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PREPARED BY N. Galitzine

LABORATORY MEMORANDUM

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SECTION ENGINE LABORATORY

DATE 16 Sept. 1958

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SUBJECT

FURTHER WEIGHT AND SIZE ESTIMATIONS OF GAS GENERATORS FOR THE POWERPLANT OF A VTOL AIRCRAFT.

PREPARED BY

N. GALITZINE.

ISSUED TO

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FURTHER WEIGHT AND SIZE ESTIMATIONS OF GAS GENERATORS
FOR THE POWERPLANT OF A VTOL AIRCRAFT

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Basic Assumptions

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Tip speed

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INTRODUCTION

In Reference 1 of May 1958 (NAE-ENG-64) the weight and size of a 4500 h.p. gas generator was estimated, from a sketchy design, for the powerplant of a VTOL aircraft with an all-up weight of 20,000 lb. Four of these 'hot' cycle gas generators, totalling 18,000 h.p., were then considered necessary, either to drive wing-immersed fans for vertical lift, or for conventional jet propulsion in horizontal flight.

Since that time, the number and power of the gas generators for the given aircraft were reconsidered, and it was concluded that aside from weight, 6 x 3000 h.p. might be a better combination than 4 x 4500 h.p. for the same total power.

Also, discussions were held with a manufacturer of jet engines, revealing possible changes in the basic assumptions for the weight estimation of small engines.

In the present memorandum, the weight and size of a 4500 h.p. gas generator is re-estimated, using changing assumptions, the preference for a 3000 h.p. unit is discussed, the same assumptions are then applied to estimate its weight, and finally a general discussion is made about the powerplant weight as a whole.

BASIC ASSUMPTIONS

In the discussions with the manufacturer of jet engines, a number of similarities in the basic assumptions, important for the weight estimation of small engines, such as minimum blade chord (1/2"), height (1"), etc., were noted, but also a number of differences were disclosed.

The comparisons were made on approximately the same thermodynamic cycles, and roughly the same order of size and power. The NAE-ENG-64 maximum temperature was 1300°K, the compressor temperature rise 300°C, whereas the manufacturer's figures were 1275°K and 275°C respectively.

The significant differences in the assumptions were as follows:

Meaning of "Accessories"

The N.A.E. estimate of the basic weight of a gas generator, treated as a jet engine, included a large item for the fuel and oil systems (40 lb. in a 4500 h.p. unit), which were not considered as "accessories." That term covered such items as the starter, jet pipe, etc., not essential for the performance of the unit.

On the other hand, the engine manufacturer implied by the term "accessories" precisely the fuel and oil systems, the total weight of which (45 lb. in a unit of somewhat larger h.p. than the

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N.A.E.) was to be added to the weight of the "main" engine before any performance could be imagined from it.

Presumably the manufacturer might have been favouring the arrangement of a bank of small engines operating from a common fuel and oil system, with considerable reductions in total weight, thus making it reasonable to consider individual engine weight without a separate fuel and oil system for each engine.

However, it was felt that for the VTOL aircraft under consideration, each gas generator should have its own individual fuel system for safety, and therefore in the remainder of this memorandum it is to be understood that the former meaning of "accessories" holds, making the total weight estimate of a gas generator cover an item for the fuel and oil systems, but not for the starter, jet pipe, etc.

Materials

The weight of the small jet engine designed by the manufacturer was estimated on the assumption of plastic blading in the compressor, whereas the N.A.E. gas generator had blading of magnesium, aluminum and titanium alloys, depending on the stage temperature in the compressor, and the creep properties of the metal.

Top temperature of the plastic (an asbestos or fiberglass reinforced phenolic) was said to be 550°F, but no creep data were discussed, and none appeared to be available in the literature from the manufacturers of such material. This question has not been pursued further for reasons given below, and in what follows a re-estimate of the weight of the gas generator is made, using the plastic and its given density of 0.065 lb/in³.

The density (0.066 lb/in³) of the magnesium alloy is virtually the same as that of the reinforced phenolic plastic, so that these two materials may be considered as interesting competitors for lightness in the VTOL field, with creep, elasticity, ductility, formability, etc., as criteria. This seems to call for a separate careful comparative study which is not in the scope of this memorandum.

A suggestion was made that the plastic could also perhaps be used in the compressor casing, inlet frame, etc., but as such parts were assumed of magnesium alloy in the N.A.E. estimate, no significant saving in weight would have resulted.

Material Thicknesses

In the N.A.E. weight estimate a number of arbitrary assumptions had to be made concerning the minimum feasible material thicknesses in components where strength was not the guiding factor.

A minimum casting and forging thickness of 3/8" was assumed for various compressor and turbine components of the 4500 h.p. gas

generator, and a minimum sheet metal thickness of 0.050" for the combustion chamber, turbine stator, and exhaust parts.

The discussions with the manufacturer disclosed that considerably thinner material was feasible. Thicknesses of about 0.022" - 0.032" were mentioned for the sheet metal parts, depending on support and other factors, and a minimum of 3/16" for the castings, depending on size. No figure could be given for the forgings.

It was felt that 3/8" for the castings and forgings in the N.A.E. design could not be reduced to 3/16", because most of the parts using that figure constituted the backbone of the unit, where stiffness was the governing factor. On the other hand, the way was seen open to reducing the sheet metal thickness from 0.050" to 0.025", because rigidity was provided by the neighbouring cast and forged parts, and the weight is therefore re-estimated accordingly.

Tip Speed

The N.A.E. estimate assumed a compressor tip speed of 800 ft/sec, which with the axial inlet velocity of 560 ft/sec gave a maximum relative inlet velocity of 980 ft/sec or about Mach 0.87, thus safely assuring the assumed 85% compressor efficiency, and the corresponding specific fuel consumptions.

The manufacturer's small jet engine assumed a tip speed of 1116 ft/sec, which with an axial inlet velocity of about 620 ft/sec, gave a maximum relative inlet velocity of about 1275 ft/sec, or Mach 1.14, thus operating the compressor in the transonic region.

In the re-estimate that follows a tip speed of 1100 ft/sec is assumed, with the proviso that the 85% compressor efficiency is maintained, and a calculation is made showing the penalty in fuel consumption and increase in size if it is not.

RE-ESTIMATE OF 4500 h.p. GAS GENERATOR

In the weight estimate of reference 1, then, the following basic assumptions, among others, had been used:

- Fuel and oil systems included.
- Compressor blading of magnesium, aluminum, and titanium metal alloy.
- Sheet metal thickness 0.050".
- Compressor tip speed 800 ft/sec.
- Compressor inlet axial velocity 560 ft/sec.

In the present memorandum the re-estimate is made in three consecutive steps, each step showing the effect of changing a basic assumption. With the same fuel and oil system weight and the same compressor inlet axial velocity retained throughout, the basic changes are:

Compressor blading from metal to plastic.
Sheet metal thickness from 0.050" to 0.025".
Compressor tip speed from 800 ft/sec to 1100 ft/sec.

The results are shown in Table I. Estimate A of 340 lb. is the original one from Reference 1, and the re-estimates, B, C, D, follow.

Effect of Plastic Blading

Estimate B of 325 lb. shows that 15 lb. is saved by using plastic instead of magnesium-aluminum-titanium alloy blading in the compressor.

Roughly half of this saving is due to the blading itself, and half due to a lighter compressor rotor drum, resulting from the lessened centrifugal forces.

The same saving would have resulted had magnesium alloy been extended to the last stages of the compressor, but the available creep data precluded its consideration there at present, despite claims of utility up to and above 600°F (Reference 2).

Effect of Halved Sheet Metal Thickness

Estimate C of 300 lb. shows that 25 lb. is saved by reducing the sheet metal thickness in the gas generator design from 0.050" to 0.025".

This is virtually all due to the saving in nickel-chromium alloy metal in the combustion chamber, part of the turbine stator, and exhaust-nozzle unit.

Effect of Increased Tip Speed

Estimate D of 270 lb. shows that 30 lb. is saved by increasing the compressor tip speed from 800 to 1100 ft/sec and gives the final and lowest figure for the basic weight of the 4500 h.p. gas generator, as far as this Memorandum is concerned.

In order to retain the over-all uniform tubular geometry of the unit, the turbine tip speed is increased by the same amount as the compressor's.

The effect of increasing the compressor tip speed is twofold, one favourable, the other unfavourable, with the net result being favourable in the case considered.

The favourable effect results from the greater work possible per stage, both in the compressor and turbine, thus giving a decreased number of stages in each and a shorter length of the whole unit. The

compressor stages are reduced from 14 to 10, and the turbine stages from 3 to 2. An additional benefit is the decreased shaft diameter, due to the higher rotational speed, but the latter has also an adverse effect on the bearings.

The unfavourable effect results from the increased centrifugal force, and the attendant thickening, strengthening and change in the design of the rotors.

Assuming that the 85% compressor efficiency is maintained, the whole of the 30-pound saving may be claimed for the higher tip speed, or the "transonic" relative inlet velocity in the compressor.

However, should the required efficiency be not obtained, a penalty results in higher fuel consumption and lower specific power or thrust, when the gas generator is used both in the hovering and cruising of the VTOL aircraft which was visualized in Reference 3.

In that reference a mission of 500 miles range, with ten minutes hovering, was stipulated.

The penalty resulting from the possibly reduced compressor efficiency may perhaps be most clearly stated by showing that the 30-pound saving in gas generator weight through use of the transonic compressor would be wiped out by 30 lb. of extra fuel per generator, and larger generator size, for the mission specified, if the compressor efficiency fell by 2% from the 85% assumed (derived by the author of Reference 4).

PREFERENCE FOR 3000 h.p. UNIT

In Reference 3, four 4500 h.p. interconnected gas generators were visualized for driving eight 3-foot diameter lifting fans.

The intention of the interconnection on the gas generator delivery end was to ensure the safety of the aircraft in case of one-generator failure, when all the fans would continue to receive the driving gas from the three live generators at a reduced but equally distributed rate.

Upon further detailed examination, however, the scheme appeared less attractive, for the following reasons:

1. A special one-way-flow valve would have been required at the gas delivery end of each generator, before joining the interconnecting duct. This would have been necessary to prevent the blow-back of hot gases through the failed generator, with consequent waste of gas and injury to the compressor.
2. The hot interconnecting duct would have had to pass through the useful space in the fuselage of the aircraft.

3. In case of one-generator failure, the reduced gas flow rate would have been mismatched with the fixed flow areas of the fan drive turbine nozzles, thus leading to a serious drop in efficiency and available power.

Out of several other schemes, three alternatives presented themselves to satisfy the safety requirement. These, and the original scheme of Reference 3, with all its implications, are shown diagrammatically in Figure 1.

In the first alternative, the four 4500 h.p. gas generators would have been supplemented by a fifth, stand-by, unit of the same power, installed in the fuselage. This would have satisfied objection 3, but not the others, and would have raised the powerplant weight by the extra gas generator and its accessories.

In the second alternative, the four 4500 h.p. gas generators, and the eight 3-foot diameter fans, would have been retained, but instead of interconnection, each generator would have driven a pair of fans, one in each wing. Thus, in case of one-generator failure, the pair of fans would go out of action, still leaving the aircraft stable, and with three-quarters of the installed lifting power remaining. Objections 1 and 3 would have been satisfied, but objection 2 would have been magnified, since the scheme would have required four different (but smaller) ducts to cross the fuselage, instead of the one duct in the original scheme.

In the third, and now favoured, alternative, six 3000 h.p. gas generators were visualized, each independently driving a somewhat larger fan, of about 3 1/2-foot diameter, or a scheme of three generator-fan pairs in each wing. In the case of one-generator failure (or one-fan failure) in one wing, automatic control would be intended to switch out the corresponding opposite pair in the other wing, still leaving the aircraft stable, with two-thirds the installed lifting power remaining, and with all three objections satisfied.

The two-thirds figure is equivalent to the figure of 1.5 assumed for the ratio of installed lift to all-up weight in Reference 3, or the excess power margin allowed for hovering in non-standard ambient conditions (6000 feet altitude, 95°F) and/or powerplant failure in Reference 4. If that figure is justified, then the six-generator scheme fits it exactly; if not, then a weight penalty is to be set against it due to excessive installed power.

In view of the attractions of the six-generator scheme, it was thought worthwhile to estimate the weight of a 3000 h.p. gas generator, to see if any benefit or penalty was involved in the total weight of the gas generators.

ESTIMATE OF 3000 h.p. GAS GENERATOR

Estimate E in Table I gives the details and total weight of a 3000 h.p. gas generator.

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The same favourable basic assumptions were used as in the last-mentioned estimate (D) of the 4500 h.p. unit, i.e., plastic blading in the compressor, 0.025" sheet metal thickness and 1100 ft/sec tip speed, but against these, the minimum blade chord (1/2") and casting and forging thickness (3/8") were necessarily kept the same.

Thus it is seen that for the installed powerplant of the same total 18000 h.p., the six 3000 h.p. gas generators would weigh $190 \times 6 = 1140$ lb. against the four 4500 h.p. gas generators of $4 \times 270 = 1080$ lb., a penalty of 10 lb. on each of the six generators. A further small penalty might be involved as a result of increasing the fan size, but it must be remembered that the scheme eliminates all interconnecting ducts and blowback valves.

Had the 4500 h.p. gas generator been hypothetically scaled down proportionately in all sizes to 3000 h.p., based on the air mass flow, the weight, following the so-called "square-cube" law, would have been equal to $270 \times (23.6/35.4)^{3/2}$ or 147 lb., and if scaled down according to the 'modified' square-cube law of Reference 3, the weight would have been equal to $270 \times (23.6/35.4)^{1.35} = 157$ lb.

As it is, the same minimum casting, forging, sheet metal, and blade chord dimensions are imposed on both units, the 3000 h.p. fuel and oil systems are only slightly reduced in weight, and as well, the combustion chamber length remains fundamentally the same, fixing with it certain shaft and stator backbone dimensions.

EFFECT OF ASSUMPTIONS ON POWERPLANT WEIGHT

In Reference 3 the total powerplant system weight was defined to include the fuel. For an aircraft of 20,000 lb. all-up weight on a mission of 500 miles range, 10 minutes hovering, the weight figures were as follows:

Installed 4500 h.p. gas generators	= 4 x 480	= 1920
Installed 3-foot diameter fans with drives, ducts and valves	= 8 x 340	= 2720
Cruising fuel		= 2200
Hovering fuel		= <u>1160</u>
Total powerplant-system weight		= 8000 lb.

Thus the powerplant + fuel weight amounted to 40% of the all-up weight of the aircraft.

The preceding considerations of this memorandum have shown that considerable weight reductions in the gas generators may be obtained by changing certain basic assumptions. Some of these basic assumptions may affect the fuel, as was also shown, and some may affect the fan, drive, duct, and valve weight estimates.

The use of plastic would not affect the fan, etc., estimates, because these were made using magnesium alloy, of virtually the same

density as the plastic, wherever possible, and within clearly defined limits.

Thinner sheet metal thickness may have a large effect on the weights of the fan manifolds, ducts and valves, since these were all estimated on a basic assumption of 0.050" instead of the 0.025" now proposed, but it must be noted that the manifolds are of about 4-foot diameter against the only 14 inches or so of the 4500 h.p. gas generator, so that perhaps a difference in thickness is justified.

Increased tip speed would have some effect on the fan and drive tip turbine weights, since these were estimated on a basis of 800 ft/sec fan tip speed. The fan, although single stage, could have a fewer number of blades. The turbine stages might be reduced from two to one, but the turbine blade support ring would become more of a problem due to the increased centrifugal forces.

An interesting sidelight on the tip speed was provided by another engine manufacturer who was also proposing a fan-lift aircraft driven by small gas generators. The fans were to have a discharge velocity of 600 ft/sec with a tip speed of 950 ft/sec, both limited by the factor of noise.

Model fan tests are now under way (Reference 5) which should show the limits of tip speed, as controlled by efficiency (and perhaps noise), not only for the fans themselves but also perhaps as an indication for the transonic compressor in the gas generator.

Also, detailed designs are proceeding for a 3-foot fan, tip turbine drive, and gas valves. When these, and the model fan tests, will have reached a certain stage, it might be profitable to re-estimate the total powerplant + fuel weight, and compare it with the 40% of the all-up weight of the aircraft originally calculated in Reference 3.

CONCLUSIONS

1. The original basic weight estimate of 340 lb. for a 4500 h.p. "hot cycle" gas generator may be reduced to 270 lb. by changing certain basic assumptions.
2. Of the total 70-pound saving, 15 lb. is saved by substituting plastic for metal blading in the compressor. An interesting competition is thereby disclosed between the equally light, and new, plastic and magnesium alloy materials.
3. 25 lb. is saved by reducing the sheet metal thickness from 0.050" to 0.025" in the combustion chamber, turbine stator and exhaust parts.
4. 30 lb. is saved by increasing the tip speed from 800 to 1100 ft/sec, but this may be wiped out by 30 lb. of extra fuel and increased generator size, on an aircraft mission of 500 miles range, 10 minutes hovering, if the assumed compressor efficiency of 85% cannot be maintained, and falls by 2%.

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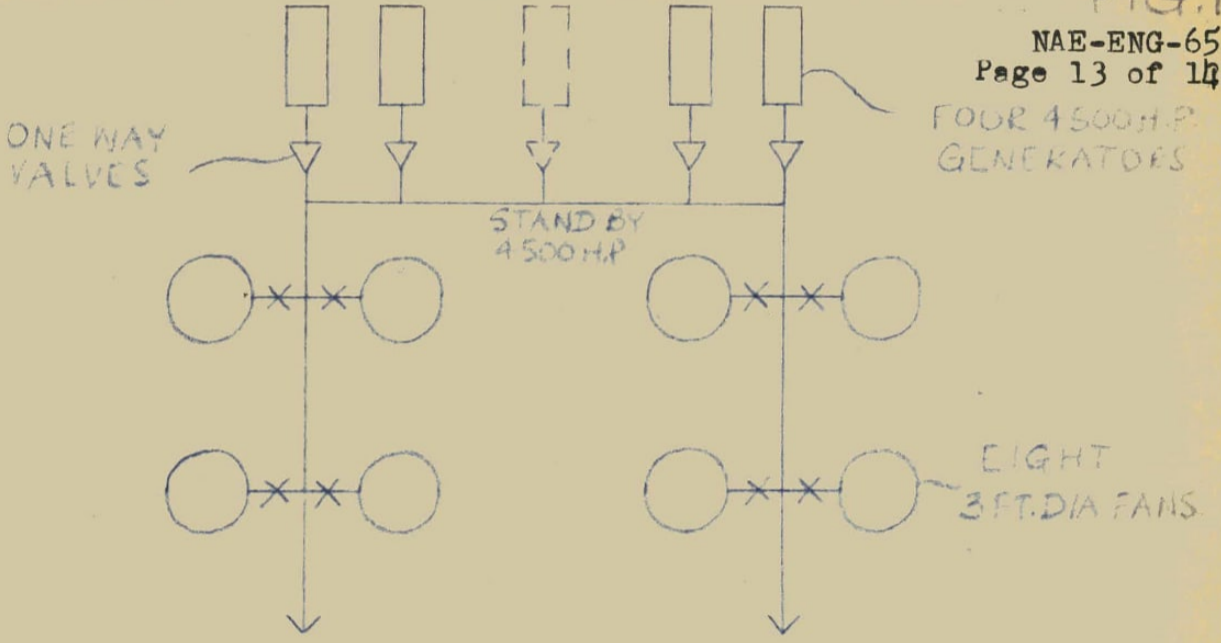
5. For the total 18,000 h.p. required to be installed in the aircraft, six 3000 h.p. gas generators are found to be better, aside from weight, than four of 4500 h.p. Making the most favourable assumptions in each case, their weights total $6 \times 190 = 1140$ lb. and $4 \times 270 = 1080$ lb. respectively, a penalty of 10 lb. on each 3000 h.p. unit in the six-generator scheme.

T A B L E I

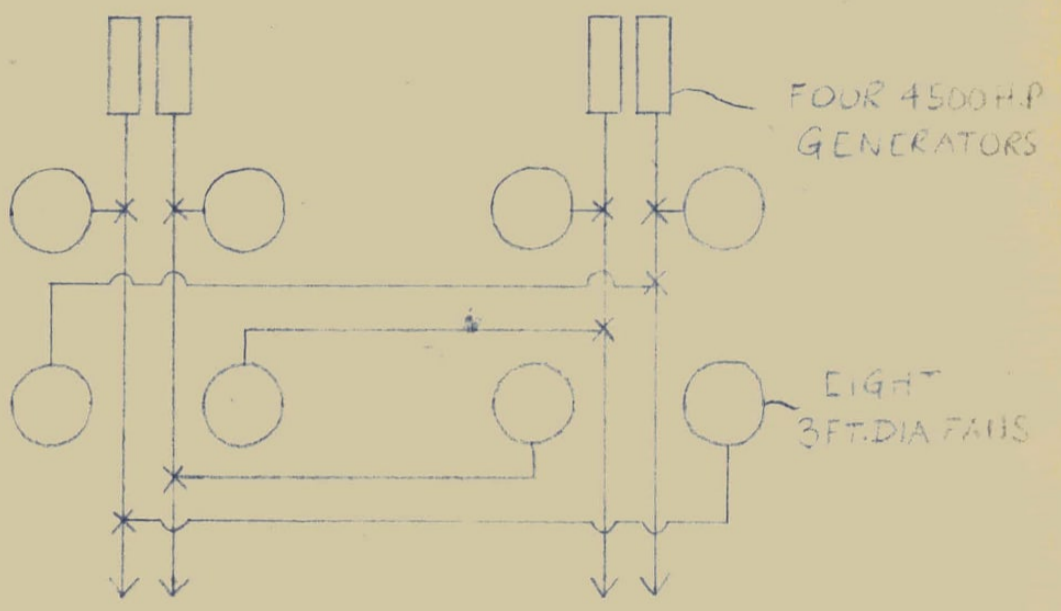
Weight and Size Estimates of "Hot" Cycle Gas Generators

Maximum Temperature 1300°K
Compressor Temperature Rise 300°C

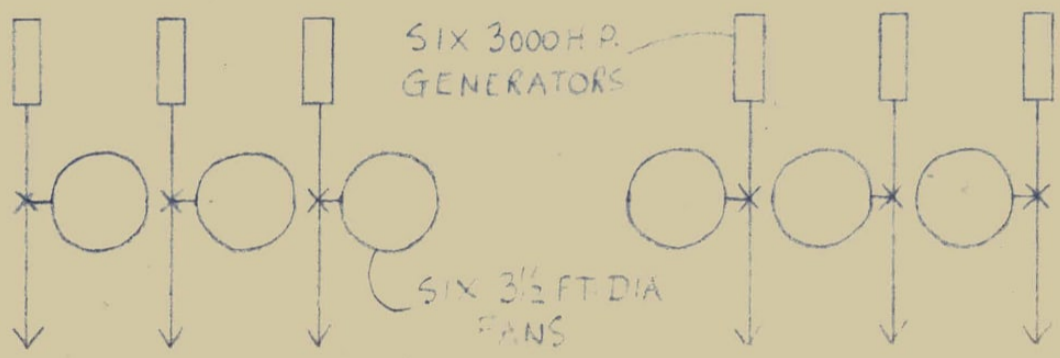
Estimate reference	A	B	C	D	E
Generator h.p.	4500	4500	4500	4500	3000
Generator thrust lb.	2670	2670	2670	2670	1780
Generator air mass flow lb/sec	35.4	35.4	35.4	35.4	23.6
<u>Assumptions</u>					
Compressor blading material	Metal	Plastic	Plastic	Plastic	Plastic
Sheet metal thickness ins.	0.050	0.050	0.025	0.025	0.025
Compressor tip speed ft/sec	800	800	800	1100	1100
<u>Weights lb.</u>					
Compressor rotor	59	49	49	50	32
Compressor stator	68	63	63	55	36
Combustion chamber	36	36	18	18	15
Turbine rotor	52	52	52	39	25
Turbine stator	38	38	34	28	20
Exhaust and nozzle	7	7	4	4	3
Shaft and bearings	34	34	34	30	19
Fuel and oil Systems	40	40	40	40	35
Nuts and bolts	6	6	6	6	5
Total weight	340	325	300	270	190
<u>Sizes inches</u>					
Overall diameter	18	18	18	18	15
Rotor diameter	14.2	14.2	14.2	14.2	11.6
Overall length	51	51	51	43	40



ORIGINAL & STAND-BY INTERCONNECTION SCHEMES



TWO FANS PER GENERATOR SCHEME



SIX GENERATOR SCHEME

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5. NAE Laboratory Memorandum Eng-57 entitled "Preliminary Note on the 12-inch Fan Test Rig for Testing Models of VTO Wing Fans." By H.S. Fowler, February 1958.