both evaluations, and the order of preference deviates only with those systems deemed to be poor candidates.

GE carried the VIGV fan/shaft concept on into the detailed mission evaluation along with the prop/shaft. Indeed, the VIGV fan/shaft is their baseline convertible system. DDA carried only the prop/shaft forward into the detailed mission evaluation.

The chief penalty for the variable pitch fan as compared to the VIGV fan system is weight. The separate turbine systems are heavy, and although some have improved SFC, this does not offset the weight. Those systems using separate rotor and fan turbines initially appear attractive. They offer convertible capability using a few simple valves or 'doors' in the ducting thereby avoiding clutches and shafts. Unfortunately the energy losses and ducting and insulation requirements tend to eliminate these powerplants as reasonable candidates for powering the main rotor and the fans.

As an example of the numerical scoring associated with the initial screening, Table IV is presented. This particular table presents only differences in SFC and engine weight. The numbers indicate percent difference from the SFC and engine weight of the VIGV fan/shaft baseline. Thus a negative number denotes an improvement.

The prop/shaft engine is 2 percent higher in engine weight than the VIGV engine. The remote turbine systems vary from the baseline in fuel efficiency from 14 percent better for a prop/shaft remote system to 14 percent worse for one of the other systems. All the remote turbine systems are more than 20 percent heavier than the VIGV fan system. The order of preference chosen reflects the judgemental factors as well as the fuel efficiency and weight.

Table V present a list of the candidate types screened by GE for the X-wing and DDA for the FTR. An initial decision was made by Bell-Textron that propellers when added to the two folding tilt rotors would add complexity to the FTR. Placement of the propellers would result in more complex, heavier drive systems than would be required with fans. At the very least the use of propellers would have necessitated preliminary design studies to determine placement of propellers, placement of engines, and routing of shafts. Such work was beyond the scope of the study. The prop/shaft configuration was never evaluted, therefore, for the FTR, and only fan/shaft configurations appear in this list.

GE did consider the prop/shaft for the X-wing configuration, and in this preliminary screening it appears as the system of choice on a cost and fuel consumption basis. The top fan/shaft contender for GE in this initial screening is the VIGV type. DDA choices include both the VIGV type (their convertible baseline) and a fixed pitch fan connected to the engine via a fluid coupling.

The more detailed mission studies performed upon those concepts surviving the screening utilized those missions previously defined. For the design cases rotorcraft size and weight were allowed to vary, the range and payload being held constant. This approach involved resizing the aircraft for SFC and weight differences as well as for installation effects. Figures 11 and 12 illustrate the resulting vehicle layouts, sizes and power requirements.

Table VI presents a summary of the results of these evaluations for the ABC. DAA/Sikorsky estimate that changing from a separate-engine system to a convertible system saves 6.6 percent in fuel and reduces DOC by 12 percent. This DDA/Sikorsky comparison is between a separate-engine turboprop-turboshaft configuration base line and one utilizing a prop/shaft convertible powerplant. GE/Boeing benefits from utilizing a convertible VIGV powerplant are 15.1 percent for fuel and 12.7 percent in DOC. The GE/Boeing comparison, however, is based upon the comparison of a separate-engine turbofan-turboshaft configuration with a convertible fan/shaft powered ABC.

GE/Boeing also estimate that there is a significant advantage obtainable in fuel use and cost by selecting a convertible prop/shaft rather than a convertible fan/shaft configuration as is also noted in Table VI. Note that the percent improvements quoted by GE/Boeing are only greater than those of DDA/Sikorsky because of the turbofan-turboshaft separate engine datum used by GE/Boeing rather than the turboprop/turboshaft used as the datum by DDA/Sikorsky. Takeoff gross weight changes, unlike DOC and fuel use, differ very little from fan/shaft to prop/shaft systems. This is due to propulsion system weight. The added installation penalties associated with the prop/shaft, including propeller, gearbox and shaft weights, result in a total propulsion system weight larger than that associated with a fan/shaft.

Recommended engine cycles and arrangements are displayed in figure 13. These 4700 to 5200 SHP class engines would require approximately the same cycles and basic turbo-machinery arrangements as non-convertible powerplants of this size: 22-26 overall pressure ratio and 2500-2600°F maximum turbine inlet temperature. In actuality DDA/Sikorsky slightly modified the OEI requirement. For example, a 400 foot runway for landing was permitted. As a result, the cruise requirement resulted in an engine size a bit greater than the OEI requirement.

Table VII contains a summary of the evaluation results comparing both of the X-wing convertible concepts, the VIGV fan/shaft and the prop/shaft. The improvements over a separate engine craft are all substantial. DOC improvements are about 21 percent with the convertible VIGV fan/shaft engines and roughly 25 percent with the prop/shaft engine. The acquisition cost improvements are about the same for both convertible concepts, 18 percent. The lowest improvement is the 13.4 percent change in gross weight with the prop/shaft system. A substantial difference in fuel-use savings exists. The savings of 16 percent using the fan/shaft convertible engines is certainly appreciable. However, using the prop/shaft powerplants nearly doubles the improvement. In spite of the additional savings possible from utilizing the prop/shaft system, the fan/shaft was finally selected to be the the powerplant of choice. This was based primarily on the fact that the actual market for such an aircraft might in reality be more heavily military than civilian. The X-wing, were it to have military commonality, especially for sea type duty, would be hampered by its very high tail with the the large propellers. Military application might very well have lower utilization than the 2000 hours used in the study, and speed growth beyond the 400 knot groundrule would be expected. In addition, fuel price seems to be holding at levels lower than those predicted (ref. 6).

Figure 14 shows the impact of these factors. With a reduction in utilization to 700 hours per year and a decrease in fuel cost to $1.25 per gallon, the DOC advantage of the prop/shaft disappears. If there is a speed increase to 500 kns., the SFC advantage drops to only a 10 percent savings in fuel. This is still a substantial difference, but with low utilization the impact may not be significant. Although the fan/shaft is the preferred system for the reasons just stated, the prop/shaft concept is still a very strong candidate.

Although it was beyond the scope of the study, there is a possibility of additional improvement of performance using the fan/shaft. The VIGV fan/shaft, when combined with the X-wing, may offer a unique synergism that can reduce the weight of this craft. The X-wing is the only configuration studied that requires an additional system for vehicle torque control during vertical and low speed operations. The VIGV fan/shaft, as it is conceived, is not clutched and simply rotates during shaft operations causing about 20 percent of the engine power to be dissipated. If this wasted power could be used for torque control, then the fenestron tail rotor could be eliminated and a weight savings might well be achieved. For clarification, additional work is being contemplated to quantify the differences in the convertible engine benefits, if any, that might result from using the DARPA-type X-wing rotorcraft as a datum and from replacement of the fenestron.

Figure 15 presents the two X-wing engine candidates along with several of their parameters. The turbine inlet temperature and the pressure ratios are those expected for 1990 technology engines. A pressure ratio at the outer portion of the fan of 1.65 was chosen. That pressure ratio was deemed appropriate for the cruise speed of 400 kns. (Mach number 0.70) based on past experience. The pressure ratio at the inner portion of the fan of 1.46 was determined from a compromise between pressure ratio effects on costs, weight, fuel flow, and OEI operation.

Table VIII is a summary of the evaluation of the FTR convertible fan, a fixed pitch fan connected to the engine by means of a torque converter. A 10 percent savings in fuel with nearly a 15 percent savings in DOC is predicted.

The corresponding engine definition is presented in figure 16. In actuality, DDA/Bell-Textron sized the engine for a 460 kn. cruise although the actual cruise in all mission studies was at 400 kn. The 460 kn. sizing resulted in an engine size slightly larger than the OEI requirement. The fluid coupling that was chosen by DDA is a torque converter. This concept was proposed before, ref. 7, and with the controls available today seems even more desirable. Closed inlet guide vanes with their noise potential and their losses during shaft operation are avoided. Further, the need for a clutch with its possible material problems is not required. However no torque converter at this power level with this torque requirement has ever been built. With the requirements of being light weight, highly reliable and durable, this falls into the area of advanced technology.

IMPACT OF GROUNDRULES

The groundrules of any study can have a strong impact on the results. Here there are three whose effect requires examination; OEI, annual utilization and fuel cost. The effect of fuel cost and annual utilization have been illustrated in conjunction with the discussion of the X-wing convertible powerplant choice. OEI effects remain to be addressed.

The OEI operation out of ground effect at sea-level on a hot day at maximum gross weight is a requirement that no helicopter meets today. The DDA approaches to the OEI requirement were mentioned earlier. It may be inferred from that work that either a relaxation of the OEI requirement, as shown for the ABC, or the use of a somewhat higher cruise speed for engine sizing than for engine design, as shown for the FTR, results in an engine sized by cruise demands rather than by the OEI requirement.

In order to illustrate the maximum possible impact of the OEI criterion stated in this study, a rotorcraft was first designed using this OEI requirement with no modifications in either the requirement or in any segment of the design mission. The craft was then redesigned for the same mission but with no OEI requirement at all. Table IX is an estimate of the effect on a small X-wing of total removal of the OEI requirement. As might be expected the shaft power required is about half that of the craft meeting the OEI criterion of the studies. Yet the gross weight differs little, and thus cruise power and thus fuel consumption would differ little. The total propulsion system for the 36500 gross weight vehicle is about 9500 lb. If all 2500 lb. reduction in gross weight were due only to propulsion system weight reduction, the propulsion system would be reduced only by a bit over 25 percent. Further, it is certain that a civilian vehicle will be required to have at least some OEI capability which will cut somewhat into this 25 percent reduction. The impact upon this study of lessening the OEI requirement, therefore, would be very small indeed.

RESEARCH AND TECHNOLOGY REQUIRED

Table X presents the research and technology required to bring the convertible engine to a technology ready state by the late 1980's. Only areas considered to be unique to convertible powerplants were addressed. The major categories are fan performance integrated engine/rotorcraft control, high-torque, high-power torque converters, turbine design, air flow for rotorcraft torque control, compressor bleed for lift flow, and transmission and clutch requirements.

During these studies it became evident that knowledge was lacking to properly evaluate the performance of some of the systems, to evaluate the magnitude of their possible problems and to effectively address effort towards improving the performance or alleviating the problems. For example, the fan noise problem with closed, or nearly closed, variable inlet guide vanes could not be determined, nor could methods of noise reductions be recommended. The advantage of using fan airflow for vehicle torque control during helicopter type operation could not be computed with accuracy. The design of torque converter blades under the extreme loadings required is not well understood. The integration of aircraft and engine control for a rotorcraft with engines that go from shaft operation to fan or propeller operation while the aircraft changes from vertical to horizontal mode is a significant challenge. Further, a systems study is needed in this area of controls.

What is required, then, is the acquisition of the basic knowledge of the behavior of the systems required for convertible rotorcraft operation. With such information in hand methods can be created that will permit the design of efficient, quiet, reliable, high-speed rotorcraft utilizing convertible powerplants.

CONCLUDING REMARKS

The studies indicate that high speed rotorcraft flying civil missions would be greatly enhanced by the use of convertible engines, from 12 to 24 percent in DOC, for example. They point out alternative methods of achieving convertibility and the required technologies. More details are presented in references 1 and 8.

In addition, it should be noted that an experimental VIGV investivation has started. The General Electric TF-34 is being modified into a VIGV convertible engine in a joint NASA-DARPA funded project. Also the Army has funded both an analytic investigation regarding the modification of the T700 engine into a convertible engine and an experimental investivation of the ASTFAN modified into a variable-pitch-fan convertible engine. The results of all of this work will also help to define future technology requirements.

The determination of the actual groundrules for the design of such high-speed rotorcraft and the exact configuration of these craft lies ahead.

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TABLE I - MISSON AND GROUND RULES (GE)

	A B C	X-WING
DESIGN		
Mission	TRANSPORT	OIL RIG SUPPORT
Seats	48	48
Speed	250 kn	400 kn
Range	200 nmi	450 nmi
Altitude	10 000 ft	30 000 ft
OEI Req't	Hover out of ground effect altitude 2000 ft Temp. +27° F	Hover out of ground effect altitude 1000 ft Temp. +27° F
TECHNOLOGY		
Readiness year	1990	1990
First production year	1995	1995
TECHNOLOGY EVALUATION		
Criterion	DOC	DOC
Mission	Design	Design
Passenger load factor	65% (31 pass.)	85% (41 pass.)
Fuel cost	$2.00/gallon	$2.25/gallon
Annual utilization	2500 hr	2000 hr
Economics	1981 $	1981 $

TABLE II - MISSION AND GROUND RULES (DDA)

	A B C	FTR
DESIGN		
Mission	COMMUTER	COMMUTER
Seats	30	30
Range	217 nmi	600 nmi
Altitude	3000 ft.	20 000 ft.
OEI Req't	Altitude 1000 ft Temp. 90° F	Altitude 1000 ft Temp. 90° F
TECHNOLOGY		
Readiness year	1990	1990
First production year	1995	1995
TECHNOLOGY EVALUATION		
Initial screening criterion	SFC	SFC
Final criterion	DOC	DOC
Mission Altitude Range	 3000 ft 87 nmi	 2000 ft 200 nmi
Passenger load factor	100%	65% (19 pass.)
Fuel Cost	$2.00/gallon	$2.00/gallon
Annual utilization	2800 hr	2800 hr
Economics	1981 $	1981 $

TABLE III - ABC POWERPLANT INITIAL SCREENING

G E		DDA	
RANK	POWERPLANT	RANK	POWERPLANT
1	PROP/SHAFT	1	PROP/SHAFT[a]
2	VIGV FAN	2	VIGV FAN
3	VP FAN	3	VP FAN
4	REMOTE PARALLEL LPT (CLOSE TO GG)	4	REMOTE SERIES LPT
5	REMOTE FAN/PARALLEL LPT	5	REMOTE PARALLEL LPT COMMON TO BOTH GG's
6	REMOTE SERIES LPT	6	FLUID COUPLING PROP/SHAFT
7	REMOTE PARALLEL LPT (COMMON TO BOTH GG's)	7	FLUID COUPLING FAN/SHAFT
8	REMOTE PARALLEL LPT (CLOSE TO PROP)		

[a]Without clutch, wet clutch slightly worse.

TABLE IV - NUMERICAL SCORING OF THE ABC, GE/BOEING

FINAL RANKING	ENGINE TYPE	PERCENT DIFFERENCE	
		SFC	ENGINE WEIGHT
1	PROP/SHAFT	-14	+2
2	VIGV FAN/SHAFT	0	0
3	VP FAN/SHAFT	+1	+3
4	REMOTE PARALLEL LPT CLOSE TO GAS GENERATOR	-8	+25
6	REMOTE SERIES LPT	-14	+24
7	REMOTE PARALLEL LPT COMMON TO BOTH GAS GENERATORS	-3	+20
8	REMOTE PARALLEL LPT CLOSE TO PROPELLER	-8	+25
5	REMOTE FAN/ PARALLEL LPT	+14	+23

TABLE V - FTR AND X-WING INITIAL POWER PLANT SCREENING

GE X-WING COST AND FUEL USE ONLY		GE X-WING ALL FACTORS		DDA FTR ALL FACTORS	
RANK	SYSTEM	RANK	SYSTEM	RANK	SYSTEM
1	PROP/SHAFT	1[a]	VIGV FAN	1	FLUID COUPLED FAN
2	VIGV FAN	2	PROP/SHAFT[b]	2[a]	VIGV FAN
3	REMOTE FAN	3	REMOTE FAN	3	VP FAN
				4	REMOTE TURBINE SYSTEM

[a]Baseline Convertible.
[b]Also Mission Evaluated.

TABLE VI - ABC CONVERTIBLE BENEFITS

	IMPROVEMENT OVER SEPARATE ENGINES, %		
	DDA / SIKORSKY	GE / BOEING	
	CONVERTIBLE PROP/SHAFT ENGINES[a]	CONVERTIBLE VIGV TURBOFANS[b]	CONVERTIBLE PROP/SHAFT ENGINES[b]
DESIGN GROSS WEIGHT	11.9	7.2	1
TYPICAL MISSION FUEL	6.6	13.1	27.3
ACQUISITION COST	16.3	12.1	17.7
DOC ($2.00/GAL)	12.0	12.7	22.1
($1.00/GAL)		12.1	20.8

[a]Base is separate engine rotorcraft using turboprop propulsion.
[b]Base is separate engine rotorcraft using turbofan propulsion.

TABLE VII - X-WING CONVERTIBLE BENEFITS

[General Electric/Boeing Vertol]

	IMPROVEMENT OVER SEPARATE ENGINES,[a] %	
	CONVERTIBLE VIGV TURBOFANS	PROP/SHAFT ENGINES
GROSS WEIGHT	15.3	13.4
ACQUISITION COST	18.1	18.6
BLOCK FUEL	16.1	30.6
DOC at $2.25/GAL	20.8	25.3
DOC at $1.25/GAL	21.8	24.2

[a]Base is separate engine rotorcraft using turbofan propulsion.

TABLE VIII - FTR CONVERTIBLE BENEFITS

[Detroit Diesel Allison/Bell Textron]

	FAN/SHAFT CONVERTIBLE ENGINE FIXED PITCH FAN WITH TORQUE CONVERTER	IMPROVEMENT OVER SEPARATE ENGINES[a]
DESIGN GROSS WEIGHT	36,526 LB	9.0 %
DESIGN MISSION FUEL	4,457 LB	10.5 %
TYPICAL MISSION FUEL	1,467 LB	10.0 %
ACQUISITION COST	$13,856,000	14.9 %
DOC - TYPICAL MISSION	17.02¢/ASSM	14.7%

[a]Base is separate engine rotorcraft utilizing turbofans.

TABLE IX - APPROXIMATE ANALYSIS OF THE EFFFECT OF HOVER ONE ENGINE INOPERATIVE OUT OF GROUND EFFECT CRITERIA

AIRCRAFT	X-WING (CONVERTIBLE ENGINES)	
NUMBER OF PASSENGERS	30	
ALTITUDE	SEA LEVEL	
CONDITIONS	STATIC, STANDARD DAY	
	OEI SIZED	OPERATIONS SIZED
GROSS WEIGHT - LB	36 500	34 000
SHAFT POWER - HP	19 100	8900

TABLE X - RESEARCH AND TECHNOLOGY

FAN PERFORMANCE
- VIGV
  - PERFORMANCE CLOSED MODE
  - OPERABILITY CLOSED MODE
  - NOISE
- DECLUTCHED
  - WINDMILLING CHARACTERISTICS

INTEGRATE ENGINE/ROTORCRAFT CONTROL
- ENGINE/AIRFRAME DYNAMICS STUDY
- ENGINE/AIRFRAME DIGITAL CONTROL STUDY

TORQUE CONVERTER DESIGN CAPABILITY
- BLADE DESIGN METHODS
  - HIGH POWER
  - HIGH TORQUE
- FLUID EMPTY/REFILL SYSTEMS
  - RELIABILITY
  - WEIGHT

OFF-DESIGN TURB. BLADE INC. ANGLE (OPERATION AT TWO DESIGN SPEEDS)

X-WING VECTORING SYSTEM
- CORE FLOW FOR TAIL ROTOR
- WARM FLOW USING WASTE VIGV CHURNING ENERGY

COMPRESSOR BLEED FOR AUGMENTED LIFT FLOW (X-WING),

TRANSMISSION REQUIREMENTS
- BEARING LIFE AND RELIABILITY
- ELASTOMERIC SHAFT MOUNTING
- CLUTCH PLATE MATERIALS
- GEAR LIFT AND RELIABILITY

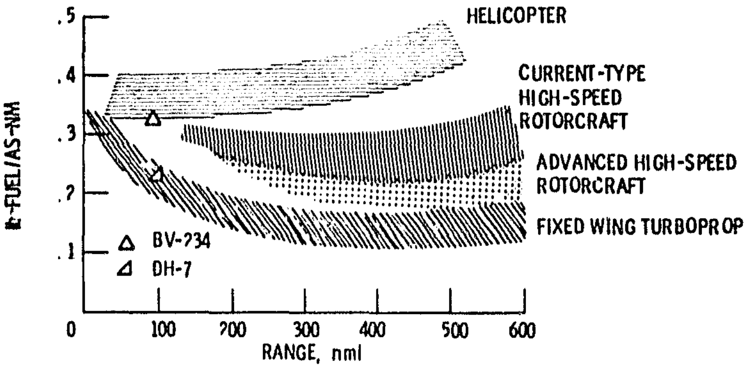


Figure 1. - Fuel consumption trends for four classes of aircraft.

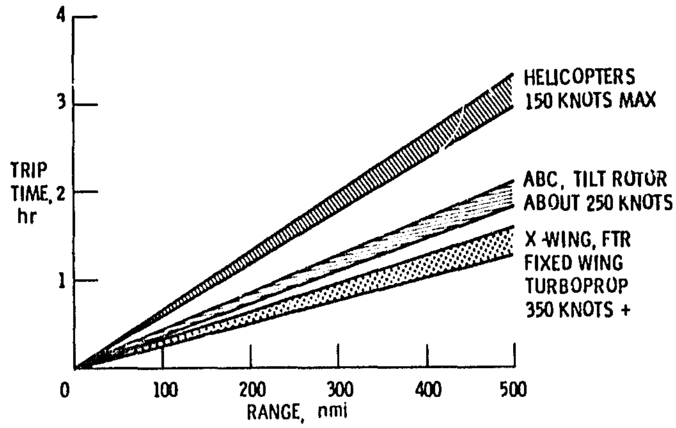
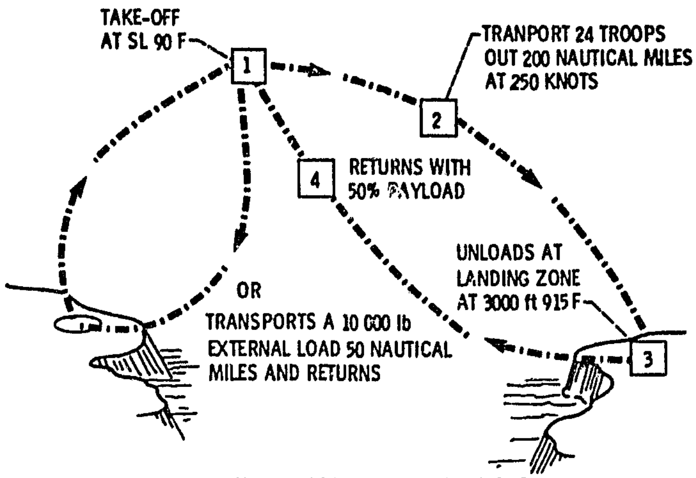
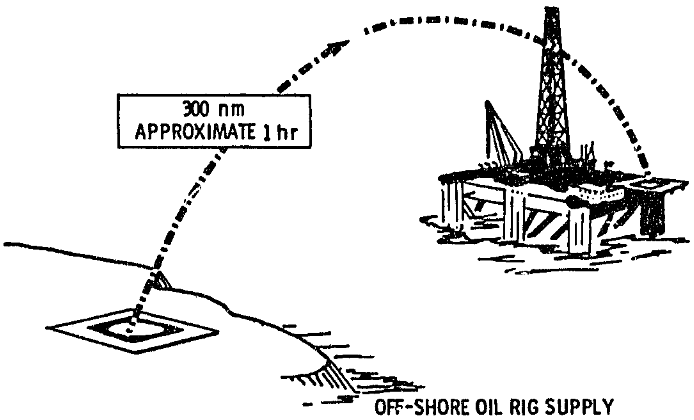


Figure 2. - Flight trip time for several aircraft.



TYPICAL MARINE ASSAULT (HXM) MISSIONS



OFF-SHORE OIL RIG SUPPLY

Figure 3. - Example high speed rotorcraft uses.

VERTICAL CAPABILITY OF A HELICOPTER
CRUISE SIMILAR TO FIXED WING - HIGH SPEED, HIGH L/D

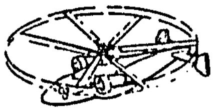
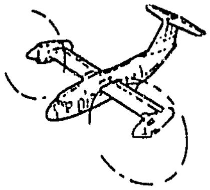
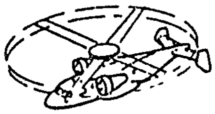
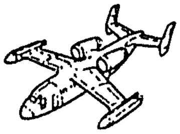
	TYPE	CRUISE SPEED	PREDICTED CIVILIAN TYPICAL RANGE
	ADVANCING BLADE	250 KT. +	200 - 300 NMI
	TILT ROTOR	250 KT. +	200 - 300 NMI
	X - WING	400 KT. +	400 - 500 NMI
	FOLD TILT ROTOR	400 KT. +	400 - 500 NMI

Figure 4. - Rotorcraft types.

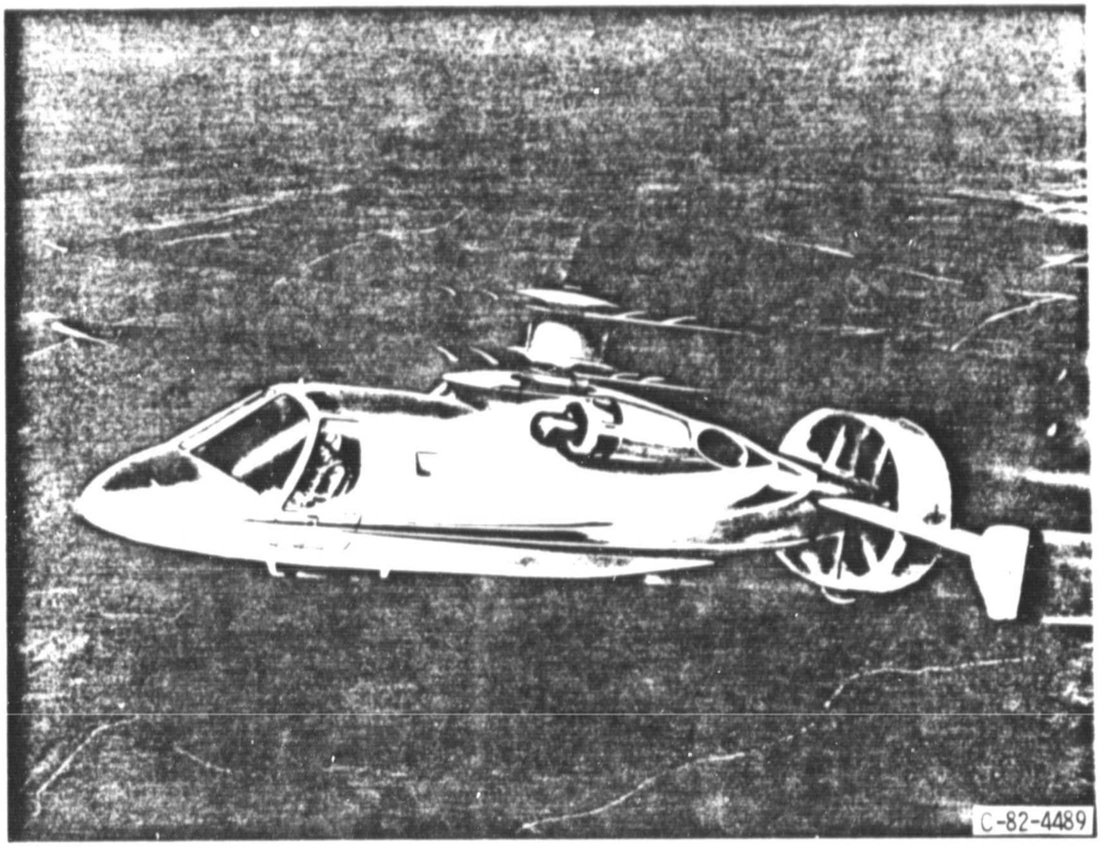


Figure 5. - A Sikorsky conceptual ABC.

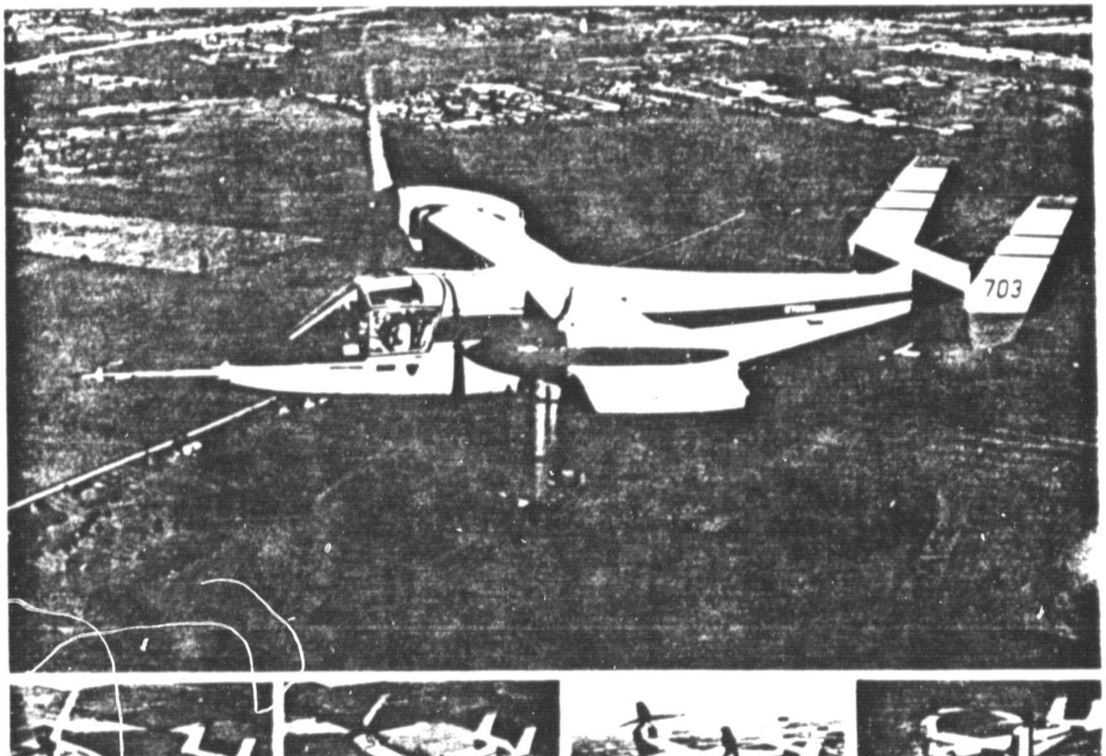


Figure 6. - Bell-Textron tilt rotor.

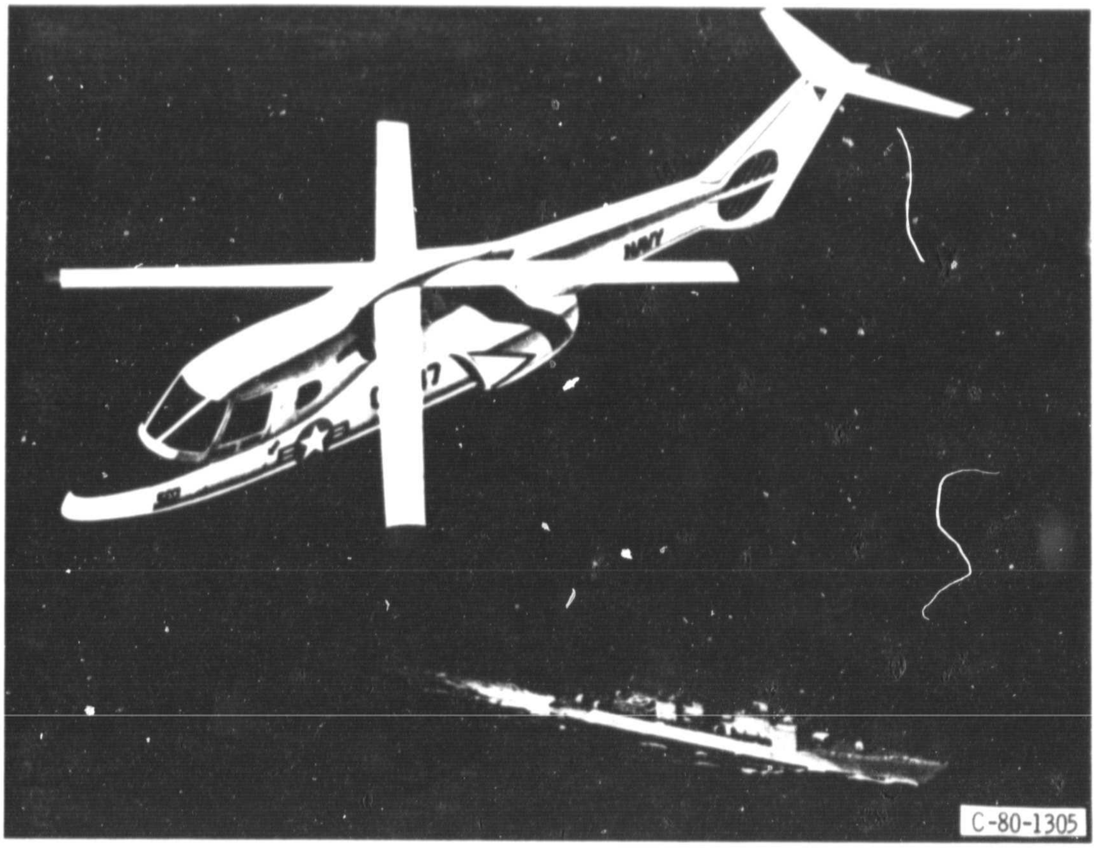


Figure 7. - X-wing conception.

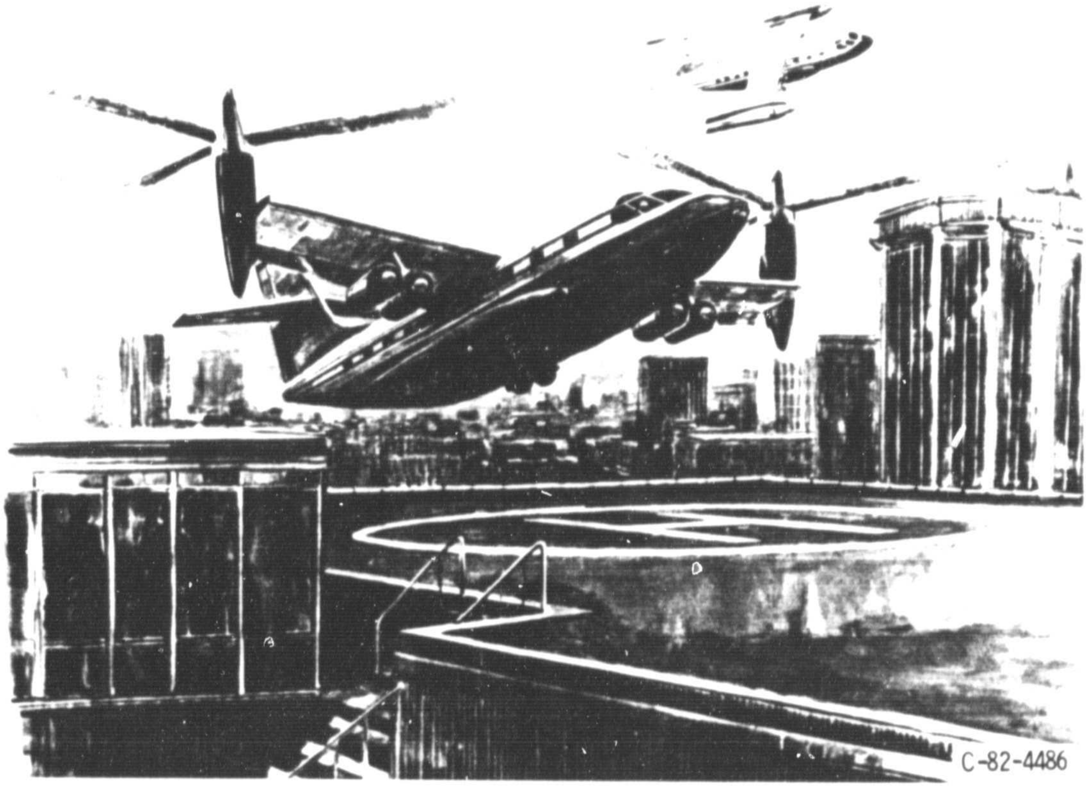


Figure 8. - Bell-Textron conception of a fold tilt rotor.

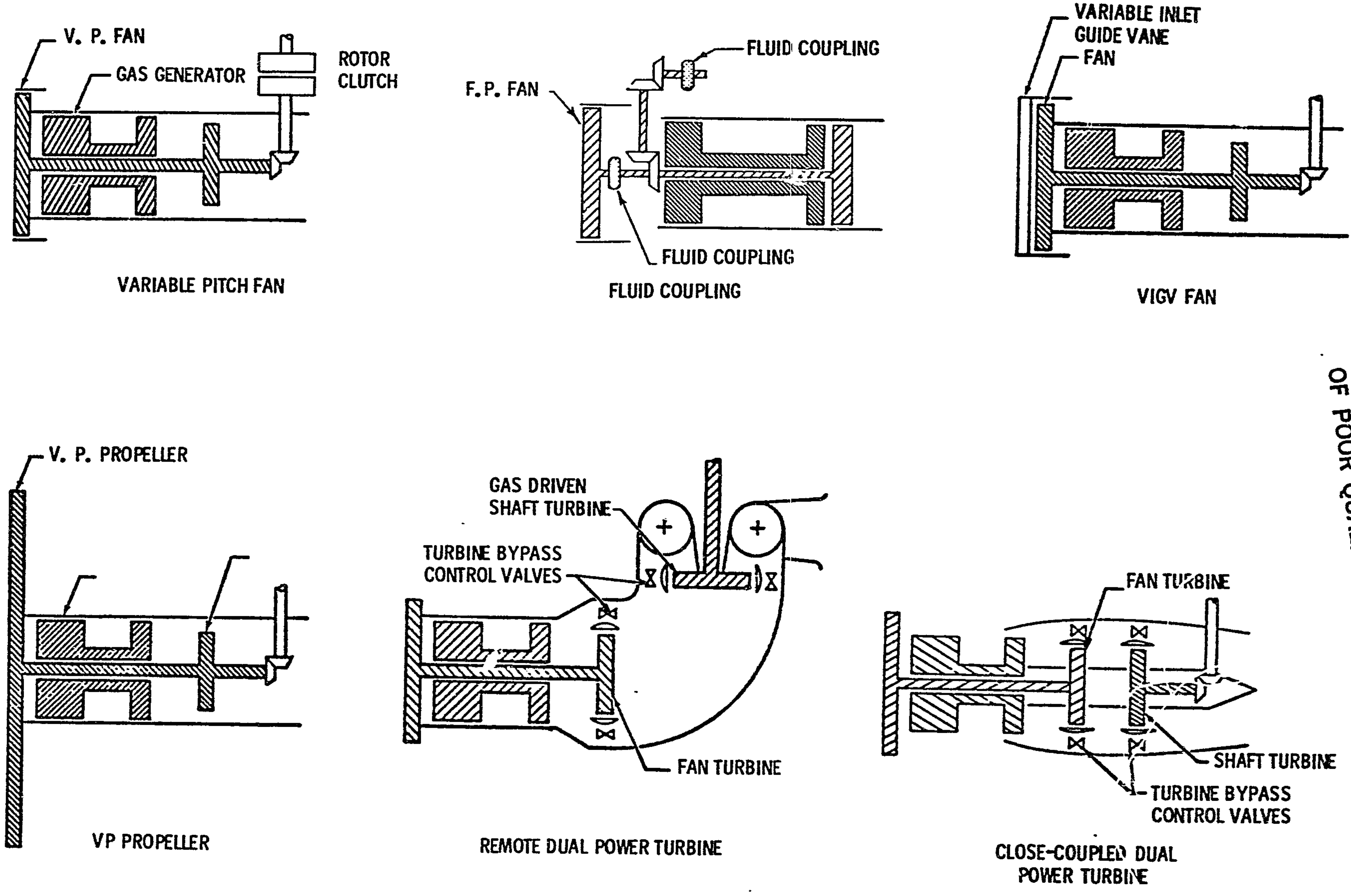


Figure 9. - Powerplants studied.

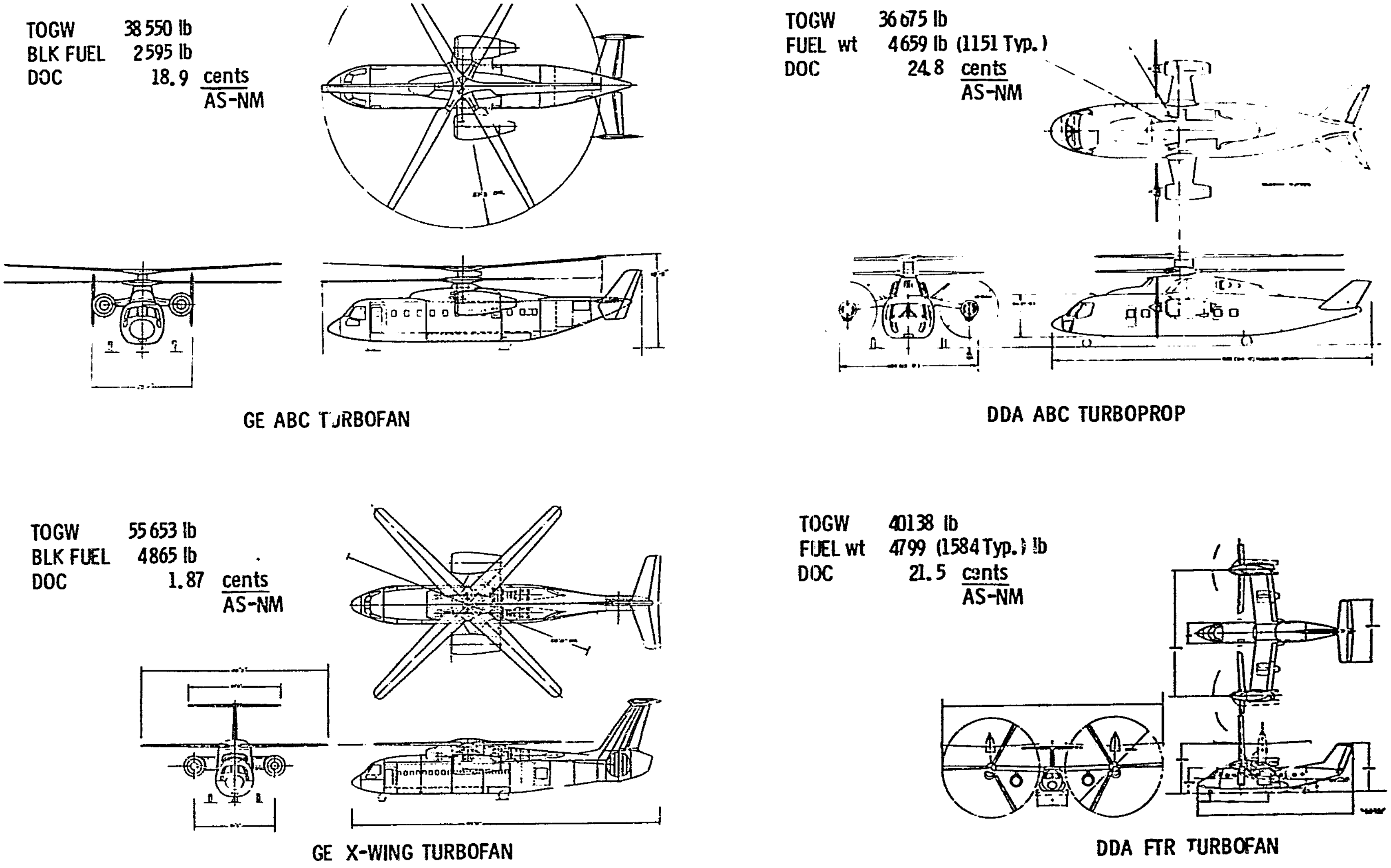


Figure 10. - Separate engine baseline rotorcraft.

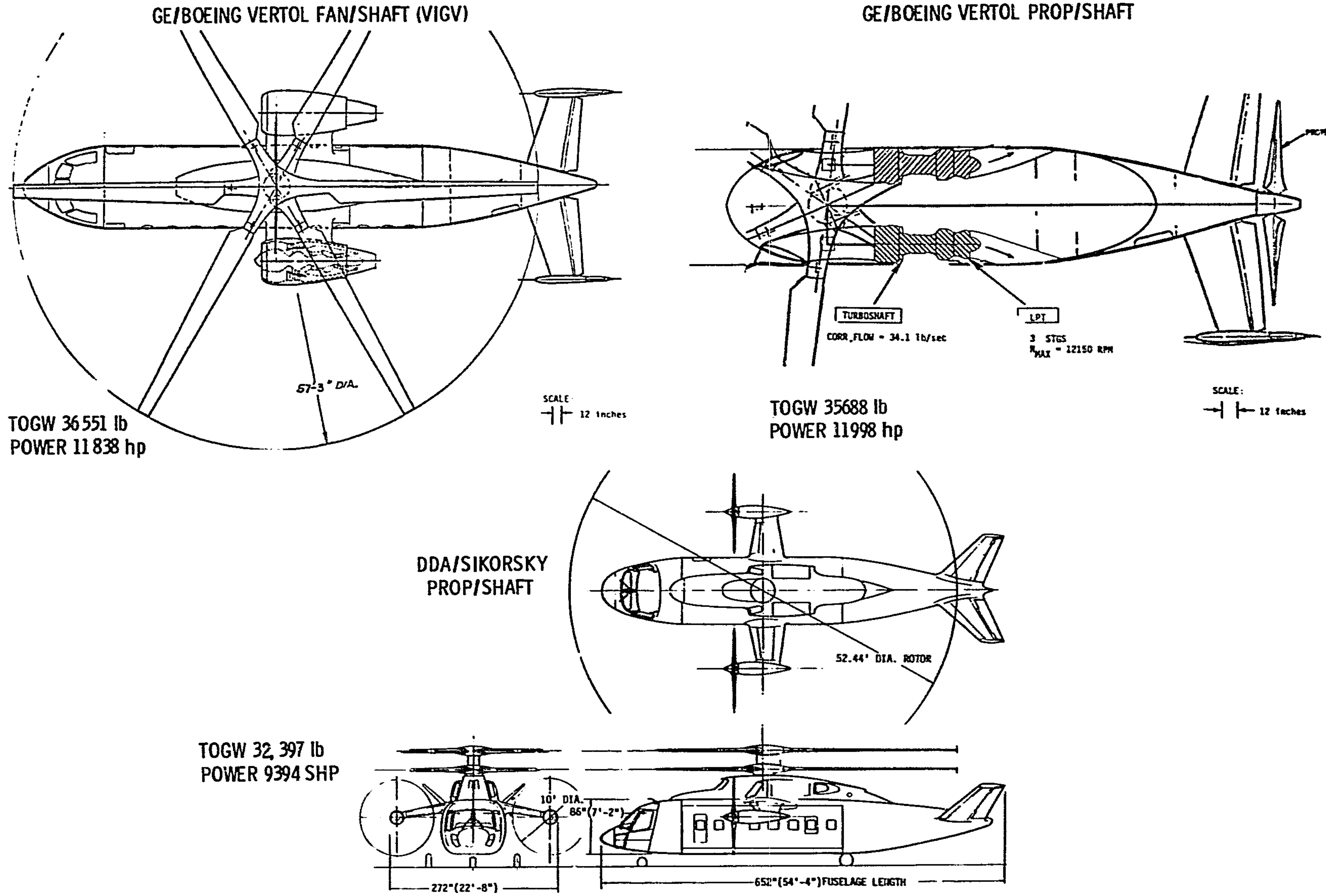


Figure 11. - Convertible ABC configurations.

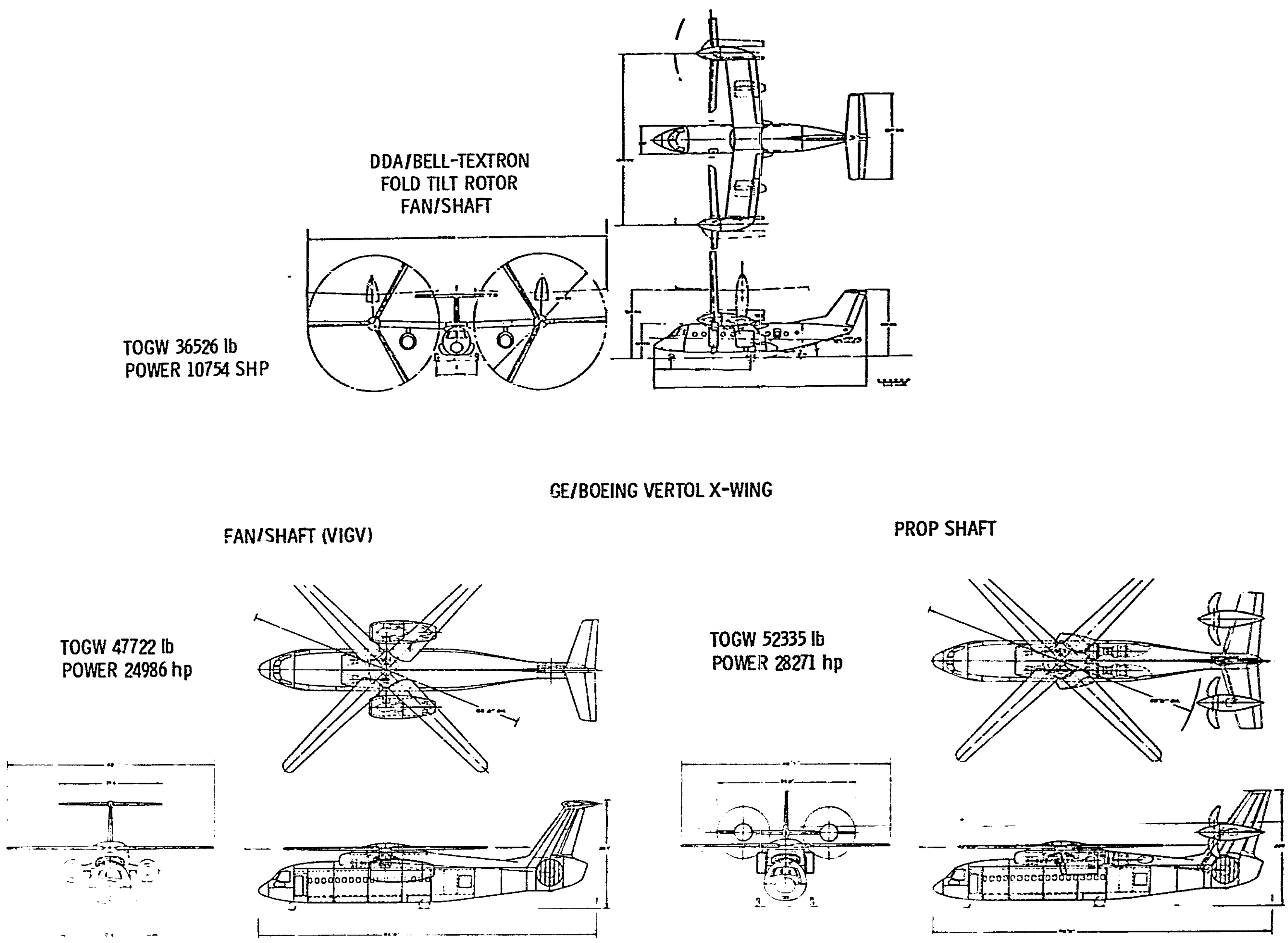


Figure 12. - Convertible FTR & X-wing configurations.

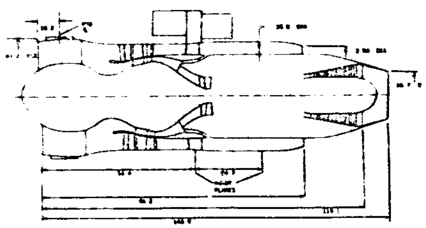
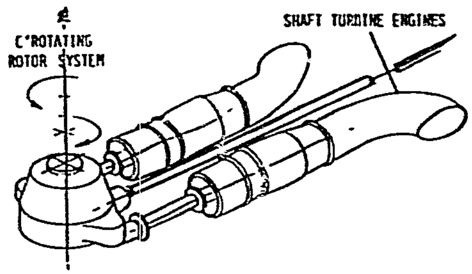
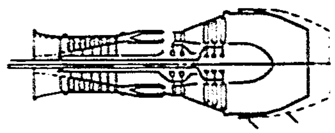
	GE FAN/SHAFT	GE PROP/SHAFT	DDA PROP/SHAFT
			
CRUISE SHP/lb THRUST (DESIGN)	1795/1790	3350	3235
CRUISE FUEL FLOW lb/hr	1490	1265	1212
SHP OEI (SIZING CRITERION), EACH	5210	4810	4690
SHP TAKEOFF, EACH	2135	2085	2859
TOTAL SHP/TOG W	0.117	0.117	0.176
OVERALL PRESS RATIO	22	21.6	26.6
FAN PRESS RATIO	1.36	----	
TURBINE INLET TEMP, °F (CRUISE/OEI)	2200/2500	2205/2500	2300/2600
ENGINE WEIGHT, lb, EACH	1285	1172	1011
COMPRESSOR	AXIAL	5A1C	AXIAL
NO. OF STAGES			
LPC/HPC	1/6	/5A1C	/6A
HPT/LPT	2/5	2/5	2/3

Figure 13. - Convertible powerplants for ABC.

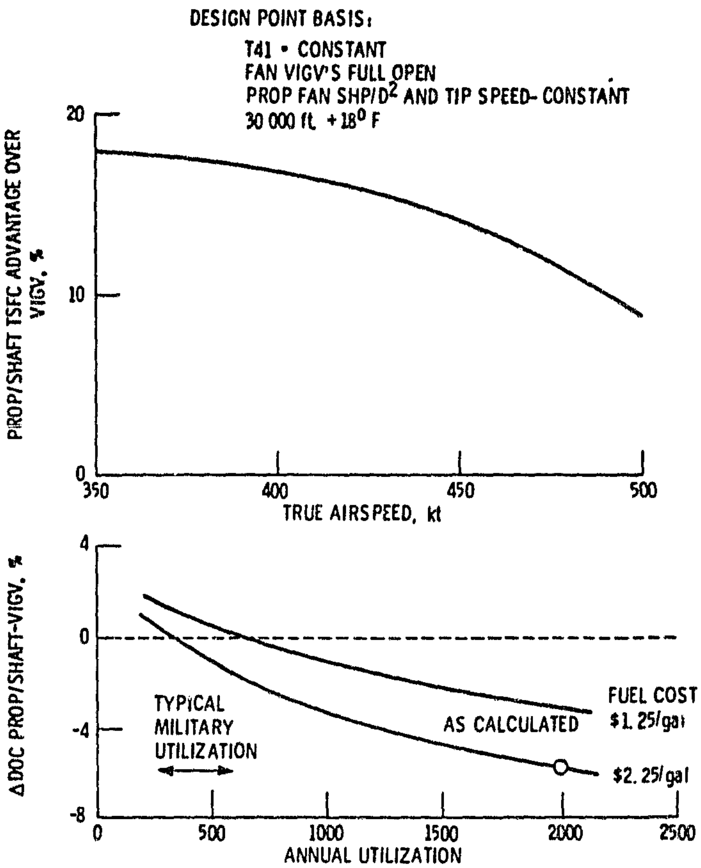
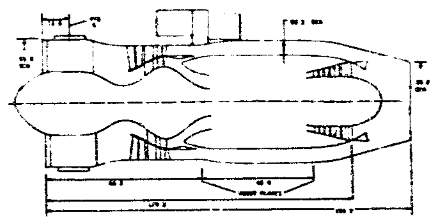
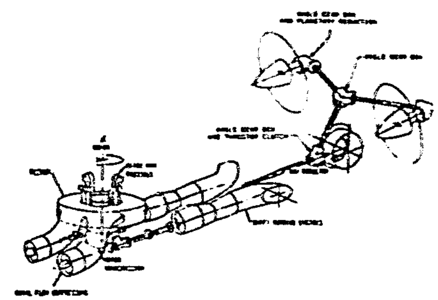


Figure 14. - X-wing ground rule sensitivity.

	CONVERTIBLE FAN/SHAFT, VIGV	CONVERTIBLE PROP/SHAFT
		
CRUISE SHP/lb THRUST (DESIGN)	310/2380	4360
CRUISE FUEL FLOW lb/hr	1570	1412
SHP OEI (SIZING CRITERION), EACH	9945	11960
SHP TAKEOFF, EACH	4670	5560
TOTAL SHP/TOGW	0.196	0.196
OVERALL PRESS. RATIO	22	22
FAN PRESS. RATIO (TIP/HUB)	1.65/1.46	—
TURBINE INLET TEMP, °F (CRUISE/OEI)	2055/2500	1974/2500
ENGINE WEIGHT, lb, EACH	2320	1525
COMPRESSOR	AXIAL	AXIAL
NO. OF STAGES		
LPC/HPC	1/10	0/5
HPT/LPT	2/4	2/4

.5. - Convertible powerplants for X-wing.

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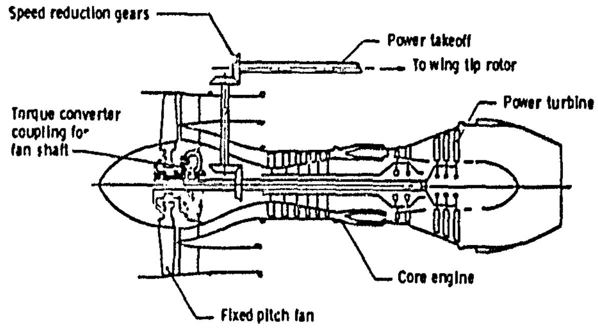
CONVERTIBLE FAN/SHAFT TORQUE CONVERTER



CRUISE SHP/lb THRUST (DESIGN)	2696
CRUISE FUEL FLOW lb/hr	1632
SHP OEI (SIZING CRITERION), EACH	6725
SHP TAKEOFF, EACH	5377
TOTAL SHP/TOGW	0.294
OVERALL PRESS. RATIO	18
FAN PRESS. RATIO	1.65
TURBINE INLET TEMP, ^{0}F (CRUISE/OEI)	2267/2600
ENGINE WEIGHT, lb, EACH	1356
COMPRESSOR	AXIAL
NO. OF STAGES	
LPC/HPC	1/6
HPT/LPT	2/3

Figure 16. - Convertible powerplant for FTR.