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American Helicopter Society

1995 Student Design Competition

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List of Symbols and Abbreviations

σ	rotor solidity = $bc/\pi R$
μ	speed ratio = $V_{INFINITY} / \Omega R$
θ	temperature ratio (T_{ALT} / T_{SLS}) degree Rankin
δ	pressure ratio (P_{ALT} / P_{SLS})
ΩR	rotor tip speed
AGL	above ground level
b	number of blades per rotor
c	blade section chord (ft)
C_D	coefficient of drag
C_L	coefficient of lift
C_Q	coefficient of torque
C_T	coefficient of trust
deg C	degrees Celsius
$ESHP_{REQ}$	engine shaft horsepower required
FF	fuel flow (lb./hour)
GW	Gross Weight
hp	horsepower
IGE	in ground effect
ISA	international standard atmosphere
lb.	pounds mass
MCP	max continuos power (engine rating)
MCP	maximum continuos power
MGW	max gross weight @ TRP, SLS conditions
MSL	mean sea level
Nm	nautical miles
N_R	rotor speed (rpm)
OGE	out of ground effect
R	blade radius (ft)
RFP	request for proposal
rpm	revolutions per minute
SDGW	structural design gross weight
sfc	specific fuel consumption
shp	shaft horsepower
SL	sea level
SLS	sea level standard
TOGW	take-off gross weight
TRP_{ALT}	Takeoff Rated Power at altitude
TRP_{SLS}	Takeoff Rated Power at SLS cond
UAV	unmanned air vehicle
V_{BE}	velocity for best endurance
V_{BR}	velocity for best range
V_{MCP}	velocity at max continuous power
VROC	vertical rate of climb
VTO	vertical take off
VTOL	vertical takeoff and landing
WE	Weight Empty

Introduction

This UAV program is conceived as an autonomous VTOL search and rescue/payload delivery aircraft. It is capable of emergency vertical extraction of two people, delivery of a payload capsule weighing up to 400 lbs., video surveillance and is VTOL capable to a landing gear footprint of a 20 ft. by 20 ft. hard surface. The UAV is to be designed to meet the three missions included in this document. The aircraft is navigated from a ground control station; commands are sent through a data-link to the airborne computers.

There are two categories of proposals, undergraduate and graduate. Please note that there are additional proposal requirements for graduate student teams. A turboshaft engine model has been provided in the data package to be used by both undergrad/grad students. Also a weight prediction package is included, but alternate weight methodology may be used if adequate supporting data is provided. Several required items that must be included in your design have already been developed, and will be furnished by other subcontractors (see data package for weights and dimensions):

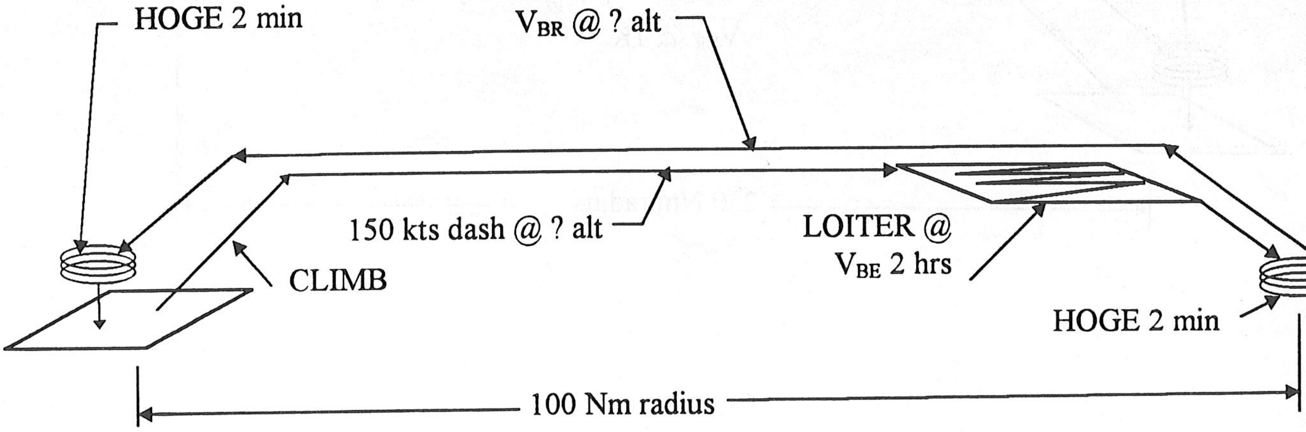
Electro-optical package
Turboshaft engine (420 SHP specified for undergraduates)
Payload capsule
Payload winch
4 Blackboxes (data link, flight control computer, inertial navigation computer, misc. avionics)
7 antennas (GPS, IFF, UHF, 2 C-band, 2 radar altimeter)

Cost studies have determined that this UAV can be produced profitably if the weight empty is less than or equal to 1500 lb. The less the weight empty the lower the cost. The UAV is defined by three mission scenarios. All three missions are intended to preserve or save lives.

Aircraft Design Mission Requirements

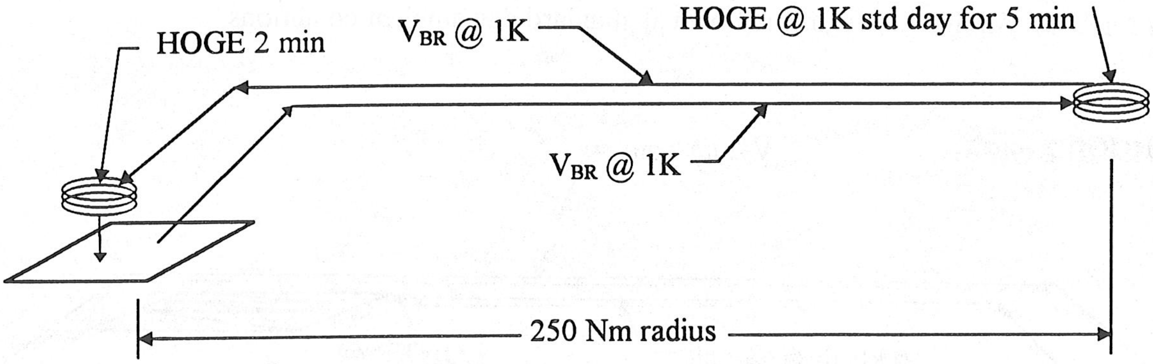
Mission 1

This mission is known as a 'force multiplier'. Several UAV aircraft launch and dash out to sea ahead of the Coast Guard SAR helicopter to find a boat that has just radioed a distress call. Each aircraft carries an emergency aid capsule containing: life-jackets, emergency locating transmitter, raft, chemical heat blankets, first-aid, two-way radio, etc. The capsule weighs 200 lb. When a UAV locates the people in distress it lowers the care package. Then it returns to its base. Details of the mission are as follows: The engine is started and the aircraft completes a 2 min. warm-up/diagnostic preflight. The aircraft launches vertically from a coastal base at SLS then climbs to an optimum cruise altitude not to exceed 10,000 ft MSL. Then the UAV dashes at 150 knots to the search area located 100 Nm from the launch point. The UAV loiters in a search pattern for 2 hours (until it locates the hapless boaters). Then the aircraft descends to an OGE hover at 100 ft MSL and delivers the package by lowering it on a cable while hovering. The aircraft hovers for 2 minutes and then returns to the home base at optimum altitude. Upon arrival at the helipad the aircraft hovers OGE for 2 minutes while slowly approaching to a landing. It performs a 2 minute cool down at flight idle and then is shut down with a 15 min fuel reserve (calculated at power required for V_{BE}). All mission segments flown at standard day ambient conditions.



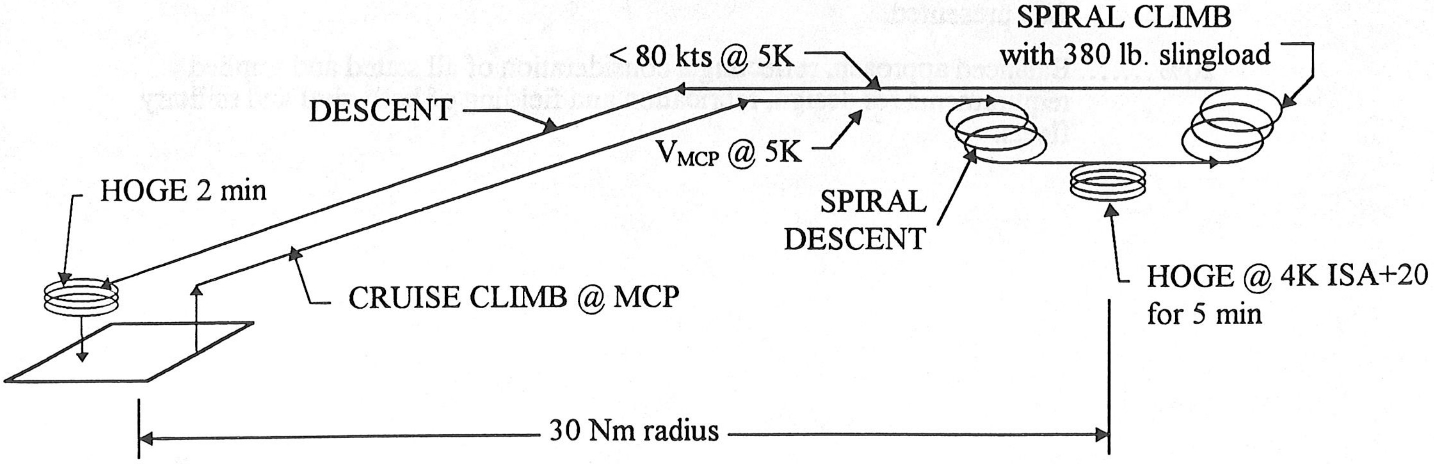
Mission 2

A small nation in the midst of a civil war has closed it's borders. Several of our citizens have become isolated inside. Our government can not risk any of our pilots or citizens becoming hostages of the other factions. Therefore UAV's will provide supplies to the agents from the decks of small ships located in International Waters. The mission is to deliver a 400 lb. package to a remote forest clearing 250 Nm away and return to the ship. The ship is small and therefore the aircraft size is limited by the ships geometry to a rotors turning envelope of a 25 ft. diameter circle. Details of the mission are as follows: The engine is started and the aircraft completes a 2 min. warm-up/diagnostic preflight. The aircraft launches vertically from a ship's deck at SLS. Climbs to 1000 ft MSL and cruises 250 Nm to the drop site. Then the aircraft hovers OGE at 1000 ft MSL (200 AGL) and delivers the package by lowering it on a cable while hovering. The aircraft hovers for 5 minutes and then returns to the ship at the same altitude and flight path. Upon arrival at the ship the aircraft hovers OGE for 2 minutes while slowly approaching the deck and lands. It performs a 2 minute cool down at flight idle and then is shut down with a 15 min fuel reserve (calculated at power required for V_{BR}). All mission segments flown at standard day ambient conditions.



Mission 3

This mission is to find some forest rangers who have become trapped while fighting a forest fire in the mountains and rescue them. The engine is started and the aircraft completes a 2 min. warm-up/diagnostic preflight. The aircraft launches vertically from a base camp located at 2,000 ft MSL on an ISA +20 deg C day. Cruise climb is performed at 200 ft/min (engine(s) MCP rating) to 5,000 ft MSL while crossing a mountain ridge, followed by a dash for the remainder at MCP to a radius of 30 Nm. The aircraft locks on to the ranger's emergency distress beacon and spiral descends to an OGE hover at 4,000 ft MSL. The aircraft is now hovering 200 ft AGL over the trapped people (this is confirmed by the video image sent to the ground control station) and lowers a 200 lb. care package on a cable, a ranger removes the payload capsule and unpacks it. The capsule contains: fire suppression equipment, protective clothing, breathing apparatus, first aid supplies, two-way radio, two person harness with helmet intercom and hoist/evacuation instructions. Two people (190 lb. each) attach themselves to the harness and establish radio contact with the ground operator and signal they are ready to depart. The aircraft has been hovering OGE for 5 minutes. The aircraft spiral climbs at 200 ft/min minimum back to 5,000 ft MSL and then returns to the base camp, leaving behind the remaining people and the care package to be rescued by another UAV enroute. The return trip is accomplished at a speed less than or equal to 80 knots for the safety of the sling loaded passengers. Upon arrival at the base camp the aircraft hovers OGE for 2 minutes while the passengers unload and then lands. It performs a 2 minute cool down at flight idle and then is shut down with a 10 min fuel reserve (calculated at MCP). All of the mission is flown at ISA + 20 C.



Judging Criteria

The proposal is the means by which a customer evaluates each offeror's concept. Clear and concise descriptions are required, with appropriate use of illustrations. Data charts should include requirements, constraints or other data for reference. Spelling, grammar and neatness are important, but unnecessary or extravagant presentations are not required.

20% .... Creativity...Credit is given for innovative approaches to the design or integration of a component, a system, the aircraft or the fleet. Primary benefits and drawbacks (if any) should be identified.

20% .... Compliance with mission/system requirements, or thorough discussion of justification for deviations taken to the stated requirements.

20% .... Realism of the design(s).

20% .... Rigor of the design process, including appropriate application of technology, substantiation of assumptions, documentation of trades, and completeness of data presented.

20% .... Balanced approach, reflecting a consideration of all stated and implied requirements for design, fabrication and fielding of both civil and military fleets.

Proposal Requirements

I **Preface** (not numbered and not included in the page limit)

- Cover page with the name of the school and the judging category (grad/undergrad)
- Names and signatures of all the proposal participants
- Executive Summary (up to two pages)
  Description of the aircraft significant features and the teams approach to meeting the design criteria
- Table of Contents
- List of Figures and Tables
- List of Symbols and Abbreviations
- Proposal Requirements Matrix

II **Aircraft Overview**

- Describe the aircraft layout and it's unique features. Explain the inboard profile, and how the various systems are integrated (The main transmission is attached to a box beam running the length of the fuselage roof ...).

III **Design Considerations**

- Explain the methodology used to arrive at your aircraft configuration and sizing solution. What constraints dictated your configuration? If not all criteria can be met, define which requirement was relaxed and the rationale behind your selection.

IV **Drawings**

- A three view drawing of the aircraft on an eleven by seventeen sheet of paper. Provide major dimensions.
- Inboard profile that shows all the major features of the aircraft including: engine, fuel system, avionics, payload, payload winch, dynamic components, antennas and any unique features.

V **Physical Data**

- Table of pertinent physical data including basic weights (WE, GW, fuel capacity, payload), overall dimensions, engine ratings, transmission ratings, max electrical load, speeds, ceilings, etc.

VI **Systems Description**

- Describe each primary aircraft system (rotor, controls, airframe, payload mount, landing gear, transmission, etc.
- Provide a schematic of the drivetrain with gear ratios, shaft speeds, and direction of rotation.

Additional Graduate student requirements

- Substantiate the choice of control actuation system for your UAV: electro-mechanical, hydraulic, or combination of both. Support your choice with analysis; What is the impact on accessory losses (power available to the rotor)? What is the sensitivity of the actuation type to vehicle size(GW)?

VII Weight and Balance

- Provide a group weight statement like the one shown in the appendix.
- Use the weights methodology plots provided in the appendix. An explanation of the assumptions and limitations of these plots is also provided in the appendix. If your concept or any subsystems deviate from normal conventions then supplement these plots with your own methodology, and provide an explanation of your assumptions and rationale.
- Plot the weight and balance extremes (gross weight vs. center-of-gravity) from MGW to WE similar to the example plot shown in the appendix. The plot shall include all payload and fuel excursions, the forward and aft center-of-gravity limits (fuselage station # in inches) and note the mast(s) location. If your configuration is a convert-a-plane such as a tilt-wing/rotor or articulated mast, be sure to include the center-of-gravity effect of the configurations transformation.
- Provide aircraft inertia's about the three major axis for the take-off GW of MISSION 2.

IIX Mission Performance

- Graphs of MGW vs. altitude for HOGE at TRP for ISA standard day and ISA + 20 C.
- Graph of Useful Load (payload + fuel) vs. Range at SLS (assume HOGE MGW at TRP)
- Graph of Useful Load vs. Endurance at SLS (assume HOGE MGW at TRP)
- Graph of Speed / Altitude envelope (assume: (1) HOGE MGW at TRP, (2) MCP available above 40 kts, (3) absolute envelope - or zero rate of climb
- Graph of. Max Rate of Climb vs Altitude at TOGW for Mission 3 (ISA + 20 C)

Additional Graduate student requirements

- What is the sensitivity of weight empty to range?
- What is the sensitivity of take-off power available to range?

IX Aerodynamic Data

- Include a complete drag buildup of your configuration including the two sling-load passengers in mission 3. (show zero-lift and induced parts)
- Define the download at MGW.
- Describe all engine installation losses, accessory and transmission losses.
- Graphs of Power Required and Installed Power Available vs. Airspeed at SLS for max TOGW and zero fuel weight with and without the sling load (mission 3). If your configuration is articulated (tilt-rotor/wing/body...) then provide graphs for each major mode of flight.
- Include a table with all significant performance attributes (aerodynamic coefficients, performance limitations, etc.)

Additional Graduate student requirements

- C_P vs. C_T for each rotor at hover, V_{BE} and V_{MCP}.
- Max Rate of Climb vs. Altitude at MGW and WE + 400 lb.

X Handling Qualities

- Demonstrate static longitudinal and directional stability.
- V-n Plot (limit load factor n_Z vs. airspeed).

Additional Graduate student requirements

- Define the max crosswind HOGE capability and provide substantiation.

XI Manufacturing

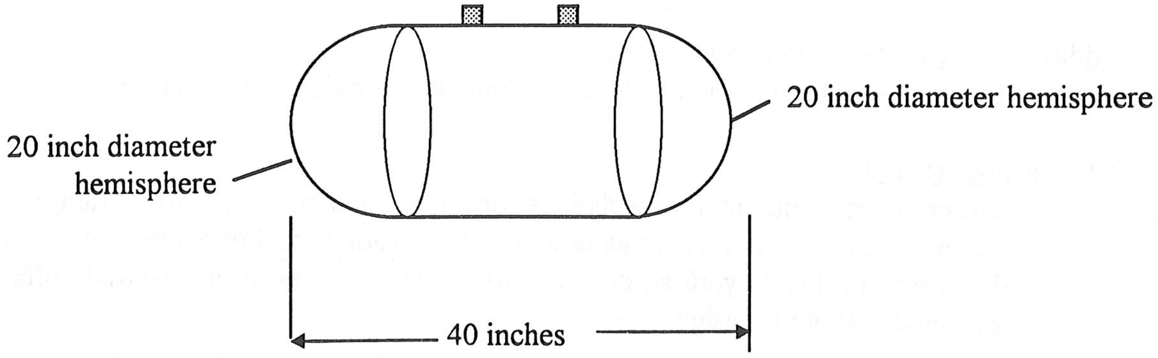
- Describe the manufacturing technique for the primary structure, drive-train, and rotor system. Explain the choice of materials used and tooling and/or equipment required to fabricate them. Justify your strategy and identify the cost/performance trade-offs associated with your design.

Note: Any additional analysis you wish to provide that adds to your designs credibility is welcome.

Data Package

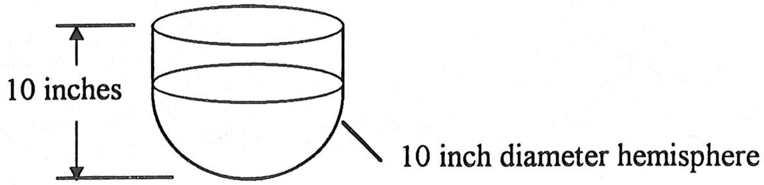
I Payload Capsule

200 lb and 400 lb version same dimensions.

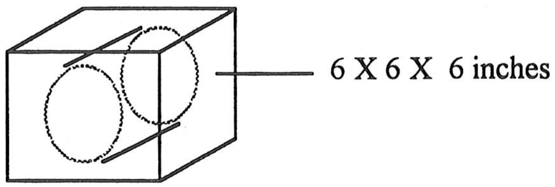


II Required Equipment

Electro-optical package: weight =15 lb

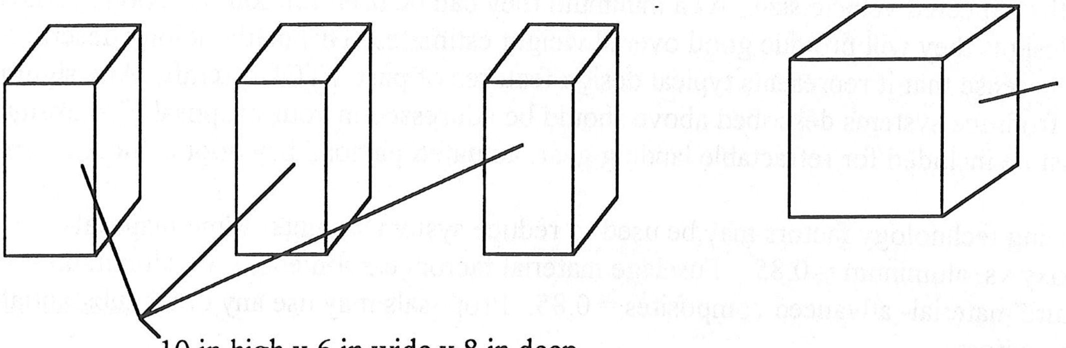


Payload winch (with 200 ft of cable): weight = 15 lb



4 black-boxes (data link, flight control computer, inertial navigation computer, misc. avionics)

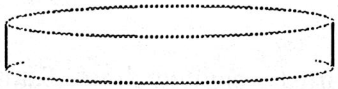
data link = 15 lb fcc = 15 lb nav computer = 20 lb misc. avionics = 15 lb

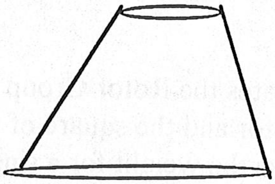


7 antennas (GPS, IFF, UHF, 2 C-band, 2 radar altimeter) total weight = 3 lb

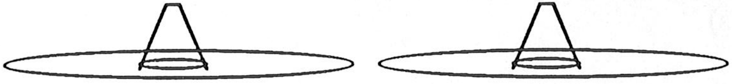
GPS: 4in diameter x 1/2 in thick

IFF and UHF: 10% thick symmetrical airfoil,
$\text{Chord}_{\text{ROOT}}$ = 5 in, $\text{Chord}_{\text{TIP}}$ = 2.5 in, 5 in tall





2 C-band (data link): 3 in diameter base, 2 in tall cone with 1 in base
Flush mount one on top and one on the bottom.



2 Radar altimeter: 3 in x 3 in plates
Flush mount externally at least 36 in apart, coplanar on the bottom of the UAV

III Weight Estimation Equations

Trends that relate design criteria to system weights are included in this section to assist in developing aircraft weight estimations. The included plots represent trends to a single design parameter, and are tuned to aircraft in the expected vehicle size. As a minimum they can be used for configuration synthesis, yet for "normal" designs they will provide good overall weight estimates. This methodology describes a "normal" design in the sense that it represents typical design features of past VTOL aircraft. Any significant deviations from the systems described above should be addressed in your proposal. For example: additional weight must be included for retractable landing gear, actuated payload bay doors, ducted rotors, etc.

The following technology factors may be used to reduce system weights: Wing material- carbon/epoxy vs. aluminum = 0.85. Fuselage material factor- carbon/epoxy vs. aluminum = 0.90. Tail structure material- advanced composites = 0.85. Proposals may use any other substantiated technology factors.
The following explains each graph individually.

Wing Group

The curve will provide the weight for both Tiltrotor or Conventional aircraft wings. It assumes that the wing aluminum skin, stringer, rib construction.

SDGW = Structural design gross weight (LB)
Nz = limit flight load factor (g's)

Rotor Group

The chart relates the Rotor Group weight to the product of the Thrust weighted chord, Radius, Number blades per rotor and the square of the tip speed. All lengths are in feet, the tip speed is feet per second. The trend will give the weight for a single rotor including the blades and hub. The curves do not include controls. The Tiltrotor line also includes the spinner and a constant velocity joint.

C = Thrust weighted chord (ft)
R = Radius of main rotor (ft)
B = Number of blades per rotor
VT = Tip Speed (ft/s)

Structure Group

This is a simple linear relationship between weight and area for aluminum structure. It can be used for any structural components (i.e. tails, body etc.) that do not have dedicated trend curves.

Area is in square feet

Landing Gear

The landing gear curve will approximate the weight of a fixed, wheel type landing gear.

Gross weight = Design landing weight (LB)

Propulsion Group

This group includes the : Cowling, pylon support, air induction, exhaust, engine starting, and engine installati components. The start system is a 4.5 KVA starter generator.
The weight is a function of the uninstalled Take-off rated power of the engine (hp).

Engine

A curve relating the dry weight to the Take-off rated power of the engine has been provided.

Fuel System

The weight for Integral tanks and Bladder tank fuel systems have been provided on this chart. The weight of system includes all of the lines, valves, pumps and cells.

Capacity = total fuel capacity (gal.)

Gearboxes

This curve can be used to obtain a weight estimate for an individual gearbox. It will predict the weight of a single stage bevel gearbox, including supports and lubrication system. The predicted weight includes the wei of the oil and an aluminum case.

Torque = output torque of the gearbox (ft-lb.)

Transmission Shafts

Tail rotor driveshafts or Tiltrotor interconnect shafting systems can be estimated using the provided curve. T weight includes shafts, couplings and hangers. The weight obtained will be the weight per linear foot . This result should be multiplied by the total shaft system length to derive the total system weight. The weight represents a metal shaft with Thomas couplings.

Torque = shaft design torque (ft-lb.)

Mast (Rotor Shafts)

The mast weight may be obtained using the provided curves. Two lengths are provided, interpolation may be required to estimate a specific design point. The weight includes bearings and support.

Torque = design torque of mast (ft-lb.)
Length = overall length (ft)

Flight Controls Group

The flight controls group has been divided into three sections: the fixed wing controls, rotary wing controls, a pylon conversion controls. All three may be required for some designs, while only one may be appropriate fo others. The fixed wing curve includes all fixed wing actuators and control tubes and mechanism. The rotary wing equation predicts the main rotor actuators and the operating mechanism. Pylon controls consists of conversion actuators and the associated hardware.

Gross weight = Design Gross Weight (LB)
C = thrust weighted chord (ft)
R = radius of the main rotor (ft)
B = The number of main rotor blades per rotor.
V_T = Main rotor tip speed

Hydraulics Group

The hydraulics curve includes the weight for pumps, filters, reservoirs, fluid and plumbing. It is plotted as a function of the ideal horsepower required (i.e. Total pump capacity).

PSI = hydraulic pressure (psi)
GPM = Flow rate (gallons per minute)

Electrical System

The electrical system weight prediction includes the weight of a Ni-Cad battery, distribution, relays, busses, a power generation. The abscissa is the total power requirement for the aircraft.

Power = total aircraft electrical power required (KVA)

Avionics

The total installed weight for the avionics equipment is 55 pounds including the Data link, Flight computer, inertial navigation computer, antennas and sensors.

Video imaging sensor weight = 15 LB.

Load & Handling Group

The weight for the load & handling group shall be estimated by the design team. It should include any hoist equipment needed to complete the mission, as well as, the weight for the support structure and the weight penalties to the surrounding structure.

IV Engine Data

The following equations represent the general uninstalled lapse rate and fuel flow characteristics for a turbosh engine in the 350 to 450 horsepower class. It is assumed that the engine is operating at 100 % RPM with no recovery. The estimate of engine installation losses is left to the design team. Graduate students may modify power available equations for ram air and RPM effects if they wish.

Takeoff power available as a function of altitude

$TRP_{ALT} = TRP_{SLS} * \delta^{C4} / \theta^{C5}$

where:

TRP_{ALT} = Takeoff Rated Power (5 minute limit) at altitude

TRP_{SLS} = Takeoff Rated Power (5 minute limit) at SLS conditions

δ = pressure ratio (P_{ALT} / P_{SLS})

θ = temperature ratio (T_{ALT} / T_{SLS}) degree Rankin

$C4 = 1.12$

$C5 = 1.53$

For undergraduates: $TRP_{SLS} = 420$ SHP (uninstalled)

For graduates: TRP_{SLS} = variable

Other Ratings

$MCP = 0.881 * TRP_{ALT}$

Flight Idle = $0.15 * TRP$

Engine Fuel Flow (uninstalled)

$FF = C_1 * TRP_{SLS} * \delta * \theta^{0.5} + C_2 * ESHP_{REQ}$

where:

FF = fuel flow (lb / hour)

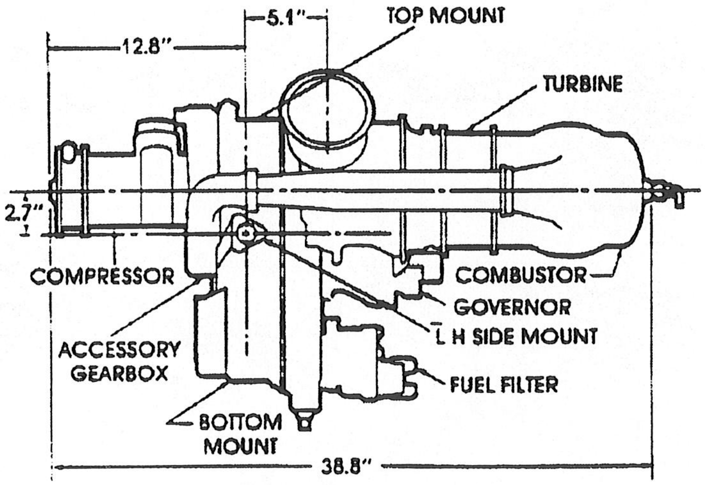
$ESHP_{REQ}$ = uninstalled engine power required

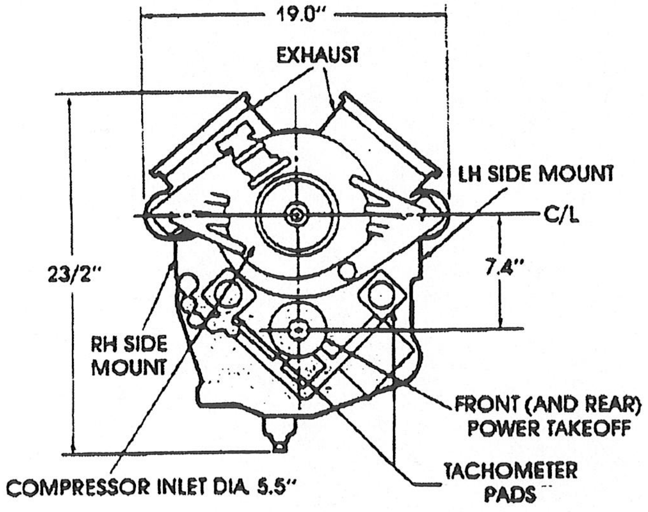
$C_1 = 0.144$

$C_2 = 0.456$

Specifications

Basic Engine	250-C20B
Weight	158 lb
Power/weight ratio (T.O.)	2.66:1
Airflow (T.O.)	3.45 lb/sec
Pressure ratio (T.O.)	7.1
Design speeds @ 100% rpm	
Power output shaft	6,016 rpm
Gas producer rotor	50,970 rpm
Power turbine rotor	33,290 rpm
Fuels	JP-4, JP-5, ASTM-1655, Type A, A1, B
Oils	MIL-L-7808, MIL-L-23699
Type certificate no.	E4CE (Feb. 74)





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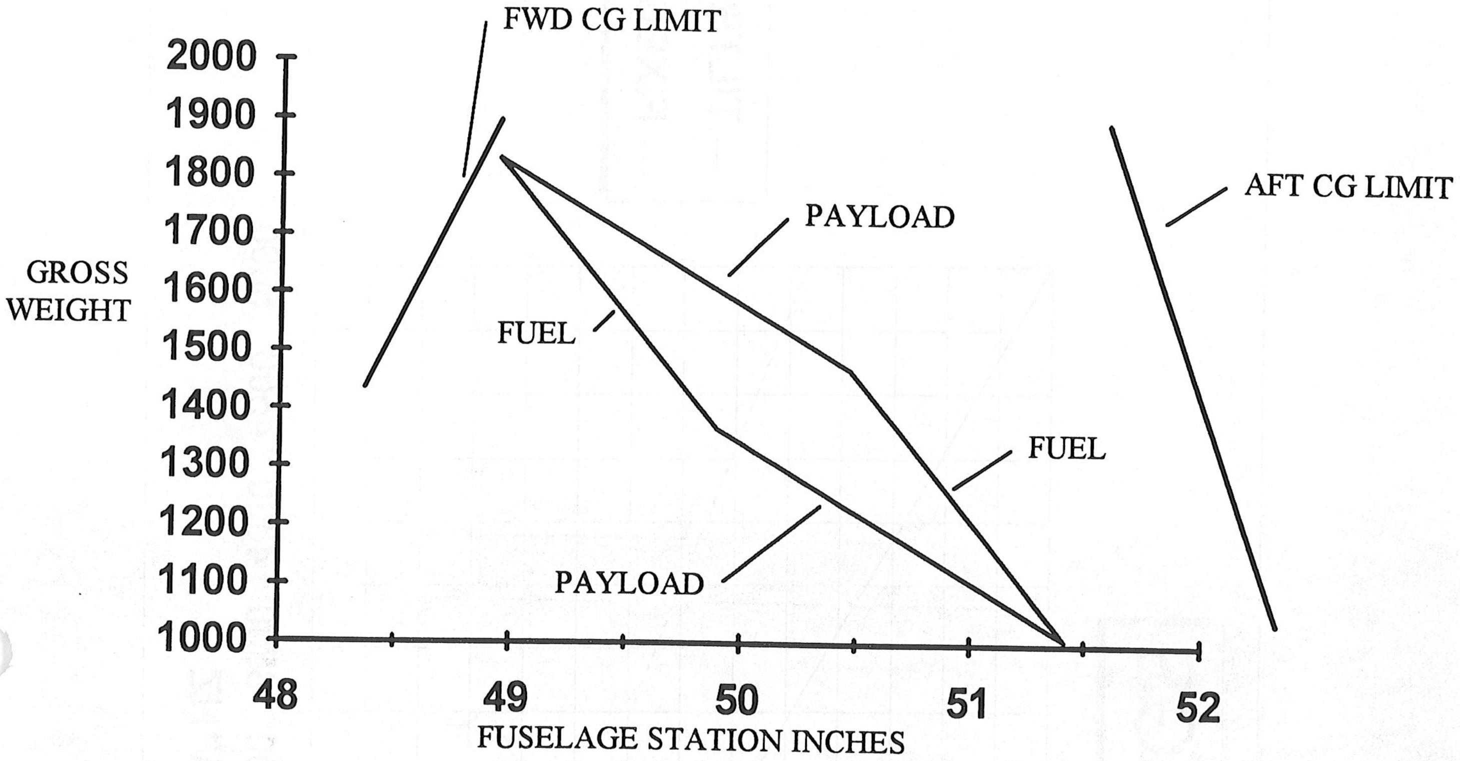
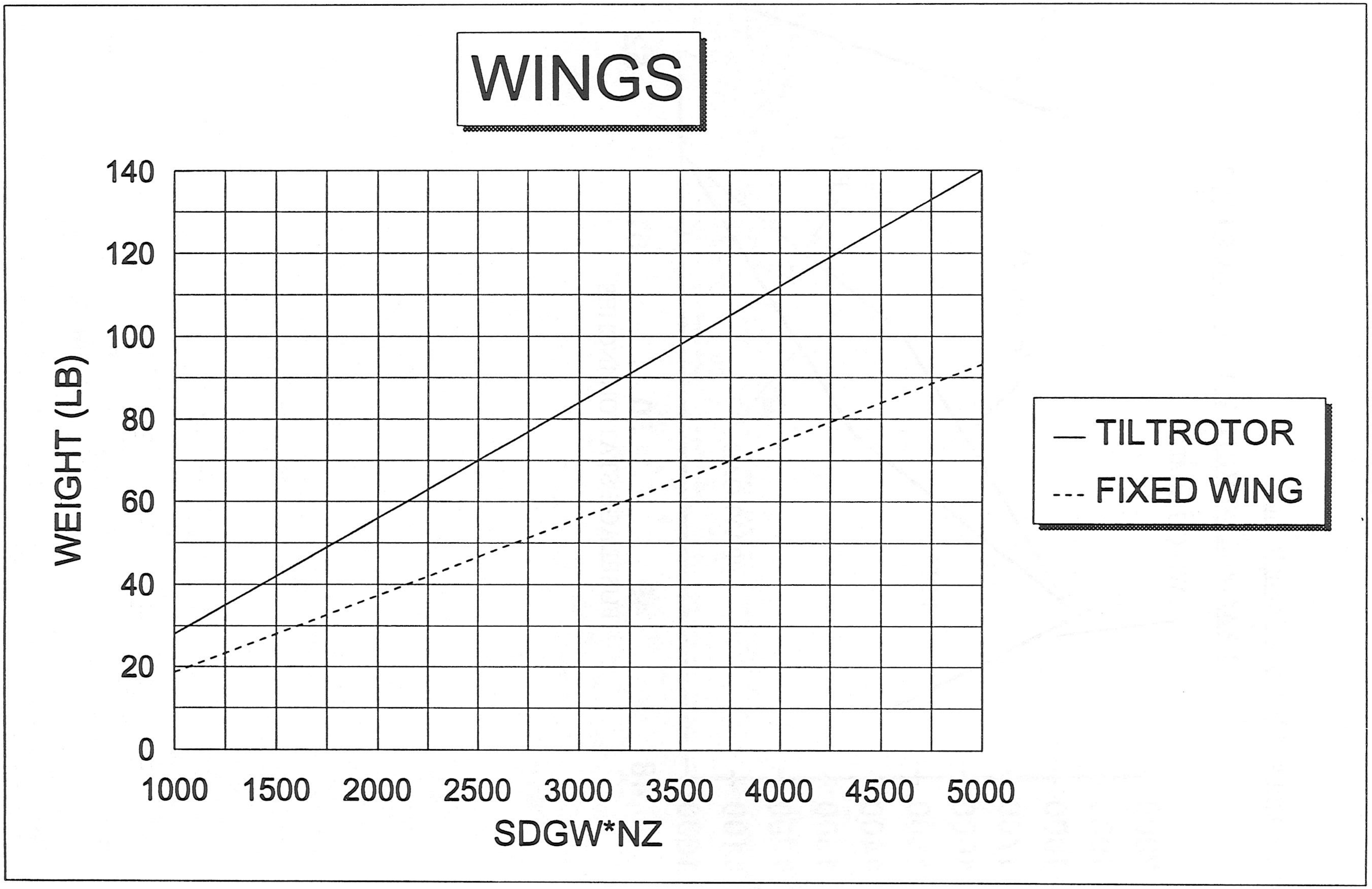
Appendix

I Group Weight Statement

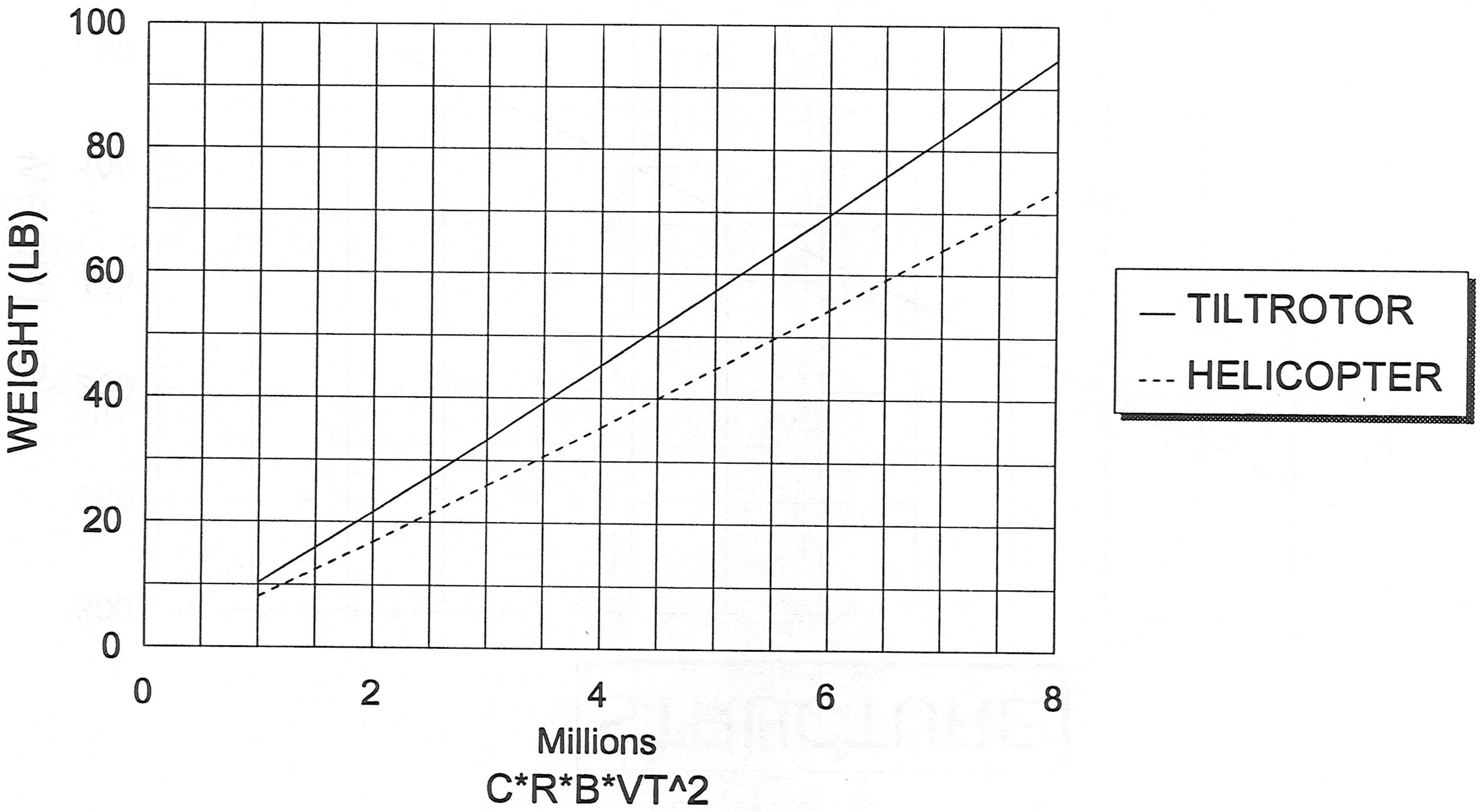
GROUP WEIGHT STATEMENT	
WING	
ROTOR AND HUB	
AIRFRAME STRUCTURE	
LANDING GEAR	
PROPULSION	
ENGINE	
FUEL SYSTEM	
GEARBOXES	
TRANSMISSION SHAFTS	
ROTOR SHAFTS	
FIXED CONTROLS	
PYLON CONTROLS	
ROTATING CONTROLS	
HYDRAULICS	
ELECTRICAL SYSTEM	
AVIONICS (DATA LINK, FLIGHT COMPUTER AND SENSORS)	68
LOAD AND HANDLING (winch)	
VIDEO IMAGING SENSOR	15
MISCELLANEOUS	
WEIGHT EMPTY	
PAYLOAD (200 OR 400)	
FUEL	
GROSS WEIGHT	

II Weight and Balance Example Plot

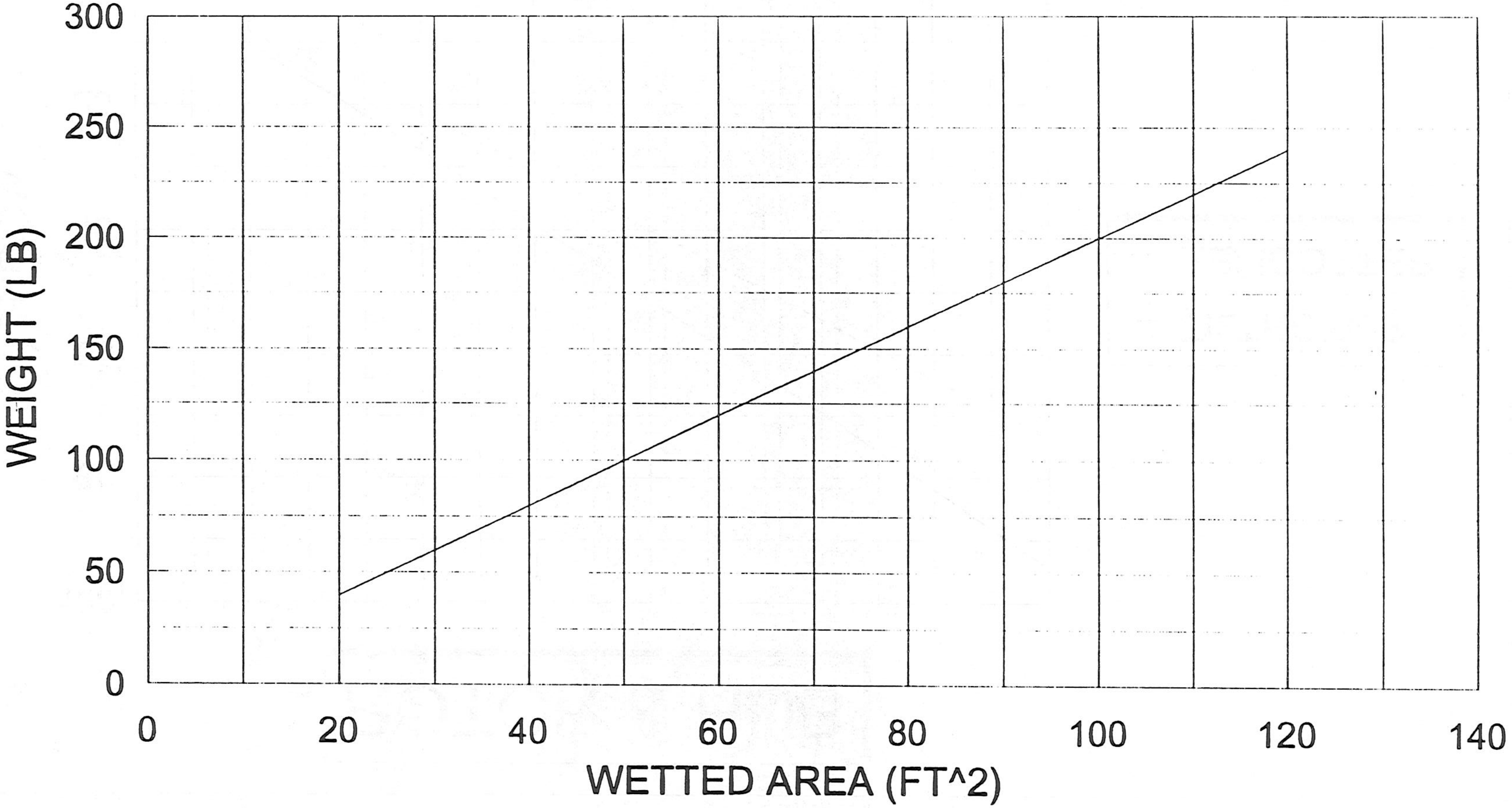



WINGS
WEIGHT (LB)
140
120
100
80
60
40
20
0
1000
1500
2000
2500
3000
3500
4000
4500
5000
SDGW*NZ
— TILTROTOR
--- FIXED WING

ROTOR & HUB

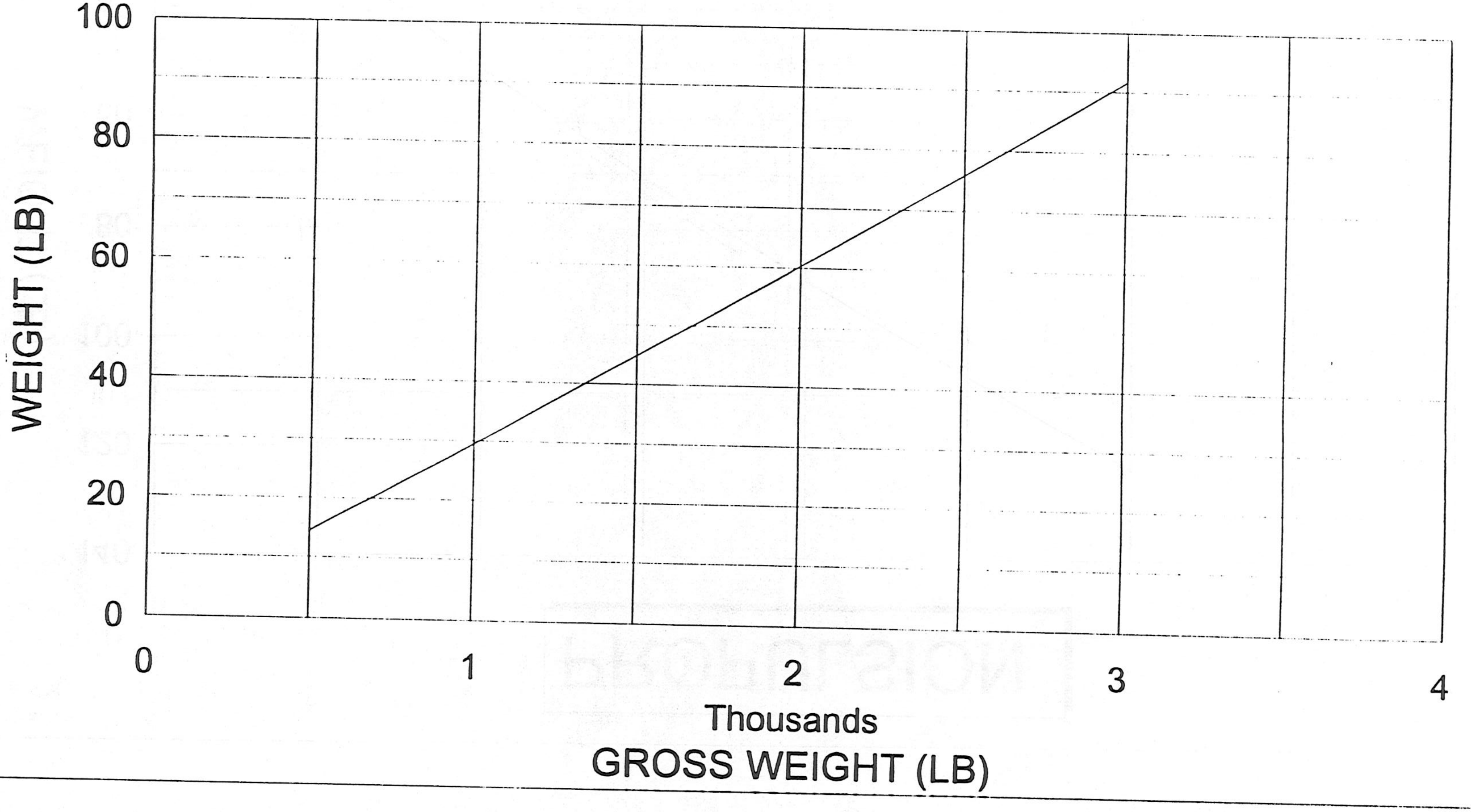

100
80
60
40
20
0
WEIGHT (LB)
0
2
4
6
8
Millions
C*R*B*VT^2
— TILTROTOR
--- HELICOPTER

STRUCTURE

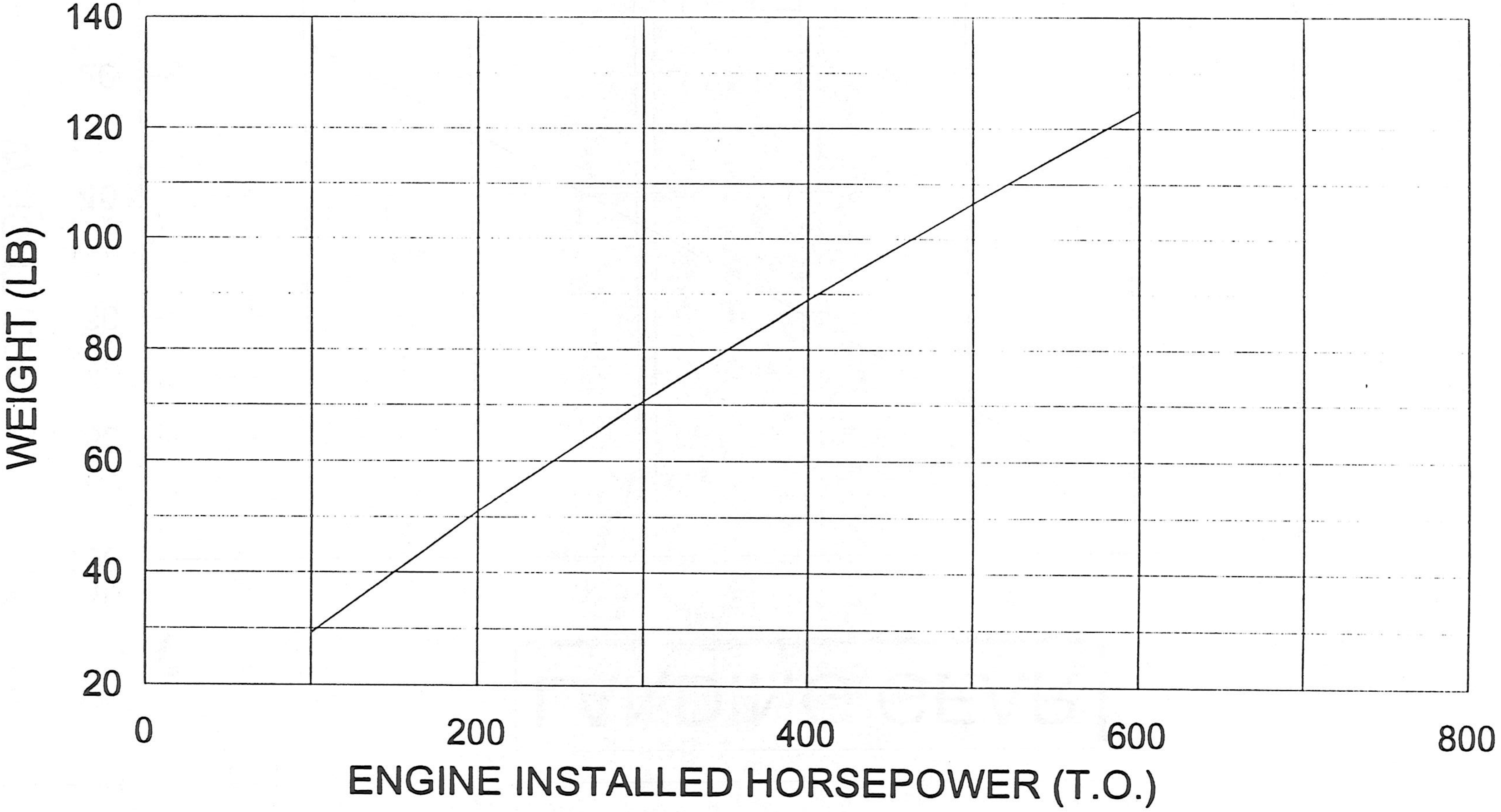


WEIGHT (LB)
300
250
200
150
100
50
0
0
20
40
60
80
100
120
140
WETTED AREA (FT^2)

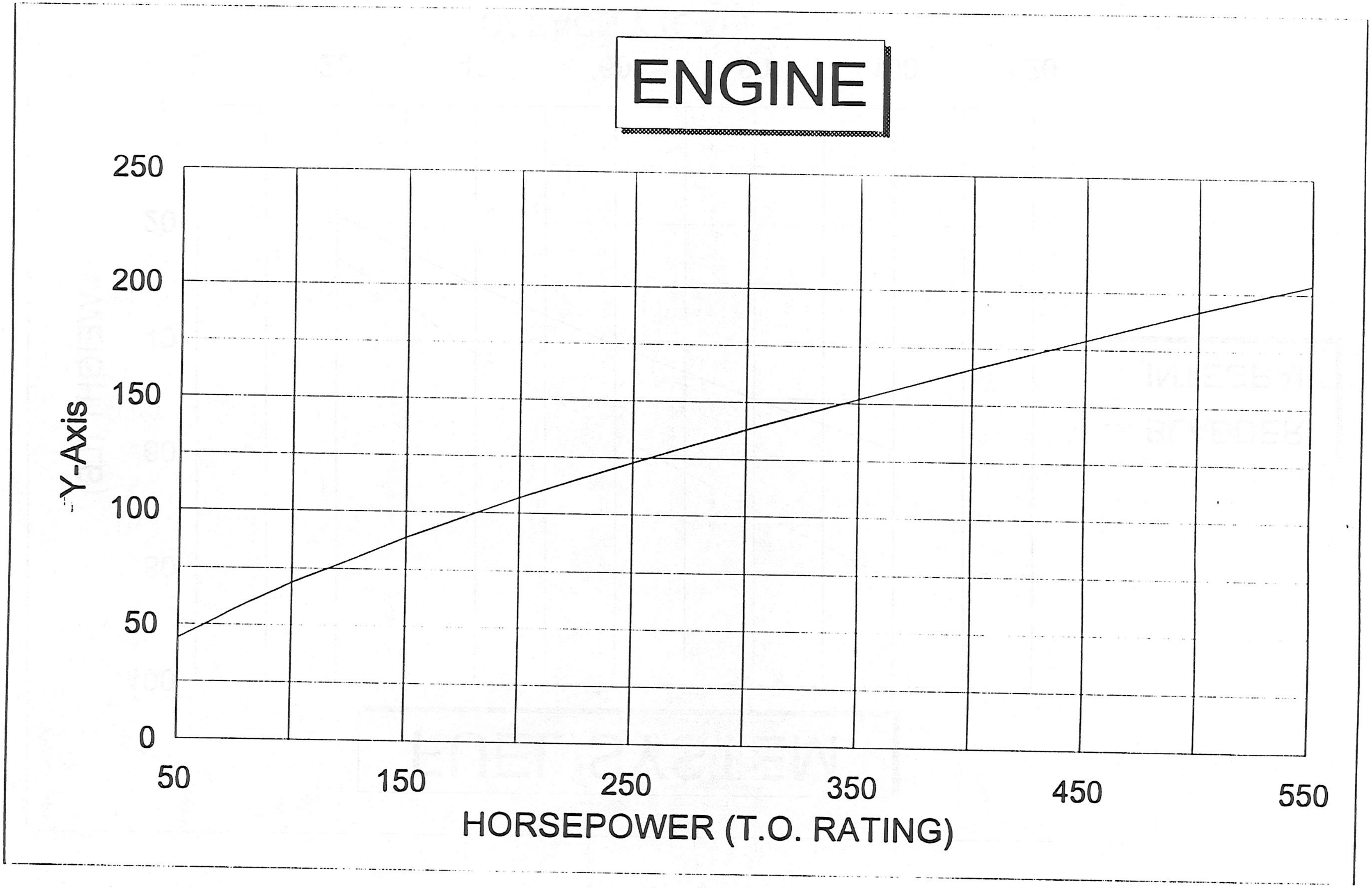
LANDING GEAR

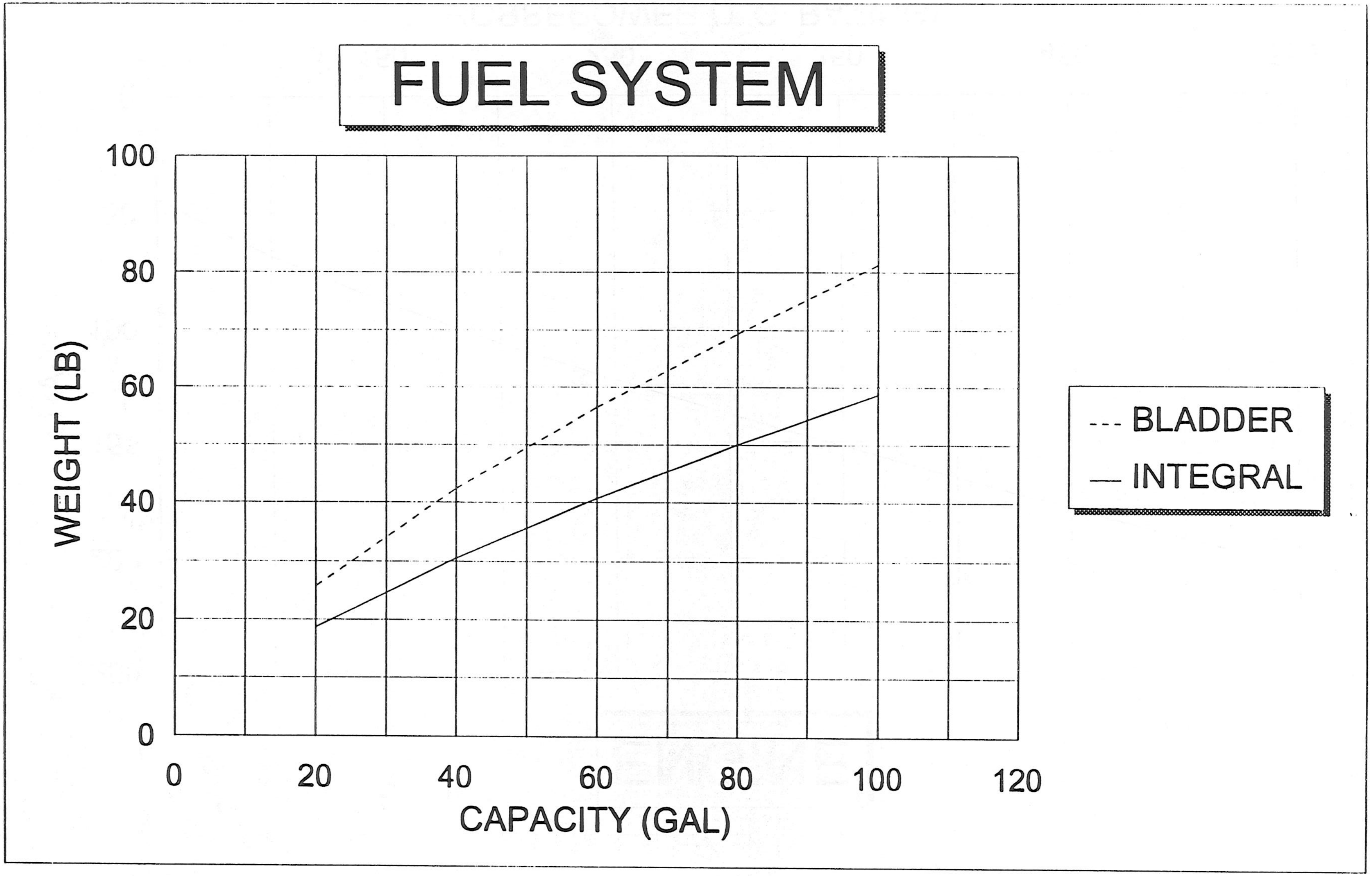


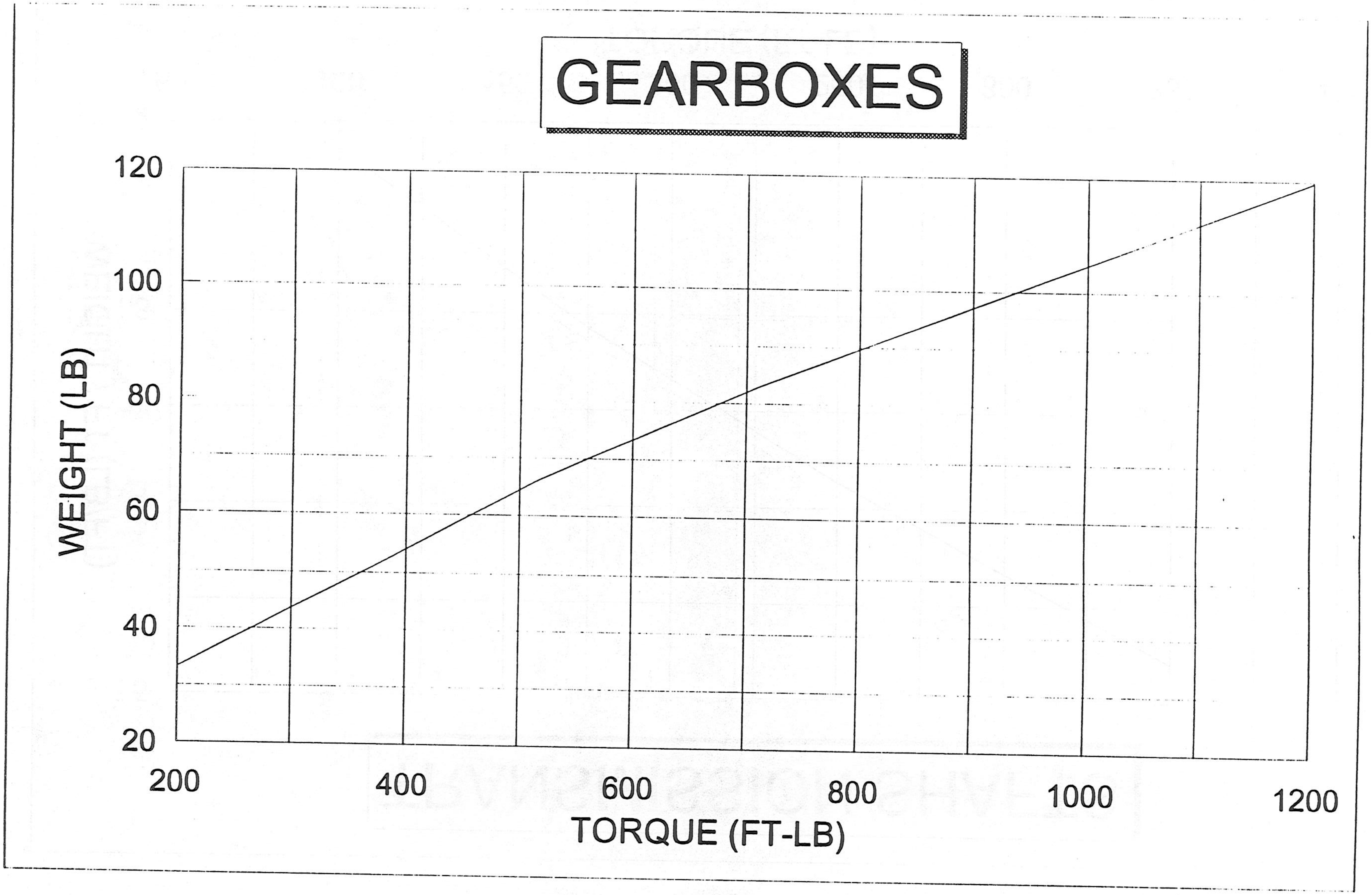
PROPULSION

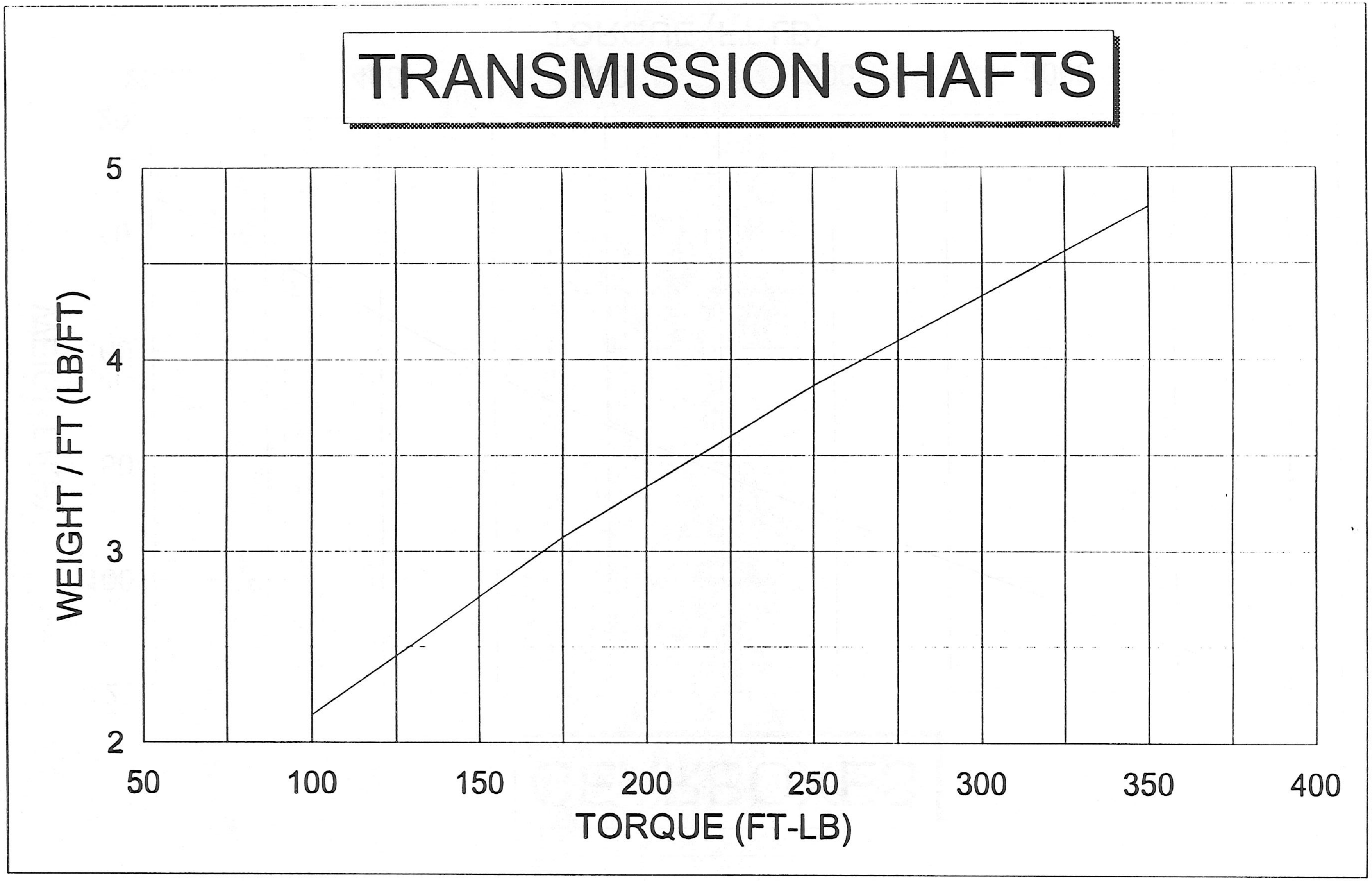


140
120
100
80
60
40
20
WEIGHT (LB)
0
200
400
600
800
ENGINE INSTALLED HORSEPOWER (T.O.)

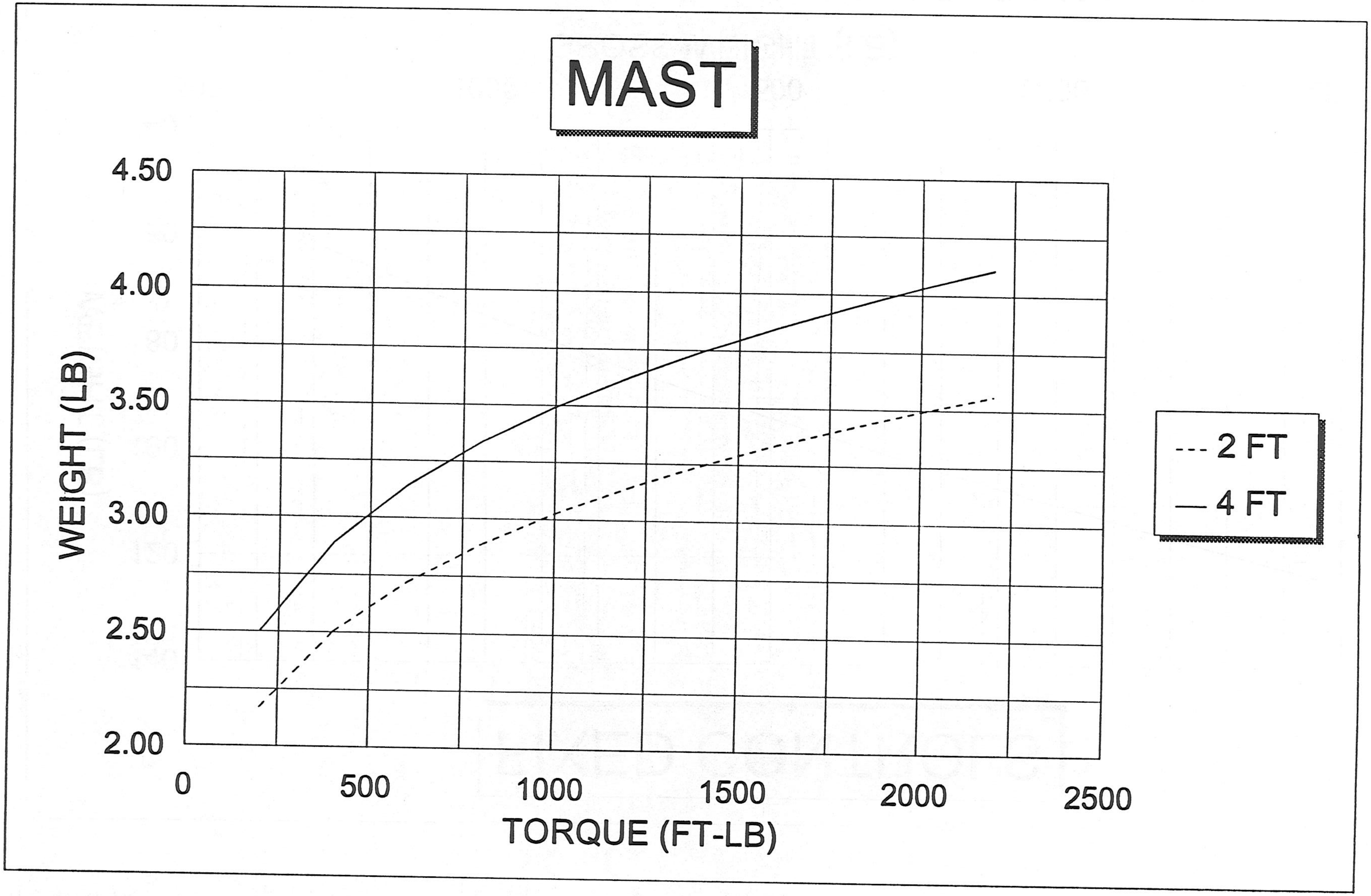

ENGINE
250
200
150
100
50
0
Y-Axis
50
150
250
350
450
550
HORSEPOWER (T.O. RATING)

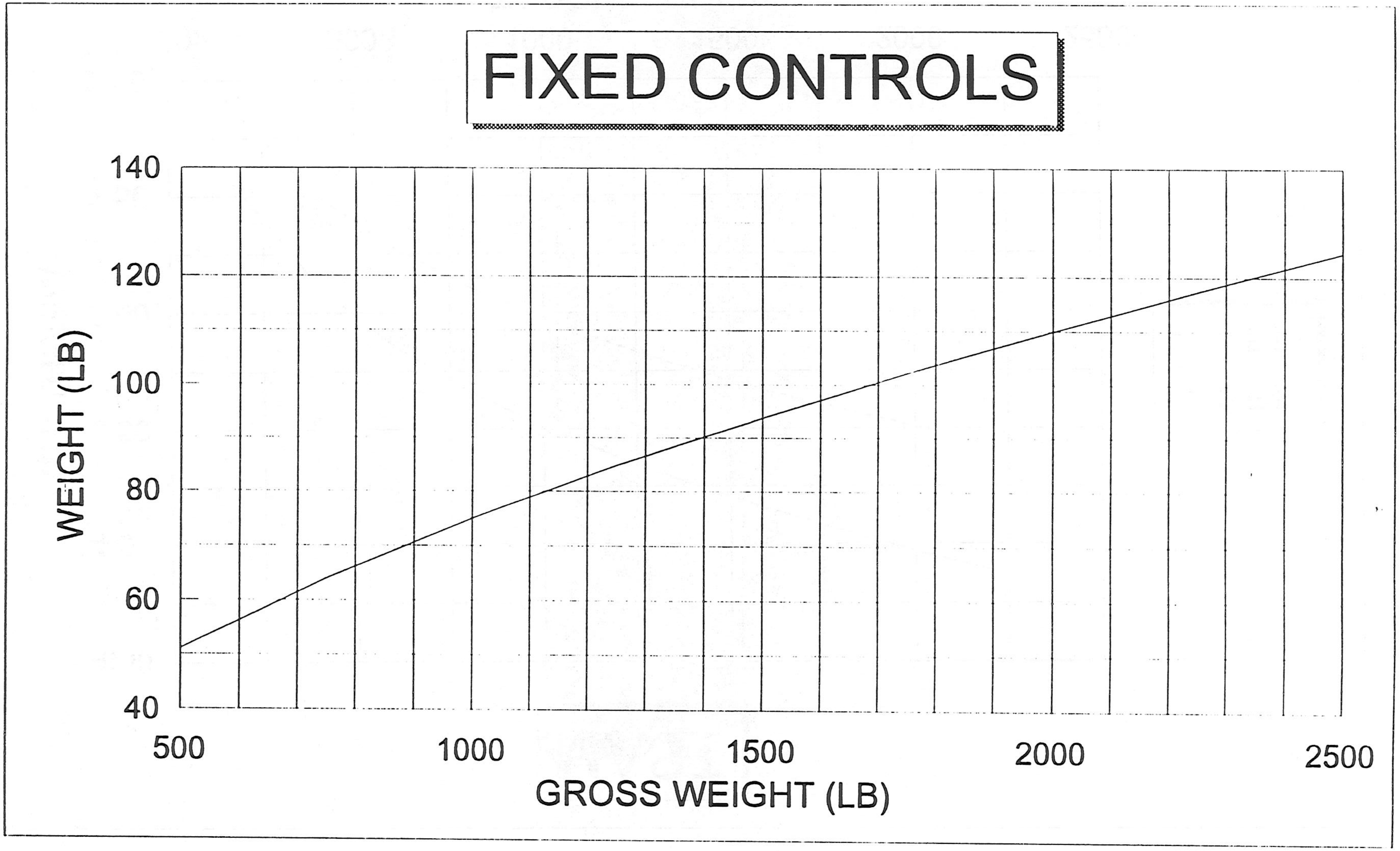

FUEL SYSTEM
100
80
60
40
20
0
WEIGHT (LB)
0
20
40
60
80
100
120
CAPACITY (GAL)
BLADDER
INTEGRAL


GEARBOXES
120
100
80
60
40
20
WEIGHT (LB)
200
400
600
800
1000
1200
TORQUE (FT-LB)

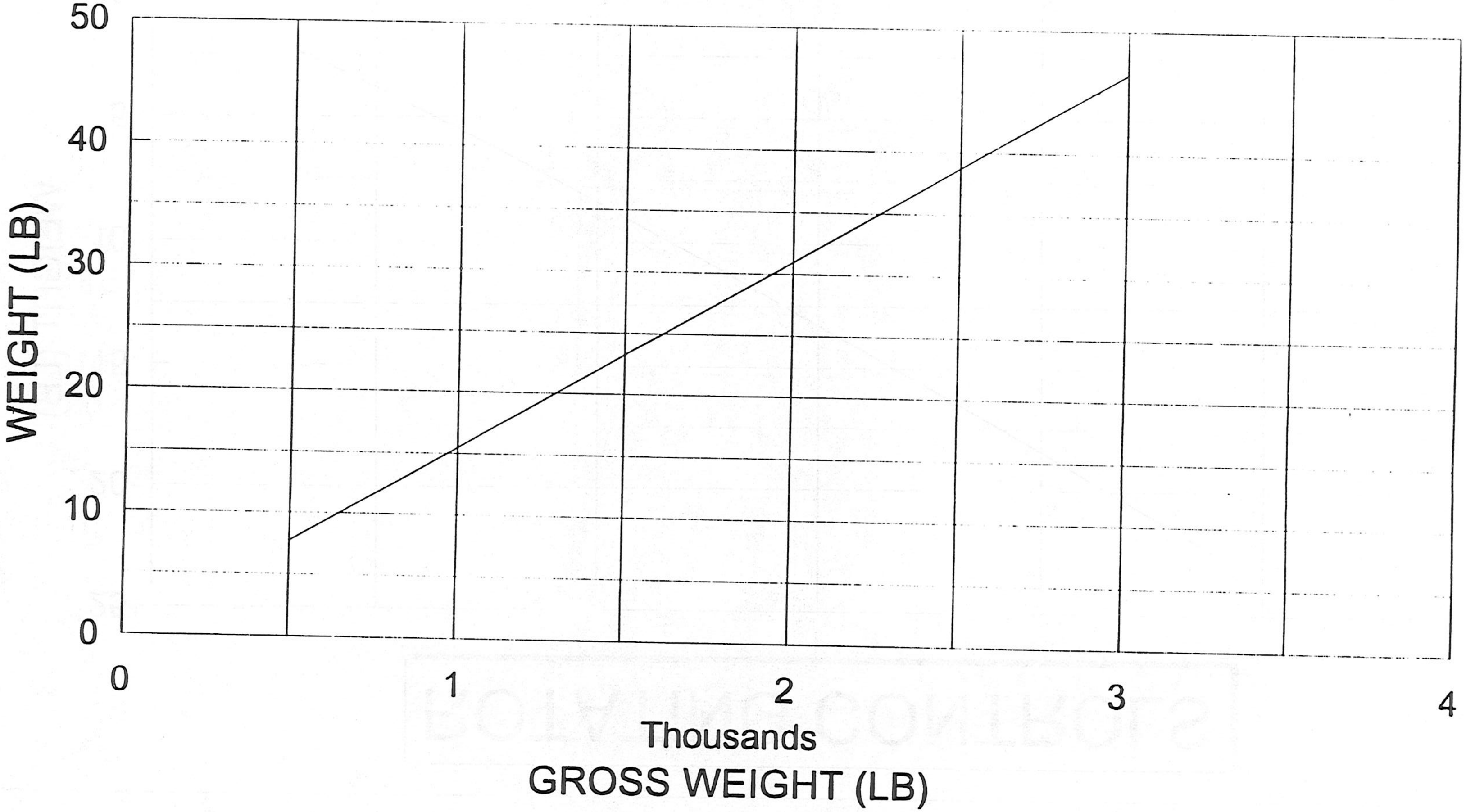


TRANSMISSION SHAFTS

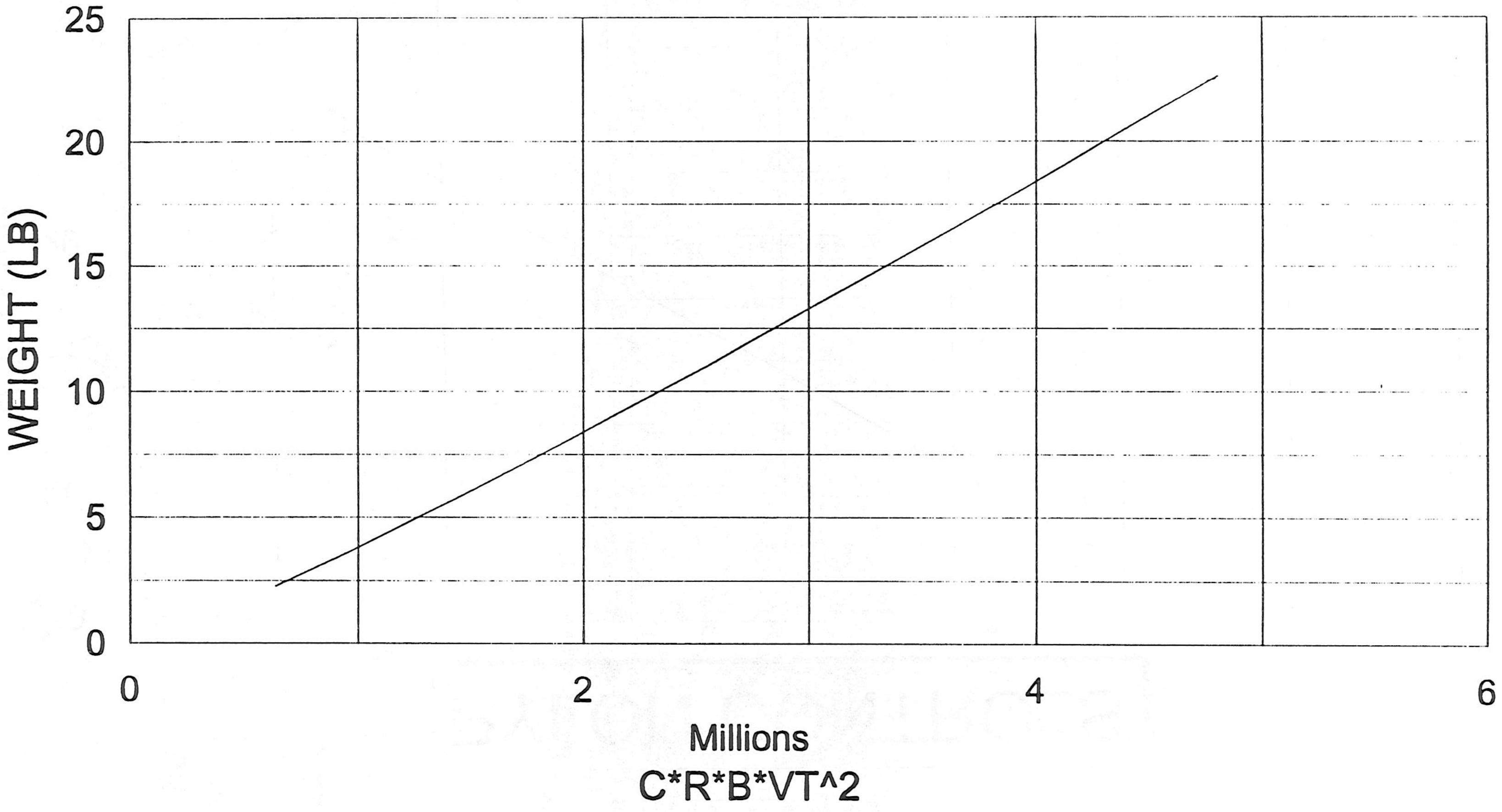

MAST
WEIGHT (LB)
4.50
4.00
3.50
3.00
2.50
2.00
0
500
1000
1500
2000
2500
TORQUE (FT-LB)
--- 2 FT
— 4 FT

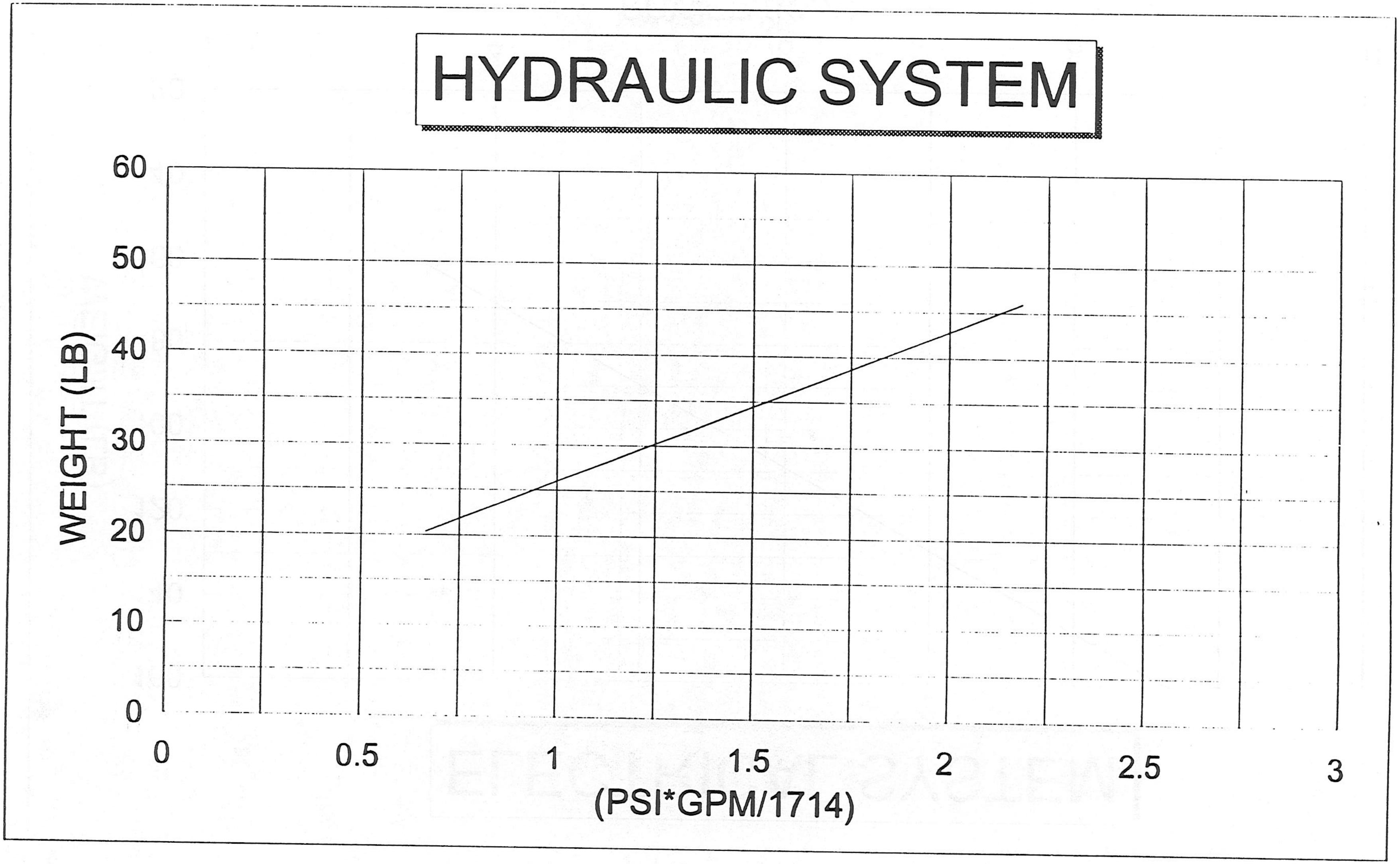

FIXED CONTROLS
WEIGHT (LB)
140
120
100
80
60
40
500
1000
1500
2000
2500
GROSS WEIGHT (LB)

PYLON CONTROLS



ROTATING CONTROLS




HYDRAULIC SYSTEM
WEIGHT (LB)
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
(PSI*GPM/1714)

ELECTRICAL SYSTEM