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ADVANCED TECHNOLOGY LANDING GEAR
Volume I - Design

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5000 East McDowell Road
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AVIATION APPLIED TECHNOLOGY DIRECTORATE
US ARMY AVIATION SYSTEMS COMMAND
FORT EUSTIS, VA 23604-5577

AVIATION APPLIED TECHNOLOGY DIRECTORATE POSITION STATEMENT

The objective of the Advanced Technology Landing Gear (ATLG) Program was to design, fabricate, and test a crashworthy retractable main landing gear system suitable for an 8500-pound utility helicopter. Among the technical issues addressed and resolved as a result of the ATLG development effort were landing gear system integration and structural compatibility in a limited space airframe, MIL-STD-1290 crashworthiness for a compact landing gear configuration, hydraulic/electrical support systems redundancy, and extention/retraction reliability and fail-safety. Landing gear testing was accomplished using conventional platform drop tests, as well as "iron bird" drop tests. Test results were compared with KRASH analytical predictions to evaluate landing gear performance and characterize system dynamic behavior. The results of the ATLG demonstration effort will be used to guide the development of future Army helicopter landing gear systems.

Mr. Ned Chase of the Aeronautical Technology Division served as Project Engineer for this effort.

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13. ABSTRACT *(Maximum 200 words)*

This report describes the development of a retractable, crashworthy, main landing gear system for an LHX-size utility helicopter. The landing gear is of a tricycle configuration and is designed to absorb 60 percent of the energy from a 42 fps level impact condition. The landing gear extends automatically in less than two seconds in an emergency. In the event that the hydraulic and electrical systems fail, the gear is extended with the hydraulic accumulator that primarily supports the helicopter APU. Five sets of landing gears were fabricated in the program. The tests included single-gear platform drop tests with level and simulated roll and pitch conditions, and combined pitch (+15°) and roll (10°) conditions with an iron-bird fixture simulating a helicopter. The tests were conducted for five impact velocities from 10 to 42 fps. The crashworthiness analyses were conducted using program KRASH. The correlation between test and crashworthiness analysis results was very good and demonstrated how analyses can be used to predict the response of landing gears without utilizing expensive tests. The cost of 5000 shipsets over a 13-year production cycle has been projected from the cost of landing gears fabricated in this program.

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FOREWORD

This Design report is Volume I of the final report of the Advanced Technology Landing Gear Program; the final report covers the work performed under Contract DAAJ02-85-C-0049 from 20 September 1985 to 31 May 1989. This contract with McDonnell Douglas Helicopter Company was conducted for the Aviation Applied Technology Directorate, U.S. Army Aviation Research and Technology Activity (AVSCOM), Fort Eustis, Virginia. The program was under the direction of Mr. Ned Chase.

This volume describes the design and analysis in the development of the advanced technology landing gear. Volume II, "Test," includes the results of all the tests conducted in the program and the correlation with analytical prediction of crash-impact behavior.

The program was accomplished by the Structures Department of McDonnell Douglas Helicopter Company, Mesa, Arizona, with Dr. J.K. Sen as Program Manager and Project Engineer. Subcontracting to McDonnell Douglas Helicopter Company was Menasco California Division, Burbank, California. The Program Manager at Menasco was Mr. R.J. Hernandez.

The key personnel associated with the program and their areas of responsibility were:

McDonnell Douglas Helicopter Company

J.K. Sen	Project Engineer
L. Bohorquez	Design
M. Jones	Structures
A. Bolukbasi	Crashworthiness
R. March	Weights
L. Richmond	Requirements & Systems Analysis
E. Murgia	Maintainability
J. Williams	Reliability

Menasco California Division

D. Martin	Project Engineer and Design
H. Kawada	Stress Analysis
C. Wilson	Test

The contract was performed under the general direction of Mr. F.J. Widmann, Manager, Research Projects.

This program was undertaken to develop a retractable, crashworthy landing gear system for an LHX-size utility helicopter with extensive energy absorption trade-off study and crashworthiness analysis to verify the design concepts. The design and crashworthiness analysis have been verified by single-gear platform drop tests, and by tests for combined roll and pitch impact attitude with an iron-bird test fixture simulating a helicopter. This program has demonstrated the differences in the behavior of landing gears in platform and iron-bird drop tests, and the close correlation that can be achieved between crashworthiness analysis and impact tests for helicopters.

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1.0 INTRODUCTION

1.1 PROGRAM OBJECTIVES

The objectives of the program were to assess the technical potential of a crash-worthy, retractable landing gear for an LHX-size utility helicopter with regard to structural and operational capability, system integration, and crashworthiness characteristics. The assessment was validated through:

1. The design of a landing gear for an 8,500-pound utility helicopter with an alternate gross weight of 10,625 pounds.
2. The manufacture of five main landing gears.
3. The correlation of the crashworthiness behavior in test with results from analysis using program KRASH.
4. The prediction of the crashworthiness behavior of the utility helicopter for the entire envelope of crash-impact attitudes and velocities using program KRASH.
5. Tests to verify the extension-retraction mechanism, and to validate the landing gear design to emergency extension.
6. Single-gear platform drop tests and iron-bird drop tests to evaluate the response of the landing gears to crash impacts.
7. An analysis estimating the projected cost of 5000 shipsets over a 13-year production cycle.

Particular emphasis was placed on reliability and maintainability, and to a redundancy in the extension-retraction system such that the gear can be extended in the event of failures of the hydraulic and electrical systems.

1.2 PROGRAM PLAN

The program was designed to be accomplished in two phases:

Phase I - Landing Gear Design

Task 1 - Preliminary Design Analysis
Task 2 - Detail Design
Task 3 - Design Support Testing
Task 4 - Detail Design and Manufacturing Update
Task 5 - Government In-Process Review

Phase II - Landing Gear Fabrication/Structural Tests

Task 1 - Tooling Fabrication
Task 2 - Main Landing Gear Fabrication
Task 3 - Full-Scale Drop Testing
Task 4 - Government/Industry Briefing

The landing gear design was initiated to coordinate with the then requirements for an LHX-size utility helicopter. As such, the landing gear is based on the design of an LHX-size utility helicopter as existed in February 1986. The analysis for compatibility with the LHX SCAT helicopter is also based on the SCAT configuration from the same time period.

The Advanced Technology Landing Gear (ATLG) was designed to specific requirements for handling and ground operations, transportability, and environment. In addition, the ATLG is crashworthy, retractable, and capable of automatic extension in an emergency. The design was developed through structural and crashworthiness analyses, which were verified through impact drop tests, firstly, of only the landing gear and then of the landing gear mounted on an iron-bird fixture simulating a helicopter.

Apart from the structural requirements, the detail design was influenced largely by the requirements for retraction and for crashworthiness. Retraction of the landing gear into the allocated stow-volume was achieved by the design of a pivot crank to interface between the landing gear components and the fuselage. With the pivot crank, a very compact, reliable, and highly maintainable design was achieved. The systems approach to crashworthiness, utilizing the landing gear, fuselage and seat as the three elements in the energy-absorbing chain to provide a survival environment of noninjurious accelerative loads for the occupants, was used to optimize the percentage of impact energy to be absorbed by the landing gear.

2.0 PRELIMINARY DESIGN

2.1 GENERAL

The structural configuration of the ATLG was analyzed following the definition of the baseline utility helicopter. Several landing gear concepts were studied and evaluated from which three concepts were selected for more detailed investigation. Following this investigation, one concept was selected as the final configuration. Detailed investigation of the selected configuration consisted of structural and KRASH analyses, dynamics analyses, weight estimation, and reliability and maintainability analyses.

2.2 BASELINE HELICOPTER

The baseline utility helicopter for the ATLG was designed for a crew of two and six troops. The design gross weight is 8,500 pounds with an alternate gross weight of 10,625 pounds. The helicopter was powered by a four-bladed rotor driven by two engines. The tail rotor was replaced by the "NOTAR" concept. The principal physical characteristics of this baseline helicopter are shown in Figure 1. The inside configuration and arrangement of the baseline helicopter are shown in Figures 2 and 3.

The helicopter is a nosewheel configuration and is 515 inches long with the widest section of the fuselage 100 inches and with the rotor 125 inches above the static ground position. This helicopter can be transported in C-141, C-17 and C-5 aircrafts. The helicopter dimensions for the design of the landing gear, as shown in Figure 1, are:

- ground height, extended = 29.0 inches, maximum
- ground height, static = 16.0 inches
- ground height, kneeled = 3.0 inches
- wheel tread width = 110.0 inches
- wheelbase = 192.0 inches

The nosewheel configuration was selected for the utility helicopter because of the following three reasons:

1. To provide a troop floor level with the ground for easy access and egress by the occupants.
2. If the main landing gears are positioned forward of the cabin, the gears when retracted will occupy volume in the cabin area. This would reduce the available volume for troops and cargo.
3. In order to protect the troops in a crash condition, a strong aft bulkhead is required to prevent the cabin area from compressing

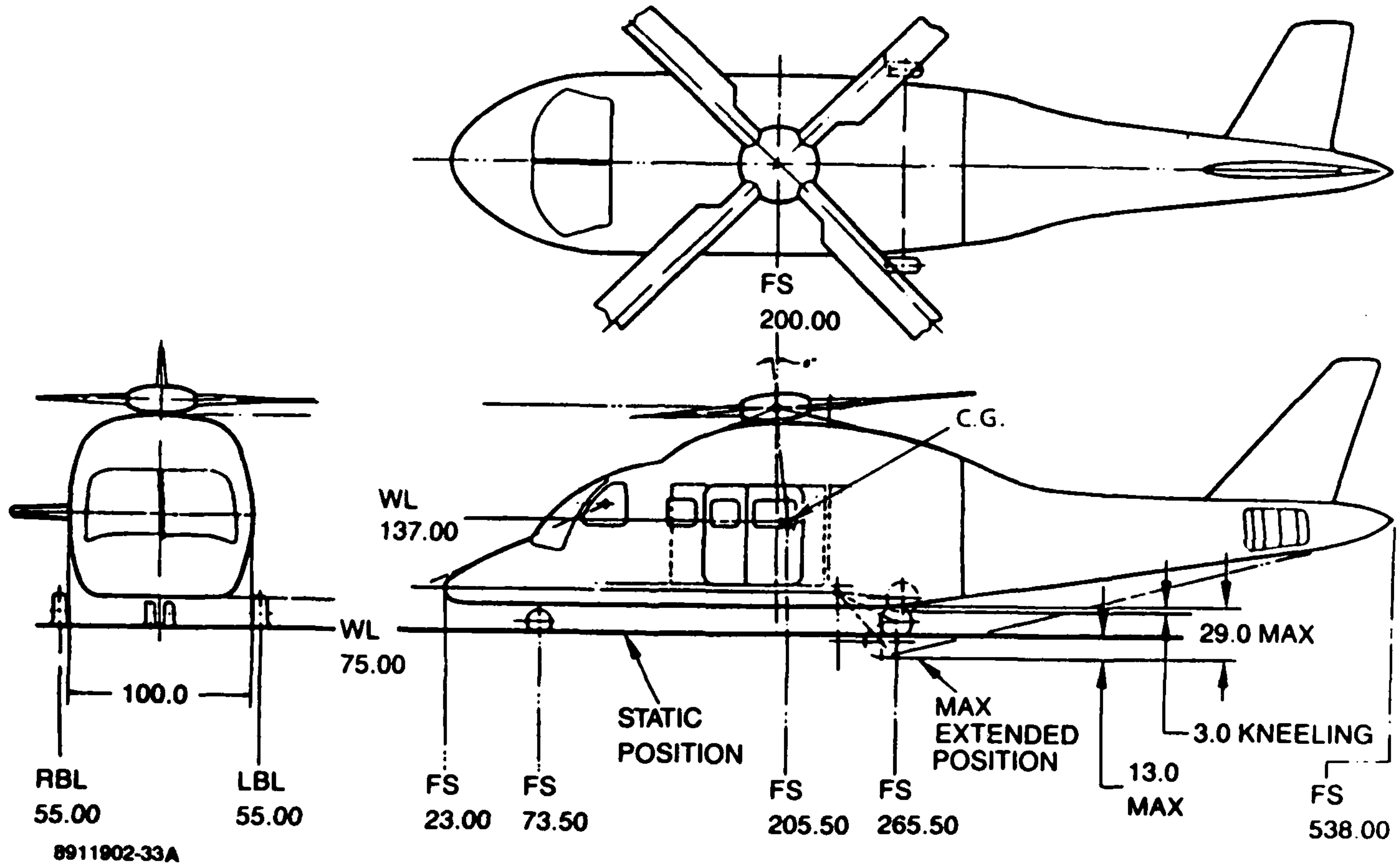


Figure 1. Physical characteristics of the baseline utility helicopter.

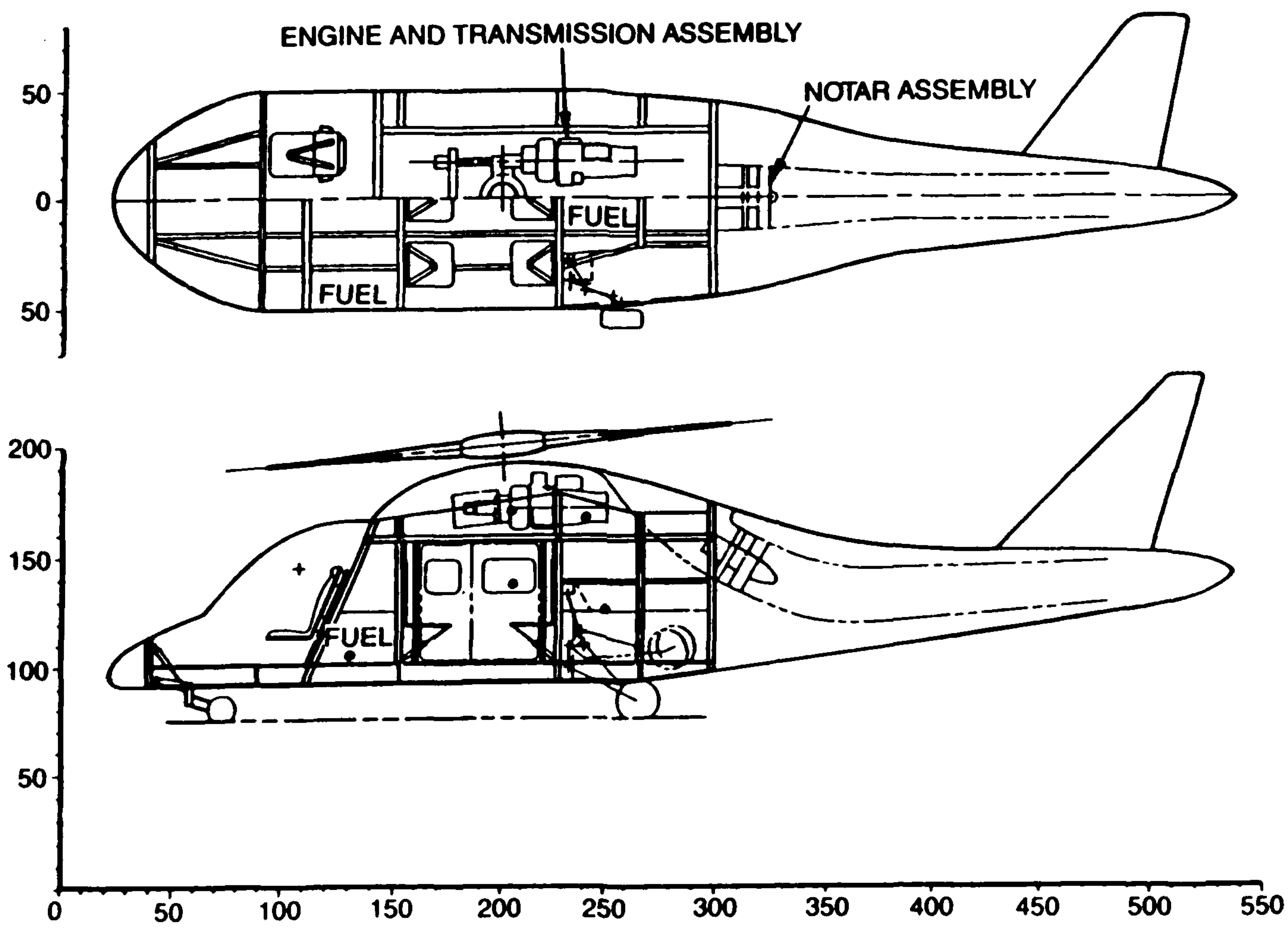


Figure 2. Inside configuration of the baseline helicopter.

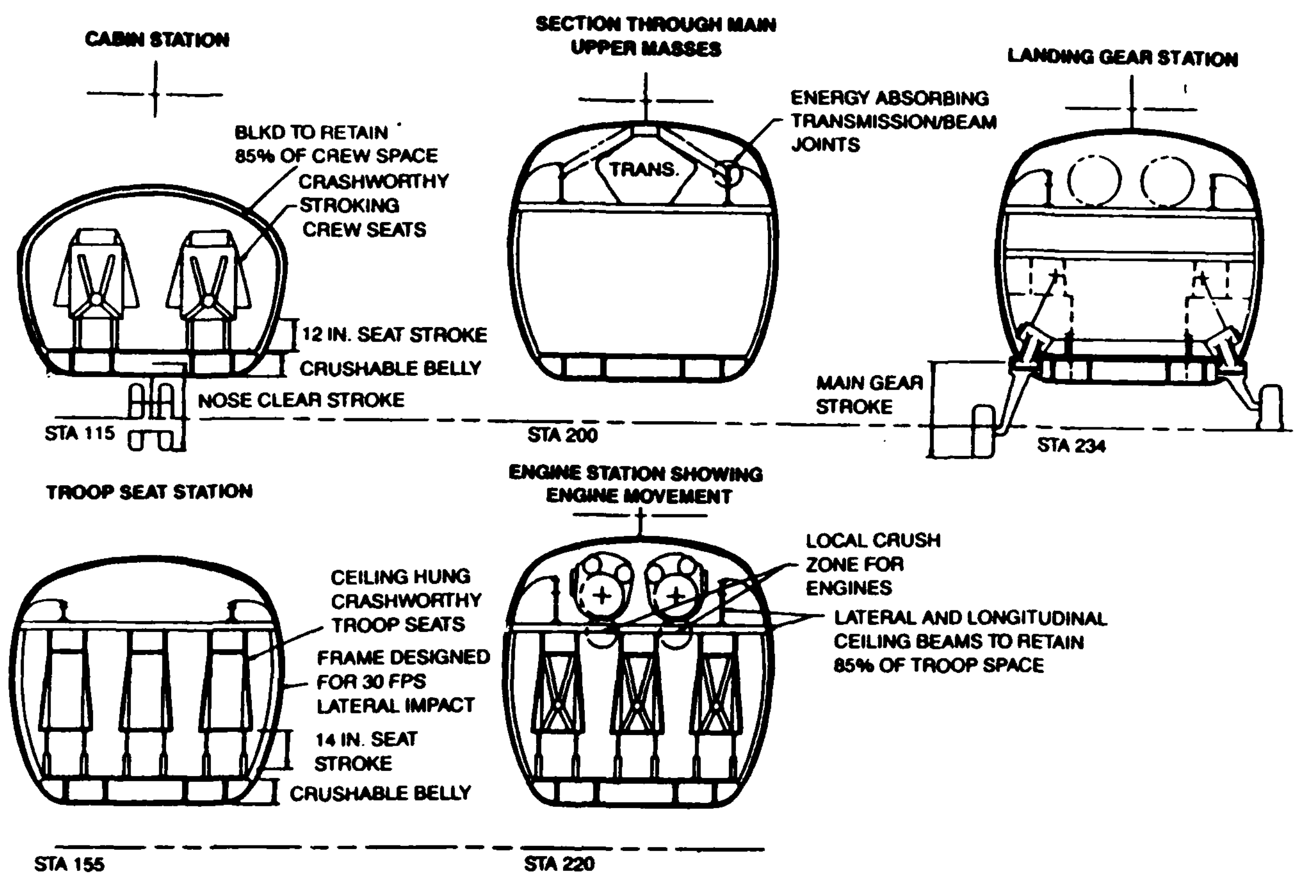


Figure 3. Details of the inside of the baseline helicopter.

more than 15 percent and to support the heavy-mass items above the cabin during a crash condition, as required by MIL-STD-1290. Since the main landing gears were designed to react crash loads, it is therefore logical to interface the main landing gear with the fuselage at the strong aft bulkhead rather than provide a separate support in a forward area with consequent weight penalty.

The location of the center of gravity in relation to the landing gear is also shown in Figure 1.

The crashworthiness features of the fuselage include a lower fuselage with two major and two supplemental keel beams permitting a crushable depth of 7.5 inches. The total depth of the underbelly structure is 10 inches. The cabin bulkheads at Stations 155 and 233 extend full-depth from below the floor to the upper roof beams which support the high-mass items. The bulkheads, therefore, influence the crashworthiness of the fuselage through the crushing of the underbelly section and the reduction in the cabin volume. The energy-absorbing frame of the fuselage is shown in Figure 4. Additional crashworthiness features include load-limiting seats for the crew and troops, crashworthy fuel system, retention of high-mass items, and energy-absorbing supports for the retraction actuator. These energy-absorbing supports are attachment fixtures which yield at loads greater than 8g to allow localized crushing of the bulkhead to which the retraction actuator is attached. The available strokes of the components of the energy-absorbing chain, for a systems approach to crashworthiness analysis, remain unchanged and are given below:

- Landing gear vertical stroke = 29 inches maximum
- Subfloor crushing depth = 7.5 inches maximum
- Crew seat stroke = 12 inches maximum

The weight and mass properties of the major items of the baseline helicopter are given in Table 1.

2.3 TRADE-OFF STUDY OF LANDING GEAR DESIGN CONCEPTS

In the preliminary design investigation, several concepts of tailwheel and nosewheel configurations were investigated. The design of a helicopter landing gear must address two problems:

1. In landing maneuvers, it must absorb the energy of descent in order to reduce the vertical velocity to zero and avoid rebound, and
2. For taxiing on the ground, it must provide a spring chassis.

The evaluation of a landing gear was therefore made in conjunction with the design of the helicopter it services. This method of evaluation not only ensures the fit, form and functional requirements of the landing gear but, through the systems approach to crashworthiness, optimizes the total design.

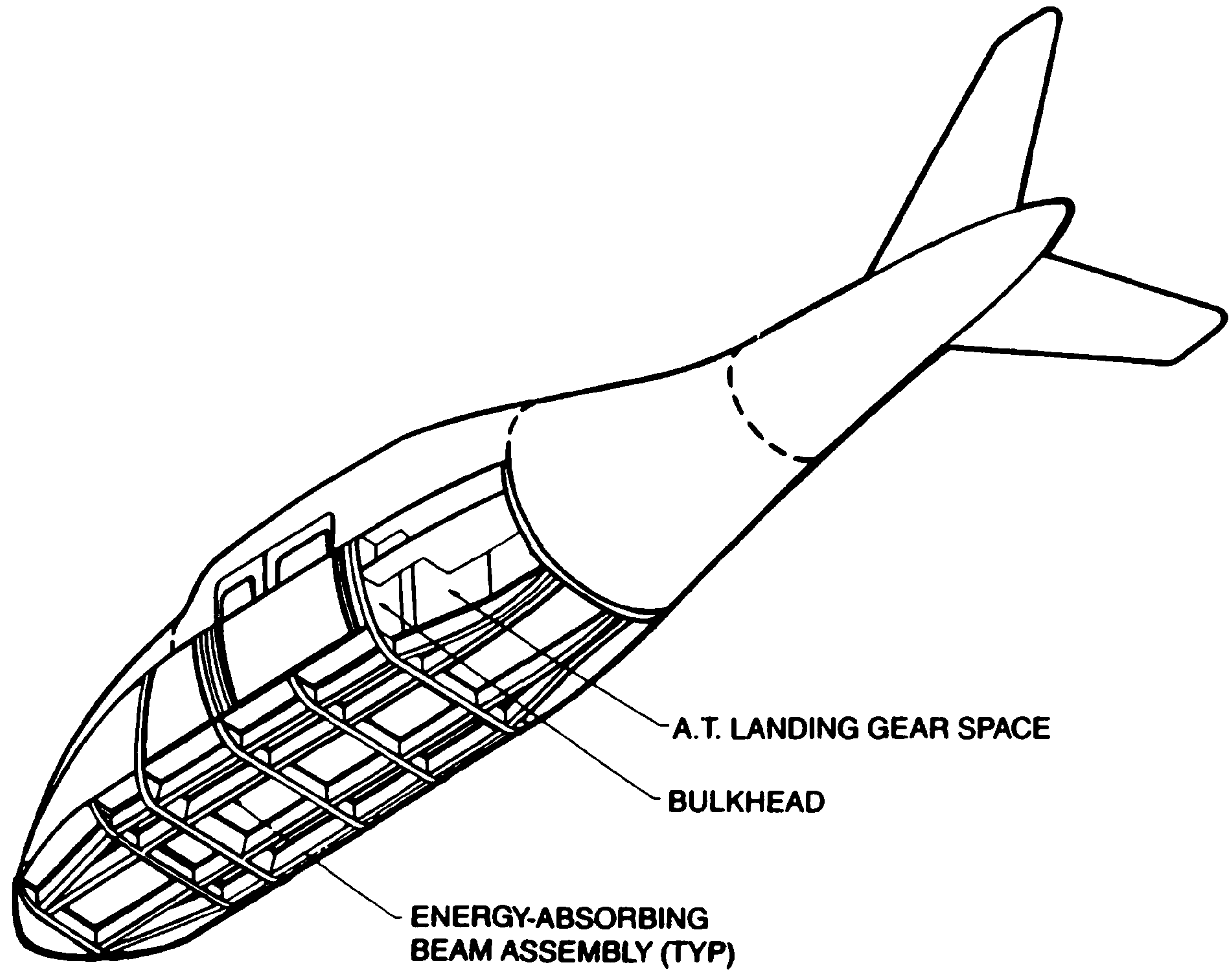


Figure 4. Configuration of the energy-absorbing fuselage.

TABLE 1. WEIGHT AND MASS PROPERTIES OF MAJOR ITEMS OF THE BASELINE HELICOPTER

Item	Weight (pounds)	Station (inches)	Buttline (inches)	Waterline (inches)	Inertia in Slug - Feet^2		
					I - Pitch	I - Roll	I - Yaw
LH Engine	298	241.0	10.0	167.0	6.77	2.21	6.61
RH Engine	298	241.0	10.0	167.0	6.77	2.21	6.61
Drive System*	600	205.0	0.0	170.0	9.07	9.07	9.32
Forward Fuel**	760	131.0	0.0	104.7	55.68	11.41	54.23
Aft Fuel**	1410	250.0	0.0	125.6	44.72	58.38	92.67

*Drive system includes transmission and engine gearboxes, actuators, mast base assembly, and static mast.

**Fuel includes the system of fuel cell, plumbing and controls.

This task was developed in three phases:

1. Survey of existing landing gears that fit the requirements; basic evaluation of concepts for compliance with crashworthiness and survey of literature on crashworthy landing gears.

2. Formulation of several concepts compatible with the baseline helicopter.

3. Evaluation of concepts, using a matrix system and selection of the preferred landing gear concept.

2.3.1 Survey and Evaluation of Existing Landing Gears

Five configurations of main landing gears were reviewed. Where a landing gear of a specific configuration for a helicopter exists, the specific gear was used in the evaluation matrix. For the nonexisting configurations, a generic unit of that particular configuration was "created" for evaluation. The landing gear concepts surveyed are listed below:

1. Trailing Arm Type:

    a. MDHC Apache

    b. Sikorsky

    c. Agusta 129

    d. Gulfstream.

    Only the first two gears were evaluated because sufficient information was not available for the other two gears.

2. Leading Arm Type:

    One concept of the leading arm type landing gear from McDonnell Douglas Helicopter Company was reviewed.

3. Direct Type:

    Very few examples of direct type landing gears exist in helicopter applications, but several examples exist for fixed-wing aircraft. The following gears were reviewed:

    a. Learjet 24 and 25

    b. Westland EH.101

    c. Aero Commander 685, 690

d. Rockwell International Sabreliner

e. Westland Navy Lynx.

For evaluation, the general features of these main landing gear systems were used to "create" a generic unit.

4. Lever Type:

No example of this type of main landing gear was found in use in helicopters, but the following examples were reviewed:

a. Vought A-7 and A-8 Crusader (nose)

b. Dassault-Breguet Falcon 10 (nose)

From these examples a generic concept was used for evaluation.

5. Quadricycle:

This landing gear, found in the CH-47 type helicopters, was eliminated from evaluation because of the weight, volume and controls required for application in this program.

The specific advantages and disadvantages of the five landing gear configurations, including Apache-type and Sikorsky-type trailing arm configurations, are discussed below. Schematic views of generic types of these gear configurations are included for illustration only.

The Apache-Type Trailing Arm Offers: (Figure 1)

- Simple and direct load paths with low loads factor
- Nonredundant landing gear support
- Energy absorption through large displacements
- Energy absorption not sensitive to side loads
- Rough field and obstructed runway capability
- Simpler kneeling capability
- Minimum entanglement with brush, landing mats, obstructions
- Good pitch and roll alignments at ground impact
- Good towing capability on soil with CBR 2.5
- Good running landings and takeoffs
- Good crash energy attenuation at 42 feet per second

- Improved safety during autorotation landings
- Simplicity in components

  BUT

- Requires relatively more space for retraction than other designs.

The Sikorsky-Type Trailing Arm Offers: (Figure 5)

- All the benefits and disadvantages of the Apache type
- Perhaps lower weight/cost
- Simplicity in the trailing arm design/construction

  BUT

- On the small LHX utility, location problems related to doors and openings may arise
- Requires more space for retraction.

The Leading Arm Offers: (Figure 6)

- Improves ingress/egress of troops

  BUT

- Poses difficulty in designing for running takeoffs and landings
- Requires stiffer gear; longer arm
- Will not share most of the qualities of the trailing arm systems
- Interferes with a gun system.

The Direct System Offers: (Figure 7)

- Requires small stowage volume
- Perhaps very low weight

  BUT

- Is difficult to obtain good control of the mechanical instability
- Length to load factor is a problem

High load factors.

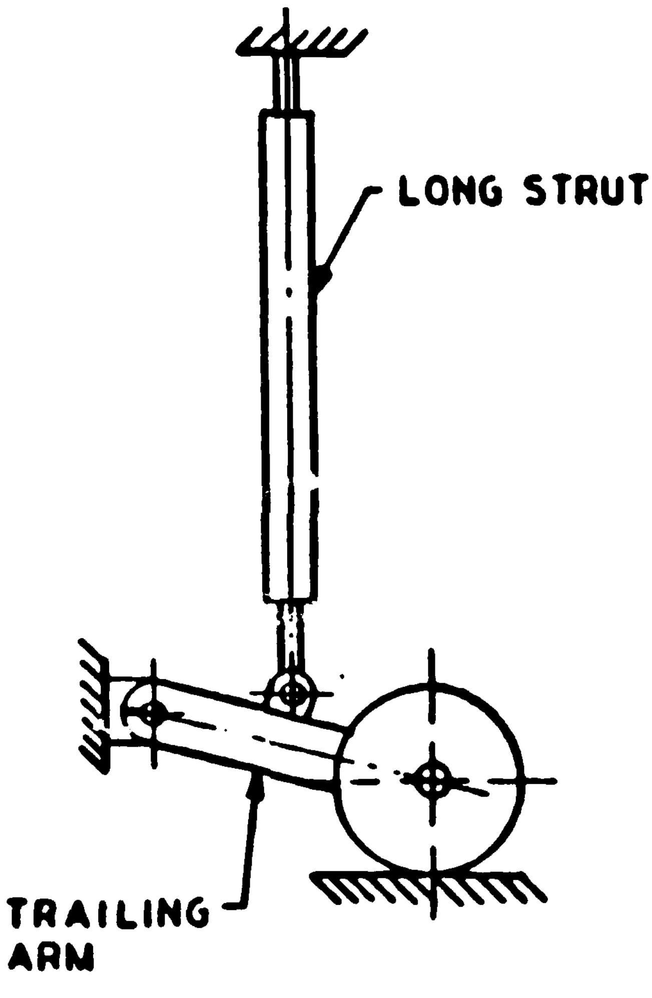


Figure 5. Schematic view of Sikorsky-type trailing arm

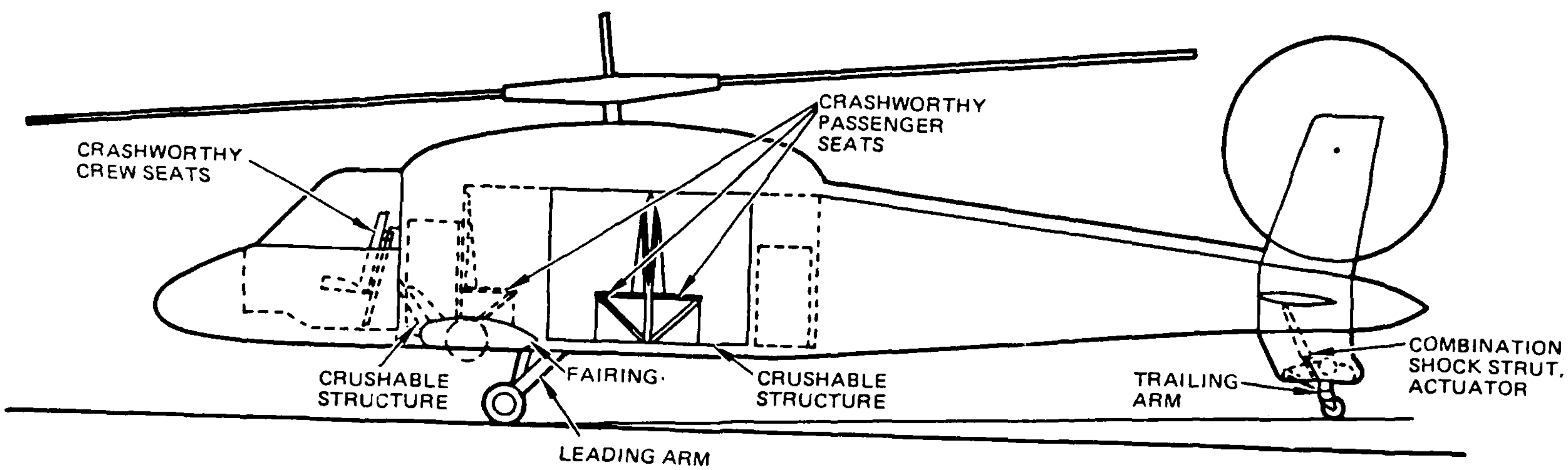
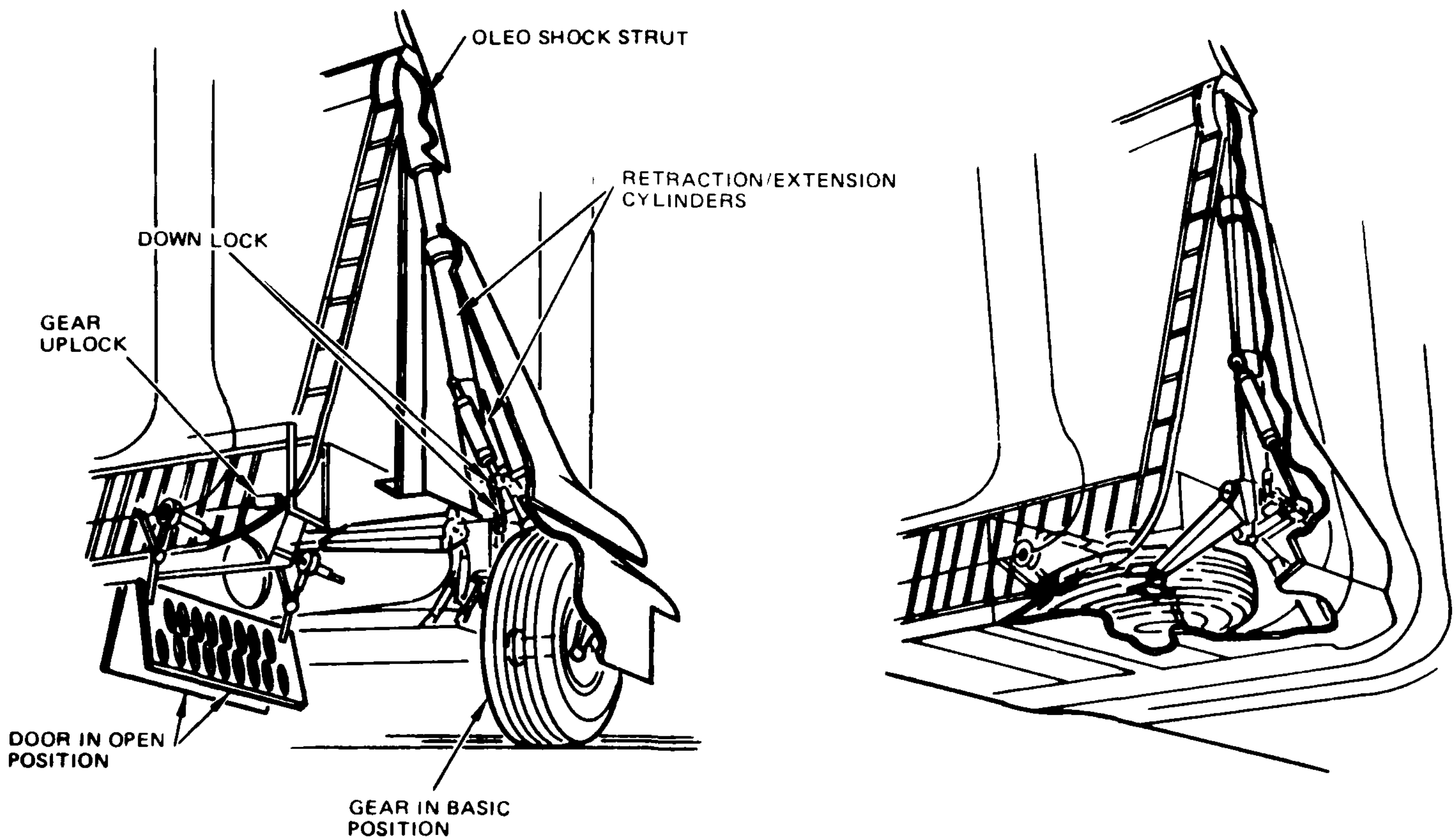


Figure 6. Retractable leading arm landing gear configuration.



MAIN LANDING GEAR - EXTENDED

MAIN LANDING GEAR - RETRACTED

Figure 7. Retractable direct landing gear configuration in the extended and retracted modes.

The Lever System Offers: (Figure 8)

- Very compact volume
- Good mechanical advantage to minimize size shocks
- Easy towing

  BUT

- Weight increases very rapidly with increase in ground clearance
- Simplicity in design is related to side loading
- High load factor.

The Quadricycle System Offers:

- Low ground loads
- Small stowage volume per unit
- Easy ground handling
- Redundant system

  BUT

- Costs more due to the multiple gear
- May be heavier

The evaluation matrix is shown in Table 2. The basic landing gear configurations are compared and rated. Five landing gear configurations, including two types of trailing-arm gears, identified earlier as those from Apache and Sikorsky, are compared. Since the Apache landing gear does not retract, the retraction parameters are not compared in this evaluation. The Apache-type trailing arm configuration is rated the best while the Sikorsky-type trailing arm concept is rated second-best.

The Apache-type trailing arm concept is the prime candidate for the present program. A schematic view of the concept together with the advantages of this design are shown in Figure 9. This concept satisfies normal and crash load requirements and presents a minimum of design interface problems. The crash-worthy landing gear for this program has therefore been designed around a simple articulated trailing arm concept.

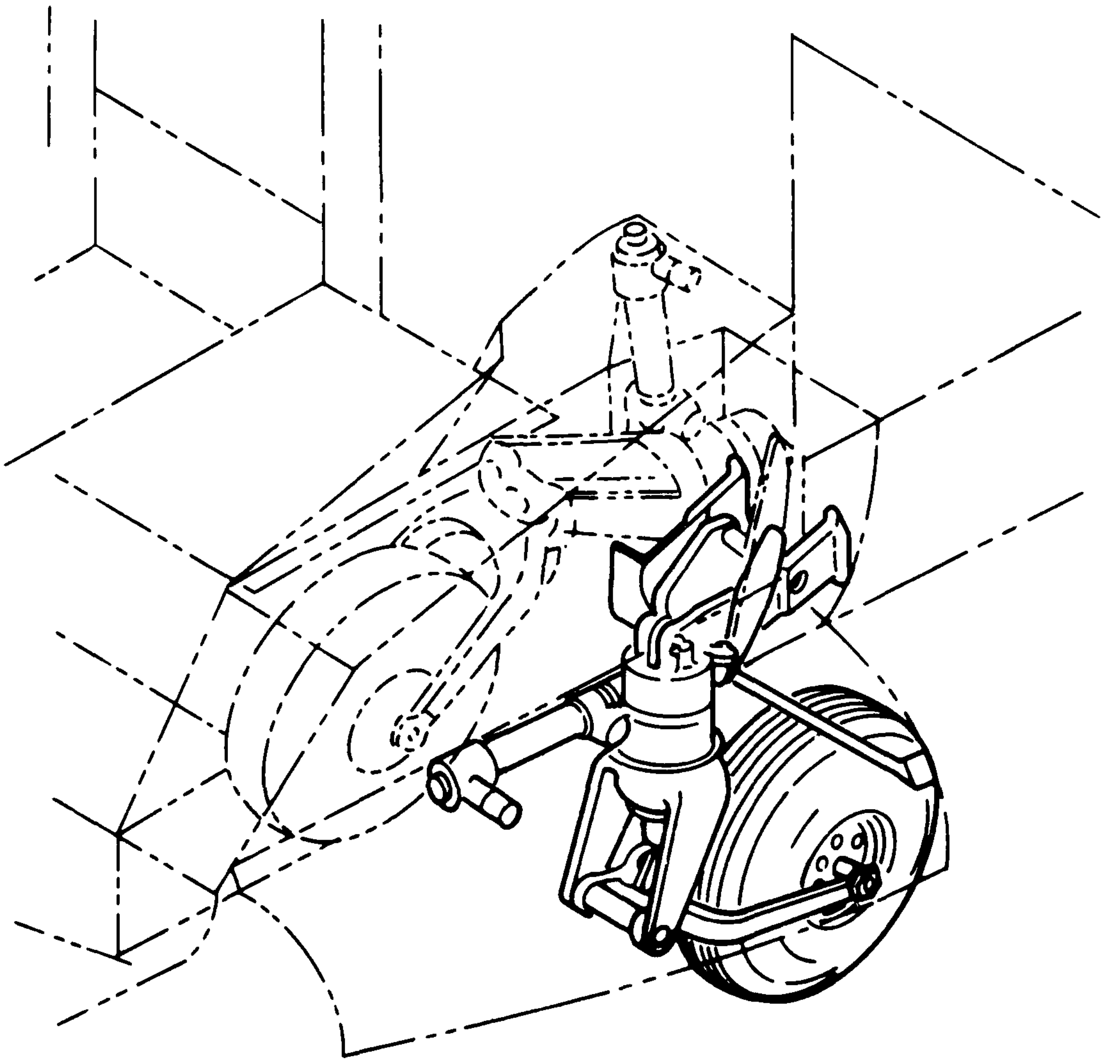


Figure 8. Retractable lever arm landing gear configuration showing extended and retracted modes.

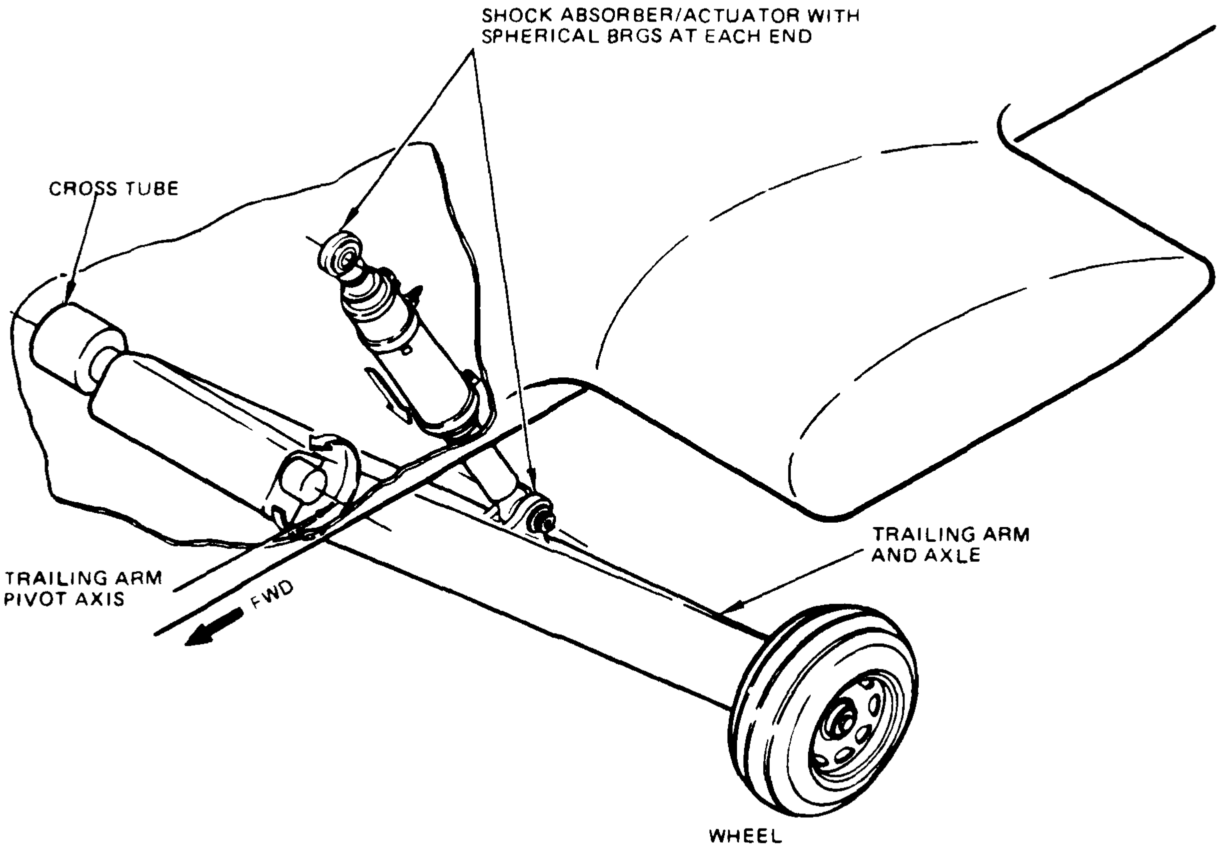
TABLE 2. EVALUATION OF LANDING GEAR CONFIGURATIONS

Trade-Offs Parameters	Trailing Arm, Apache Type	Trailing Arm, Sikorsky Type	Leading Arm	Direct	Lever
Ingress/Egress	5	4	5	5	5
Structural Requirements	4	4	3	3	3
Side Loads	4	4	4	3	3
Transportability	5	4	5	5	5
Ground Control	5	5	4	4	5
Ground Resonance	5	5	4	4	4
Cost	3	2	3	3	3
Weight	3	3	3	2	2
Intrusion into Cabin	5	5	5	5	5
Energy Absorption	5	5	5	5	5
Drag	4	3	4	3	2
Flare Angle	5	5	5	5	5
Materials/Composite	3	4	3	2	2
Crashworthiness	5	5	5	5	5
Producibility	4	4	4	3	3
Maintainability	4	4	4	4	4
Reliability	5	5	5	5	5
Safety	5	5	5	5	5
Towing	5	5	5	5	5
Fail-Safe	5	5	5	5	5
Total Points	89	86	86	85	80

Points 1 - 2 - 3 - 4 - 5

Poor ⟷ Best

Maximum Points - 100



TRAILING ARM CONCEPT DESIGN FEATURES

- SIMPLE AND DIRECT LOAD PATHS
- SUPPORTED BY EXISTING FUSELAGE STRUCTURE
- NON-REDUNDANT LANDING GEAR SUPPORT
- ENERGY ABSORPTION THROUGH LARGE DISPLACEMENTS
- NEARLY CONSTANT GROUND LOAD FACTOR
- ROUGH FIELD AND OBSTRUCTED RUNWAY CAPABILITY
- ENERGY ABSORPTION IS UNAFFECTED BY SIDE LOADS

Figure 9. Structural and design features of the Apache-type trailing arm concept.

2.3.2 Landing Gear Design Configurations

An efficient landing gear design is one that reacts favorably to ground handling loads, normal landing conditions, and crash-impact loads, and also provides for simple and direct load paths into the supporting fuselage structure. The simplest and lightest landing gear configuration would be similar to that of the AH-64A Apache helicopter. The landing gear articulates about a single pivot point which results in only one degree of freedom.

The rearward rake of the trailing arm is favorable for ground maneuvering on rough fields or obstructed runways. Additional benefits from this configuration are the short direct load paths from the gear attachment points to the main fuselage, a nearly constant ground load factor, and insensitivity to side loads. In addition, the landing gear design limits the crash deceleration by absorbing energy through large deflections. This design concept has already been proven on the AH-64A Apache helicopter.

The trailing arms are supported by the crosstube, which runs laterally across the airframe between pivot fittings at each end. The trailing arms pivot to constrain wheel travel to a buttline plane, restrained only by the oleo. This arrangement has the advantage of reacting all lateral and drag loads on the wheel at the crosstube while loading the oleo only in the axial direction.

Among all the landing gear concepts reviewed, five concepts are discussed. All five concepts use the simply articulated trailing arm configuration of the Apache landing gear and comply with the program requirements.

The individual components and systems were designed in accordance with the military specifications noted in Table 3. These specifications cover the design considerations given to handling requirements, ground operation, landing gear detailed component design, and crashworthiness requirements. The specific crashworthiness requirements used to establish the design loads are summarized in Table 4.

2.3.2.1 Geometry and Positioning Parameters. The geometry and positioning parameters of the landing gear are based on the following requirements (Reference 1):

- Ground handling, for a given ground height:
  - 0.8g braking load, determines the minimum longitudinal distance between the main gear and the helicopter cg
  - 0.5g turning load, determines the minimum lateral distance between the main gear and the helicopter cg.
- Structural:
  - Landing gear hard points should be close, along the longitudinal axis, to the helicopter cg in order to minimize the lengths of the load paths and the magnitude of the loads.

TABLE 3. LANDING GEAR DESIGN REQUIREMENTS AS GIVEN BY MILITARY SPECIFICATIONS

Description	Specification	Comment
A. Handling requirements at design gross weight		
1. Towing and Jacking	MIL-A-8862	
2. Mooring	MIL-A-8862	Except as amended by HHI 85-311 Appendix I, Page 2-11
B. Ground operation at maximum alternate gross weight		
1. Braking	MIL-A-8862	
2. Pivoting	MIL-A-8862	
3. Taxiing	MIL-A-8862	
C. Landing gear component design		
1. Wheels and brakes	MIL-W-5013 MIL-A-8862 MIL-A-8866	Method II analysis of MIL-W-5013 to be used
2. Brake control subsystem	MIL-B-8584	Type I
3. Shock absorber struts	MIL-L-8552	
D. Crashworthiness	MIL-STD-1290	Except as amended by this contract

TABLE 4. HELICOPTER CRASHWORTHINESS REQUIREMENTS

Per MIL-STD-1290

Impact Direction (Aircraft Axis)	Objected Impact	Velocity Chg. Av (Ft/Sec	Lift Factor	Attitude			Velocity Chg. Av (Ft/Sec	Lift Factor	Attitude		
				Roll°	Pitch°	YAW°			Roll°	Pitch°	YAW°
Longitudinal (cockpit)	Rigid vertical barriers	20	---	---	---	---					
Longitudinal (cabin)	Rigid vertical barriers	40	---	---	---	---					
Vertical	Rigid horizontal surface	40	W	±10°	+15° to -5°	---	42	2/3 W			
Lateral Type II	Rigid horizontal surface	30	---	---	---	---					
Combined high angle Vertical	Rigid horizontal surface	40	W	---	---	---					
Combined high angle Longitudinal	Rigid horizontal surface	27	W	---	---	---					
Combined low angle Vertical	Flowed soil	14	W	---	---	---					
Combined low angle Longitudinal	Flowed soil	100	W	---	---	---					
Combined side Vertical	Rigid horizontal surface	40	W	---	---	---					
Combined side Lateral	Rigid horizontal surface	27	W	---	---	---					

- Hard points should be located near structural members capable of reacting the landing loads.

- Aerodynamic:

  - Landing gear stance width should be minimized to reduce drag area.

- Energy absorption:

  - Ground clearance should be maximized to reduce fuselage loading in crash conditions.

The first three requirements are optimized when the ground clearance is minimized. This is in direct opposition to the energy absorption requirement. An attempt to optimize all of the conditions led to the concept of the dual-position landing gear. The helicopter would initially contact the ground with the gear in the fully extended "crash" position. Under normal loads, the helicopter would automatically settle to a "low" (static) ground handling position.

This dual-position concept allows the longitudinal and lateral positioning of the landing gear to be determined for a low ground handling height and yet provide a high ground clearance for the energy absorption and fuselage loading requirements. The concept of a simply articulated gear was motivated by the requirement for kneeling the helicopter for the convenience of transporting it and for increased energy absorption capability with the gear retracted.

2.3.2.2 Landing Gear Concepts. The five main landing gears discussed below are the last five design iterations studied. All five concepts are based on an Apache-type trailing arm configuration. The preferred landing gear concept is developed from these five designs.

Concept 1. This concept uses a secondary retraction-extension actuator. On reviewing this concept, it was found to be a very slow (time-wise) system that requires sequential control to operate properly. The large loads generated by this concept require heavy airframe fittings. The most commendable feature of this concept is that it is a unitized system: all working parts are attached to a common bracket to form a closed loop load path that transfers all reaction loads to the frame through an attachment fitting. The gear kinematics is good with the possibility of commonality of a large number of components between right and left units. This concept is schematically shown in Figure 10.

Concept 2. This concept was designed to reduce the number of components used in Concept 1 and to decrease the extension response time of the system. In this concept, the secondary retraction-extension actuator was eliminated and all the energy-absorbing, extension-retraction and kneeling features were integrated into a two-stage shock absorber. This concept is schematically shown in Figure 11.

In this design, the trailing arm is free to move with the displacement of the shock absorber. The shock absorber was located at an angle in relation to the center line of the aircraft to maintain the arm fully extended at its maximum track width position and to displace it to its maximum retracted position

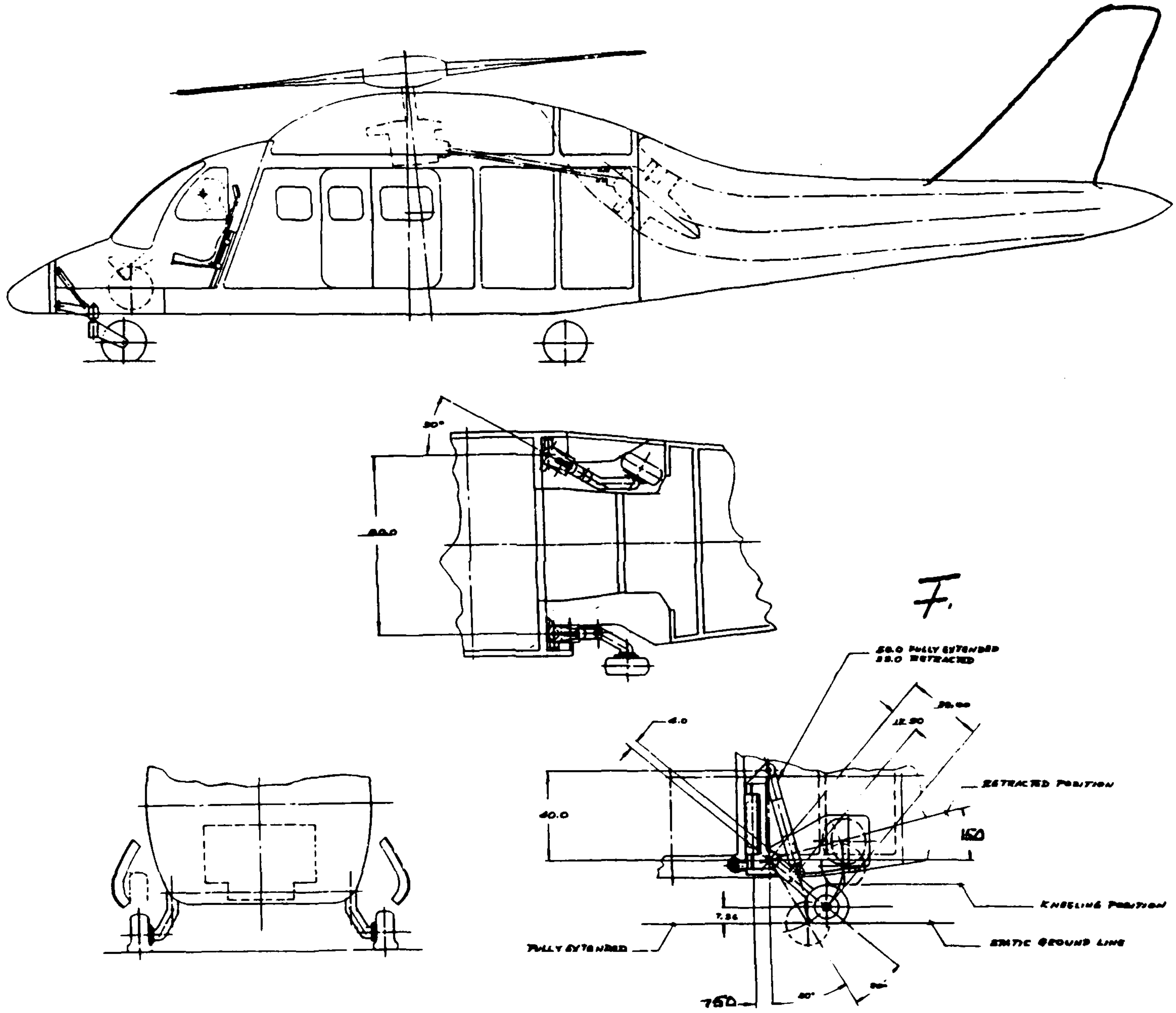


Figure 10. Layout and kinematics of landing gear concept 1.

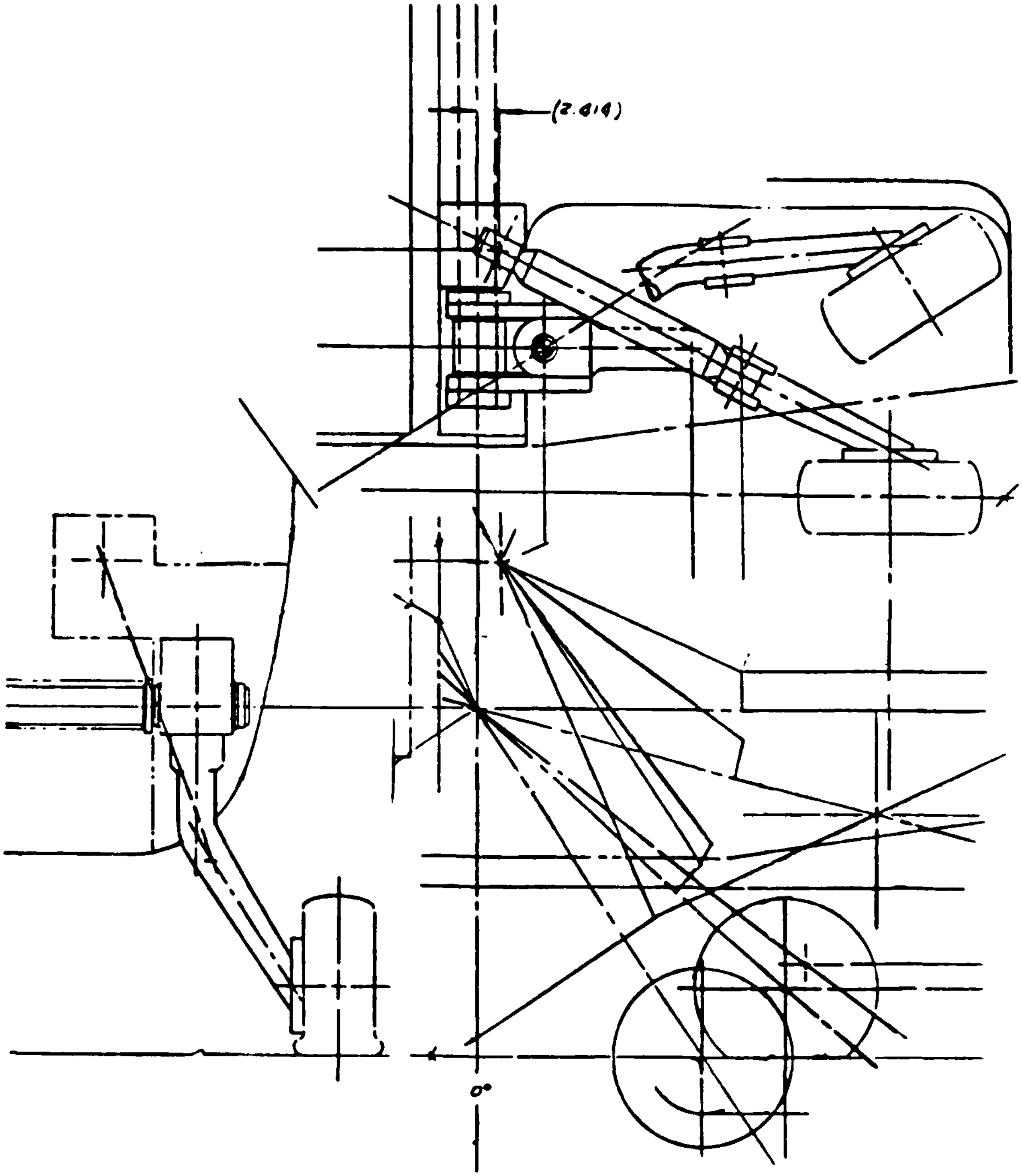


Figure 11. Layout and kinematics for landing gear concept 2.

without the need of a second actuator. In reviewing this concept, several areas of concern were identified. Using the shock strut to fix the location of the trailing arm and relying on the reactive forces of the aircraft weight to keep the arm positioned were conditions that did not offer a positive system. Although the system offered simpler operation, fewer number of components, good kinematics and limited side-load control with the slanted shock absorber, this concept requires locking one of the axes of the trailing arm to avoid instability under all roll and pitch conditions in order to avoid using the shock absorber as the locator for the arm.

Concept 3. This concept, schematically shown in Figure 12, is an improvement over Concept 2 because it provides a locked pivoting axis (horizontal plane axis) and eliminates the need for the use of the shock absorber as a locator for the trailing arm. Furthermore, this concept uses a crosstube as the main attachment fitting for the trailing arm assembly, thus reducing and simplifying the load path of the system and improving frame design.

The pivoting axis is locked by an internal plunger housed in the hollow trailing arm; this plunger, acting in shear, is spring-loaded. The plunger keeps the trailing arm and its pivot assembly as one unit, from the fully extended position through the kneeling position. When that position is reached, a cam pushes the plunger out of its locking position, allowing the trailing arm to pivot inward on its horizontal plane as well as to continue travelling to its final position. The retraction, extension and kneeling is done with one shock actuator similar to that used for Concept 2. During extension, the arm will move to its final position following the extension path of the shock actuator until the trailing arm joint is locked in place.

In reviewing this design concept, the extension time was found to be excessively long for an emergency situation because the actuator required greater hydraulic volume (flow) than that assigned for this system. In addition, the manufacturing cost of the trailing arm would be high and the reliability of the locking plunger under different loading and environmental conditions was in question. Otherwise, this concept offered a viable solution for retraction, extension, kneeling and crash attenuation with one shock actuator per gear, commonality of components, excellent interface with the airframe, and good side-load control.

Concept 4. This design concept is characterized by having two separate units for the two stages of the shock absorber. The two units are: the first-stage oleo and the second-stage oleo, which also acts as an extension-retraction actuator. The extension-retraction actuator has an up-and-down internal locking feature, a system which has been proven on working units previously designed and fabricated by Menasco. The first-stage oleo has been designed as a piggyback configuration in order to reduce the overall length of the unit. The basic configuration of the landing gear is shown in Figure 13.

The trailing arm, the shock absorber and the interconnecting bracket form a unit that, by action of the retraction actuator, can be extended or retracted and locked in position within a very short period of time, which complies with the requirements of emergency operations. In the fully extended position, the trailing arm can be moved up and down without changing the track width, and from this position the system can also be kneeled by the action of the shock absorber.

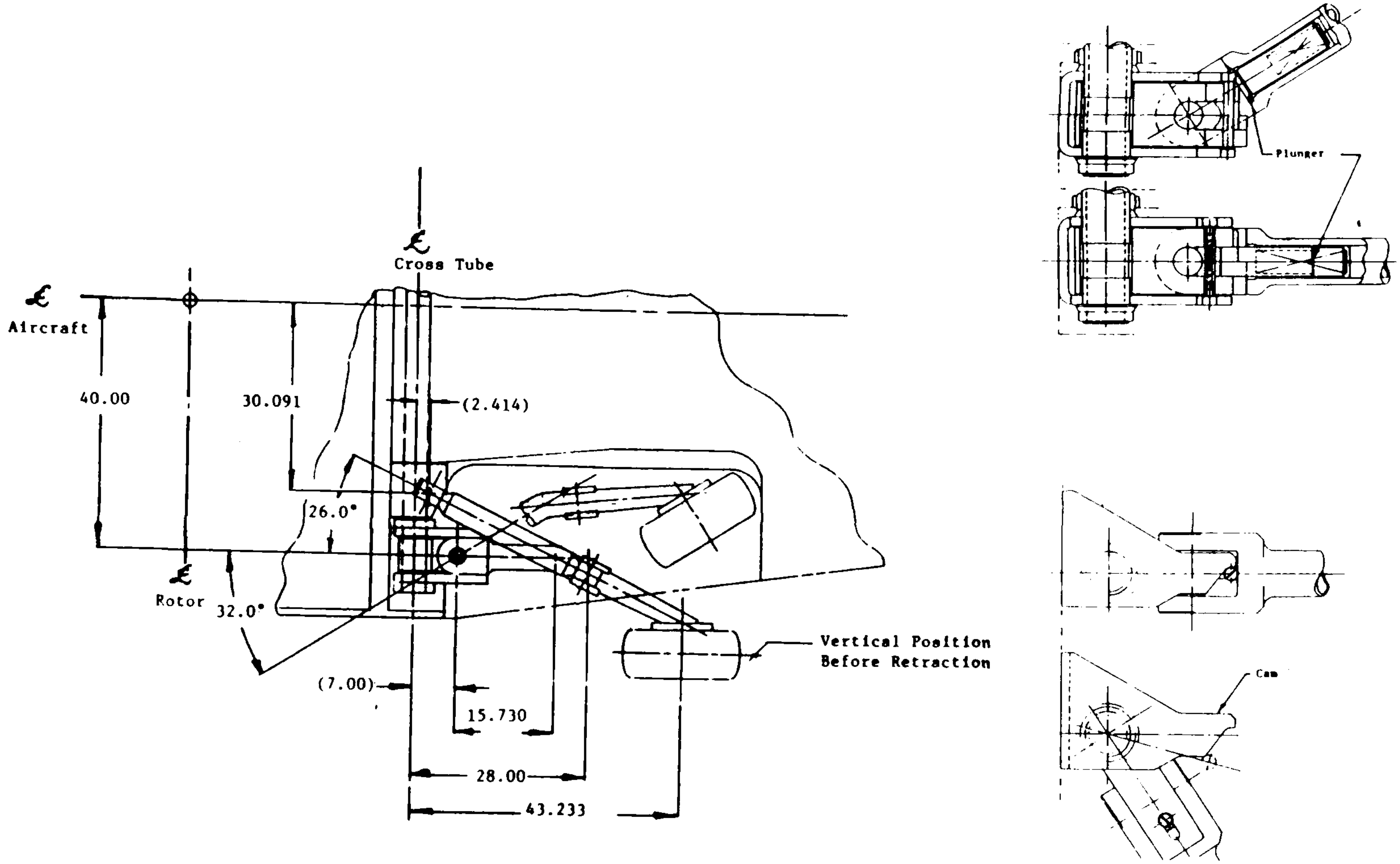


Figure 12. Schematic view of landing gear concept 3 with details of the plunger and cam arrangements.

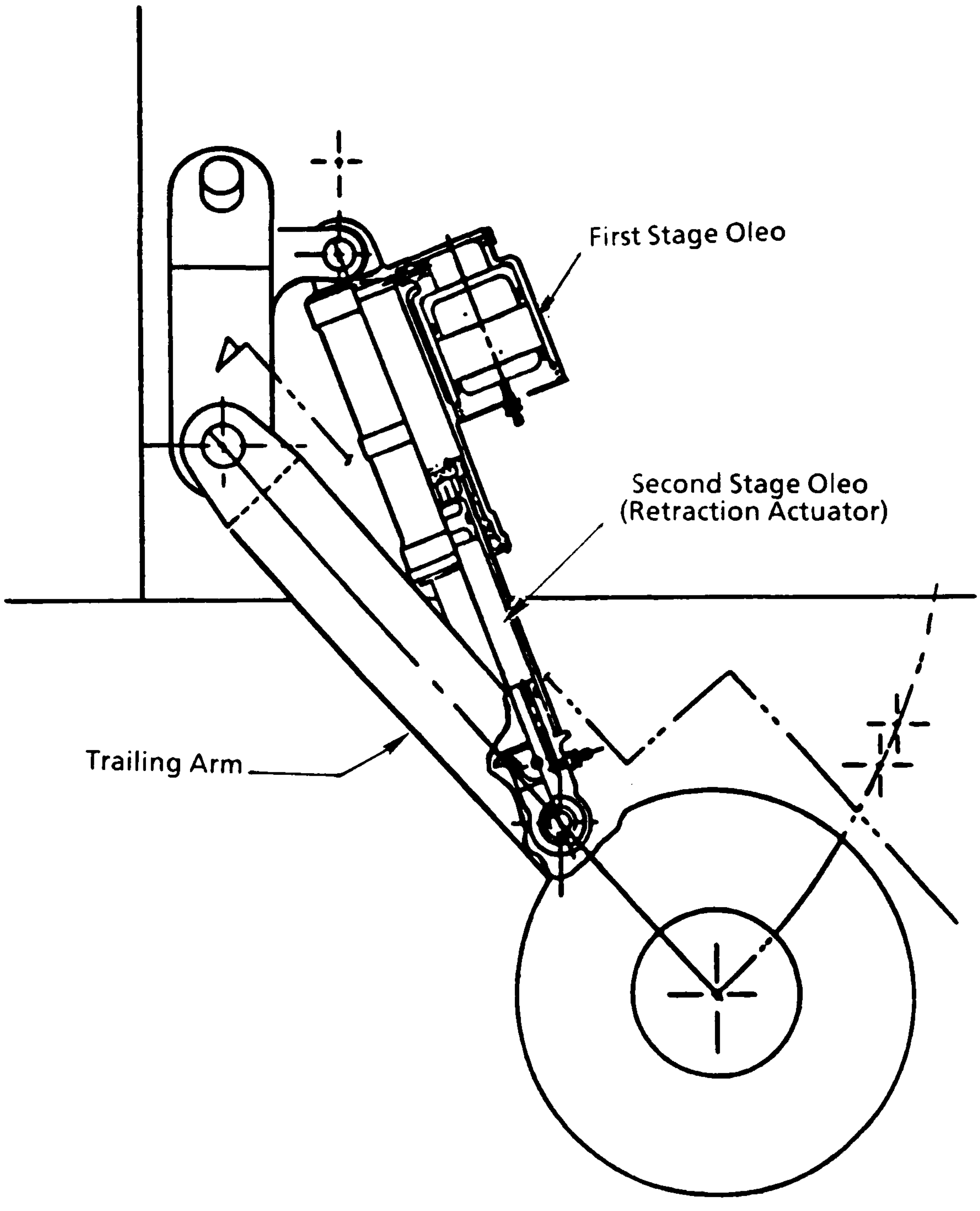


Figure 13. Basic configuration of landing gear concept 4.

In reviewing this concept, it was agreed that the extension time of this concept was very short due to the mechanical amplification of the motion of the system configuration and the low hydraulic flow needs of the actuator. Several areas of concern were found in relation to the fuselage interface, however. Typically, the concerns were the size of the attachment fittings due to the high torsional loads.

The advantages of this concept are the commonality of the components of the left- and right-hand gears, and the method of kneeling. The trailing arms, the shock absorber and the extension-retraction actuator are designed to be common to both sides of the gear. The design of the shock strut also has the advantage of having two alternate ways of kneeling. The first method is to release air pressure in the second stage accumulator to drop the gear to the kneeled position; the accumulator is reserviced to extend the gear. The second method is to have the strut oil controlled by system pressure to kneel and extend the gear as needed.

Concept 5. This concept, shown in Figure 14, has a different approach from that of Concept 4 and was designed to solve some of the potential problems of attachment of the landing gear. This design retains the feature of Concept 4 where the trailing arms, the shock absorber and the interconnecting bracket can be moved up and down as a unit with a secondary actuator within a short period of time. In addition, this design requires a tension shock absorber compared with the standard compression shock absorbers used for the other concepts. The main characteristic of this concept is a rocking trailing arm where the shock absorber is attached beyond the pivoting axis.

In reviewing this design, it was found that this type of trailing arm was heavier than those for the other designs to avoid elastic deformations and also required more complex attachment fittings than the crosstube proposed for the other concepts. This concept, however, was more tolerant to component location than the other systems but will require considerably more development of its tension shock absorber.

2.3.2.3 Evaluation of Final Landing Gear Concepts. Four of the five final iterations of the landing gear concepts were evaluated, and the results are shown in Table 5. Concept 5, the "walking beam" concept with a tension strut, was not evaluated in Table 5 because of its expected higher weight and lower reliability and maintainability (R&M) due to the complex design. This concept also did not permit ready comparison with the other design concepts shown in the table.

Landing gear Concepts 3, 4 and 5 were chosen for the further iterations during the preliminary design study.

2.4 PRELIMINARY STRUCTURAL ANALYSIS

The design approach for the landing gear consisted of first defining a matrix of loading and design conditions for the structural requirements of the gear and its supporting structure.

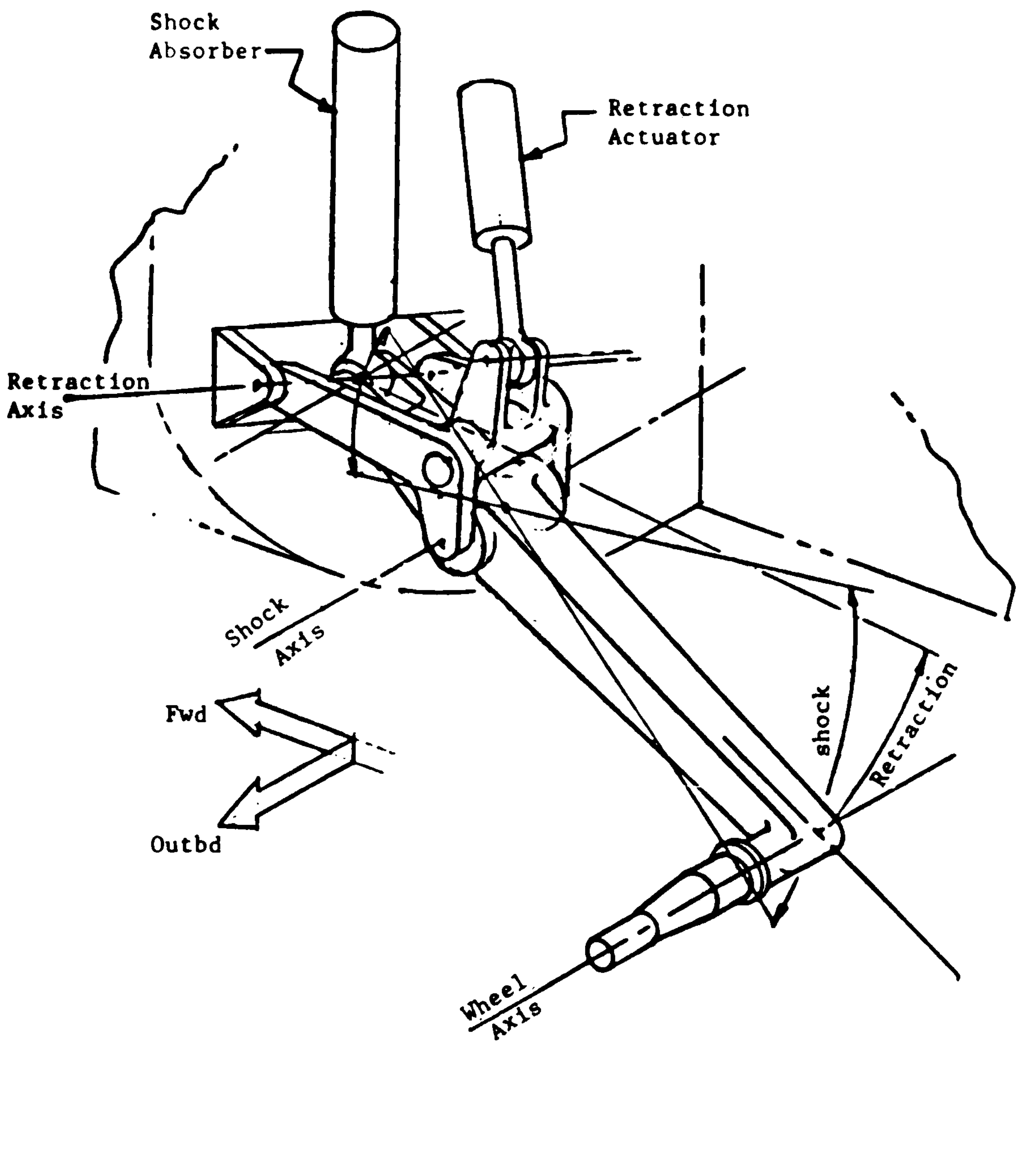


Figure 14. Schematic view of landing gear concept 5.

TABLE 5. EVALUATION OF FINAL ITERATIONS OF TRAILING ARM LANDING GEAR CONCEPTS

Trade-Off Parameters	Trailing Arm Apache Type			
	Concept			
	1	2	3	4
Ingress/Egress	5	5	5	5
Volume for Retraction	3	4	4	4
Structural Requirements	3	4	4	4
Side Loads	4	4	4	4
Transportability	5	5	5	5
Ground Control	5	3	5	5
Ground Resonance	5	3	5	5
Cost	3	3	3	3
Weight	2	3	2	3
Intrusion Into Cabin	5	5	5	5
Energy Absorption	5	5	5	5
Drag	4	4	4	4
Flare Angle	5	5	5	5
Materials/Composite	3	3	3	3
Crashworthiness	5	5	5	5
Producibility	2	3	3	4
Commonality/SCAT	2	2	2	2
Maintainability	4	4	4	4
Reliability	4	4	4	5
Safety	5	4	5	5
Towing	5	4	5	5
Fail-Safe	5	5	5	5
Extension Time/ Emergency	2	3	4	5
Total Points	91	90	96	100

Points 1 - 2 - 3 - 4 - 5

Poor ⟷ Best

Maximum Points - 115

Concept 1 - 2 Actuators, Separate Function

Concept 2 - 1 Actuator

Concept 3 - 1 Actuator, Crosstube, Locked Joint

Concept 4 - Separate Strut and Actuator, Crosstube

Concept 5 - Separate Strut and Actuator, Tension Strut

NOTE: Concept 5 was not evaluated because of its expected higher weight.

The loading conditions defined the sink speeds for normal landings, the maximum sink speeds for a hard landing, and a maximum survivable crash-impact velocity. The energy absorption requirements for these conditions, together with the available stroke and efficiency of the oleo, determined the load factors to which the gear was designed.

2.4.1 Loads Analysis

A preliminary structural analysis was conducted to determine the inertias for extremes of the cg and the landing loads of the helicopter for a basic structural design gross weight (BSDGW) of 8,500 pounds and an alternate gross weight (AGW) of 10,625 pounds. The inertias calculated are given in Table 6. The ground loads were calculated for a level 3-point limit (10 feet/second) landing and a 42 feet/second crash landing for a static ground height of 16 inches. These loads are given in Table 7. A condition that sized the landing gear structure in the past is the crash vertical load combined with obstruction loads.

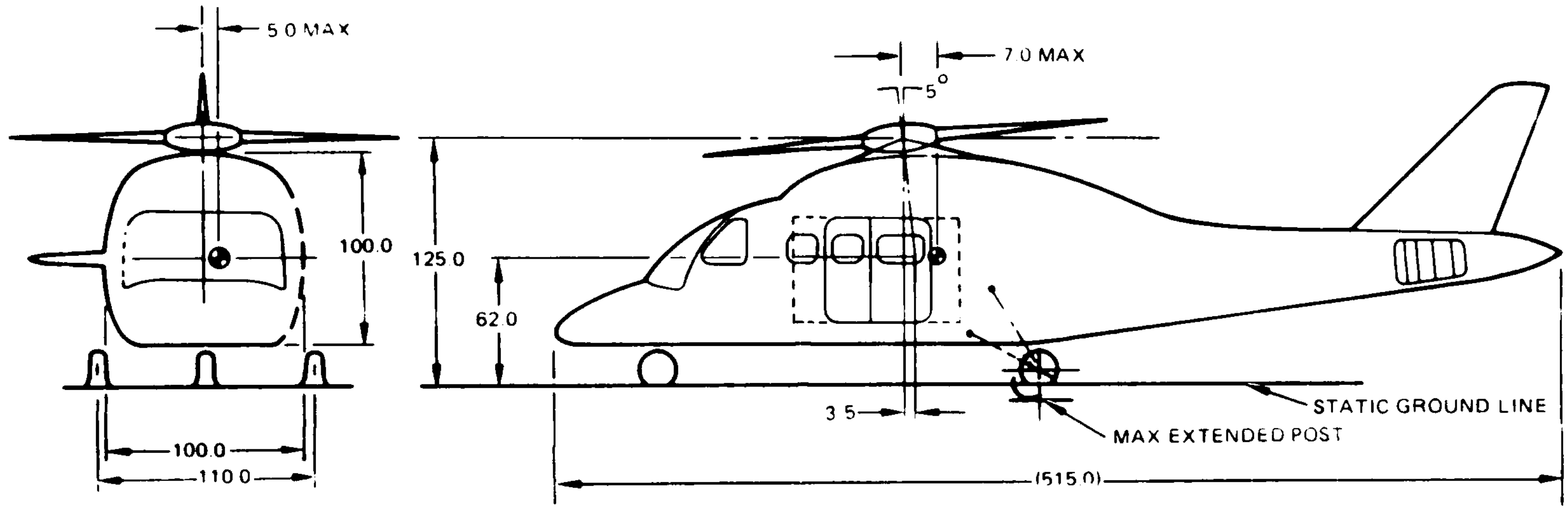
The three final design configurations, Concepts 3, 4 and 5, were analyzed for a vertical crash condition with side obstructions. The 8g crash condition with side load obstruction was chosen because it has been used to size a large number of landing gears in the past. The vertical load of 23,020 pounds was combined with a 9,060-pound side load applied at a flat tire radius of 5.8 inches acting inboard or outboard, whichever yielded the highest loads and/or moments for the components or attachments being analyzed. The lengths and loads for the three design concepts by landing gear components are compared in Table 8. Instead of calculating actual bending moments in the trailing arm, the comparison is with the average bending moment developed for a 1-pound normal load applied at the axle.

The load reactions for the three landing gear concepts were calculated at the landing gear attachments. These reactions represent the loading on the backup airframe structure. Also calculated were the loads on the trailing arm, shock absorber and the extension-retraction actuator. The loads for the three design concepts are shown in Figure 15. The upper reaction point for Concept 5 has been slightly modified for direct comparison with the other two concepts.

2.4.2 Crashworthiness Analysis

McDonnell Douglas Helicopter Company (MDHC) has successfully developed and refined helicopter crashworthiness analysis by using a systems approach in conjunction with the Army's "Aircraft Crash Survival Design Guide", Reference 3. This approach has been analytically substantiated with program KRASH (Reference 4), a crash dynamics computer program, on several MDHC programs including that of the AH-64 helicopters and for the preliminary design investigation in Reference 2. MDHC's systems approach has been experimentally correlated by crash drop tests of the AH-64A's energy absorbing landing gear and crew seats.

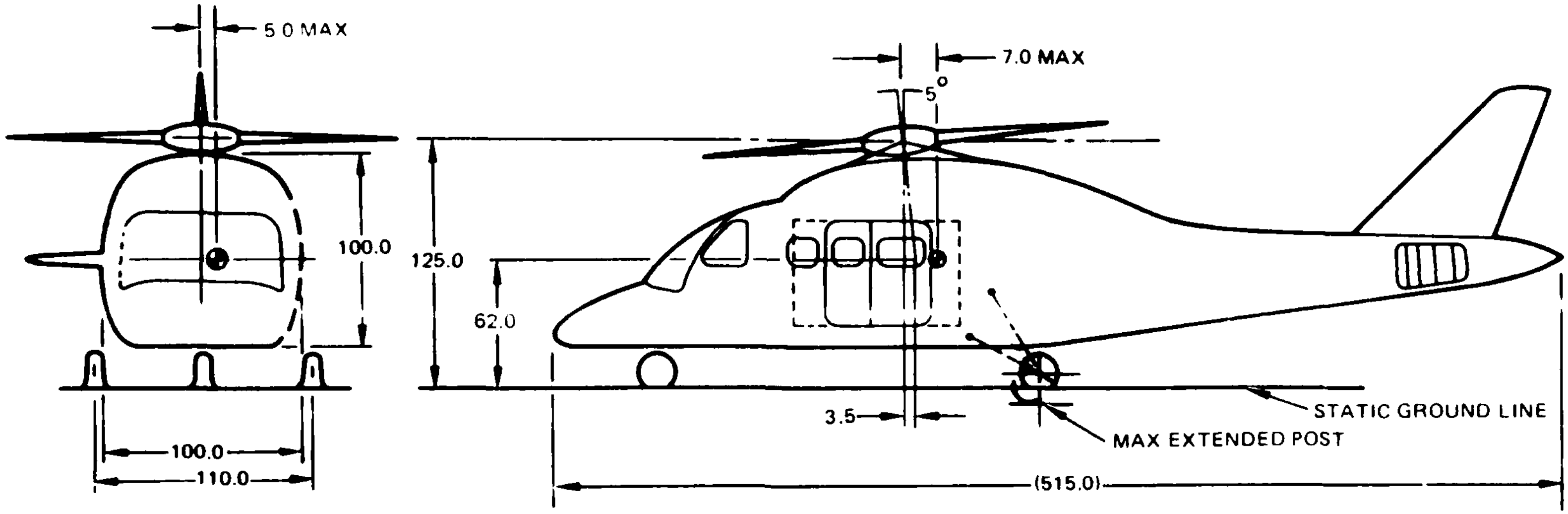
TABLE 6. PRELIMINARY INERTIAS AND EXTREMES OF C.G.



	Utility Helicopter (LHX) Basic Design GW	Utility Helicopter (LHX) Maximum Alternate GW*
Gross Weight	8,500	10,625
I_{pitch} (slug-ft^2)	19,300	21,400
I_{roll} (slug-ft^2)	4,400	4,400**
I_{yaw} (slug-ft^2)	18,100	20,800

*From Reference 2.
**Use 4400 slug-ft^2 even though roll inertia was estimated to be lower.

TABLE 7. PRELIMINARY LANDING LOADS



Condition*	Gross Weight (lb)	Sink Speed (fps)	CG Position	Load Factor (g)	Load lb, per Main Wheel**	
					V	D or S***
Level 3-point (limit) with obstruction	10,625	10	Aft, Lateral	2.33	9,385	4963
Crashworthiness (ult)	8,500	42	Nominal	8.0	23,020	7040

*Static ground height = 16 inches

**The vertical load, V, and the drag load, D, act at the wheel axle. The side load, S, acts at the ground.

***D or S act singly in conjunction with V.

TABLE 8. LENGTH OF, AND LOADS ON, COMPONENTS OF THE THREE FINAL LANDING GEAR CONCEPTS

Landing Gear Configuration or Concept	Trailing Arm		Shock Absorber		Retraction Actuator	
	Length (Excluding Axle) (inches)	Average Bending Moment/Unit Normal Load (inch-pound/pound)	Length (Fully Extended) (inches)	Maximum Axial Load (pounds)	Length (Fully Extended) (inches)	Maximum Axial Load (pounds)
Concept 3 (Figure 12)	45	0.19	42.00	-73,000	-	-
Concept 4 (Figure 13)	39	0.15	30.30	-65,000	19.1	-99,000
Concept 5 (Figure 14)	41	0.50	45.20	+64,000	45.6	-87,000

NOTES: (1) The analysis is for a vertical ultimate load V_{ult} = 23,020 pounds, and an ultimate side obstruction load S_{ult} = 9060 pounds.

(2) The 'Average Bending Moment/Unit Length' is calculated for 1 pound of normal load acting at the axle.

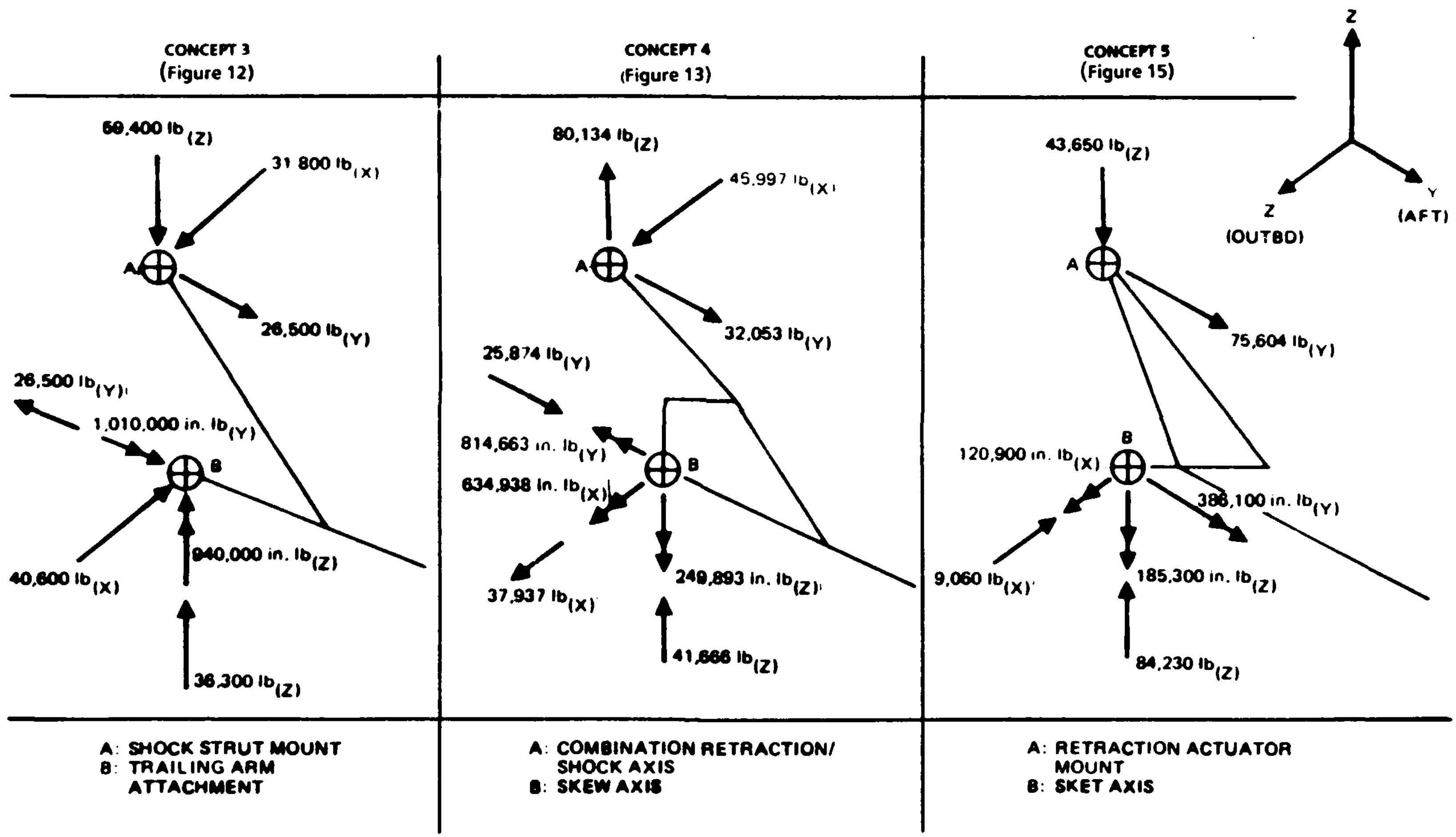


Figure 15. Comparison of structural loads for landing gear concepts 3, 4 and 5.

A survivable impact implies that, for a particular crash condition, the crew will not be incapacitated by injurious accelerative loads. A crashworthy helicopter design protects the crew by considering the many criteria affecting the crew environment. Two paramount design considerations are:

- Providing a protective structural shell around the occupants that will not collapse or allow heavy mass items to penetrate into the occupied space.

- Minimizing the effect of the crash impulse on the crew.

To design efficiently and effectively to meet these requirements, a systems approach to crashworthiness was adopted.

For severe, yet survivable impacts the system of energy absorption consists of three elements: the landing gear, the crushable floor structure, and the load-attenuating crew seat. This has been illustrated in Figure 16. To develop a well-balanced and consistent design approach, any one particular element is not considered to be more important than any of the other two in providing crash protection. Instead, a systems approach is adopted in which each element is considered an integral link in the chain of energy absorption, where each link is as important as the rest and the whole system provides the desired protection for the crew.

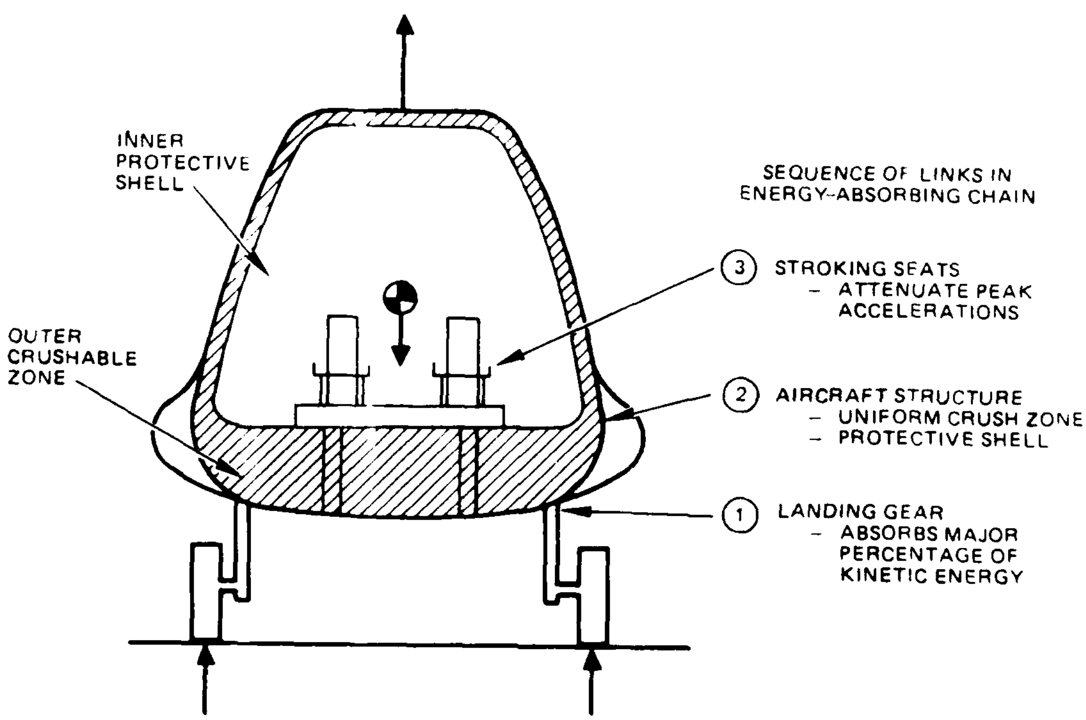


Figure 16. Principle of systems approach to crashworthiness.

At the onset of this preliminary design effort, several crashworthy main landing gears were considered to roughly size their configuration parameters. These parameters were the landing gear ground load factor, landing gear stroke and the geometry of the trailing arm/oleo. Initial sizing of the gear geometries was based on the conservation of energy relationship (Volume III of Reference 3) and on the earlier preliminary investigation (Reference 2) The landing gears selected for analysis were represented by the following parameters:

- Landing gear load factor: 7.0 to 9.0g
- Landing gear stroke = 29 inches
- Fuselage crushing depth = 7.5 inches
- Crew seat load factor = 13.5g
- Crew seat stroke = 12 inches
- Occupant DRI ≤ 21.4.

The energy absorbed by this configuration of landing gears for a 42 fps level impact was at least 50 percent of the helicopter's original crash impact energy. Although 12 inches of crew seat stroke is allowed, previous analysis (Reference 2) has shown a marked increase in crew seat stroke for rolled crash conditions. As a result, a maximum of 8.5 inches of seat stroke was allowed for the preliminary 42 fps vertical crash impact, leaving a margin of 3.5 inches for rolled impact conditions.

To focus on these design parameters, a simple five-mass KRASH model was generated (Figure 17) and subjected to the idealized crush pulses, representing the chain of energy absorption shown in Figure 18. Preliminary KRASH analyses were conducted for a vertical velocity of impact at 42 fps, with 0.67g rotor life and 82 percent efficient main landing gear. The configuration selected focused on an 8g landing gear with a 15g fuselage.

Several concepts were explored to optimize the cabin design for energy absorption. The lower fuselage, with the subfloor sections of the bulkheads, was designed to undergo uniform controlled crushing to a maximum depth of 7.5 inches. The upper bulkhead in turn was permitted to deform a maximum of 15 percent of its height, while the roof beams displace a maximum of 3 inches to attenuate the energies of the high mass items. The estimated total weight of all the energy-absorbing elements of the fuselage as a percentage of the energy from a 42 fps impact is shown in Figure 19. The extent of fuselage reinforcement required for different percentages of energy absorbed was also identified. A 26 fps impact with the landing gear up was identified as the minimum energy to be absorbed by the fuselage. A 30 fps impact with the gear up represented 51 percent of the energy from a 42 fps impact. For such an impact, local reinforcement of the fuselage structure was inadequate in absorbing the impact energy. Any impact requiring the fuselage to absorb over 45 percent of the energy from a 42 fps impact would require reinforcement of the overall fuselage structure.

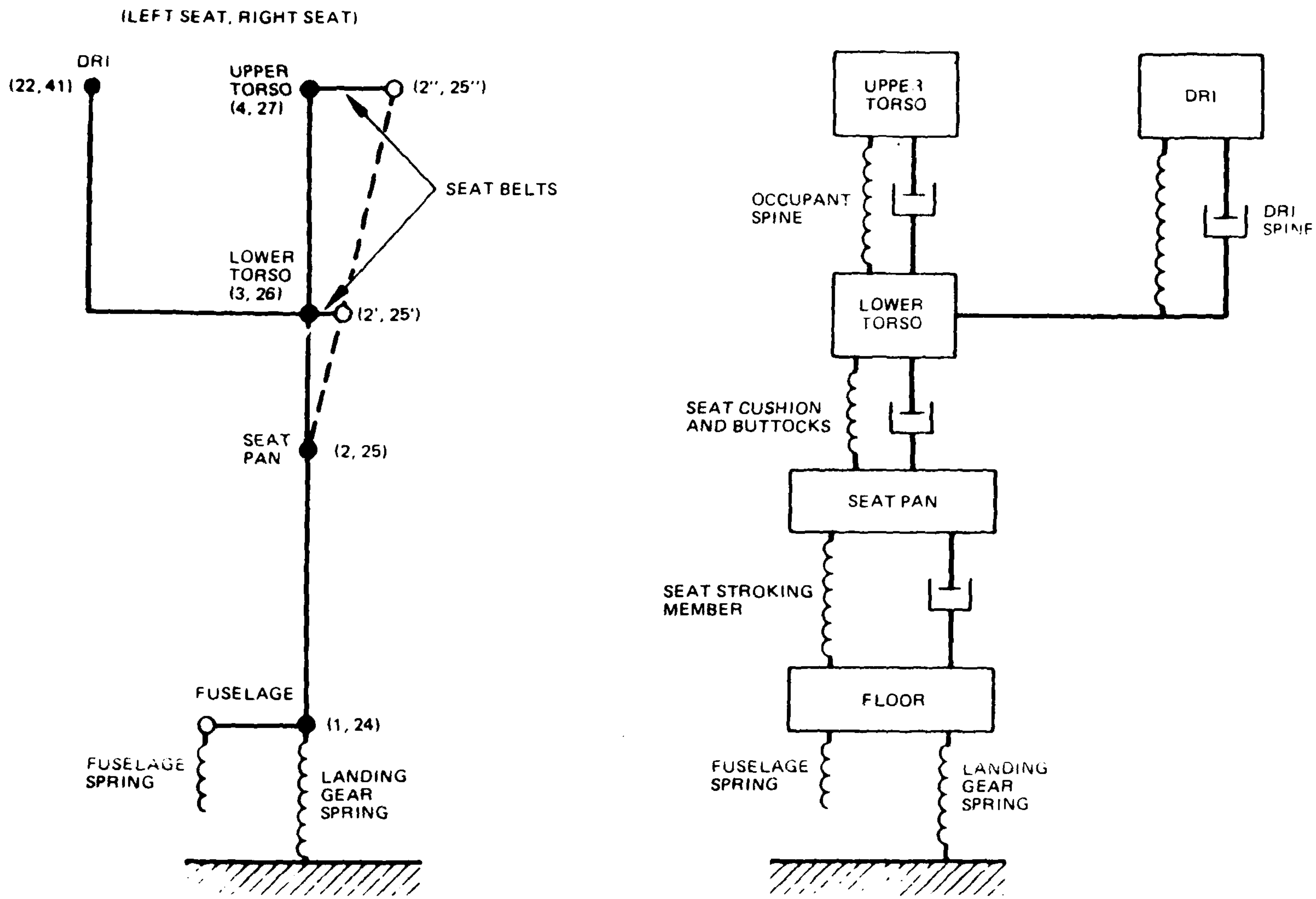


Figure 17. Simple and occupant KRASH model.

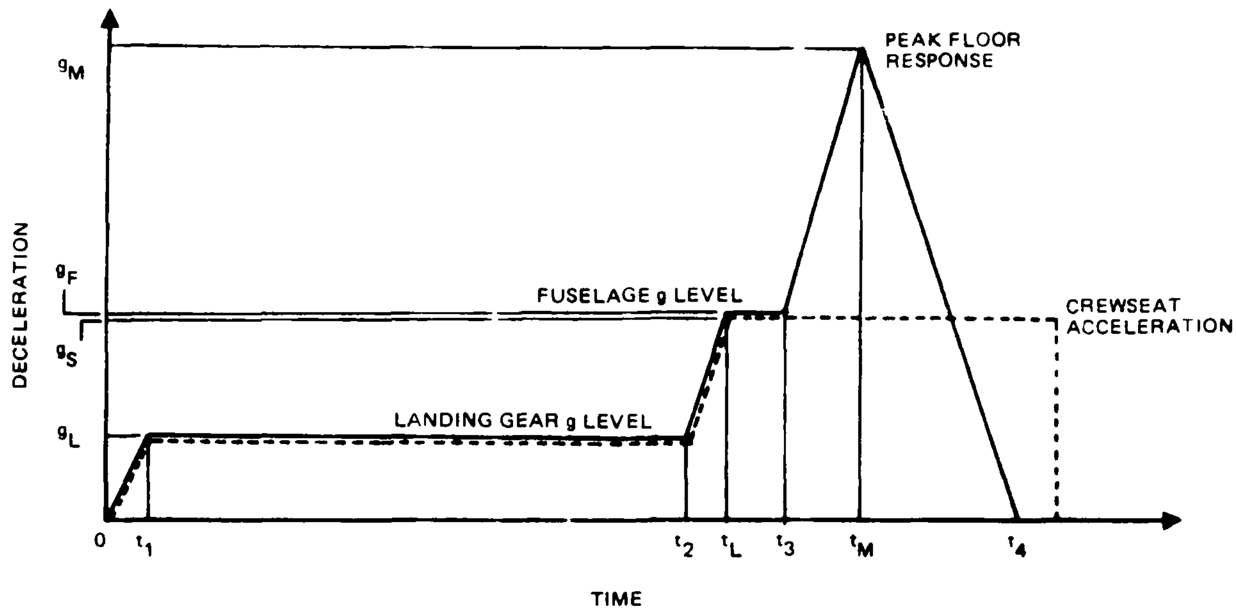


Figure 18. Idealized landing gear, fuselage and crew seat crash pulses.

2.5 PRELIMINARY WEIGHT ESTIMATES

Initially, the advanced landing gear study reviewed the weights of existing landing gear systems to establish the general trend of these systems independent of a sensitivity analysis of the effect of various crash conditions. The study established basic drivers for weights at different conditions by reviewing existing systems in general and the MDHC system in particular. This information was then evaluated in relation to the energy absorption levels of the different landing gear systems in order to estimate the weight of a crashworthy, retractable landing gear. The information was used to calculate the ratio of the landing gear weight to the helicopter gross weight as a general indicator of the weight trend. Based on these estimates, two weights of the three final landing gear concepts were estimated. A breakdown of the weight is shown in Table 9.

2.6 MAINTAINABILITY ANALYSIS

The maintainability parameters, consisting of initial design guidelines, optimization guidelines and design goals, for the ATLG program were determined. These guidelines were adhered to during the design stage. The initial design guidelines are given below.

- All Line Replaceable Units (LRUs) with the same function shall be interchangeable with right- and left-hand units being identical.

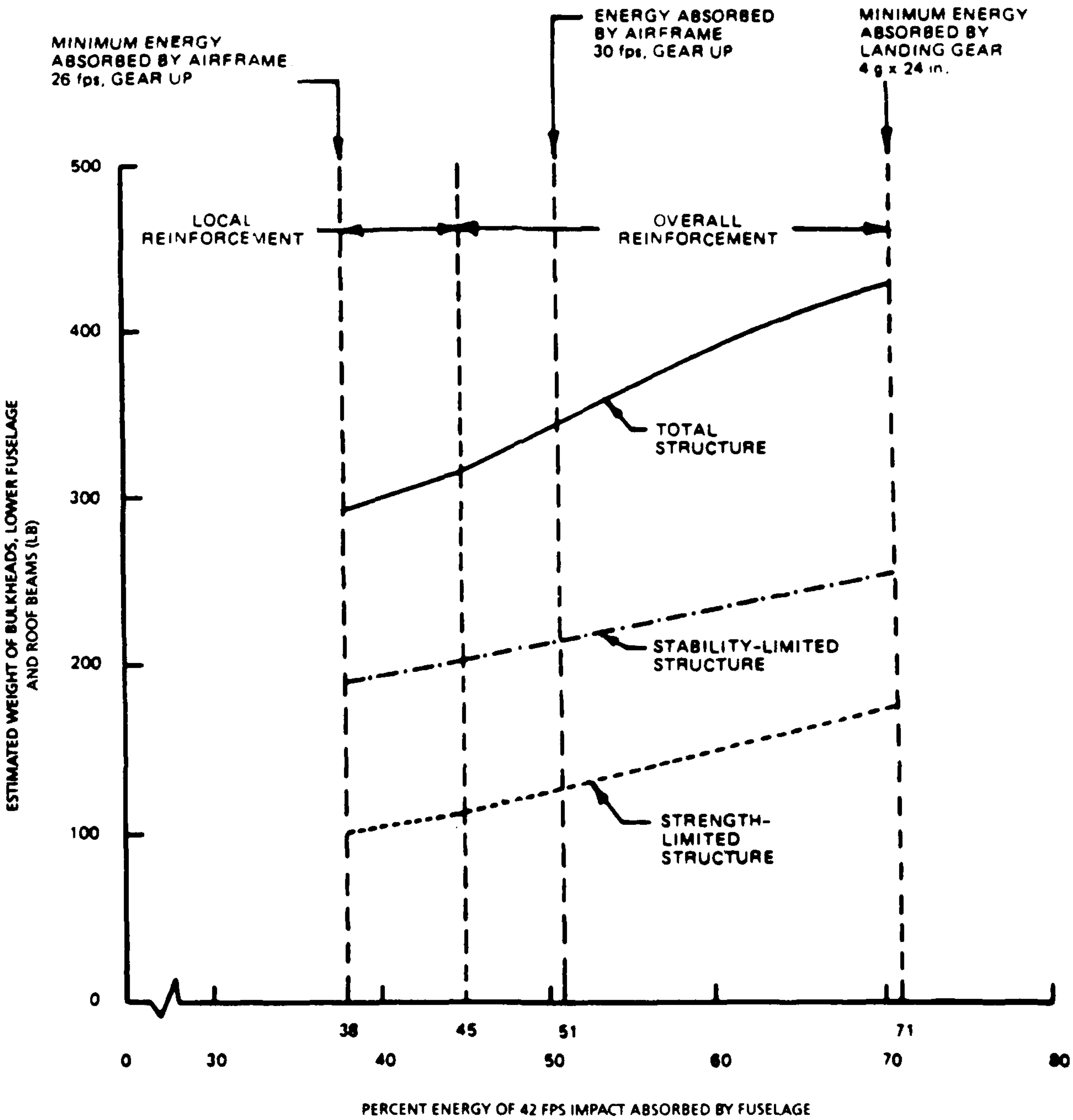


Figure 19. Typical variation of required fuselage weight versus energy absorbed for a utility helicopter.

TABLE 9. PRELIMINARY WEIGHTS OF THE THREE FINAL LANDING GEAR CONFIGURATIONS

Item	Concept 3 (Figure 12) pounds	Concept 4 (Figure 13) pounds	Concept 5 (Figure 14) pounds
Trailing Arm	95	66	160
Oleo and Shock Absorber	90	102	90
Landing Gear Fittings	5	10	10
Rolling Assembly	68	68	68
Fuselage Attachment Fittings	96	60	87
Controls	22	22	22
Total	376	328	437

- The major components shall be repairable either at Aviation Unit Maintenance (AVUM) or depot level maintenance. (AVUM level is field level.)
- The landing gear bay shall be designed such that the landing gear components are not contaminated by environmental conditions.
- Special skill shall not be required in assembling the gear. Simple "remove and replace" procedures shall be used along with any required alignment procedures.
- The landing gear shall be removable as a single component. The landing gear shall be of a modular (LRU) design; that is, it shall follow the two-level maintenance concept such that all LRUs can be removed and replaced at AVUM without realignment.
- Any adjustments and alignments to the landing gear shall be performed at AVUM.
- Special tools shall not be required at AVUM level of maintenance. This requirement includes removal and replacement of any LRUs and modules, and adjustments and alignments to any component.
- Procurer Ground Support Equipment (PGSE) shall include the capability of towing and jacking the aircraft. The landing gear shall have the capability of jacking one wheel at a time without jacking the whole aircraft. For landing gear swing, the aircraft will have to be jacked using the aircraft jacks.

- The landing gear shall be designed for ease of accessibility to each LRU and module such that the allocated maintainability requirements are satisfied.

- The landing gear shall be designed such that each LRU and module is easily replaceable in the field to eliminate downtime to the aircraft and meet the allocation requirement.

- The landing gear shall be designed such that a minimum amount of scheduled maintenance is required. Ease of inspection is required where scheduled maintenance is necessary, e.g., gauges shall be employed where maintenance actions such as checking lubrication levels and pressure levels are required. Mechanical wear-out indicators and chip detectors shall be employed where degradation or wear-out occurs.

Optimization guidelines were based on improving maintenance through ease of troubleshooting and system simplicity. The following design criteria were established:

- There shall be no purging requirements to the actuator upon removal and replacement.

- Sufficient data marks and reference points are required when adjustment is needed to a component after replacement.

- Hydraulic fittings attached to actuators and/or other components shall be designed such that cross-connecting cannot occur. This includes cross-connection between primary systems and backup systems on the same component.

- A tire pressure gauge shall be provided to monitor pressure.

- Interacting surfaces, e.g., bearings, gears and joints, shall be designed such that no specific lubricant replenishment actions are required. They shall be designed for the life of the aircraft.

- When lubrication is necessary, lubrication points shall be provided. There shall be no disassembling of bearings when lubrication is needed.

- The brakes shall have mechanical wear-out indicators indicating when the brakes need replacement.

- Access shall be provided to any LRUs or components for alignment as required.

- No wire locking shall be permitted on any LRU. Where locking is needed, self-locking securing devices must be employed.

- The landing gear bay shall be designed for ease of accessing the landing gear for maintenance actions including LRU cleaning, repair, removal and installation.

- No scheduled adjustments to LRUs or modules shall be required and unscheduled adjustments shall be minimized by design.

- If sequencing switches are used to retract the landing gear, they shall be solid-state and bit tested. This testing procedure shall be part of the landing gear diagnostic system.

- All connectors, wherever they can be contaminated by environmental conditions shall be of sealed type.

- The braking system shall utilize disk brakes and hydraulic power from the hydraulic power generation system.

The maintainability design goals for the total landing gear system in terms of Mean Time Between Unscheduled Maintenance (MTBUM), Mean Time To Repair (MTTR), and Maintenance Man-Hour per Flight Hour (MMH/FH) were:

MTBUM = 41.02 hr (= 33.94 Hr for AH-64A after 2205 flight hrs)

MTTR = 1.53 hr (= 1.354 Hr for AH-64A after 2205 flight hrs)

MMH/FH = 0.0846 (= 0.0765 for AH-64A after 2205 flight hrs)

The maintainability analysis of landing gear Concepts 3, 4 and 5 evaluated their respective advantages and disadvantages from the maintainability point of view, and determined the rationale for calculating the maintainability parameters. The MTBUM was calculated by taking the MTBF for this design and factoring it by the LHX-utility induced failure rate as compared to the inherent failure rate predicted in the BTA. The Maintenance Man-Hour (MMH) and MTTR were based on the LHX-utility-BTA predictions. Following the results of the evaluation, the three concepts were rated in order of their best maintainability features.

1. Landing Gear Concept 3: (Figure 12)

   Landing gear Concept 3 had two main components which included a trailing arm and a two-stage shock absorber. Both these components were attached to the airframe by a fixture having two rotating points of contact. The two-stage shock absorber was a single component which included a shock absorber and an extension-retraction actuator.

   Maintainability Advantages. The advantage of this landing gear design was easier access because there were only two major components/LRUs. Easier access results in a decrease in repair time of the main landing gear.

Maintainability Disadvantages. The disadvantage of this landing gear design was handling because of its greater weight. This increased repair time with an increase in handling equipment. Since the two-stage shock absorber included both a shock absorber and an extension-retraction actuator as an LRU, complete unit replacement will be required when a failure occurs either in the actuator or the shock absorber. Because of the two-stage shock absorber, the frequency of repair to the landing gear increased, and consequently increased both field and depot level repair.

After evaluating this design the induced maintenance was increased, thereby decreasing the MTBUM by 3.33 percent. In this design the MMH and MTTR increased by 2.50 percent. The result of the changes in MTBUM and MMH resulted in an increase in the MMH/FH by 6.00 percent.

2. Landing Gear Concept 4: (Figure 13)

This main landing gear design included three major components: a shock strut, an extension-retraction actuator and a trailing arm. The shock strut, designed with an attached pressurized component, permitted hard landings. The design also provided for an emergency system to aid the extension-retraction actuator in case of failure. These components were attached to the airframe through a fixture having four rotating points of contact.

Maintainability Advantages. The landing gear was of a modular (LRU) design which could be replaced as a complete unit. The major components of the landing gear were sub-LRUs to the landing gear and could be removed independently. The advantage of a modular-design landing gear was that it could be replaced as a complete LRU when damaged or it could be repaired by one person replacing faulty sub-LRUs. Also, a modular landing gear had the advantage of making components more accessible. This resulted in a decrease in repair time with the possibility of reducing ground support equipment. This design also allowed for interchangeability, including right- and left-handed components. The result, therefore, decreased the repair time as well as parts count.

Maintainability Disadvantages. A possible disadvantage was an increase in the repair interval due to the modular/sub-LRU design concept.

After evaluating this design, the MTTR and MMH were decreased by 7.67 percent and 8.75 percent, respectively. The result of the MTBUM BTA prediction and the decreased MMH resulted in the MMH/FH to be decreased by 8.75 percent.

3. Landing Gear Concept 5: (Figure 14)

This main landing gear included a tension shock absorber which was separate from the retraction actuator. The main components included

a trailing arm, retraction actuator and tension shock absorber. These components were attached to the airframe through a fixture having three rotating points of contact.

Maintainability Advantages. The landing gear was designed such that each component of the landing gear was a separate LRU and could be replaced independently from the other LRUs. As separate LRUs, each component was easily handled by one person. This decreased the repair time of the main landing gear.

Maintainability Disadvantages. The design entailed removing the attachment fixture LRU to gain access to the shock absorber LRU. Therefore, the repair time increased due to the increased time to replace the shock absorber. The additional provision to access the shock absorber posed a higher risk of induced maintenance, which could increase the repair intervals.

After evaluating this design the induced maintenance was increased, thereby decreasing the MTBUM by 10 percent. In this design the MMH and MTTR increased by 3.33 percent. The change in MTBUM and MMH resulted in an increase in the MMH/FH by 15 percent.

In comparing the three landing gear concepts, Concept 4 was considered the best design from the maintainability point of view. The maintainability parameters of the three gears are given in Table 10 in the order of their ranks.

2.7 RELIABILITY ANALYSIS

The reliability analysis was based on the failure rates predicted for advanced design concepts currently attainable. The analyses did not include the influence of position indicators and switches, which are normally included in the instrument subsystem. Historically, these components have high failure rates, which in turn contribute to the total failure rate.

The reliability analyses were conducted in terms of the mission reliability block diagrams and corresponding reliability curves. Landing Gear Concept 4 was analyzed for four possible configurations evaluating redundancies in retracting actuators and "gas bottles", the air chamber mounted on the shock strut.

2.8 PREFERRED LANDING GEAR CONCEPT

Following the evaluation of the three final concepts of the landing gear, Concept 4 was chosen for this program. This concept of the crashworthy, retractable landing gear offered the best configuration. This concept complied with all the design requirements and the flexibility for the trade-off study of the multiple design parameters.

TABLE 10. MAINTAINABILITY PARAMETERS OF THE THREE FINAL LANDING GEAR CONFIGURATIONS

Main Landing Gear	MTBF	MTBUM	MTTR	MMH	MMH/FH Unscheduled	MMH/FH Scheduled	MMH/FH Total
Concept 4	564.57	266.42	1.4114	1.6079	0.0060	0.0305	0.0365
Concept 3	583.71	266.26	1.5669	1.8019	0.0068	0.0305	0.0373
Concept 5	402.22	402.22	1.57976	1.8165	0.0106	0.0305	0.0411

This is a trailing arm concept with a universal-mounted, two-stage, air-oil strut designed to absorb up to 65 percent of the kinetic energy from a vertical level impact at 42 fps. For retraction and extension, this concept used a dedicated actuator that included an internal locking system for the extended and the retracted positions. The configuration of the landing gear is shown in Figure 20. The kneeling feature was achieved by bleeding air from the strut upper stage accumulator or by bleeding and controlling the oil pressure of the strut.

For normal landing, kneeling and crash the trailing arm pivots about a crank. The trailing arm strokes in a vertical plane that will not permit the landing gear to intrude into the fuel cell, troop cabin or other critical areas. During crash the trailing arm will not interfere with the cabin door or exits, thus allowing fast evacuation of troops and crew. With the landing gear retracted, energy will not be attentuated by the landing gear since it is stowed above the crushing zone of the fuselage.

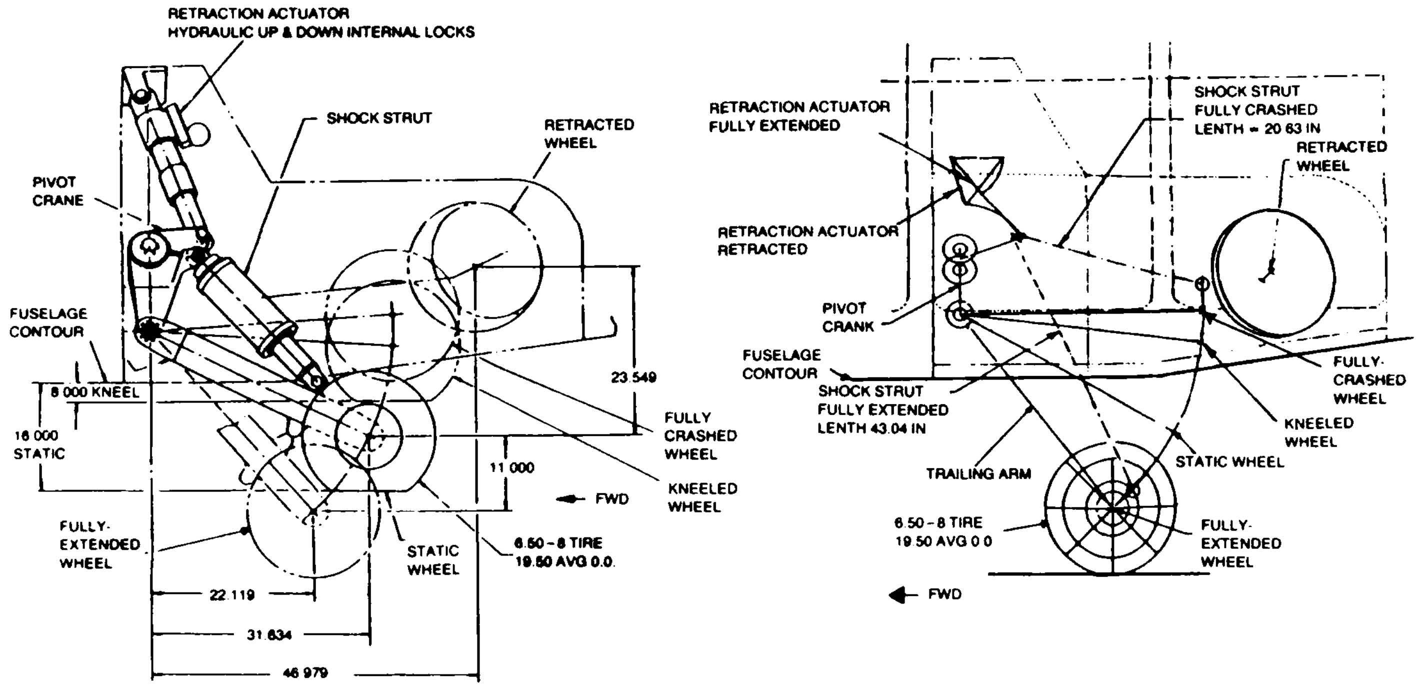


Figure 20. Configuration of the preferred landing gear concept.

3.0 DETAIL DESIGN OF LANDING GEAR

3.1 GENERAL

The design driver was to design the lightest possible main landing gear without compromising the crashworthy performance requirements. At the completion of the preliminary design, the preferred landing gear concept was selected. Based on the preliminary crashworthiness analyses described in Section 2.4.2 and the results of the investigation described in Reference 2, the landing gear was designed to absorb 55 to 60 percent of the kinetic energy from a 42 fps level impact condition. Subsequent detail analysis, described in Section 6.0, validated this choice for a weight-effective design.

A schematic view of the landing gear assembly is shown in Figure 21. The landing gear assembly in the drop test fixture is shown in Figure 22 and the major components individually in Figure 23. The following components, and the respective system design rationale, will be discussed in this section.

1. Extension-Retraction Kinematics
2. Retraction Actuator
3. Retraction Linkage
4. Crank Assembly
5. Shock Strut Assembly
6. Trailing Arm and Axle
7. Joint Interfaces
8. Wheel and Tire Selection
9. ATLG Control System

The fuselage bulkhead supports a three-clevis pivot crank, to which are attached the upper ends of the trailing arm and shock strut, and the lower end of the retraction actuator. The upper end of the retraction actuator is attached to an upper clevis on the bulkhead. A closed-loop load path for the landing loads, in conjunction with the bulkhead, is provided by this arrangement.

3.2 ATLG-AIRFRAME INTERFACE

The ATLG main gear is part of a tricycle nose gear arrangement which is attached to the bulkhead structure by means of a pivot crank oriented within the volume requirements for LHX compatibility. The detail main landing gear design was developed from the initial crosstube attachment through the airframe to the bulkhead/crank assembly.

The crosstube arrangement was the preferred concept established in preliminary design because of the structural advantages of allowing the shock strut response to be unaltered by lateral loads. These lateral wheel loads were reacted at the crosstube pivot and attachment fittings. Spherical bearings are normally mounted at the connecting points of the shock strut, which then allows the

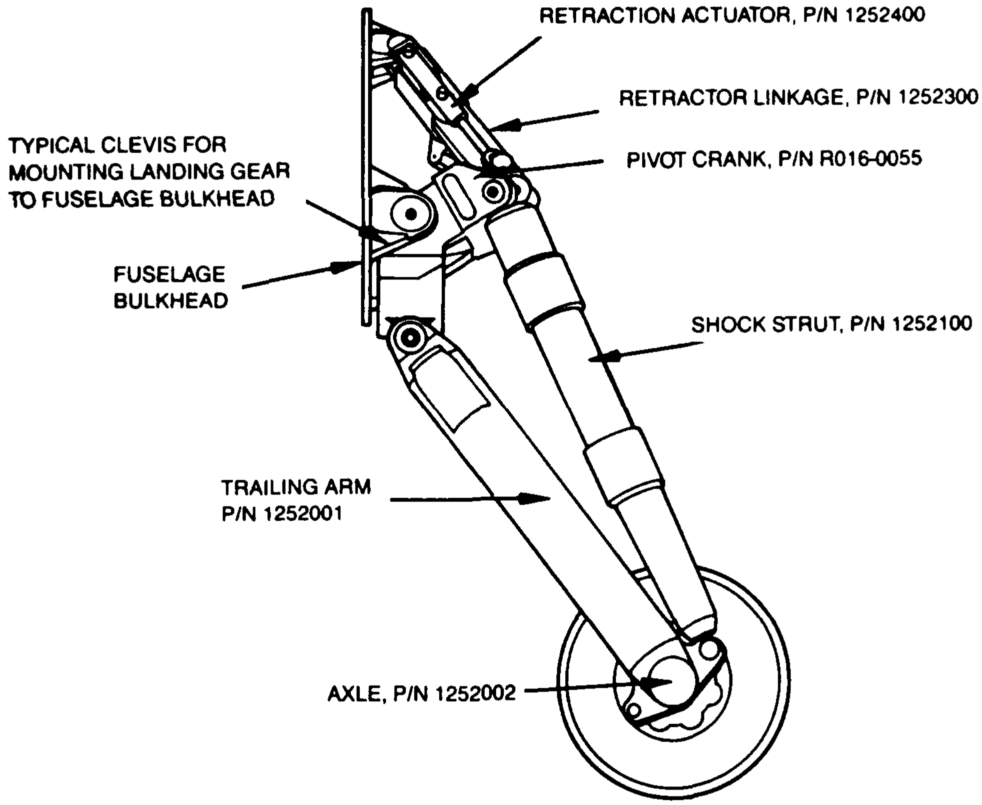


Figure 21. Schematic view of advanced technology landing gear assembly

transmission of axial loads only, minimizes the oleo weight, and optimizes its performance.

The attachment fittings for the advanced technology landing gear, however, exceeded the established weight targets due to severe interface loads from the crashworthiness requirements. The interface design was then changed from a crosstube to a pivot crank. The major reasons are as follows:

a. An estimated 50 pounds would have to be added to the airframe structure to reinforce the region of the attachment fittings and to the size of the fittings themselves if a crosstube was selected.

b. The location of the crosstube in the LHX utility helicopter interfered with the fuel cell, which in turn reduced the fuel capacity by approximately 10 percent.

c. Excessive weight of the crosstube due to the excessive fuselage width outweighed the structural advantages of this arrangement.

The improved method of attaching the landing gear to the airframe is through a pivot crank. The bulkhead is capable of withstanding a 20g vertical impact

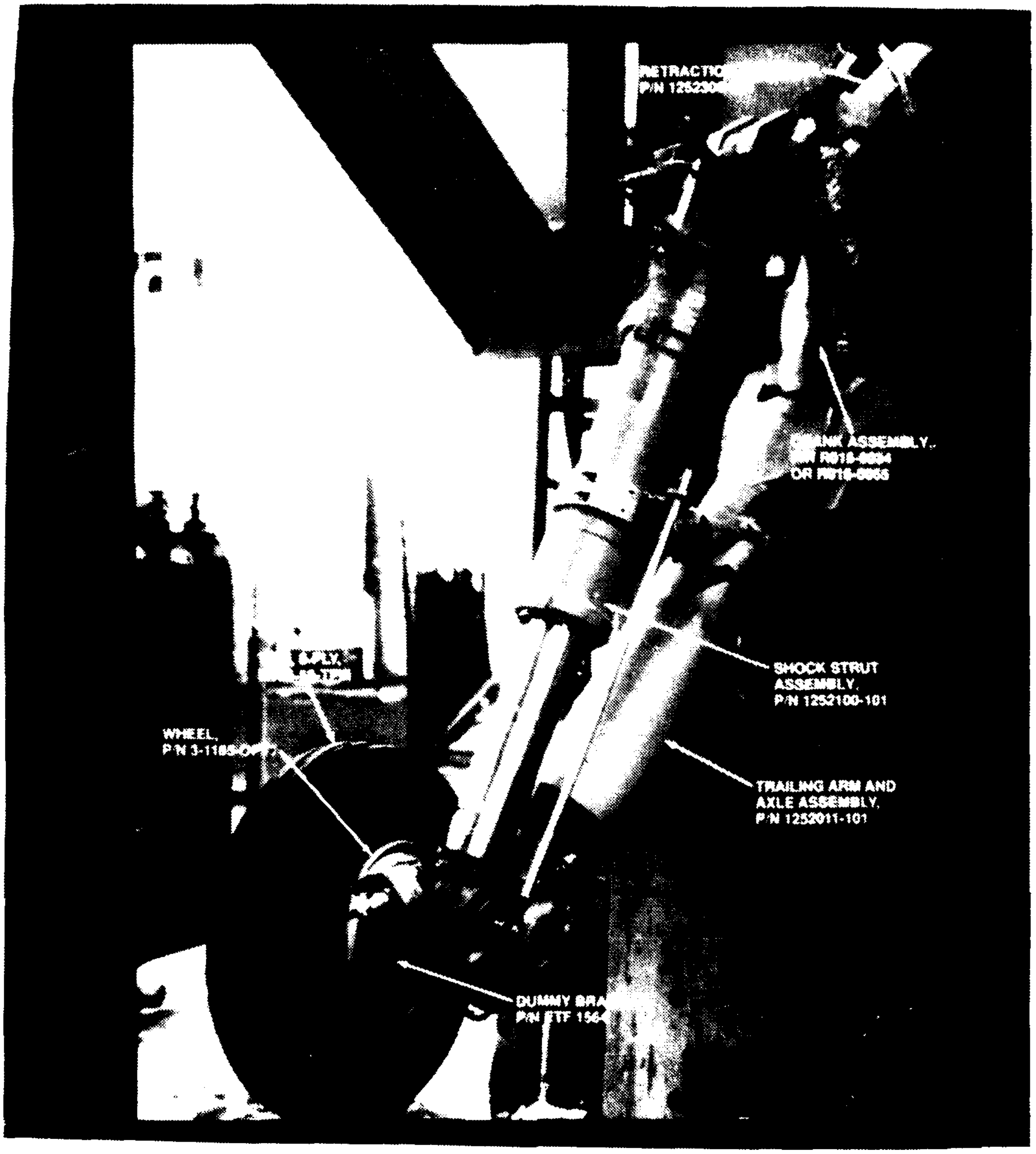


Figure 22. Photograph of the advanced technology landing gear assembly.

load; therefore, the attachment to the bulkhead does not require additional localized reinforcement. The crank also provides a closed-loop load path, and refinement of the fuselage design will integrate the clevises of the crank into the bulkhead.

The major advantages of the crank attachment to the airframe are:

a. The overall reduction in parts count of the main landing gear assembly.

b. The crank, serving as the load path for the reaction forces created by the trailing arm assembly and the retraction-extension actuator-linkage assembly, produces a closed loop for these forces before transferring the load to the bulkhead.

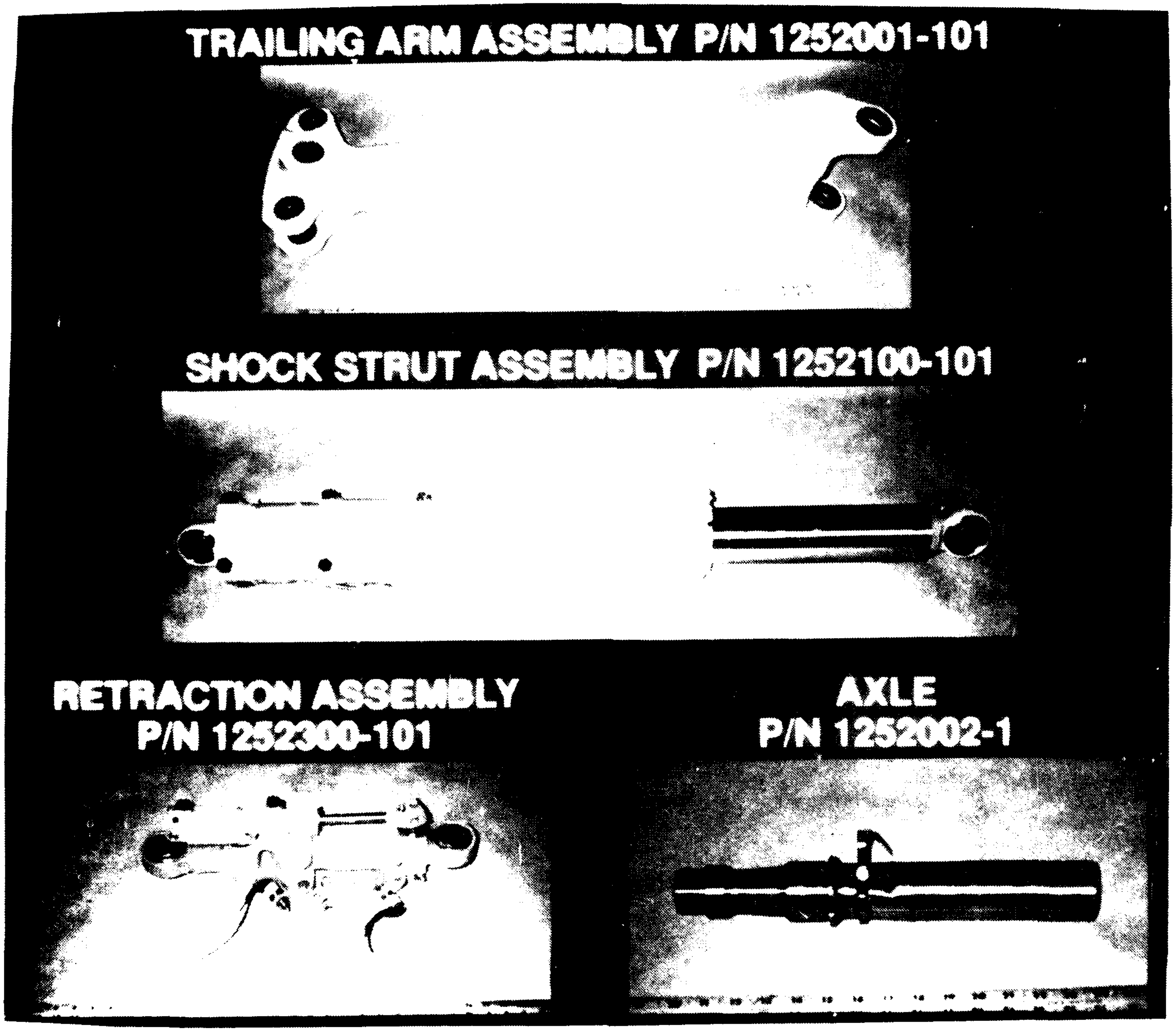


Figure 23. Photographs of the main components of the ATLG system.

c. The primary concern of increased weight is reduced by minimizing parts count and utilizing the existing stiffened bulkhead.

3.3 EXTENSION-RETRACTION KINEMATICS

The ATLG design incorporates a very compact configuration which meets the compatibility requirements for volume claim, kneeling features, and track width of the utility helicopter. In addition to these features, the requirements for emergency operation fully extend the gear in 2.5 seconds.

The kinematics of the landing gear use two orthogonal axes sequentially for retraction and extension. The horizontal axis pivots the trailing arm 60 degrees and the skew axis retracts the landing gear assembly 30 degrees inboard. The basic geometries of the gear in the fully extended, static, fully compressed, and fully retracted positions are shown in Figure 24. For extension and retraction the pivot crank rotates about the skew axis, shown as the A-B axis in the figure. The rotating crank then, in turn, rotates the trailing arm and shock strut as a unit. This unit always rotates starting from the fully extended or fully retracted positions. The major advantage is that the strut remains fully extended and fully serviced throughout the extension-retraction cycle.

The retraction actuator and its linkage are attached to the fuselage bulkhead and the pivot crank at locations E and F, respectively. The trailing arm is attached from location C-D of the crank to point J and allows for rotation about the C-D axis as well as about the crank skew axis. The shock strut is shown to be located between points G and H where G is on the crank. During landing, crash, and kneeling the gear assembly remains locked, keeping the crank from rotating and allowing the trailing arm to pivot about the horizontal axis C-D. This permits the wheel assembly and trailing arm to displace in a vertical plane only.

3.4 RETRACTION ACTUATOR

The retraction actuator, P/N 1252400, of the landing gear is a dedicated retraction system with a parallel retraction linkage to react all loads. The actuator is a standard fluid drive system which operates in either retracting or extending the rod assembly which locks and unlocks the linkage. The actuator has a cylinder made of 7075-T73 aluminum alloy capable of withstanding the ultimate system pressure of 6750 psi. The piston and connecting rod assembly is made of a 4340 steel. The rod is designed to withstand a maximum critical buckling load of 12,060 pounds.

The advantages of an independent retraction actuator allow for the trailing arm, shock strut and the interface connections to form a rapidly deployable energy absorption system. The actuator is designed to be compatible with the control system and sized for a normal extension and an emergency extension in less than 2.5 seconds.

The reaction loads occur under a normal system operating pressure of 4000 psi with a capacity flow rate of 28 GPM. The actuator piston is only 1.15 inches in diameter because the actuation loads are very small compared to those of the shock strut. The low loads have resulted in a weight-saving design and have minimal flow requirements, which results in rapid stroking capabilities. The

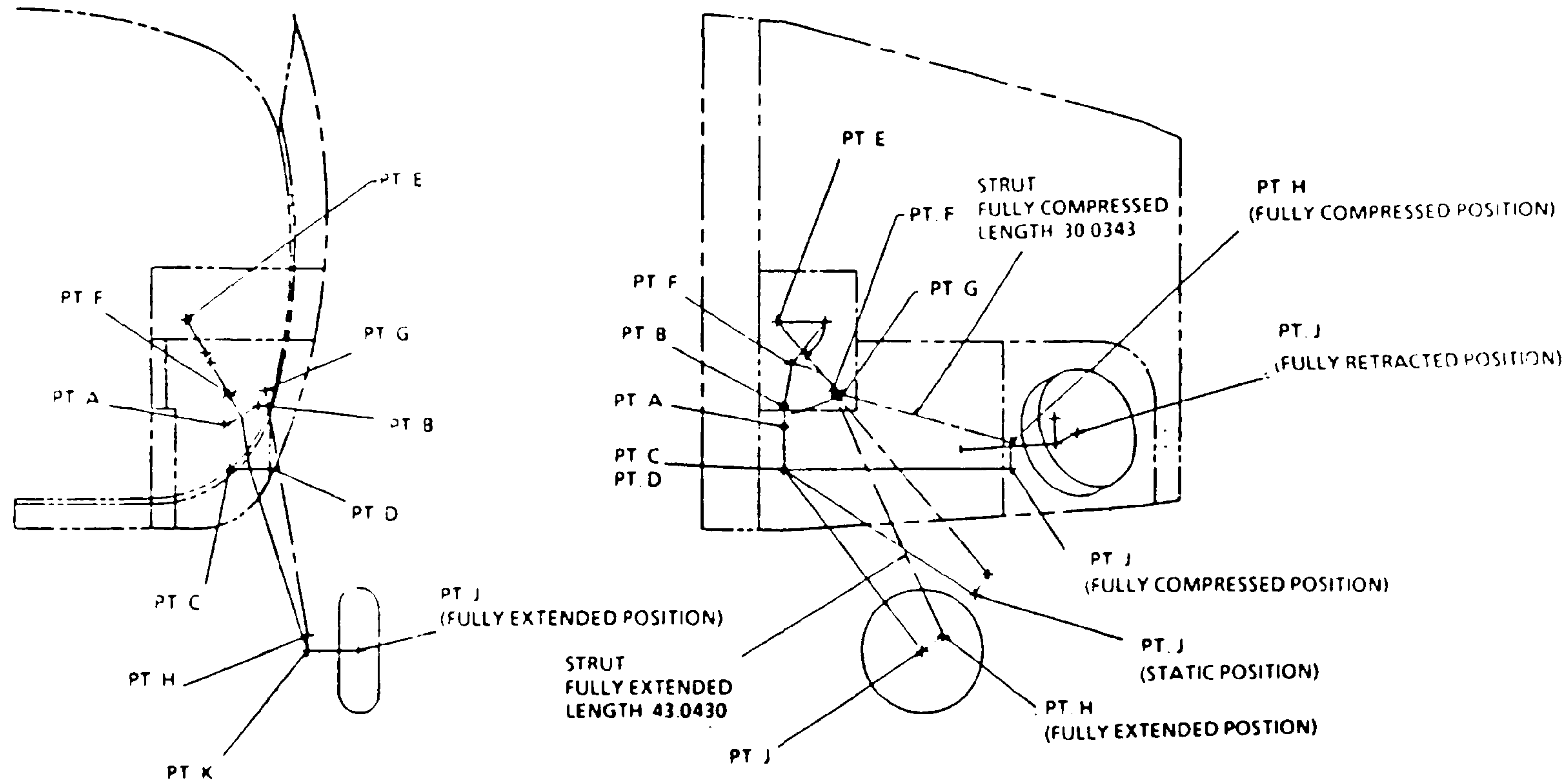


Figure 24. Kinematics of the advanced technology landing gear.

actuator for the landing gear is shown in Figure 25 indicating standard assembly arts. The maximum extension of the actuator is 13.19 inches, which locks the linkage assembly for maximum extension. The minimum retracted length is 8.822 inches which, also in conjunction with the retraction linkage, locks the landing gear in the fully retracted position.

3.5 <u>RETRACTION LINKAGE SYSTEM</u>

For the ATLG, the dedicated retraction actuator is used with a main link which is a two-bar construction with an external double locking linkage. The advantage of this design is that when the gear is fully extended and the dual-action actuator extends the external double locking links, the linkage becomes a near-rigid element. This locking of the linkage transfers the reaction loads of the main gear assembly to the fuselage bulkhead, producing the closed-loop load path.

The retraction actuator-linkage assembly is shown in Figure 26 in the fully extended position. In this position the retraction actuator, the linkage assembly, and the overcenter lock assembly are in parallel. The upper and lower links of the linkage assembly are designed to pivot about A-A during retraction and extension. The retraction actuator, mounted on the upper link, can rotate about B-B. The two jury arms of the overcenter lock pivot about C-C during retraction and extension. The upper and lower links are locked in the extended and retracted positions because the two links together form an unstable assembly. The preloaded spring keeps the jury arms locked. In the extended position, Switch No. 1 is activated and indicates, in the cockpit, that the gear is extended.

When retraction begins, the first displacement of the actuator piston rod rotates the torque tube to overcome the force of the preloaded spring and unlocks the linkage. As retraction continues, (1) the two links pivot about A-A and begin to fold, (2) the retraction actuator rotates about B-B, and (3) the jury arms, pivoting about C-C, at first, begin to fold and then to extend again. In the final retracted position, the jury arms of the overcenter lock assembly are fully extended and locked back in position. Switch No. 1 is now deactivated and Switch No. 2 is activated to indicate, in the cockpit, that the gear is fully retracted. The fully retracted position is outlined in Figure 26.

When the actuator begins to extend, the first displacement of the piston rod unlocks the linkage. Further extension of the piston reverses the operations which occur during retraction. Extension stops when the lock is again in position.

The retraction linkage, P/N 1252300, is designed of 7075-T73 aluminum alloy with standard bushings at the connections capable of withstanding a maximum column load of 84,660 pounds. Electronic indicators can be attached to the linkage to indicate whether the gear is up or down. The overcenter lock is actuated in case of a major failure.

3.6 <u>PIVOT CRANK</u>

In order to meet the volume claim requirement, as well as the requirement of an emergency extension time of 2.5 seconds, the kinematics of the main landing gear required a very compact design where the rotation and translation geometries

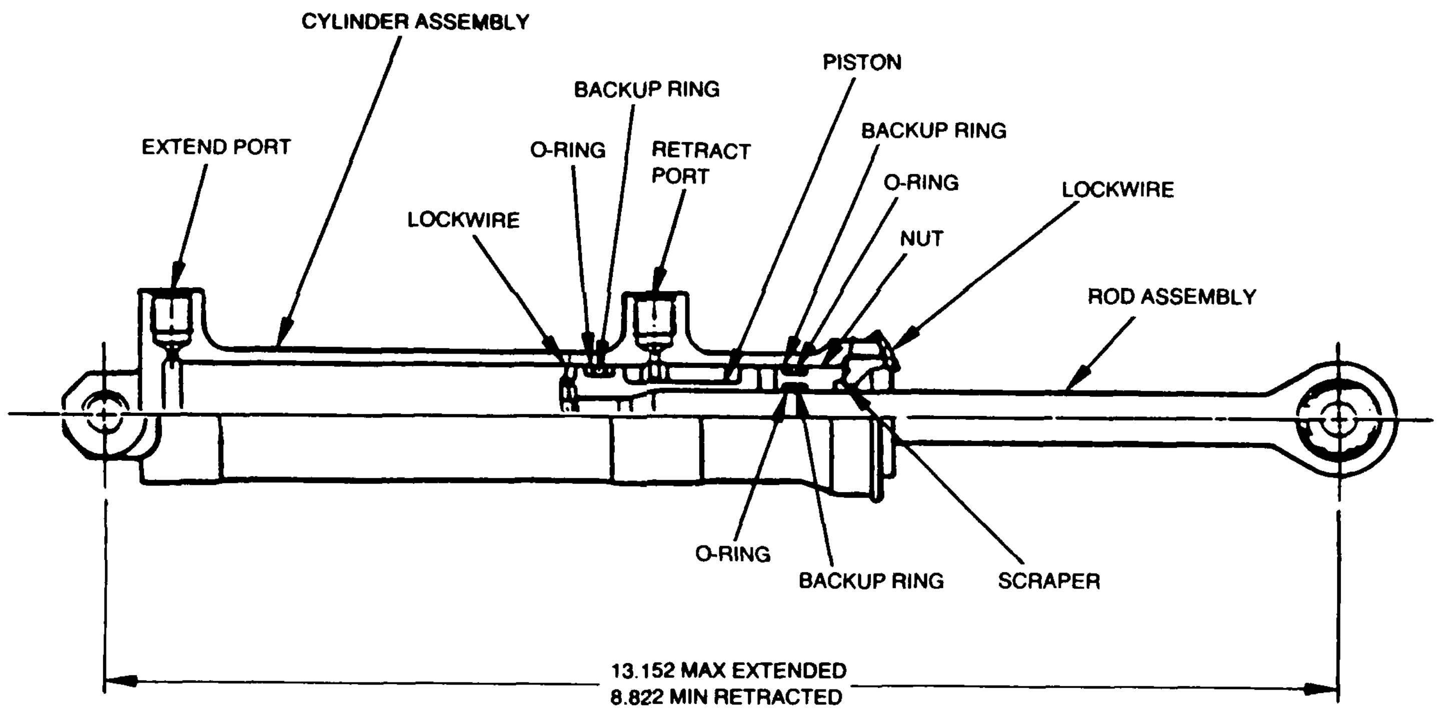


Figure 25. ATLG retraction actuator.

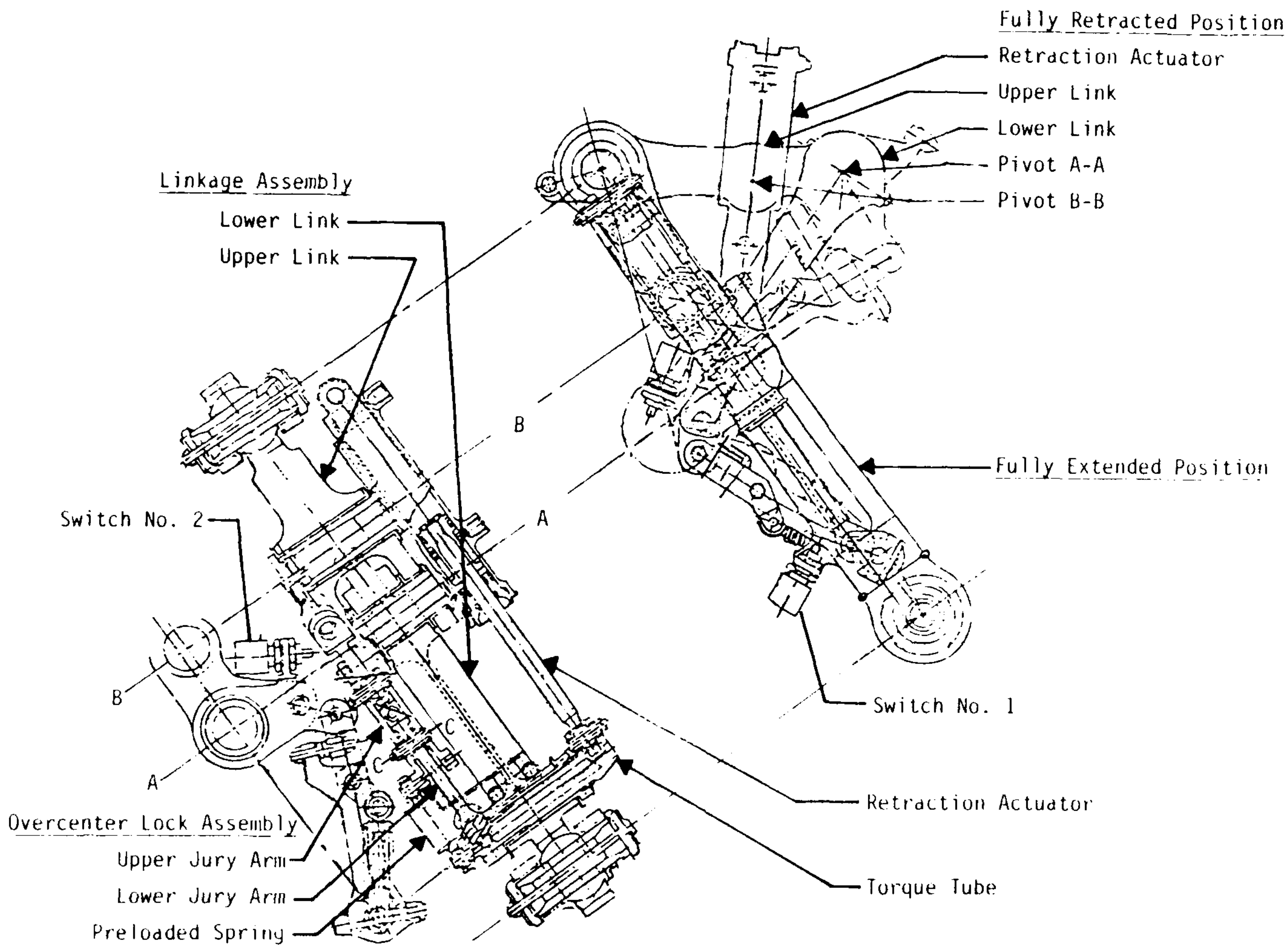


Figure 26. Retraction actuator with linkage assembly.

during gear retraction were optimized. The trailing arm and independent shock strut were selected to optimize the crashworthiness requirements. The key to achieving the desired kinematics is the pivot crank, P/N R016-0055. The pivot crank is of complicated geometry and developed through several iterations. The last two design iterations of the crank are shown in Figure 27. The design improvement in the R016-0055 crank over the old R016-0034 crank was to reduce the machining labor cost by 7.5 percent. The critical dimensions in the two cranks remain the same.

The pivot crank performs the function of the primary attachment point for the retraction actuator, the trailing arm assembly, and the shock strut. The crank itself pivots on the fuselage bulkhead. The crank, therefore, controls, in one rapid motion, the extension and retraction of the landing gear assembly. It also reacts the kneeling and landing loads.

The crank, being weight-critical, was designed of 7175-T736 high strength aluminum alloy despite the fact that the specific strengths are lower than either steel or titanium alloys. The 7175-T736 aluminum alloy is very competitive structurally for large forgings due to the dead metal associated with the complexity of the crank geometry. The aluminum crank and its location in the landing gear assembly are shown in Figure 28.

3.7 SHOCK STRUT

The design of the shock strut, P/N 1252100, is critical to the overall performance of the energy absorption capability of the main landing gear. The design incorporates a two-stage oleo-pneumatic shock strut which is attached to the trailing arm at one end and to the pivot crank at the other. The total energy absorbed by the main gear assembly and tires is predicted to be 45,380 ft-lbs at 42 fps level landing. The shock strut efficiency is 80 percent and the tire efficiency is 45 percent for a BSDGW of 8500 pounds.

The preliminary design established the vertical position, compression ratio, air volume during compression, load factors, maximum pressures inside the two stages, and the orifice size. Orifice sizing was adjusted such that the dynamic load response was relatively constant.

The ATLG shock strut design, shown in Figure 29, utilizes a common oil base and allows flow through the first stage orifice during normal landing conditions up to vertical speeds of 10 fps. The stroking action of the first stage causes the oil base to be pressurized and metered through the orifice to obtain a damping response. The air is pressurized by the piston stroking to produce a pneumatic spring action to dissipate energy with good rebound control.

During crash and hard landing conditions the velocity of the first stage strut increases rapidly, causing fluid pressure to rise in the oil chamber above the first stage orifice. As the oil flows through the orifice, the air in the first stage air chamber is compressed on the other side of the floating piston. The first stage bottoms after exceeding the maximum compression of the air at 2,292 psi and then transfers the load into the second stage. The second stage

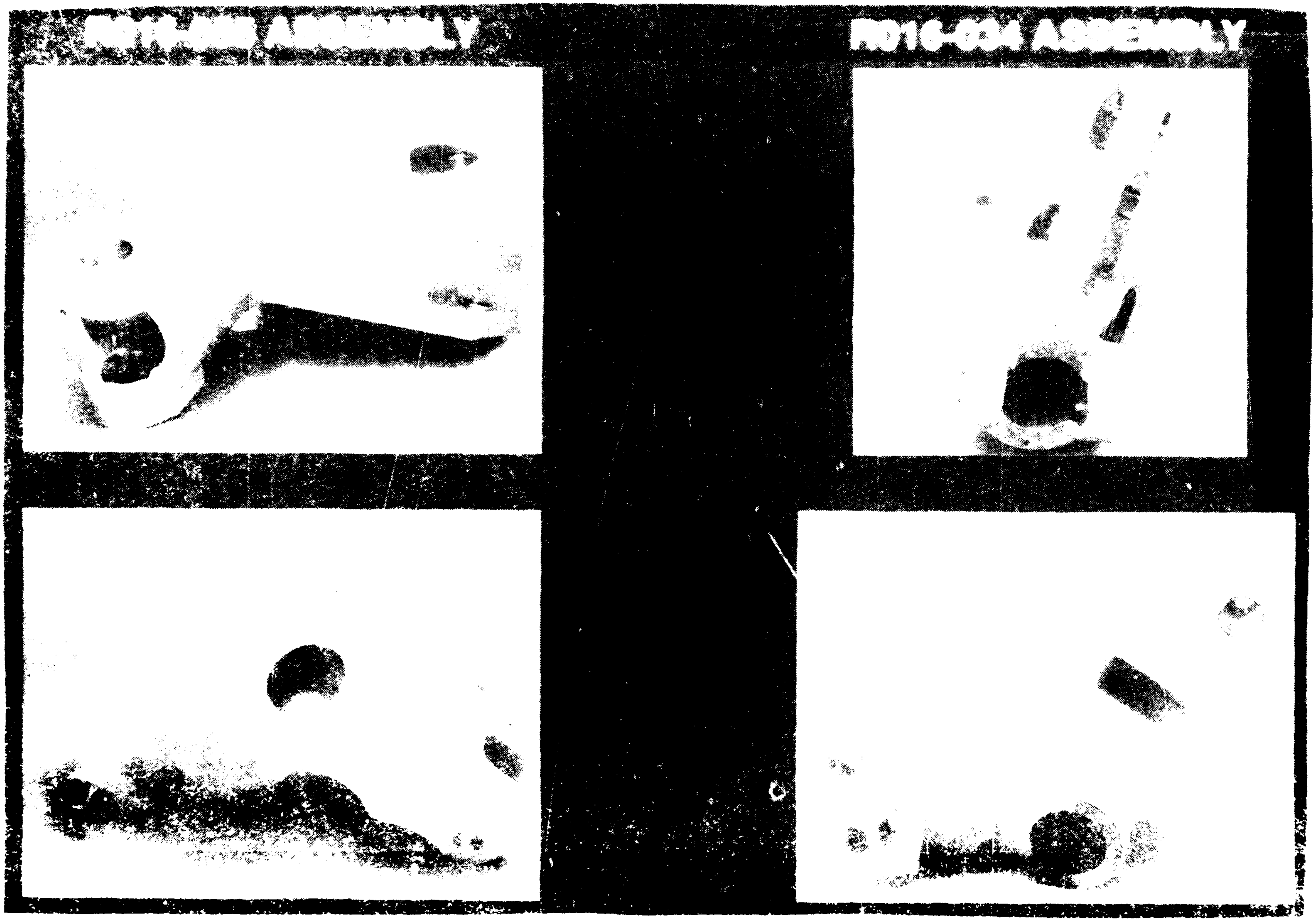


Figure 27. Photographs of the last two versions of the pivot crank.

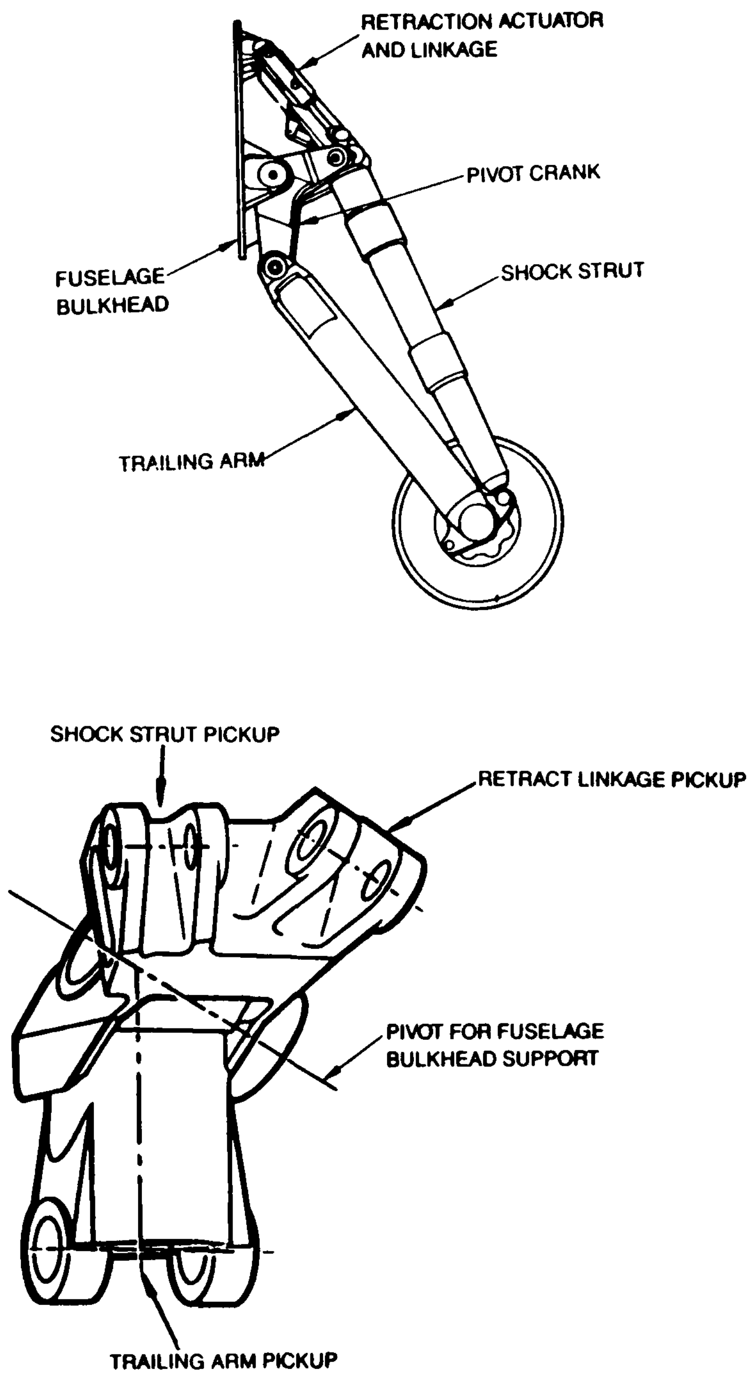


Figure 28. Schematic view of the pivot crank showing position in the landing gear assembly.

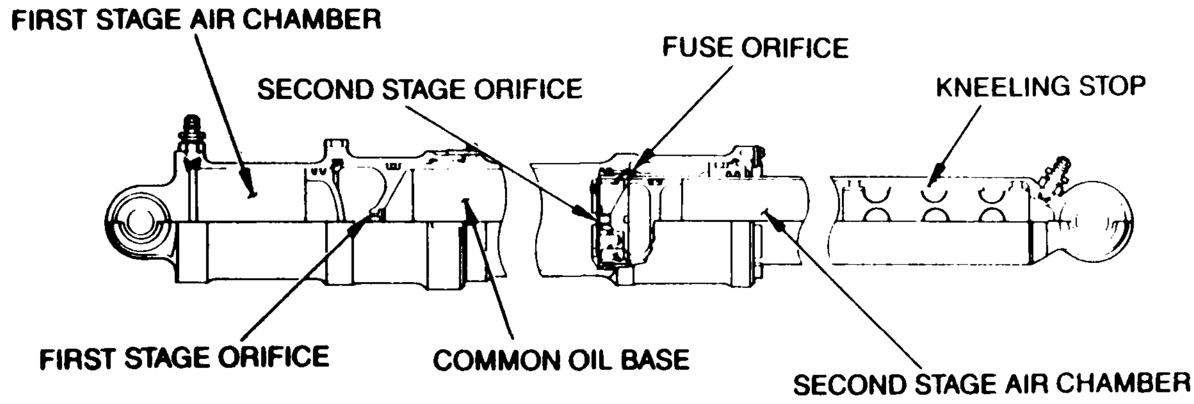


Figure 29. ATLG shock strut assembly.

piston displaces, causing the oil to flow through the second stage orifice which initiates the stroking of the second stage floating piston and compresses the air in the second stage air chamber. The pressure in the second stage will rise to a threshold pressure of 7,350 psi at which time the fused orifice, designed for loads below 8g, will shear.

In summary, landings up to 10 fps will allow flow through the first stage orifice. For vertical velocities greater than 10 fps and up to 20 fps, designated as hard landing conditions, oil flow is through both first and second stage orifices. For crash conditions, the fused orifice is designed to shear such that sudden peak loads are not induced in the remaining energy absorption system.

The inner and outer cylinders of the ATLG shock strut utilize 7174-T74 aluminum alloy, which minimizes the weight of the main landing gear. The internal piston and the floating pistons are designed with 4340 alloy steel.

3.7.1 Method of Kneeling

The concept that was selected to meet the kneeling requirements of the landing gear was by releasing air pressure from a second stage control volume to stroke down to an internal kneeling stop. A pneumatic control system is part of the kneeling system and controls the flow or release of nitrogen to or from the shock strut second stage. Nitrogen supply, at 2,500 psi, is available aboard the aircraft as part of the weapon systems and can be shared by the landing gear system.

Consequently, the kneeling concept consists of controlling the volume and pressure of the nitrogen gas in the second stage of the shock strut. By bleeding the nitrogen, the second stage bottoms on the positive kneeling stop to a position such that the aircraft has a 3-inch ground clearance. In this position, the first stage of the strut is still operational and provides cushioning from vibrations or shock during transportation. The nitrogen gas can

be replenished at any moment by command from the cockpit, and different kneeling heights can be achieved.

The kneeling stop is a thin-wall spacer made of 7075-T73 aluminum alloy. Under crash-impact conditions the second-stage floating piston may bottom against the stop, resulting in very high strut loads. The kneeling stop is designed to yield at a ground load of 22,400 pounds in order to increase the piston stroke and reduce the strut load.

3.8 TRAILING ARM AND AXLE

From the preliminary design studies the trailing arm concept for the landing gear was selected because of its advantages in structural loading and energy absorption. The commonality between right- and left-hand gears was addressed by adding a redundant pair of lugs at 180 degrees from the existing pair of lugs for attaching the shock strut. However, this redundant pair of lugs was removed during tests when the lugs interfered with the ground in 10-degree rolled drop tests of the iron-bird fixture.

The geometry of the arm, P/N 1252001, and its relationship with the wheel, pivot crank, and shock strut is such that for a given ground load the strut load remains nearly constant as the trailing arm rotates about the axis on the pivot crank. Additionally, this design arrangement allows shorter strut strokes to be used due to the magnification effect of its lever arm. This results in a more compact oleo-pneumatic shock strut which reduces weight substantially and allows for very simple and compact retraction kinematics. Additional advantages of the trailing arm design are:

- The energy absorption of the landing gear is relatively insensitive to side loadings.
- The rearward rake of the main landing gear is safer than other designs in a forward velocity rough terrain or obstructed runway landing because of the landing gear's natural tendency to deflect up and back, over the obstruction.
- Short, direct paths for the crash loads utilize the same structure that is needed for flight and landing loads.
- Energy absorption is provided through large displacements of the shock struts. This reduces the accelerations imposed on the occupants.
- With proper strut geometry, nearly constant ground load factors are achieved throughout the landing gear stroke; this optimizes energy absorption while minimizing landing gear loads.

The trailing arm design lends itself to potential weight savings when using advanced material systems over conventional materials. The weight savings potential of these materials was evaluated by considering the restrictions to volume, joint and attachment locations, impact and fatigue considerations, and the expense of tooling and fabrication. Without the extensive cost of component development with advanced materials, these materials offer poor potential for low-cost fabrication in large quantities.

A study was performed comparing high strength aluminum alloy and 300M steel for the optimum conventional material. The trailing arm was finally designed with 7175-T74 aluminum alloy and the axle assembly from a standard 4340 steel. These materials were selected at the completion of the study due to lower cost and availability against the 7 to 8 pounds of weight savings if 300M steel was selected.

The detailed design of the trailing arm also incorporates a nonintegral axle, P/N 1252002. This feature improves maintainability by allowing replacement of a worn or broken axle without replacing the complete trailing arm. The basic geometry and attachment locations of the trailing arm and axle are shown in Figure 30. The modification of the trailing arm by removing the redundant lugs is shown in Figure 31. The design features for braking, turning, pivoting, taxiing, towing and jacking conditions are incorporated into the trailing arm in accordance with MIL-A-8862. The strut attachment lugs and the corresponding redundant lugs are shown in Figure 23.

3.9 JOINT INTERFACES

The joint interfaces incorporate standard design features with the availability of standard pins, bearing, bushings, and nuts and bolts. The interfaces allow for standard relief angles and clearances established for all designs. Data on joint interfaces and their locations are summarized in Table 11. Detail designs of the individual joint assemblies are shown in Figures 32 through 35.

3.10 WHEEL AND TIRE SELECTION

The landing gear requires operation on landing surfaces with CBR (California Bearing Ratio) of 2.5. The detailed design required an evaluation of the wheel and tire size which would meet the main landing gear design criteria. The wheel selected was a B.F. Goodrich Nose Wheel No. 3-1185 which is currently in use on the F-4 aircraft. The general specifications are given below.

- Wheel Size - 18 x 5.5 inches
- Tire Size - 6.50 - 8, 8-ply
- Wheel, Max Static Rating - 5900 pounds
- Wheel Radial Load - Limit 43,930 pounds
Yield 50,520 pounds
- Wheel Pressure - Normal 115 psi
Burst 1225 psi
- Wheel Weight - 11.45 pounds

3.11 CONTROL SYSTEM

The control system for the main landing gear uses an artificial intelligence computer system for automatic emergency extension and a fail-safe redundancy. The landing gear control system block diagram is shown on Figure 36. There are four basic groups: Cockpit, Computer System, Control System, and Landing Gear Assembly. The first three are control groups and are discussed below. The details of the landing gear assembly have already been described.

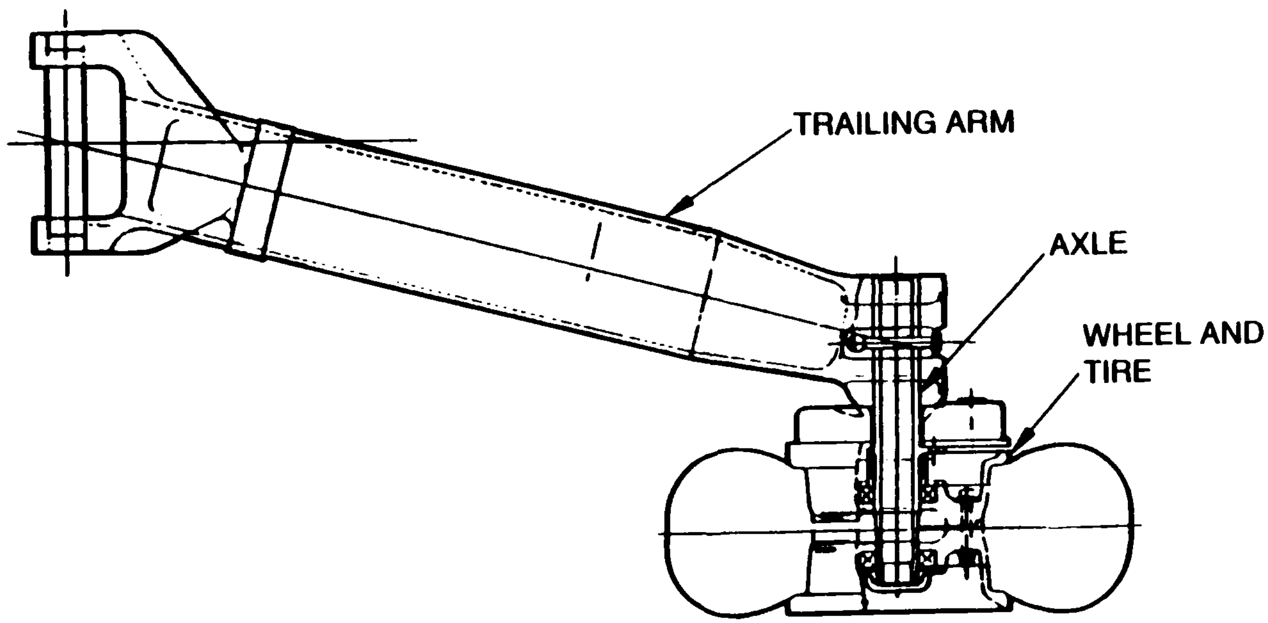


Figure 30. ATLG trailing arm and axle assembly.

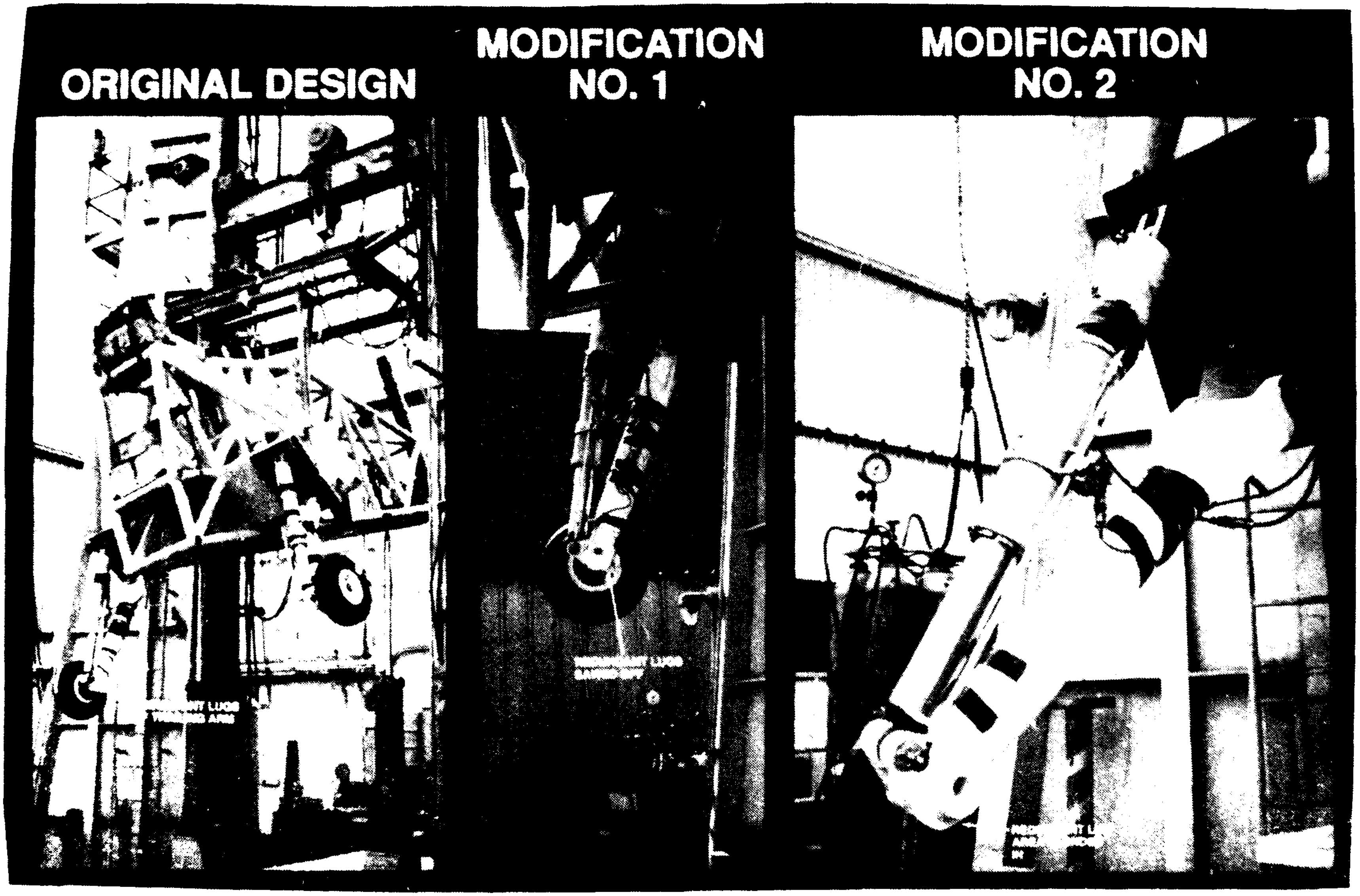
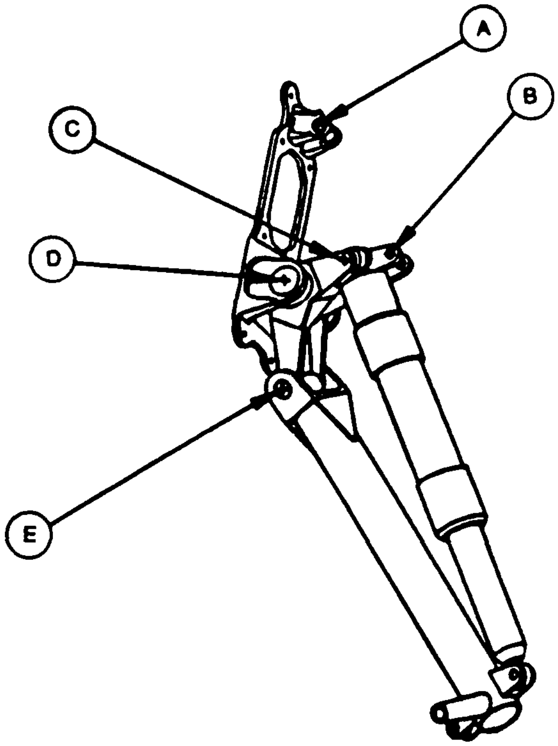


Figure 31. Modification of the trailing arm to remove the redundant pair of lugs.

TABLE 11. LOCATIONS AND SPECIFICATIONS OF JOINT INTERFACES



Joint	Pin OD	Pin ID	Pin Length	Bearing No. (Karon Brgs/ Kamatics)	Bolt	Nut
A	1.2490 1.2480	0.755 0.745	2.960 2.955	KRJ20-UDSB-018	AN6-36	MS21045C6
B	1.2490 1.2480	0.755 0.745	3.460 3.455	KRJ20-UDSB-018	AN6-43	MS21045C6
C	0.9990 0.9980	0.505 0.495	3.280 3.270	KRJ16-UDSB-024	AN4-40	MS21045C4
D	2.750 2.748	2.005 1.995	8.160 8.150	MDHC P/N TBD MDHC P/N TBD	Grade 7 or 8 500-20UNF-3B Alloy Steel 10.63 in. long	MS21045C8
E	1.750 1.748	1.080 1.070	9.465 9.455	KRJ28-UDSB-042 KRJ28-UDSB-048	Grade 7 or 8 500-20UNF-3B Alloy Steel 10.63 in. long	MS21045C8

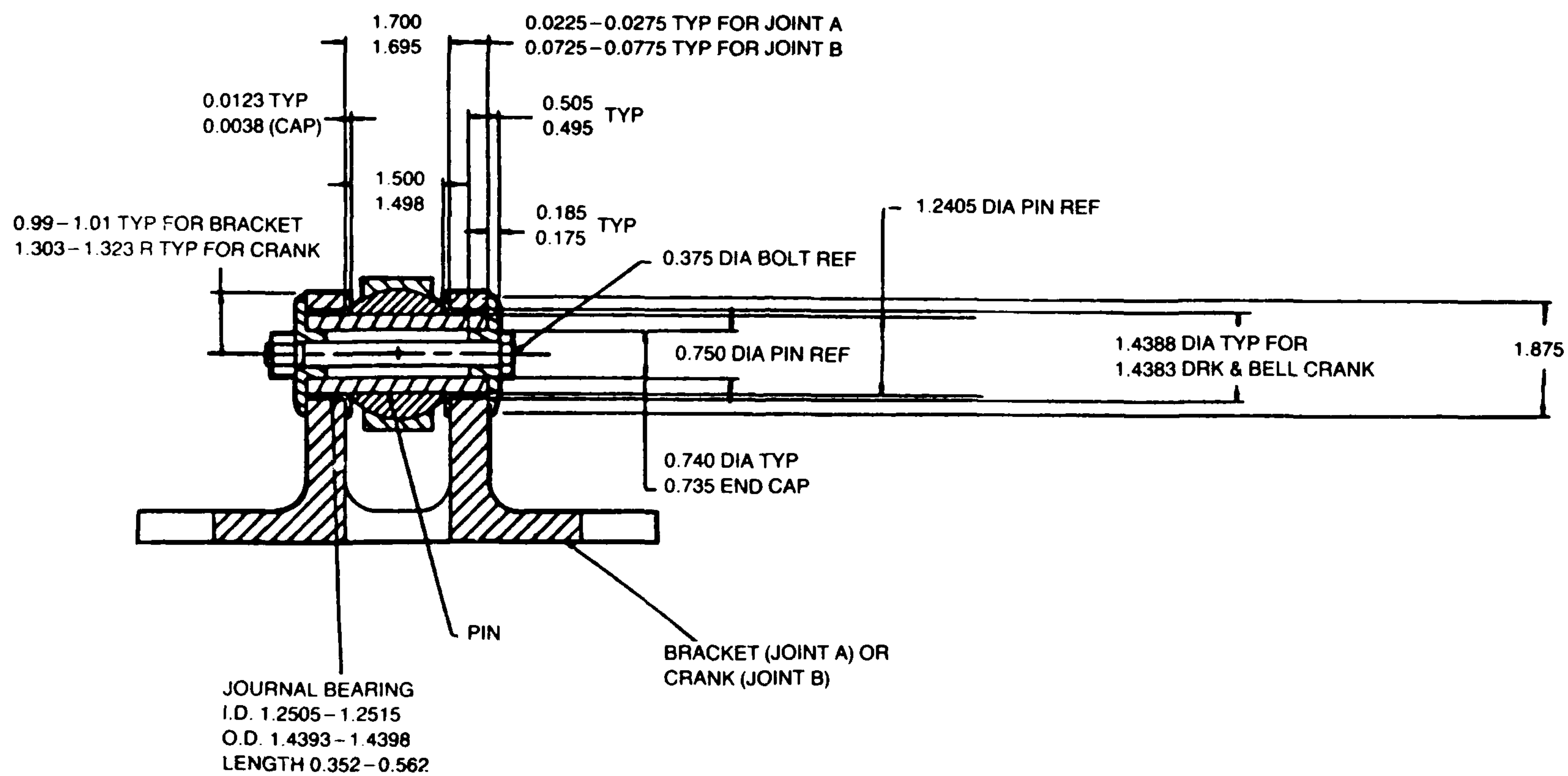


Figure 32. Details of the upper and lower attachment joints of the retractior actuator (Joints A and B in Table 11).

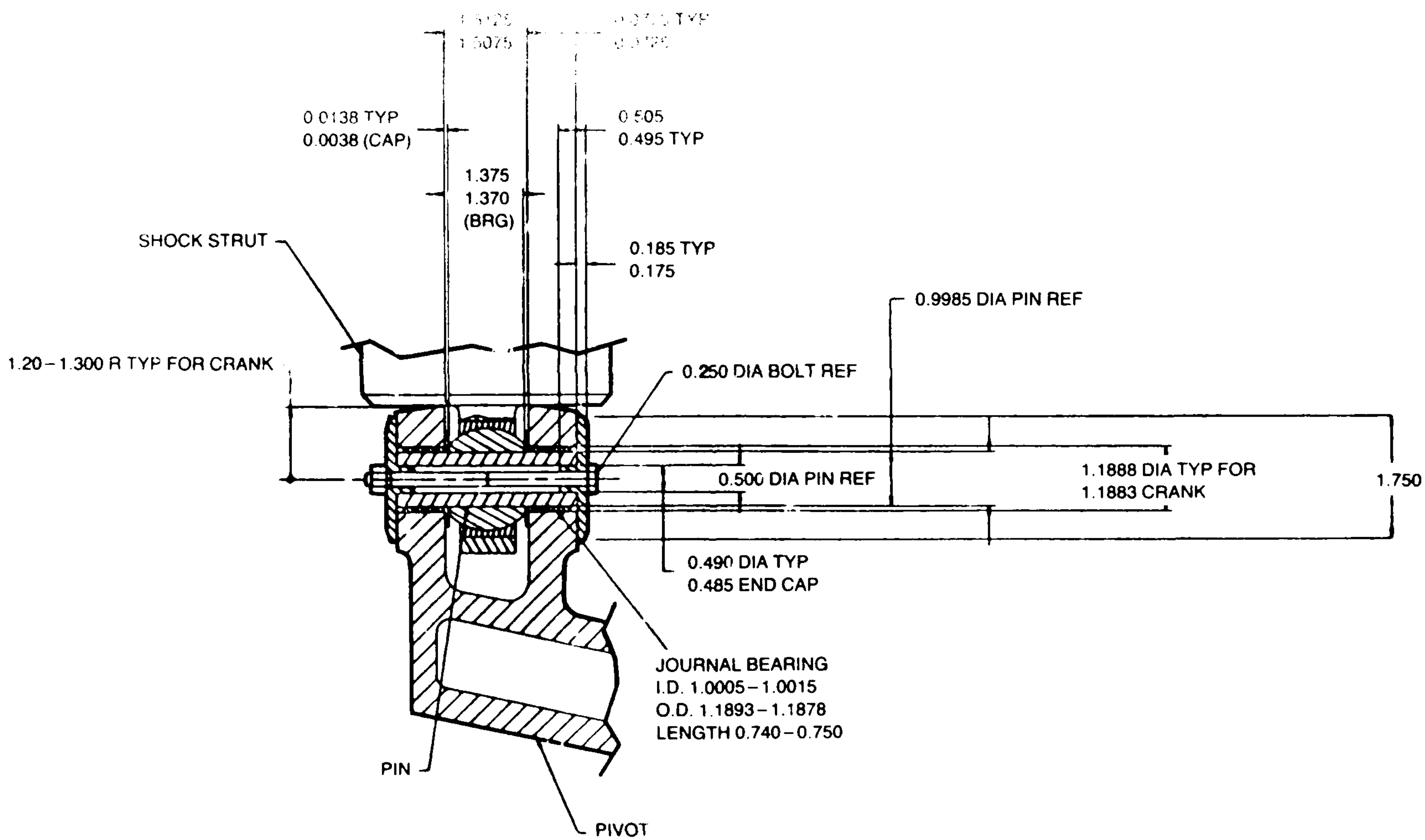


Figure 33. Design of upper attachment joint of the shock strut (Joint C in Table 11).

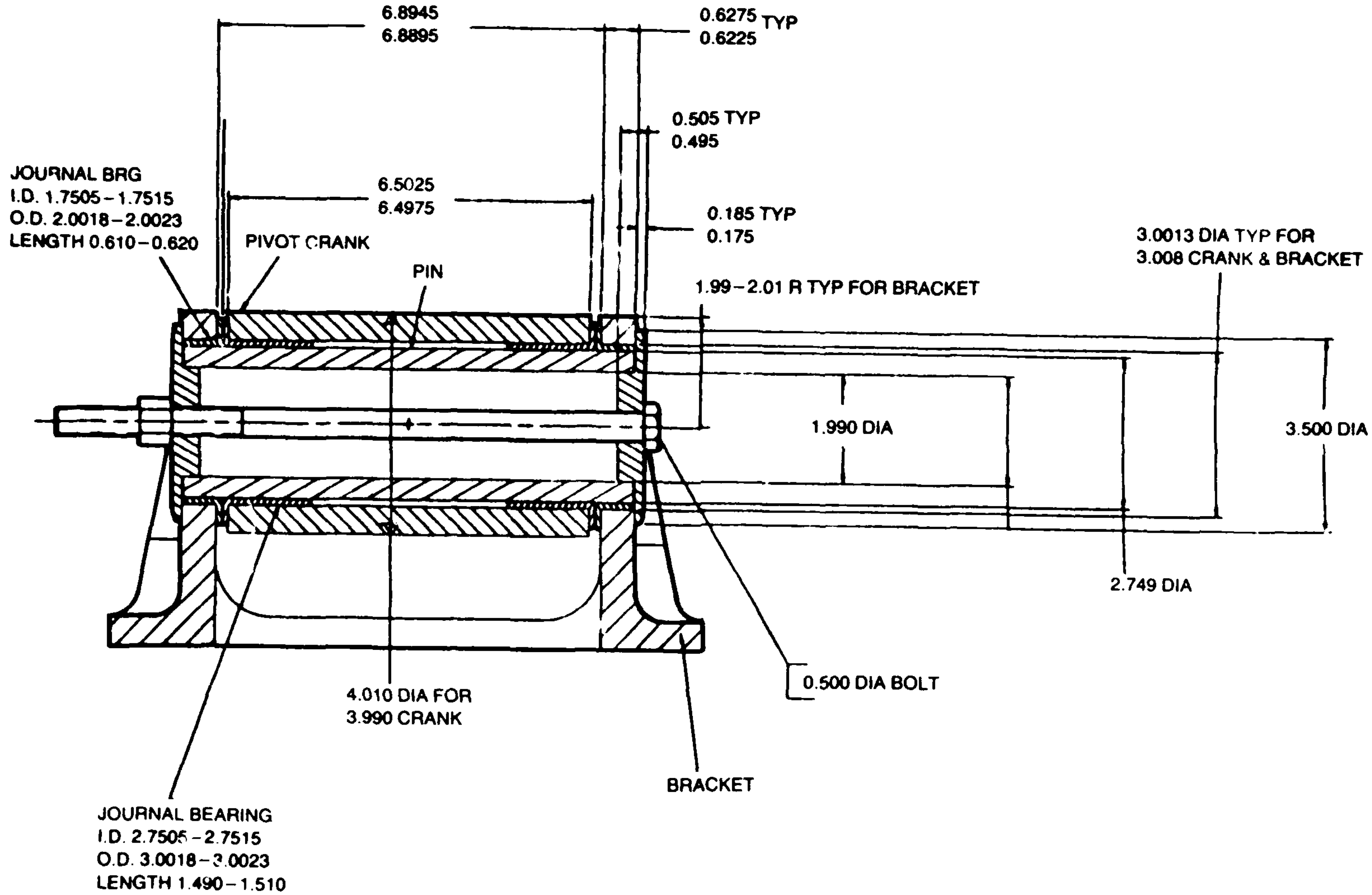


Figure 34. Design of the crank skew axis joint (Joint D in Table 11).

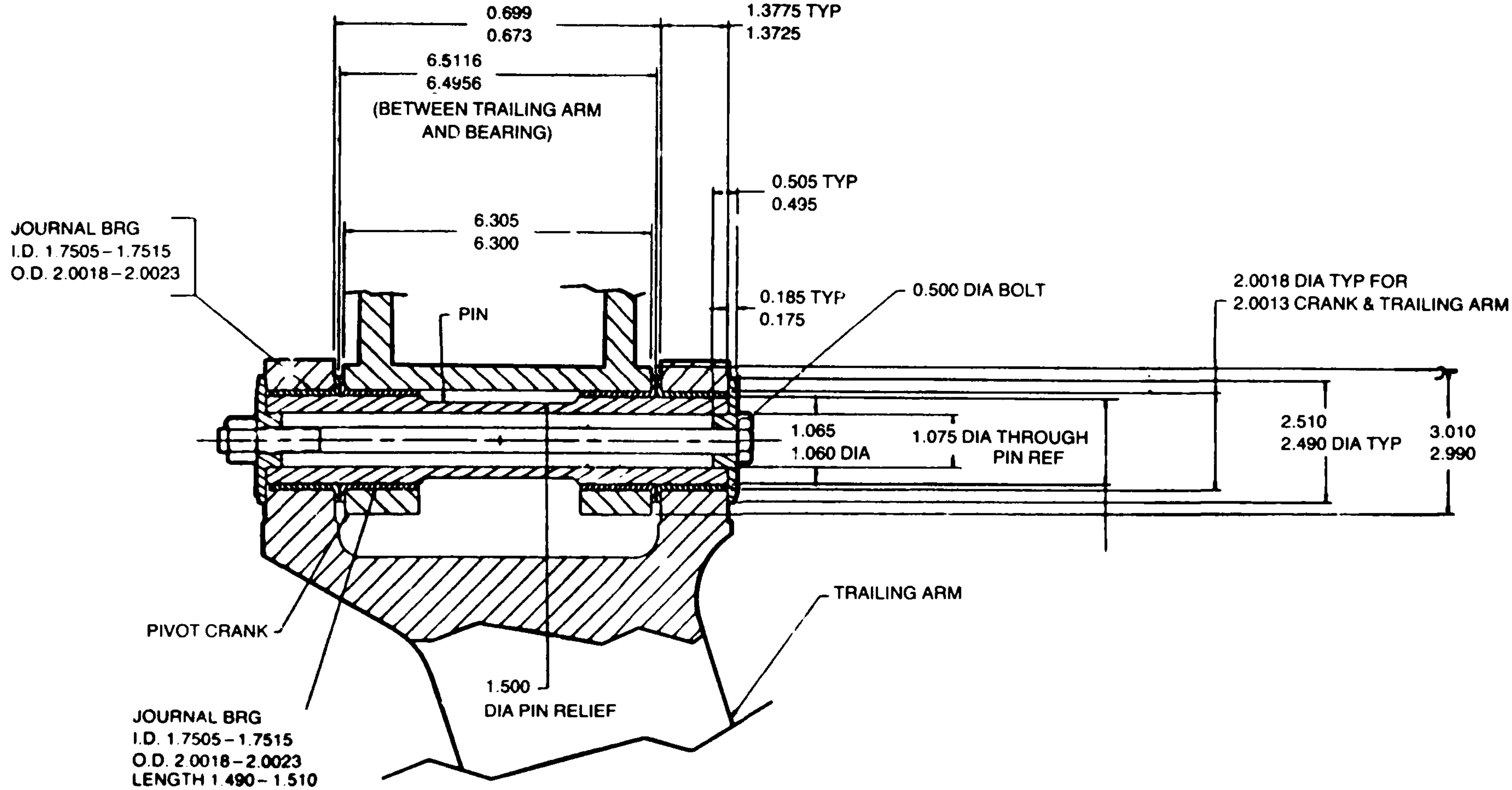


Figure 35. Design of the upper attachment joint of the trailing arm (Joint E of Table 11).

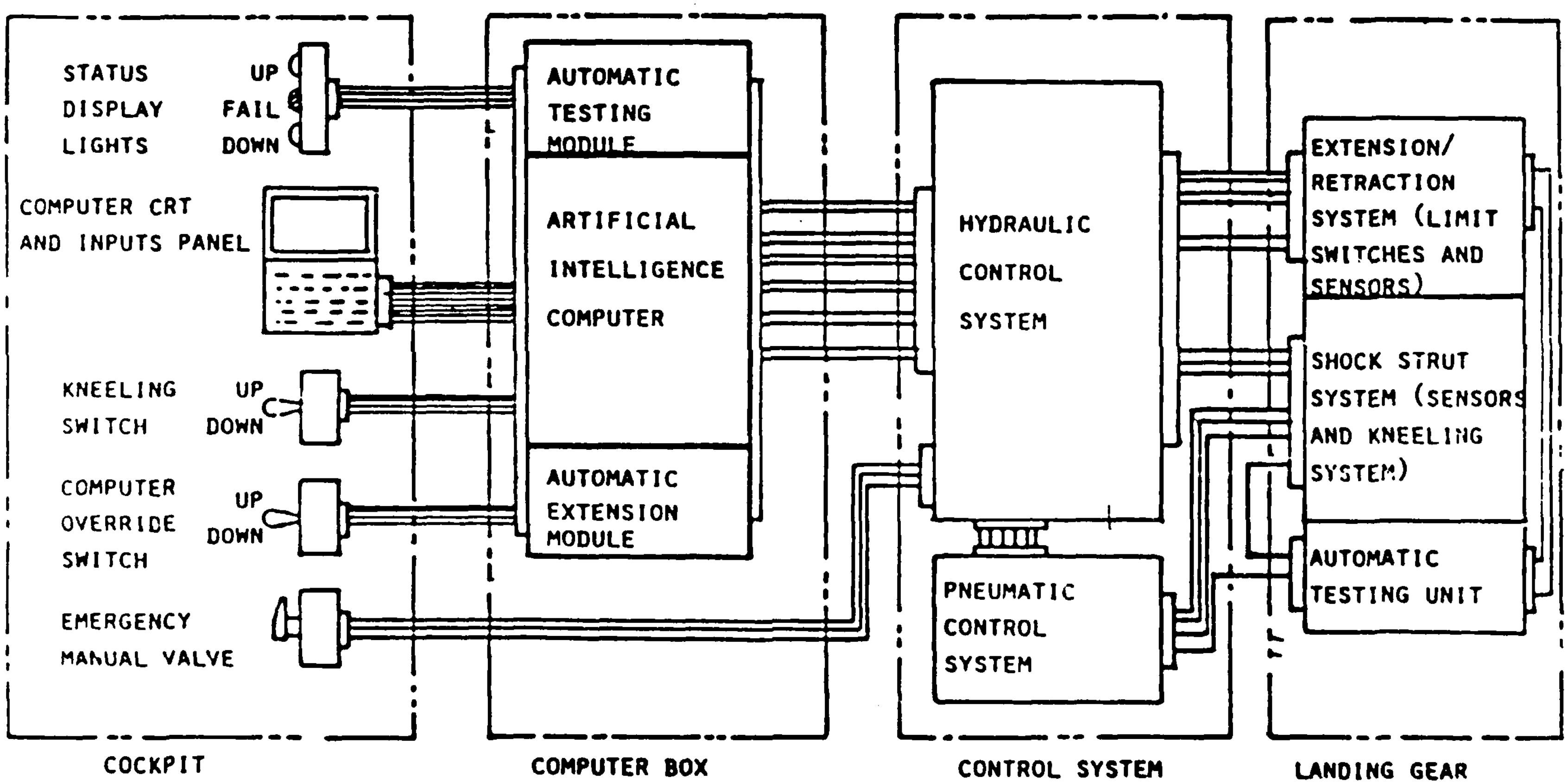


Figure 36. Block diagram of the landing gear control system.

3.11.1 Cockpit Group

Within the Cockpit Group there are five components, the functions of which are explained below.

Status Display Lights. Visual groups of lights that indicate where the gear is at any given moment. If the gear fails to actuate, a red "fail" blinking light will be on until the problem is resolved.

Computer CRT and Inputs Panel. Displays menus and inputs of programs for automatic response, real time, type of mission and other parameters to control the gear. It displays component's status.

Kneeling Switch. After "Kneeling" menu is keyed into the computer, it allows the aircraft to kneel from a static position to any height down to 3 inches ground clearance.

Computer Override Switch. The switch extends or retracts the gear, bypassing the computer programming in case of an emergency, e.g., when ice is formed, or when testing.

Emergency Manual Valve. This hydraulic valve operates the gear in case of an emergency caused by electrical and hydraulic failures; this valve opens the main control valve to the gear.

3.11.2 Computer System Group

Within the Computer System Group, there are three components. The functions of these components are described below.

Automatic Testing Module. This dedicated computer module periodically verifies the working status of the hydraulic valves, the pneumatic control system, the pressure of the nitrogen in the oleo and the electrical systems, and compares the answer to some basic parameter. In case of disagreement, a failure is reported to the main computer for further action.

Artificial Intelligence Computer. It is one of the main "Smart" computers aboard the aircraft that makes basic operational decisions based on inputs from sensors or other computers or the crew, such as deciding to extend the gear in case of an emergency by giving priority to the landing gear support equipment over any other subsystem sharing the same support system. A block diagram of the inputs affecting the decision-making process is given in Figure 37.

Automatic Extension Module. This dedicated computer module that monitors several preprogrammed parameters and reports them to the main computer for emergency decisions.

3.11.3 Control System Group

The Control System Group includes the two components described below.

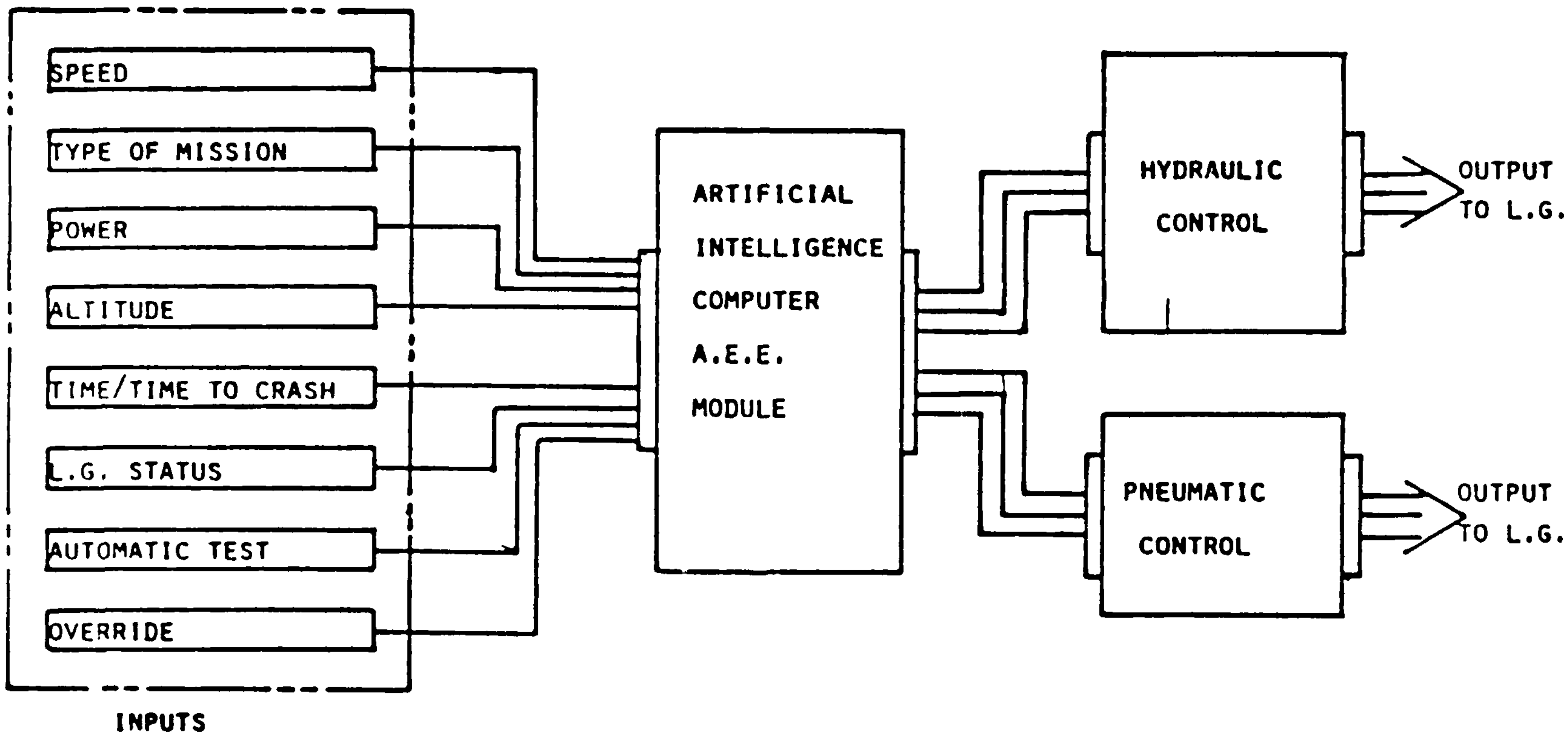


Figure 37. Block diagram of the automatic emergency extension module.

Hydraulic Control System. This control system is part of the hydraulic system for the landing gear and includes a main control valve electrically operated by solenoids, an isolation valve, a shuttle valve, an accumulator, and associated hardware. The hydraulic pressure for the system is provided by a pump in the aircraft. The system works on 4000 psi and has enough flow to satisfy the emergency extension time of 2.5 seconds.

The control valve has independent electrical inputs for extension or retraction. The isolation valve prevents hydraulic fluid losses in case of damages to the components or the lines. In case of failure, the accumulator replaces the pump. The shuttle valve allows the use of the manual emergency valve at the cockpit to extend the gear at the same time that it isolates the main control valve. The block diagram of the control system, the location of which is shown in Figure 37, is given in Figure 38. The hydraulic control system includes the landing gear actuators that are double-acting hydraulic cylinders with cushioned ends.

Pneumatic Control System. This system is part of the kneeling system and controls the flow or release of nitrogen to or from the second stage of the shock strut. There is a nitrogen supply system aboard the aircraft that operates at 2500 psi and is part of another system requirement. This nitrogen supply will be shared by the landing gear system.

The landing gear system includes the following feedback or sensor system:

- Limit switches and sensors at the retraction-extension linkage.
- Sensors at the shock strut for kneeling limits.
- Automatic testing sensors at the strut and the linkage actuator.

3.11.4 Fail-Safe Assessment

The control and power system for the landing gear were designed with redundancies and to be fail-safe under various conditions. In case of main hydraulic power loss, the hydraulic accumulator that primarily supports the APU becomes the emergency power unit for the gear. The transfer from standard power supply to the auxiliary power supply is automatic. In case both hydraulic supplies fail, a manual hydraulic valve moves the main control valve to a full return position so that the gear extends by its own weight. In case of electrical failure, the gear can be extended by a secondary electrical supply or by the manual hydraulic valve. The flow diagram for fail-safe operation is shown in Figure 39. An assessment of the designed-in options is given in Table 12.

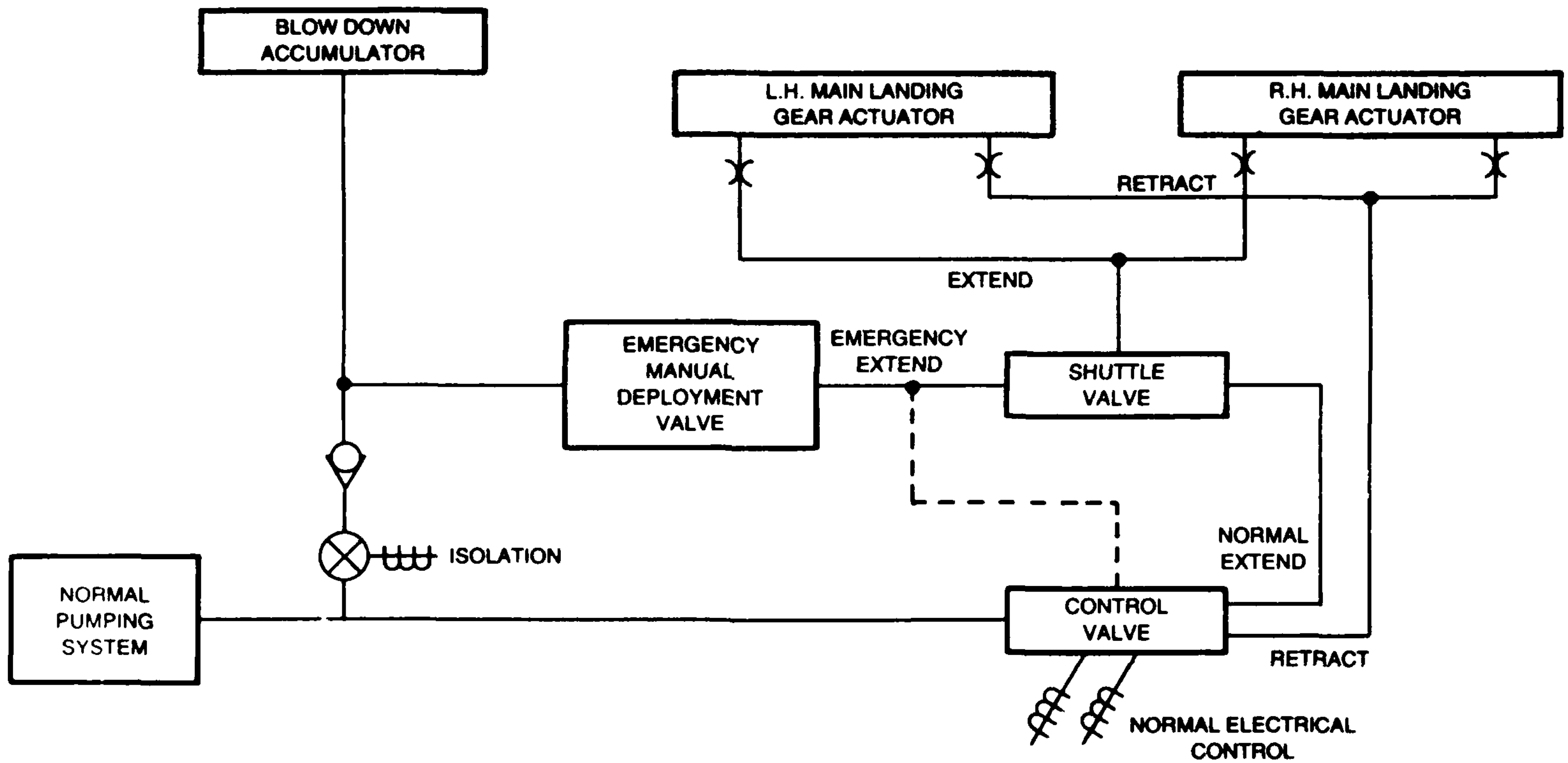


Figure 38. Hydraulic control system.

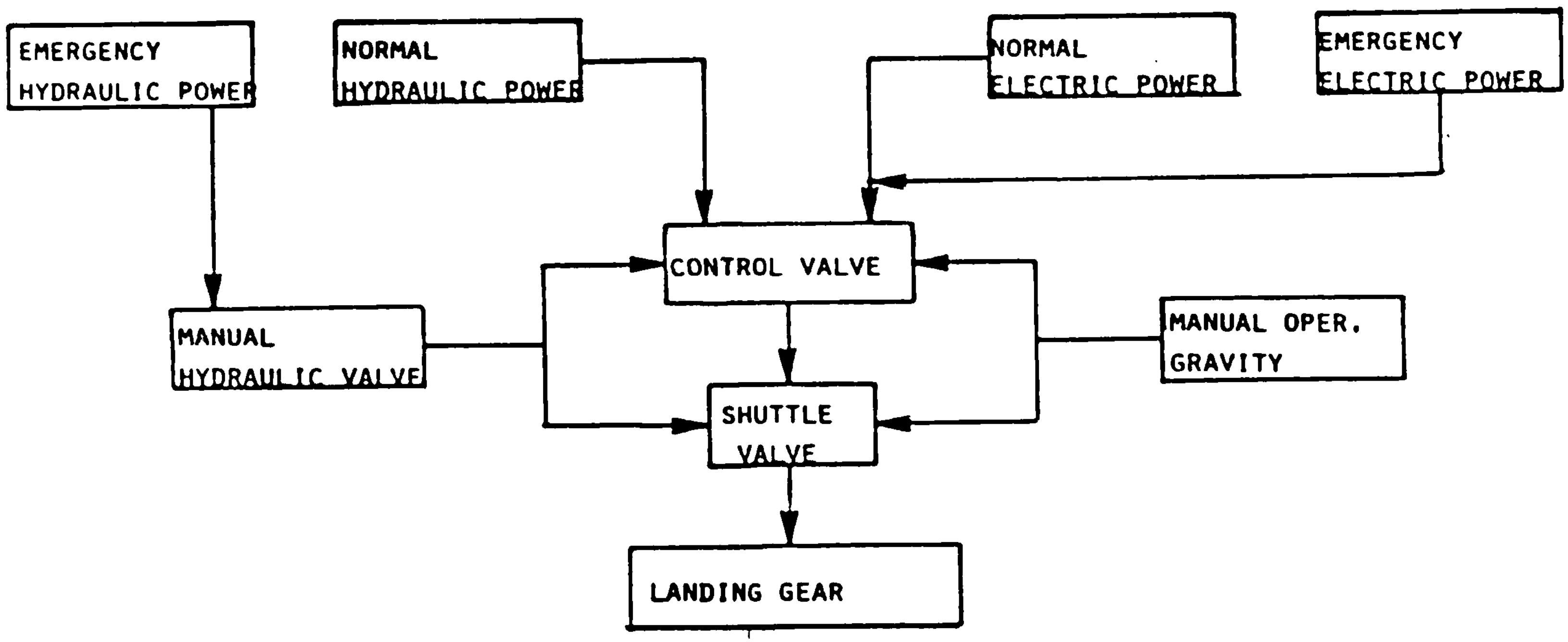


Figure 39. Flow diagram of available options for fail-safe operation of the landing gear.

TABLE 12. FAIL-SAFE ASSESSMENT OF LANDING GEAR

Hazard	Design
• Inadvertent Retraction	Weight-on Wheels Switch Interlock
• Will not Extend Using Normal System	Landing Gear Control must be in Extend position when Weight-On-Wheels senses airborne. If in Retract, it must be cycled before it will Retract.
• Pilot Fails to Extend Landing Gear	Warning
• Hydraulic Power Failure	Emergency hydraulic power is actuated and operation is with accumulator
• Electrical Power Failure	Emergency electric power is actuated and emergency manual hydraulic valve may also be used
• Backup Systems Failure	Emergency manual valve actuation; gravity will extend gear

4.0 COMPATIBILITY WITH SCAT HELICOPTER

4.1 BASELINE HELICOPTERS

The compatibility study with the SCAT-version of the helicopter is based on the designs of the utility and SCAT helicopters of February 1986, when the utility design was frozen for the ATLG program. The utility helicopter is designed with a nosewheel. The SCAT is a tailwheel configuration because the requirements of the utility helicopter are different from those for the SCAT, and because, more importantly, the tailwheel design eliminates interference of the weapon system with the landing gear. The SCAT helicopter is shown in Figure 40.

The two helicopters share common subsystems, such as the rotor and NOTAR systems; hydraulic, pneumatic and electrical systems; engines; transmission; crew seats; flight controls; ECS; fuel system and NBC suits. The landing gears of the utility and SCAT helicopters are compatible and interchangeable at the component and subassembly level, as explained below.

4.2 LANDING GEAR ARRANGEMENT

The components which are common to the utility and SCAT main landing gears are:

1. Wheel assembly
2. Retraction-extension lock
3. Trailing arm assembly
4. Strut assembly
5. Bearings and bushings
6. Joint pins
7. Controls
8. Hydraulic system
9. Installation hardware
10. Door actuators

All components of the strut assembly are common. The differences lie in the metering orifices and the ground resonance valve.

In addition to the main landing gear, commonality also exists in components of the nosewheel of the utility helicopter and the tailwheel of the SCAT helicopter. The common components are:

1. Wheel assembly
2. Retraction-extension lock
3. Castering lock
4. Bearings and bushings
5. Installation hardware
6. Hydraulic valves
7. Door actuators

The main landing gear of the utility helicopter is a unitized design concept where the entire landing gear is attached to the bulkhead at two clevices. This unit gear can be "moved" to different locations without disturbing the stroke, the energy-absorbing characteristics, or the kinematics. Depending on the specific SCAT design, the entire gear unit can be utilized in a SCAT helicopter with changes in the orifices, gas pressure and tuning for resonance.

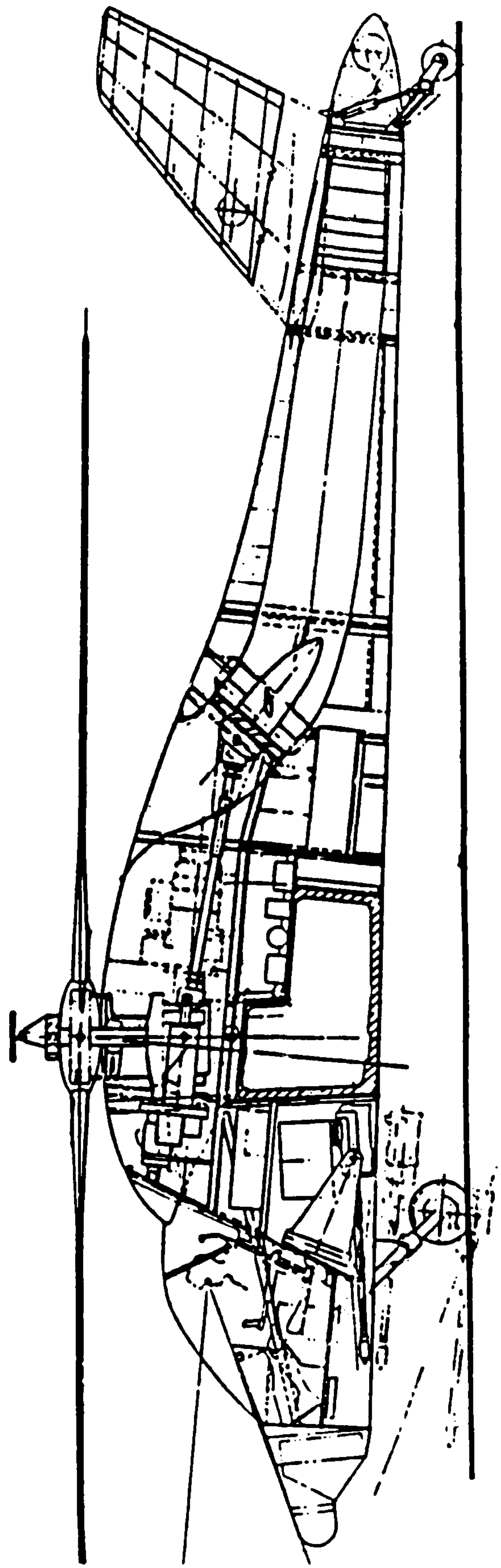


Figure 40. Configuration of the SCAT helicopter.

The parameters of the utility landing gear which can be adjusted or modified for full compatibility with the SCAT landing gear are given below.

Main Landing Gear System	Modification/Change
Skew Axis, Kinematics	The crank and the attachment to the fuselage bulkhead will be different depending on the SCAT configuration.
Shock Strut	Internal orifices and the ground resonance valve will have to be modified; the gas pressure for the first and second stages may require modification. (The orifices and the pressure changes will depend on the energy to be absorbed by the strut.)

Tail Landing Gear System	Modification/Change
Trailing Arm and Axle	New components
Shock Strut	New component
Fuselage Attachment	New design

4.3 SCAT WEIGHT

The gross weight of the SCAT helicopter is 8,500 pounds, the same as the optimized weight of the crashworthy utility helicopter. The weights of the utility and SCAT helicopters are compared in Table 13.

4.4 SCAT ENERGY ABSORPTION CAPABILITY

The SCAT helicopter is operated by a single pilot. In contrast to the utility helicopter, which has a crew of two and six troops, the SCAT helicopter has a narrower fuselage. Thus, the capability of the SCAT fuselage to absorb energy is reduced if its fuselage is scaled from that of the utility helicopter. If the SCAT landing gears are exactly interchangeable with that of the utility helicopter, the SCAT landing gear will still absorb 60 percent of the energy from a 42 fps level impact and the fuselage will be incapable of absorbing the remaining 40 percent.

In order for the SCAT fuselage to absorb the 40 percent of the energy from a 42 fps level impact, the fuselage must be redesigned. In redesigning the fuselage, two options are available: (1) use the same number of energy-absorbing elements as in the utility helicopter but space them closer in the SCAT fuselage, and (2) use different energy-absorbing elements but retain the same spacing as in the fuselage of the utility helicopter. Both options are practical; however, the first option is more likely to raise g-loads transmitted through the fuselage. The final configuration can only be determined from a detail design of the SCAT fuselage.

TABLE 13. GROUP WEIGHT STATEMENTS OF THE UTILITY AND SCAT HELICOPTERS

Item	Optimized Utility (lb)	Optimized SCAT (lb)
Main Rotor Group	668	668
Tail Group	190	190
Body Group	922	826
Alighting Gear Group	417	422
Nacelle	120	120
Air Induction	27	27
Propulsion	1443	1443
Flight Controls	422	422
Auxiliary Power Plant	60	60
Instruments	91	91
Hydraulics and Pneumatics	215	215
Electrical	229	229
Avionics	270	270
Armament	457	457
Furnishing and Equipment	372	130
Air Conditioning	180	180
Anti-Ice	16	16
Loading and Handling	5	5
Weight Empty	6104	5771
Crew	235	235
Unusable Fuel	18	18
Engine Oil	25	25
Fuel	776	776
Payload (6 Troops or Weapon System)	1342	1675
Gross Weight	8500	8500

5.0 LOAD AND STRUCTURAL ANALYSIS

5.1 GROUND LOAD CONDITIONS

The maximum landing loads of the baseline crashworthy helicopter for a basic structural design gross weight (BSDGW) of 8,500 pounds and for an alternate design gross weight (ADGW) of 10,625 pounds were established during preliminary design. The calculated inertias are shown in Table 6. The design of the landing gear was sized by a combination of vertical loads during crash-impact and obstruction loads. Preliminary landing loads were first established for a level three-point limit landing at 10 feet per second of the ADGW crashworthy helicopter and a crash landing at 42 feet per second of the BSDGW crashworthy helicopter. Concurrently, a simple five-mass KRASH model, described in Section 2.4.2, was established to size the system for crashworthiness. After optimizing the system (load factors and strokes for the landing gear, fuselage and crew seat) for crashworthiness, the ground loads were calculated for 25 landing conditions including crash impact. The ground loads for all conditions are given in Table 14 and the variations of the ground loads with stroke for the two severest impact conditions are shown in Figure 41.

5.2 ULTIMATE LOAD CONDITIONS

The ultimate loads for the design of the shock strut were based on a ground load curve that would produce an 80 percent efficient landing gear for the level landing condition of 42 feet per second. Gear efficiency is the area under the load-stroke curve divided by the product of the maximum load and the total stroke. Initially the total energy of the crash was assumed to be distributed in a ratio of 45:55 between the fuselage and the landing gear. The level crash landing load was distributed 31.2 percent to the nose gear and 34.4 percent to each of the main gears. The maximum load in the shock strut was assumed to develop at 5 inches of vertical stroke. This assumption is based on the qualification tests on the Apache landing gear reported in Reference 5. The shock strut was designed with a load-limiting device to ensure that the ground loading would remain under 22,400 pounds in the level landing condition. The shock strut limit load in this case was 47,540 pounds. The estimated load-stroke curve for the shock strut is shown in Figure 42.

The remaining ultimate load conditions were set by the limit value sustained by the shock strut. The ground loading for the pitch-down and roll cases were then based on the shock strut load of 47,540 pounds. The vertical load and the drag loads were applied at the wheel center. The side load was applied at a flat tire radius of 5.8 inches.

5.3 INTERNAL LOADS DISTRIBUTION

The internal loads distributions for the various components were calculated for the 21 loading conditions given in Table 14. These conditions are identified as "limit," "reserve energy," "no yield," and "ultimate." The criteria for analysis are modified by the factor of safety (F.S.) for these four conditions as follows: (a) limit loads, F.S. = 1.0, no failure with F.S. = 1.5; (b) reserve energy, no failure with F.S. = 1.0; (c) no yield, F.S. = 1.0; and (d) ultimate, no failure with F.S. = 1.0.

TABLE 14. MAIN LANDING GEAR DESIGN GROUND LOADS

No.	Condition	Type Impact	Sink Speed (fps)	Gross Weight (lbs)	Load Factor (g's)	Ground Load per Main Wheel (kips)		
						V	D	S
1	3-Point Level	Limit	10.00	8,500	2.05	6.70	-	-
		Reserve Energy	12.25	8,500	3.08	10.05	-	-
2	3-Point	Limit	10.00	8,500	2.05	5.78	1.45	-
		Reserve Energy	12.25	8,500	3.08	8.67	2.17	-
3	2-Point Level w/Drag	Limit	10.00	8,500	2.05	7.30	1.83	-
		Reserve Energy	12.25	8,500	3.08	10.95	2.75	-
4	2-Point Level w/Drag	Limit	10.00	8,500	2.05	7.30	±3.35	-
		Reserve Energy	12.25	8,500	3.08	10.95	±5.48	-
5	1-Wheel	Limit	10.00	8,500	2.05	7.43	-	-
6	Tail-Down 15° Pitch	Limit	10.00	8,500	2.05	8.51	-	-
7	Tail-Down 15° Pitch 10° Roll	Limit	10.00	8,500	2.05	10.47	-	-
8a	Hard Level	No Yield	20.00	10,625	4.65	17.00	4.25	-
8b	Hard Level	No Yield	20.00	10,625	4.65	17.00	-4.25	-
8c	Hard Level	No Yield	20.00	10,625	4.65	17.00	-	4.25
8d	Hard Level	No Yield	20.00	10,625	4.65	17.00	-	-4.25
9	Hard 15° Pitch	No Yield	20.00	10,625	-	22.90	-	-
10	Hard 15° Pitch 10° Roll	No Yield	20.00	10,625	-	23.30	-	-
11	3-Point Braked Roll	Limit	-	10,625	1.00		2.07	-

TABLE 14 - Continued

No.	Condition	Type Impact	Sink Speed (fps)	Gross Weight (lbs)	Load Factor (g's)	Ground Load per Main Wheel (kips)		
						V	D	S
12	2-Point Braked Roll	Limit	-	10,625	1.00	5.31	4.25	-
13	Reversed Braking	Limit	-	10,625	1.00	5.31	-4.25	-
14	Static	Limit	-	8,500	1.00	3.27	-	-
15	2g Taxi	Limit	-	8,500	2.00	6.54	-	-
16	Pivoting	Limit	-	8,500	1.00	3.27	-	-
17	Lateral Drift Left	Limit	10.00	8,500	2.05	3.35	-	-2.68
18	Lateral Drift Right	Limit	10.00	8,500	2.05	3.35	-	2.01
19a	Level Crash	Ultimate	42.00	8,500	7.66	22.40	-	5.03
19b	Level Crash	Ultimate	42.00	8,500	7.66	22.40	-	-5.03
20	Crash 15° Pitch	Ultimate	42.00	8,500	-	30.20	-	-
21	Crash 15° Pitch 10° Roll	Ultimate	42.00	8,500	-	30.67	-	-

NOTES

(1) Loading applies from 5 inches of vertical stroke to kneeling position for conditions 8 through 10.

(2) Loading applies from 5 inches of vertical stroke to fully crashed position for conditions 19 through 21.

(3) Unless otherwise noted, loading applies from fully extended to 13-inch vertical axle travel.

(4) See Figure 39 for the Variations of Ground Loads with stroke for Conditions 20 and 21.

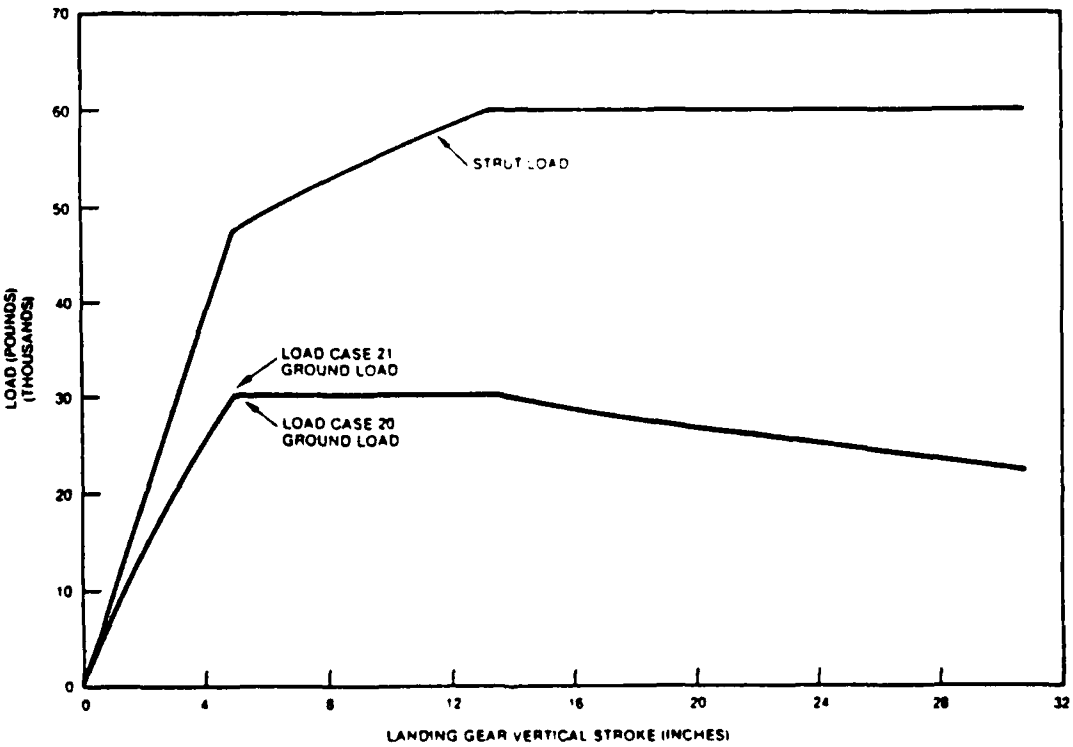


Figure 41. Variation in ground and strut loads for conditions 20 and 21 of Table 14.

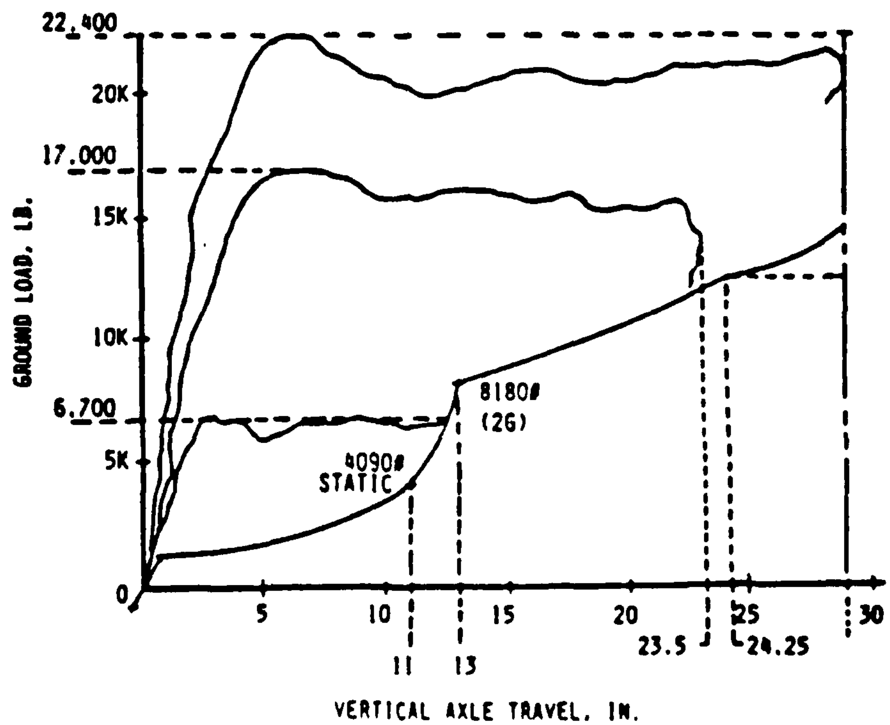


Figure 42. Estimated load-stroke curve for the shock strut in terms of vertical travel of the axle.

The stress analyses of the components of the landing gear are divided into two sections: (a) the major components and (b) the support components. For all components analyzed, the margins of safety at critical sections for the particular loading condition have been determined.

5.3.1 Stress Analysis of Major Components

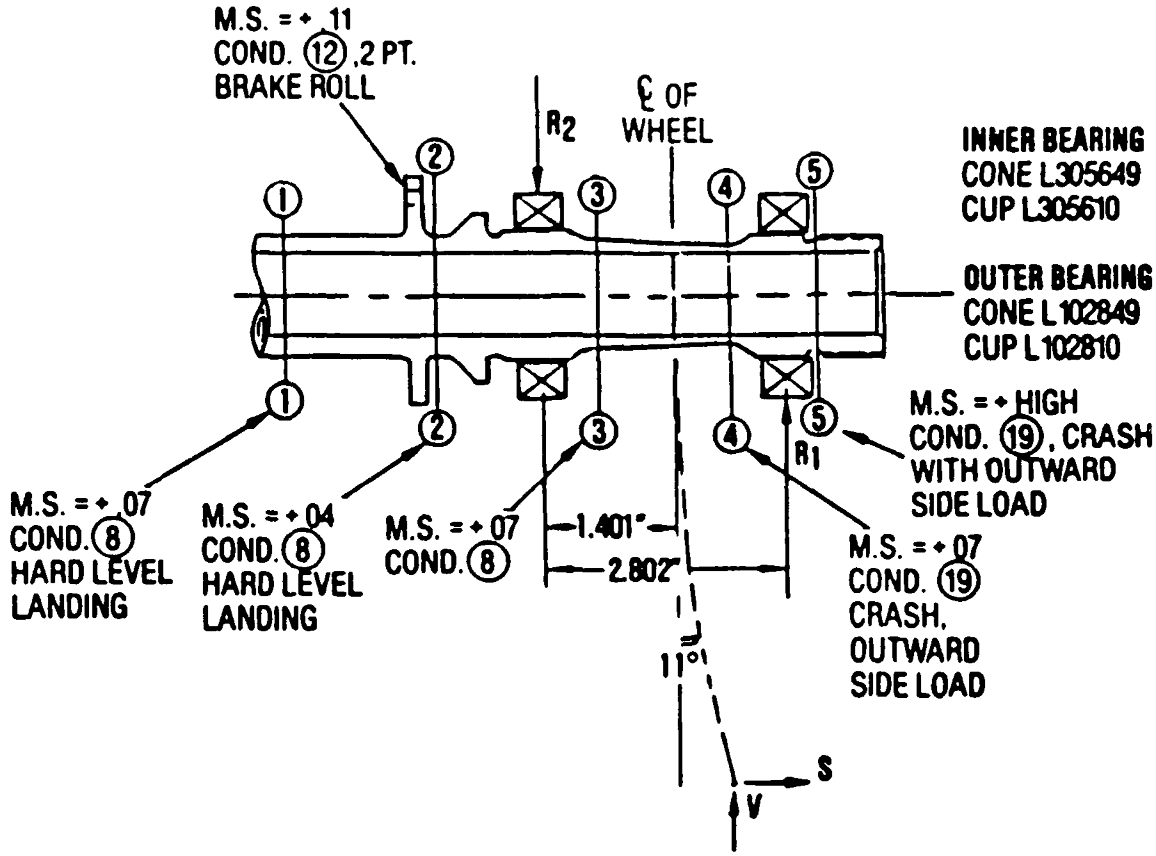
The major components of the landing gear are the trailing arm and axle, the shock strut, and the retraction actuator with the linkage assembly. The margins of safety for these components are summarized in this section.

The axle is made of 4330V steel alloy, heat treated to 200/240 ksi. The axle has five critical diametrical sections as shown in Figure 43. The minimum margin of safety for an axle section is +0.04 and occurs just outboard of the brake flange lugs. The load condition that makes this section critical is condition 8c of Table 14: hard level landing at 20 feet per second from an aircraft gross weight of 10,625 pounds with no yielding. The minimum margin of safety for the axle assembly is +0.01 and occurs at the through cross bolt holes 3.19 inches from the axle's inner end. The margins of safety for the axle, the jacking pad and the washer key are summarized in Table 15.

The trailing arm is made of 7175-T74 aluminum alloy and has been analyzed for six critical sections, in addition to its lugs and other attachment hardware. The critical sections of the trailing arm are shown in Figure 44. The minimum margin of safety of +0.03 occurs at a section 8.75 inches below the upper attachment point. This minimum is for loading condition 20 of Table 14, i.e., for crash impact at 42 feet per second with +15 degrees pitch for an aircraft gross weight of 8,500 pounds. The margins of safety for the trailing arm and attachment hardware are summarized in Table 16.

The main components of the shock strut are the piston, made of 4340 steel alloy and heat treated to 180/200 ksi; the inner cylinder, made of 7175-T74 aluminum alloy; and the outer cylinder, also made of 7175-T74 aluminum alloy. The critical sections of the shock strut are shown in Figure 45. The margins of safety for the shock strut components are higher than those for the axle and trailing arm. Only the gland nut for the second stage has a margin of safety of +0.04. A summary of the margins of safety are given in Table 17.

The retraction of the landing gear is designed such that the load is reacted by an outside linkage system parallel to the retraction actuator. The cylinder of the actuator is made of 7075-T73 aluminum alloy and the rod is made of 4340 steel alloy heat treated to 180/200 ksi. All major components of the linkage assembly - upper and lower links, clevis, bracket, and upper and lower lock arms - are made of 7075-T73 aluminum alloy. The exception is the torque tube of the linkage assembly which is made of 4340 steel heat treated to 180/200 ksi. The critical sections of the retraction actuator are shown in Figure 46, and of the upper and lower links in Figure 47. The minimum margin of safety for these components is +0.08 and occurs at the thread relief for the gland nut in the retraction actuator cylinder. The load condition, however, is for burst test pressure. The margin of safety for the upper and lower links is higher than +0.26 The margins of safety for the retraction actuator, the linkage assembly and attachment hardware are summarized in Table 18.

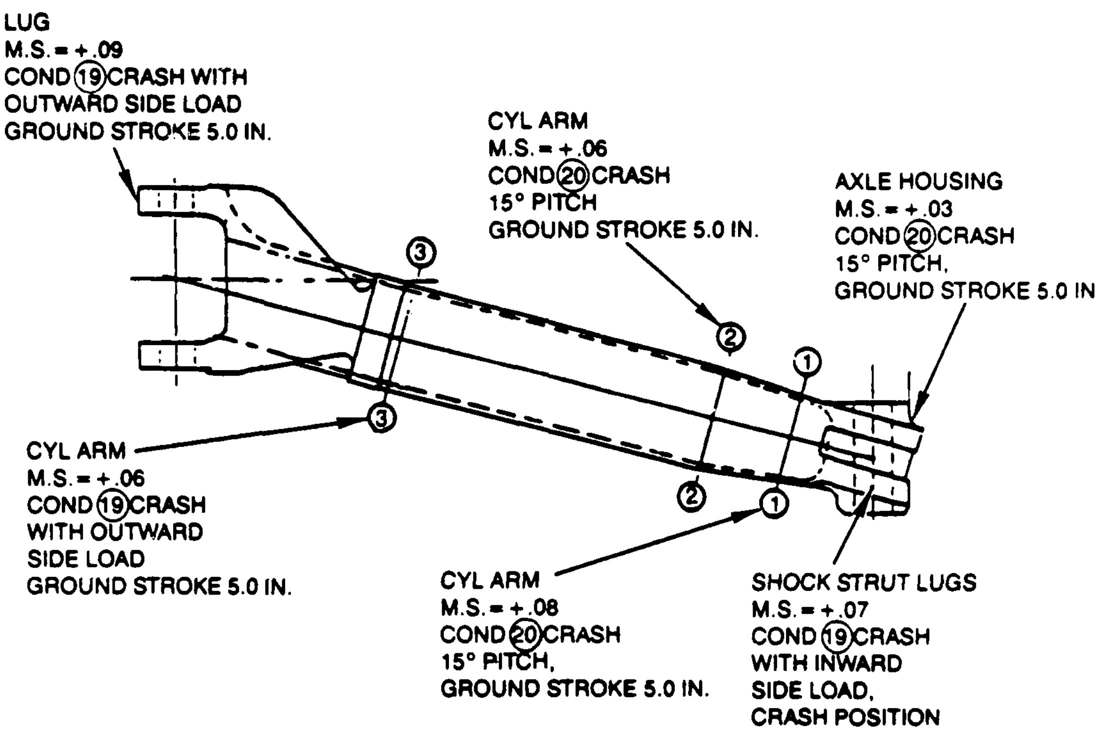


Section/Location	Load Case	Stress Condition	Margin of Safety
1-1	8c	F_{TY}, F_{BY}, F_{SY}	+0.07
2-2	8c	F_{TY}, F_{BY}, F_{SY}	+0.04
3-3	8c	F_{TY}, F_{BY}, F_{SY}	+0.07
4-4	19a	F_{TY}, F_{SUN}	+0.04
5-5	19a	F_{TU}, F_{BU}	+7.0
Through Bolt Holes	8c	F_{TY}, F_{BY}, F_{SY}	+0.01
Socket Pin Max Bending	8c	F_{TY}, F_{BY}	+0.04

Figure 43. Critical sections of the axle.

TABLE 15. SUMMARY OF MARGINS OF SAFETY OF THE AXLE AND ATTACHMENT HARDWARE

Part	Drawing No.	Material	Heat Treat (ksi)	Section	Table 14 Load Condition	Stress	M.S.
Axle	1252002	4330 V Steel	220/240	1 - 1	8C	$F_{TY}.F_{BY},F_{SY}$	+0.07
Axle	1252002	4330 V Steel	220/240	2 - 2	8C	$F_{TY}.F_{BY},F_{SY}$	+0.04
Axle	1252002	4330 V Steel	220/240	3 - 3	8C	$F_{TY}.F_{BY},F_{SY}$	+0.07
Axle	1252002	4330 V Steel	220/240	4 - 4	19a	F_{TU},F_{SUN}	+0.07
Axle	1252002	4330 V Steel	220/240	Socket Pin Max Bending	8C	$F_{TY}.F_{BY}$	+0.04
Axle	1252002	4330 V Steel	220/240	5 - 5	19a	F_{TU},F_{BU}	+HIGH
Axle	1252002	4330 V Steel	220/240	Brake Flange Lugs	12	Lug Shear-Bearing	+0.11
Axle	1252002	4330 V Steel	220/240	Thru Cross Bolt Holes of Axle	8C	$F_{TY}.F_{BY},F_{SY}$	+0.01
Axle	1252002	4330 V Steel	220/240	Jacking Pad Socket Section Analysis	Jacking Load	Lug Shear-Bearing	+HIGH
Pad, Jacking	1252005	300 M Steel	280/300	1 - 1	Jacking Load	F_{BU},F_{SU},F_{STU}	+0.64
Pad, Jacking	1252005	300 M Steel	280/300	2 - 2	Jacking Load	F_{BU},F_{SU},F_{STU}	+0.64
Pad, Jacking	1252005	300 M Steel	280/300	3 - 3	Towing Load	F_{BU},FS_{U},F_{STU}	+HIGH
Pad, Jacking	1252005	300 M Steel	280/300	4 - 4	Jacking Load	F_{CU},F_{BU},F_{SU}	+HIGH
Washer-Key, Retaining, Wheel Bearing	1252010	4340 VAC STL per MIL-S-8844	180/200	At Tang	19a	F_{BRU}	+0.51

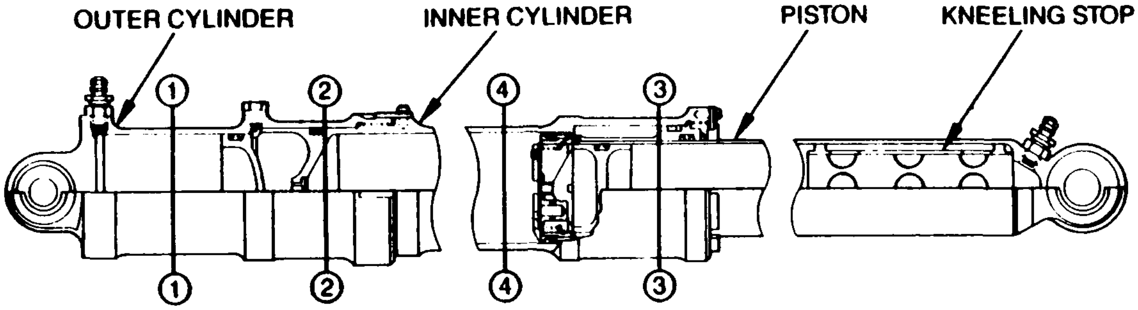


Section/Location	Load Case	Stress Condition	Margin of Safety
1-1	20	F_{TU}, F_{BU}, F_{SU}, F_{STU}	+0.05
2-2	20	F_{TU}, F_{BU}, F_{SU}, F_{STU}	+0.03
3-3	20	F_{TU}, F_{BU}, F_{SU}, F_{STU}	+0.04
4-4	19a	F_{TU}, F_{BU}, F_{SU}, F_{STU}	+0.23
5-5	19a	F_{TU}, F_{BU}, F_{SU}	+0.86
6-6	19a	F_{TU}, F_{BU}, F_{SU}, F_{ST}	+0.71
Shock Strut Attach Lugs	19b	Transverse Grain Direction - F_{TRU}	+0.04
Axle Housing	20	Axial and Transverse Loading	+0.07
Inner Lug at Upper Attachment	19a	Axial and Transverse Loading	+0.07

Figure 44. Critical sections of the trailing arm.

TABLE 16. SUMMARY OF MARGINS OF SAFETY OF THE TRAILING ARM AND ATTACHMENT HARDWARE

Part	Drawing No.	Material	Heat Treat (ksi)	Section	Table 14 Load Condition	Stress	M. S.
Trailing Arm	1252001	7175 AL-Alloy	774	1 - 1	20	F_{TU},F_{BU},F_{SU},F_{STU}	+0.05
Trailing Arm	1252001	7175 AL-Alloy	774	2 - 2	20	F_{TU},F_{BU},F_{SU},F_{STU}	+0.03
Trailing Arm	1252001	7175 AL-Alloy	774	3 - 3	20	F_{TU},F_{BU},F_{SU},F_{STU}	+0.04
Trailing Arm	1252001	7175 AL-Alloy	774	Shock Strut Attach Lugs	19b	Lug Transverse Load	+0.04
Trailing Arm	1252001	7175 AL-Alloy	774	Axle Housing	20	Lug Axial & Transverse Load	+0.07
Trailing Arm	1252001	7175 AL-Alloy	774	Inner Lug of Upper Attach	19a	Lug Axial and Transverse Load	+0.07
Trailing Arm	1252001	7175 AL-Alloy	774	Outer Lug of Upper Attach	19b	Lug Axial and Transverse Load	+0.18
Trailing Arm	1252001	7175 AL-Alloy	774	4 - 4	19a	F_{TU},F_{BU},F_{SU},F_{STU}	+0.23
Trailing Arm	1252001	7175 AL-Alloy	774	5 - 5	19a	F_{TU},F_{BU},F_{SU}	+0.86
Trailing Arm	1252001	7175 AL-Alloy	774	6 - 6	19a	F_{TU},F_{BU},F_{SU},F_{STU}	+0.71
Pin, Trailing Arm Upper Attach.	1252120-5	300 M Steel	275/300	At Maximum Shear Section	8C	F_{BY}, F_{SY}	+0.34
Stud, Trailing Arm Upper Attach.	1252009	4340 Steel	160/180	Basic Stud Section	19a	F_{TU}	+0.63
Cap, Pin, Trailing Arm Upper Attach.	1252119-5	7075 AL-Alloy	773	A - A	19a	F_{BU}, F_{SU}	+HIGH
Cross Bolt, Trailing Arm to Axle	MS21250-10056	Steel	180/200	At Maximum Shear Section	12	F_{BU}, F_{SU}	+0.04



Section/Location	Load Case	Stress Condition	Margin of Safety
Piston 3-3	10	F_{HT} (No Yield)	+0.63
Inner Cyl 4-4	10	F_{HT} (No Yield)	+0.08
Inner Cyl 2-2	10	F_{HT} (No Yield)	+0.10
Outer Cyl 1-1	10	F_{HT} (No Yield)	+0.07
Outer Cyl 2-2	10	F_{HT} (No Yield)	+0.08
Pin Outer Cyl	10	F_{BY}	+0.13
Pin Shock Strut	10	F_{BY}	+0.16
Gland Nut - 2nd	10	F_{BY}, F_{TY}	+0.04

Figure 45. Critical sections of the shock strut.

TABLE 17. SUMMARY OF MARGINS OF SAFETY OF THE SHOCK STRUT AND ATTACHMENT HARDWARE

Part	Drawing No.	Material	Heat Treat (ksi)	Section	Table 14 Load Condition	Stress	M.S.
Piston, Shock Strut	1252101	4340 Steel	180/200	1 - 1	10	F_{HT} (No Yield)	+0.63
Piston, Shock Strut	1252101	4340 Steel	180/200	2 - 2	Static Pressure	F_{BRU}	+HIGH
Inner Cylinder Shock Strut	1252102	7175 AL-Alloy	T74	1 - 1	10	F_{HT} (No Yield)	+0.08
Inner Cylinder Shock Strut	1252102	7175 AL-Alloy	T74	2 - 2	10	F_{HT} (No Yield)	+0.10
Outer Cylinder Shock Strut	1252103	7175 AL-Alloy	T74	1 - 1	10	F_{HT} (No Yield)	+0.07
Outer Cylinder Shock Strut	1252103	7175 AL-Alloy	T74	2 - 2	10	F_{HT} (No Yield)	+0.09
Outer Cylinder Shock Strut	1252103	7175 AL-Alloy	T74	3 - 3	10	F_{SY}	+HIGH
Lower Bearing Shock Strut	1252104	AL-Ni-BR	Per AMS 4880	1 - 1	10	F_{BY},F_{SY}	+0.68
Orifice, 2nd Shock Strut	1252106	7075 AL-Alloy	T73	Bearing Surface	Preloading	F_{BRY}	+0.45
Floating Piston, Shock Strut	1252107	AL-Ni-BR	Per AMS 4880	Basic Wall	19b	F_{BU}	+HIGH
Floating Piston, Shock Strut	1252108	7075 AL-Alloy	T73	Through Web	10	F_{BY}	+0.75
Piston Ring, Shock Strut	1252109	AL-Ni-BR	Per AMS 4880	Ring Analysis	Installation Load	F_{TU}	+HIGH
Gland Nut, Shock Strut	1252110	7075 AL-Alloy	T73	Thru Threads	10	F_{SY}	+HIGH

TABLE 17. - Continued

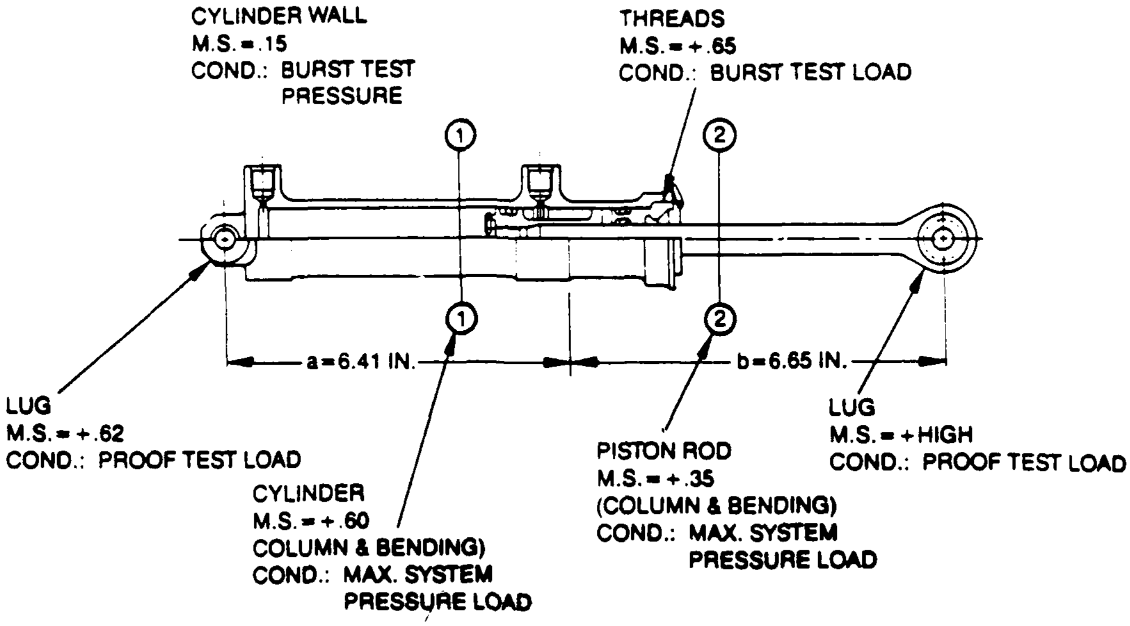
Part	Drawing No.	Material	Heat Treat (ksi)	Section	Table 14 Load Condition	Stress	M.S.
Spacer, Shock Strut	1252113	7075 AL-Alloy	T73	Basic Wall	Box Unsprung Load	F_{CY}	+HIGH
Gland Nut, 2nd Stage Shock Strut	1252115	4340 Steel	180/200	Tube Wall	10	F_{BY},F_{TY}	+0.04
Pin, Outer Cylinder S.S.	1252120-1	300 M Steel	280/300	Maximum Bending	10	F_{BY}	+0.13
Pin, Piston Shock Strut	1252120-3	300 M Steel	280/300	Maximum Bending	10	F_{BY}	+0.16
Spacer, Internal Stop, Shock Strut	1252122	7075 AL-Alloy	T73	Maximum Bending	10	Locking Load at Kneeling	+HIGH

TABLE 17. SUMMARY OF MARGINS OF SAFETY OF THE SHOCK STRUT AND ATTACHMENT HARDWARE

Part	Drawing No.	Material	Heat Treat (ksi)	Section	Table 14 Load Condition	Stress	M.S.
Piston, Shock Strut	1252101	4340 Steel	180/200	1 - 1	10	F_{HT} (No Yield)	+0.63
Piston, Shock Strut	1252101	4340 Steel	180/200	2 - 2	Static Pressure	F_{BRU}	+HIGH
Inner Cylinder Shock Strut	1252102	7175 AL-Alloy	T74	1 - 1	10	F_{HT} (No Yield)	+0.08
Inner Cylinder Shock Strut	1252102	7175 AL-Alloy	T74	2 - 2	10	F_{HT} (No Yield)	+0.10
Outer Cylinder Shock Strut	1252103	7175 AL-Alloy	T74	1 - 1	10	F_{HT} (No Yield)	+0.07
Outer Cylinder Shock Strut	1252103	7175 AL-Alloy	T74	2 - 2	10	F_{HT} (No Yield)	+0.09
Outer Cylinder Shock Strut	1252103	7175 AL-Alloy	T74	3 - 3	10	F_{SY}	+HIGH
Lower Bearing Shock Strut	1252104	AL-Ni-BR	Per AMS 4880	1 - 1	10	F_{BY},F_{SY}	+0.68
Orifice, 2nd Shock Strut	1252106	7075 AL-Alloy	T73	Bearing Surface	Preloading	F_{BRY}	+0.45
Floating Piston, Shock Strut	1252107	AL-Ni-BR	Per AMS 4880	Basic Wall	19b	F_{BU}	+HIGH
Floating Piston, Shock Strut	1252108	7075 AL-Alloy	T73	Through Web	10	F_{BY}	+0.75
Piston Ring, Shock Strut	1252109	AL-Ni-BR	Per AMS 4880	Ring Analysis	Installation Load	F_{TU}	+HIGH
Gland Nut, Shock Strut	1252110	7075 AL-Alloy	T73	Thru Threads	10	F_{SY}	+HIGH

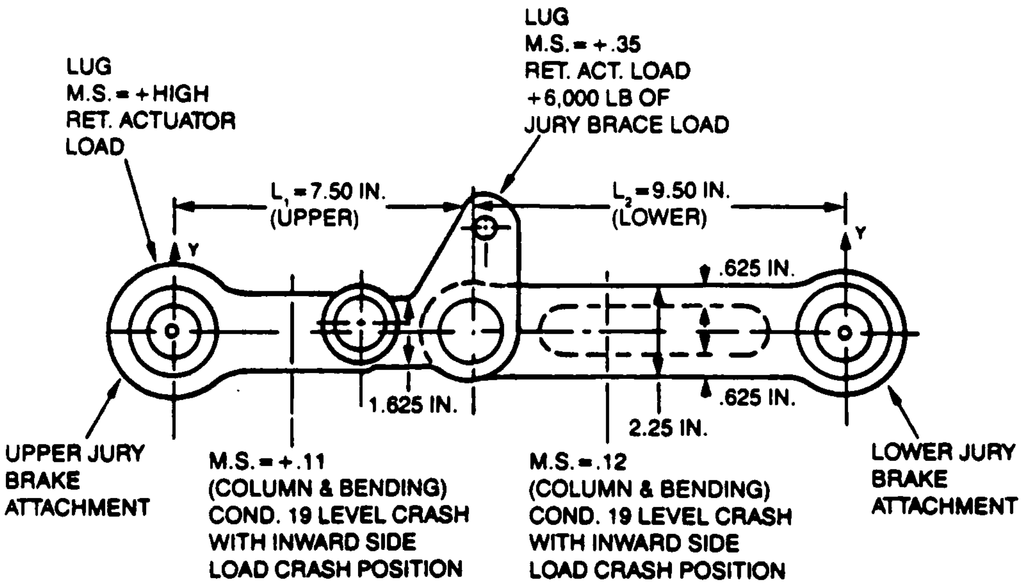
TABLE 17. - Continued

Part	Drawing No.	Material	Heat Treat (ksi)	Section	Table 14 Load Condition	Stress	M.S.
Spacer, Shock Strut	1252113	7075 AL-Alloy	T73	Basic Wall	Box Unsprung Load	F_{CY}	+HIGH
Gland Nut, 2nd Stage Shock Strut	1252115	4340 Steel	180/200	Tube Wall	10	F_{BY},F_{TY}	+0.04
Pin, Outer Cylinder S.S.	1252120-1	300 M Steel	280/300	Maximum Bending	10	F_{BY}	+0.13
Pin, Piston Shock Strut	1252120-3	300 M Steel	280/300	Maximum Bending	10	F_{BY}	+0.16
Spacer, Internal Stop, Shock Strut	1252122	7075 AL-Alloy	T73	Maximum Bending	10	Locking Load at Kneeling	+HIGH



Section/Location	Load Case	Stress Condition	Margin of Safety
Cylinder 1-1	Burst Test Pressure	F_{HT}	+0.15
Cylinder 1-1	Max System Pressure	Buckling, F_{BU}	+0.35
Piston Rod 202	Burst Test Pressure	F_C	+0.35
Gland Threads	Burst Test Pressure	F_{TU}, F_{BU}	+0.08
Gland Nut	10 Pressure	F_{BY}, F_{TY}	+0.04
Burst Test Pressure		10,000 psi	
Max System Pressure		6,750 psi	

Figure 46. Critical sections of the retraction actuator.



Section/Location	Load Case	Stress Condition	Margin of Safety
Upper Brace 1-1	19b	Buckling, F_{BU}	+0.14
Jury Brace Pins	10	F_{BY}	+0.10
Sleeve and Clevis	Proof Test Pressure	F_{BY}	+0.01
End Lugs	Retract. Actuator Load	Lug Shear - Bearing	+0.16
Bracket Pin	Lock Arm Load	F_{SU}, F_{BU}	+0.03
Linkage Pin	10	F_{BY}	+0.04
Linkage Pin	10	F_{BY}, F_{SY}	+0.05
Lower Brace 2-2	19b	Buckling, F_{BU}	+0.12

Figure 47. Critical sections of the upper and lower links of the linkage assembly.

TABLE 18. SUMMARY OF MARGINS OF SAFETY OF RETRACTION ACTUATOR, LINKAGE ASSEMBLY AND ATTACHMENT HARDWARE

Part	Drawing No.	Material	Heat Treat (ksi)	Section	Table 14 Load Condition	Stress	M.S.
Retraction Actuator	1252400	7075 AL-Alloy 4340 Steel	T73 180/200	Column, Piston Rod	Max System Pressure	Column and F_{BU}	+0.35
Retraction Actuator	1252400	7075 AL-Alloy 4340 Steel	T73	Column, Cylinder	Max System Pressure	Column and F_{BU}	+0.60
Rod, Retr Actuator	1252404	4340 Steel	180/200	Thread Relief	Burst Test Pressure	F_C	+0.35
Rod, Retr Actuator	1252404	4340 Steel	180/200	End Lug	Proof Test Pressure	Lug Shear-Bearing	+HIGH
Cylinder, Retr Actuator	1252401	7075 AL-Alloy	T73	Basic Wall	Burst Test Pressure	F_{HT}	+0.15
Cylinder, Retr Actuator	1252401	7075 AL-Alloy	T73	Gland Nut Threads	Burst Test Pressure	F_{SU}	+0.65
Cylinder, Retr Actuator	1252401	7075 AL-Alloy	T73	End Lugs	Proof Test Measure	Lug Shear-Bearing	+0.62
Cylinder, Retr Actuator	1252401	7075 AL-Alloy	T73	Gland Nut Thread Relief	Burst Test Pressure	F_{TU},F_{BU}	+0.08
Piston, Retr Actuator	1252402	AL-Ni-BR	Per AMS 4640	At Threads	Burst Test Pressure	F_{SU}	+HIGH
Linkage, Retr	1252300	7075 AL-Alloy	T73	Column Analysis	19b	Column, F_{BU}	+0.14
Link Assy Upper Retr Linkage	1252301	7075 AL-Alloy	T73	Upper Attach Lug	Gear Jammed at Retr Process	Lug Shear-Bearing	+HIGH
Link Assy Upper Retr Linkage	1252301	7075 AL-Alloy	T73	Knee Joint Lugs	Gear Jammed at Retr Process	Lug Shear-Bearing	+HIGH
Link Assy Upper Retr Linkage	1252301	7075 AL-Alloy	T73	Bracket Attach Lugs	Retr Act. Load Plus Lock Arm Load	Lub Axial and Transverse Load	+0.26
Link Assy Lower Retr Linkage	1252302	7075 AL-Alloy	T73	End Lug	Gear Jammed at Retr Process	Lug Shear-Bearing	+HIGH

TABLE 18. - Continued

Part	Drawing No.	Material	Heat Treat (ksi)	Section	Table 14 Load Condition	Stress	M. S.
Pin, Upper and Lower Retr Linkage	1252310	4340 Steel	180/200	Maximum Bending	10	F_{BY}	+0.10
Sleeve, Clevis, Retr Actuator	1252305	4340 Steel	180/200	Maximum Bending	Proof Test Pressure	F_{BY}	+0.01
Clevis Assy Retr Linkage Assy	1252307	7075 AL-Alloy	T73	1 - 1	Retr Act. Load	F_{BU}	+0.58
Clevis Assy Retr Linkage Assy	1252307	7075 AL-Alloy	T73	2 - 2	Retr Act. Load	F_{BU},F_{SU}	+0.37
Clevis Assy Retr Linkage Assy	1252307	7075 AL-Alloy	T73	3 - 3	Retr Act. Load	F_C,F_{BU},F_{SU}	+HIGH
Clevis Assy Retr Linkage Assy	1252307	7075 AL-Alloy	T73	End Lugs	Retr Act. Load	Lug Shear-Bearing	+0.16
Slip Tube Assy Retr Linkage Assy	1252311	4340 Steel	180/200	At Hoop Tens. Wall Section	Retr Act. Load	F_{HT}	+HIGH
Torque Tube, Retr Act. Linkage	1252313	4340 Steel	180/200	1 - 1	Retr Act. Load Plus Lock Arm Load	F_{BU},F_{SU},F_{STU}	+0.72
Torque Tube, Retr Act. Linkage	1252313	4340 Steel	180/200	2 - 2	Retr Act. Load at Max System Pressure	F_{BU},F_{STU}	+1.01
Torque Tube, Retr Act. Linkage	1252313	4340 Steel	180/200	3 - 3	Retr Act. Load Plus Lock Arm Load	F_{BU}, F_{SU},F_{STU}	+0.17
Gland Nut Retr Actuator	1252403	AL-Ni-BR	Per AMS 4640	1 - 1	Retr Act. Load at Max System Pressure	F_{TU},F_{BU}	+0.67
Cross Locking Bolt Torque Tube, Lower Lock Arm	MS20006-28	Steel	160 Min	At Maximum Bending Section	Retr Act. Load at Max System Pressure	F_{BU}	+0.03

5.3.2 Stress Analysis of Support Components

The major support components of the landing gear are the pivot crank and the four attachment pins for the crank. The analyses of support components were based on internal loads calculated from the ground loads. The internal loads were calculated for ten landing conditions comprising of the "no yield" and "ultimate" conditions given in Table 14. The internal loads analyses were conducted with a finite element model. A separate model analyzed each position of the gear as it stroked. Deformation effects were not taken into account in the analysis. A schematic view of the finite element model is shown in Figure 48.

Typical internal loads for three positions of vertical strokes of the landing gear are given in Tables 19, 20, and 21. Tables 19 and 20 are for 5 inches and 24.25 inches (kneeled position) of vertical stroke. The internal loads for the fully crashed position are given in Table 21, where the internal loads for conditions 8a to 10, representing the "no yield" state, are meaningless.

The pivot crank is made of 7175-T736 aluminum alloy. It consists of three lugs for attachment of the trailing arm, shock strut and the retraction actuator, and the skew axis lug to mount the crank to the fuselage bulkhead. The critical loading conditions for all four lugs are shown in Figure 49. The minimum margin of safety of +0.04 is on the barrel of the trailing arm support due to combined tension and shear for load condition 196 of Table 14.

The four pins for the four lugs of the crank are made of 300M alloy steel. The critical load conditions for the four pins are not the same. The four pins on the crank are identified in Table 11. Pin locations A and B are the upper and lower attachment points, respectively, of the retraction actuator. A margin of safety of 0.00 has been calculated for the shock strut attachment pin. The critical loading conditions and the respective margins of safety for the four pins are given in Figure 50. The margin of safety of Pin A is greater than +0.12 of Pin B in bending because its length is shorter with all other dimensions unchanged.

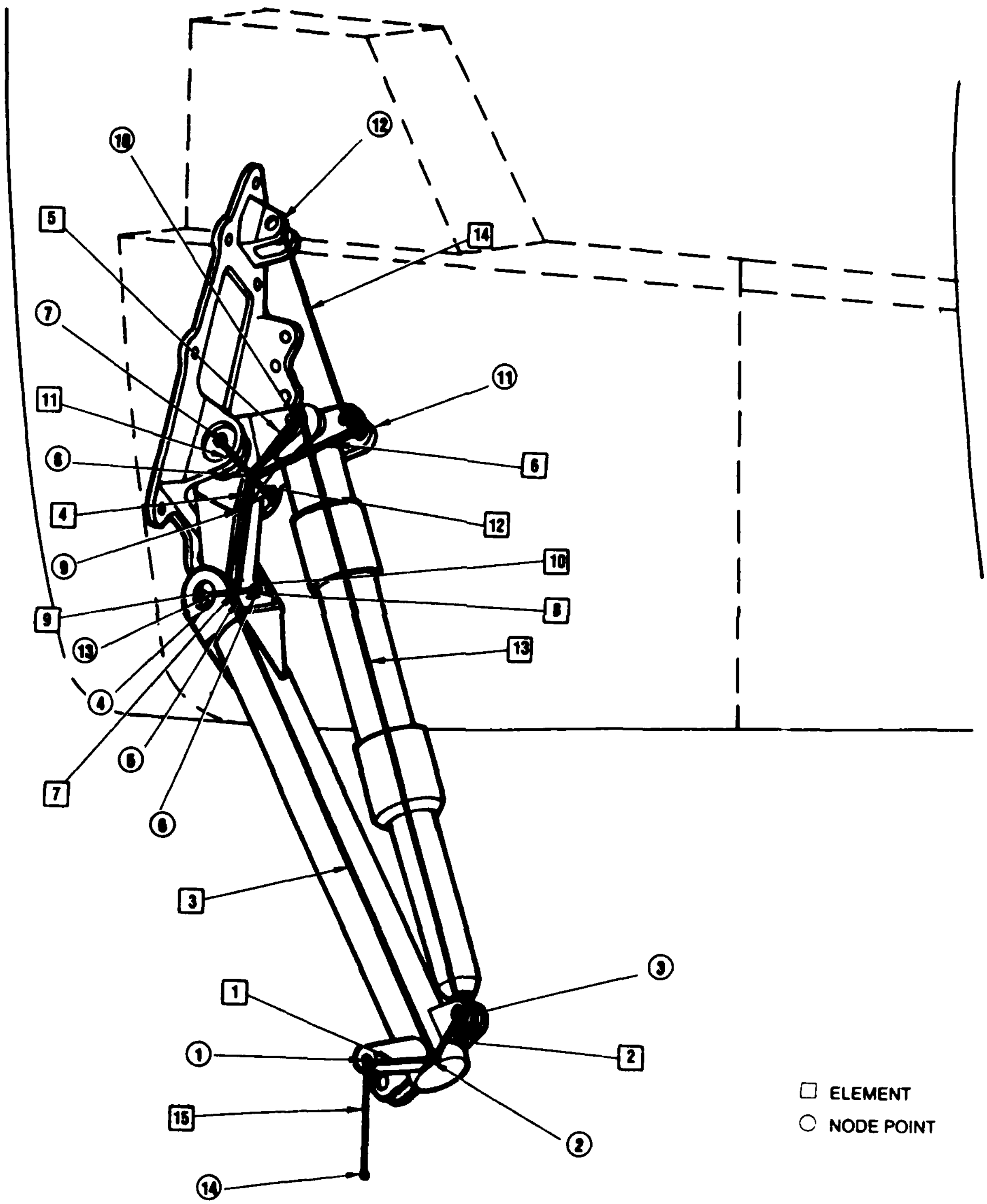


Figure 48. Schematic view of the finite element model for analysis of the support components.

TABLE 19. SUMMARY OF INTERNAL LOADS AT 5-INCH VERTICAL STROKE OF THE LANDING GEAR

GROUND LOADS IN THE HELICOPTER COORDINATE SYSTEM

Condition	S	D	V
8a	0	4250	17000
8b	0	-4250	17000
8c	4250	0	17000
8d	-4250	0	17000
9	0	-5927	22120
10	-4038	-5927	22120
19a	5100	0	22400
19b	-5100	0	22400
20	0	-7816	29171
21	-5325	-7816	29171

LOADS IN THE SHOCK STRUT AND RETRACT ACTUATOR

Load Case	Shock Strut Load	Retract Actuator Load
8a	-43890	-58960
8b	-28258	-25802
8c	-36074	-36261
8d	-36074	-48501
9	-36038	-32023
10	-36038	-37838
19a	-47533	-48499
19b	-47533	-63187
20	-47527	-42233
21	-47527	-49901
Unit S	0.0000	1.4400
Unit D	-1.8390	-3.9010
Unit V	-2.1220	-2.4930

LOADS ON THE CRANK AT THE TRUNION PIVOT

	Outboard Lug See Element 9 of FEM				Inboard Lug See Element 10 of FEM			
Load Case	Fx	Fy	Fz	Pin Shear	Fx	Fy	Fz	Pin Shear
8a	7433	25992	8628	27387	0	2665	-27352	27481
8b	4786	-5296	24642	25204	0	16766	-30652	34938
8c	10360	-7579	35955	36745	0	27642	-48323	55670
8d	1860	28274	-2686	28402	0	-8211	-9681	12695
9	6104	-8353	32811	33857	0	22474	-40038	45914
10	2066	8679	14454	16860	0	5442	-21681	22354
19a	13151	-7877	45103	45786	0	34313	-61399	70337
19b	2951	35147	-1266	35169	0	-8710	-15030	17371
20	8050	-11014	43269	44649	0	29638	-52801	60550
21	2725	11447	19062	22234	0	7177	-28593	29480
Unit S	1.0000	-4.2180	4.5468	6.2014	0.0000	4.2188	-4.5460	6.2014
Unit D	0.3114	3.6810	-1.8840	4.1351	0.0000	-1.6590	0.3883	1.7038
Unit V	0.3594	0.6087	0.9785	1.1524	0.0000	0.5715	-1.7060	1.7992

LOADS ON THE CRANK AT THE SKEW RETRACT PIVOT
LOADS ARE IN THE ORIENTATION OF THE PIVOT

Fx' - Along the Pivot Axis Outboard
Fy' - Aft
Fz' - Normal to the Pivot Axis Upward

	Outboard Lug See Element 11 of FEM				Inboard Lug See Element 12 of FEM			
Load Case	Fx'	Fy'	Fz'	Pin Shear	Fx'	Fy'	Fz'	Pin Shear
8a	0	16260	-32568	36401	8500	-55199	65527	85678
8b	0	30523	-45972	55183	8500	-41463	52114	66596
8c	0	40715	-65442	77073	12180	-62059	82170	102971
8d	0	6069	-13099	14436	4820	-34604	35471	49554
9	0	40382	-60443	72692	11060	-53308	67181	85762
10	0	23924	-35578	42874	7563	-40266	44997	60383
19a	0	51610	-83150	97865	15616	-80156	105523	132515
19b	0	10035	-20338	22679	6784	-47210	49485	68392
20	0	53255	-79711	95864	14586	-70302	88598	113102
21	0	31550	-46919	56541	9975	-53103	59342	79633
Unit S	0.0000	4.0760	-6.1580	7.3848	0.8659	-3.2300	5.4940	6.3731
Unit D	0.0000	-1.6780	1.5770	2.3027	0.0000	-1.6160	1.5780	2.2587
Unit V	0.0000	1.3760	-2.3100	2.6888	0.5000	-2.8430	3.4600	4.4782

TABLE 20. SUMMARY OF INTERNAL LOADS AT THE KNEELING POSITION OF THE LANDING GEAR

GROUND LOADS IN THE HELICOPTER COORDINATE SYSTEM

Condition	S	D	V
8a	0	4250	17000
8b	0	-4250	17000
8c	4250	0	17000
8d	-4250	0	17000
9	0	-5927	22120
10	-4038	-5927	22120
19a	5100	0	22400
19b	-5100	0	22400
20	0	-6464	24127
21	-4404	-6464	24127

LOADS IN THE SHOCK STRUT AND RETRACT ACTUATOR

Load Case	Shock Strut Load	Retract Actuator Load
8a	-45301	-64779
8b	-42555	-46504
8c	-43928	-47609
8d	-43928	-63674
9	-55242	-59655
10	-55242	-67286
19a	-57882	-63676
19b	-57882	-82954
20	-60256	-65070
21	-60256	-73394
Unit S	0.0000	1.8900
Unit D	-0.3231	-2.1500
Unit V	-2.5840	-3.2730

LOADS ON THE CRANK AT THE TRUNION PIVOT

	Outboard Lug See Element 9 of FEM				Inboard Lug See Element 10 of FEM			
Load Case	Fx	Fy	Fz	Pin Shear	Fx	Fy	Fz	Pin Shear
8a	9590	37455	20010	42465	0	7296	-20893	22130
8b	9008	9193	22048	23887	0	24610	-21845	32907
8c	13549	-212	27765	27766	0	39489	-28105	48470
8d	5049	46861	14293	48992	0	-7584	-14633	16481
9	11694	10641	28783	30687	0	32830	-28469	43455
10	7656	33003	22383	39877	0	10469	-22069	24426
19a	17353	2489	35792	35879	0	49264	-36240	61158
19b	7153	58977	19625	62156	0	-7224	-20073	21334
20	12755	11609	31395	33472	0	35808	-31052	47397
21	8351	35999	24414	43497	0	11419	-24072	26643
Unit S	1.0000	-5.5380	1.5850	5.7604	0.0000	5.5380	-1.5850	5.7604
Unit D	0.0684	3.3250	-0.2397	3.3336	0.0000	-2.0370	0.1121	2.0401
Unit V	0.5470	1.3720	1.2370	1.8473	0.0000	0.9384	-1.2570	1.5686

LOADS ON THE CRANK AT THE SKEW RETRACT PIVOT
LOADS ARE IN THE ORIENTATION OF THE PIVOT

Fx' - Along the Pivot Axis Outboard
Fy' - Aft
Fz' - Normal to the Pivot Axis Upward

	Outboard Lug See Element 11 of FEM				Inboard Lug See Element 12 of FEM			
Load Case	Fx'	Fy'	Fz'	Pin Shear	Fx'	Fy'	Fz'	Pin Shear
8a	0	19465	-30204	35933	8500	-61832	67871	91813
8b	0	49139	-37592	56321	8500	-65056	60479	88826
8c	0	53444	-48255	72005	12181	-81464	74163	110166
8d	0	7960	-19542	21101	4820	-45424	54188	70708
9	0	55619	-49258	74295	11060	-84799	78347	115452
10	0	34012	-35618	49249	7563	-67679	68858	96550
19a	0	67745	-61893	91761	15617	-105221	96545	142802
19b	0	13164	-27438	30432	6783	-61973	72575	95435
20	0	60664	-53727	81035	12064	-92494	85458	125929
21	0	37098	-38850	53718	8250	-73821	75108	105313
Unit S	0.0000	5.3510	-3.3780	6.3280	0.8660	-4.2400	2.3500	4.8477
Unit D	0.0000	-2.6440	0.8691	2.7832	0.0000	0.3794	0.8697	0.9489
Unit V	0.0000	1.8060	-1.9940	2.6903	0.5000	-3.7320	3.7750	5.3083

TABLE 21. SUMMARY OF INTERNAL LOADS AT THE FULLY CRASHED POSITION OF THE LANDING GEAR

NOTE: Conditions 8a Through 10, No-Yield Condition, do not apply here.

GROUND LOADS IN THE HELICOPTER COORDINATE SYSTEM

Condition	S	D	V
8a	0	4250	17000
8b	0	-4250	17000
8c	4250	0	17000
8d	-4250	0	17000
9	0	-5927	22120
10	-4038	-5927	22120
19a	5100	0	22400
19b	-5100	0	22400
20	0	-5991	22359
21	-4081	-5991	22359

LOADS IN THE SHOCK STRUT AND RETRACT ACTUATOR

Load Case	Shock Strut Load	Retract Actuator Load
8a	-45651	-63385
8b	-45809	-48782
8c	-45730	-47987
8d	-45730	-64179
9	-59612	-62790
10	-59612	-70483
19a	-60256	-64182
19b	-60256	-83613
20	-60257	-63470
21	-60257	-71244
Unit S	0.0000	1.9050
Unit D	0.0185	-1.7180
Unit V	-2.6900	-3.2990

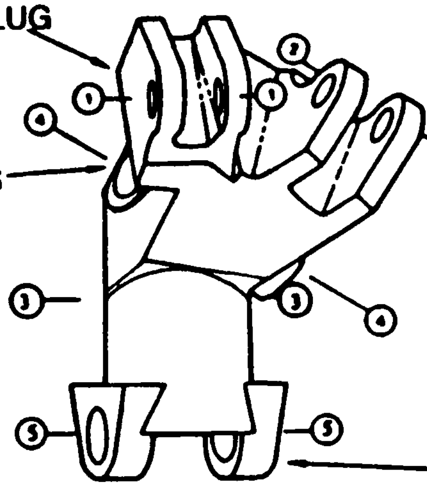
LOADS ON THE CRANK AT THE TRUNION PIVOT

Load Case	Outboard Lug See Element 9 of FEM			Pin Shear	Inboard Lug See Element 10 of FEM			Pin Shear
	Fx	Fy	Fz		Fx	Fy	Fz	
8a	10269	38760	23919	45546	0	8360	-18884	20651
8b	10233	12036	23817	26685	0	26728	-18822	32691
8c	14501	1683	27497	27548	0	41259	-22482	46986
8d	6001	49113	20239	53120	0	-6171	-15224	16427
9	13314	14412	30985	34173	0	35636	-24488	43238
10	9276	36944	27537	46078	0	13104	-21041	24788
19a	18607	5008	35804	36152	0	51575	-29196	59265
19b	8407	61924	27095	67592	0	-5341	-20487	21172
20	13458	14569	31320	34542	0	36021	-24753	43706
21	9377	37341	27835	46574	0	13249	-21269	25058
Unit S	1.0000	-5.5800	0.8538	5.6449	0.0000	5.5800	-0.8538	5.6449
Unit D	0.0042	3.1440	0.0121	3.1440	0.0000	-2.1610	-0.0072	2.1610
Unit V	0.6030	1.4940	1.4040	2.0502	0.0000	1.0320	-1.1090	1.5149

LOADS ON THE CRANK AT THE SKEW RETRACT PIVOT
LOADS ARE IN THE ORIENTATION OF THE PIVOT

Fx' - Along the Pivot Axis Outboard
Fy' - Aft
Fz' - Normal to the Pivot Axis Upward

Load Case	Outboard Lug See Element 11 of FEM			Pin Shear	Inboard Lug See Element 12 of FEM			Pin Shear
	Fx'	Fy'	Fz'		Fx'	Fy'	Fz'	
8a	0	18687	-30776	36006	8500	-60231	67315	90328
8b	0	43193	-36680	56666	8500	-67643	61409	91359
8c	0	53860	-45003	70187	12181	-82097	71217	108682
8d	0	8020	-22453	23842	4820	-45777	57507	73502
9	0	57345	-48002	74784	11060	-88360	79627	118945
10	0	35569	-37289	51533	7563	-71106	73113	101988
19a	0	68272	-57972	89565	15617	-106039	93033	141065
19b	0	13264	-30911	33637	6783	-62454	76580	98818
20	0	57965	-48521	75593	11180	-89316	80488	120232
21	0	35957	-37694	52093	7645	-71878	73905	103094
Unit S	0.0000	5.3930	-2.6530	6.0102	0.8660	-4.2730	1.6130	4.5673
Unit D	0.0000	-2.8830	0.6945	2.9655	0.0000	0.8719	0.6949	1.1149
Unit V	0.0000	1.8200	-1.9840	2.6923	0.5000	-3.7610	3.7860	5.3366

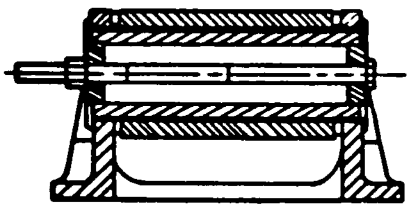


Lug/Section	Load Case	Stress Condition	Margin of Safety
Shock Strut, 1-1	20	F_{TU}	+0.19
Shock Strut, 1-1	10	F_{TY}	+1.04
Retract Actuator, 2-2	19b	F_{TU}	+0.67
Retract Actuator, 2-2	19b	F_{SU}	+0.60
Trailing Arm Support, 3-3	19b	F_{TU}, F_{SU} (Plastic)	+0.04
Upper Lugs Support, 4-4	19b	F_{TU} (Plastic)	+0.35
Trailing Arm Lugs, 5-5	19b	F_{TU}	+0.08

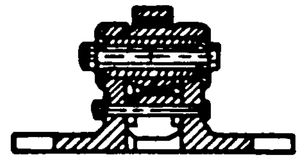
Figure 49. Critical sections of the crank.

R016 - 0025 THROUGH - 0028 PINS, 300M STEEL

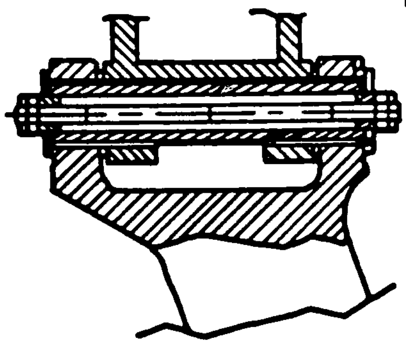
R016 - 0025 SKEW AXIS PIN
CASE 19A
BENDING MS=0.66



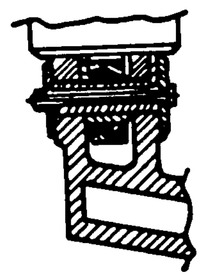
R016 - 0028 RETRACT ACTUATOR PIN
CASE 10
BENDING MS=0.12



R016 - 0026 TRAILING ARM PIN
BENDING MS=0.05



R016 - 0027 UPPER STRUT PIN
CASE 19A
BENDING MS=0.00



Locations From Table 11	Pin P/N	Load Case	Margin of Stress Condition	Safety
D	R016-0025 R016-0025	19a 19a	F_{SU} F_{BU}	+1.76 +0.66
E	R016-0026 R016-0026	8d 19a	F_{SU} F_{BU}	+1.76 +0.66
C	R016-0027 R016-0027	19a 19a	F_{SU}, F_{BU} F_{BU}	+0.00 +0.04
B	R016-0028	10	F_{BU}	+0.12

Figure 50. Critical sections of attachment pins.

6.0 ENERGY ABSORPTION TRADE-OFF ANALYSIS

6.1 GENERAL

The energy absorption trade-off analysis was conducted during preliminary design analysis to determine a weight-efficient landing gear. The calculation of energy was made by both classical formula and by a simple five-mass KRASH model. The results of the analysis were used in sizing the elements of the energy-absorbing structures of the helicopter: the landing gear, the fuselage, and the stroking crew seat.

6.2 PRELIMINARY ENERGY TRADE-OFF ANALYSIS

The results of the preliminary energy trade-off analysis are shown in Figure 51. The first left-side table shows the energy values as a function of the crash-impact velocity assuming that at 42 fps the energy to be dissipated is 100 percent. By proportion, the percentage of energy to be dissipated can then be tabulated for each sink speed. For normal operations up to 12.25 fps, only 8.5 percent of the energy is to be dissipated. For 20 fps, the condition for hard landing without fuselage ground contact, only 22.7 percent of the energy is to be dissipated. At 30 fps, the condition for the fuselage to impact with the gears retracted, the energy to be dissipated is 51.0 percent.

In evaluating the crash energy versus sink speed, shown in the second left-hand figure in Figure 51, we find that different energy absorption levels are assigned to each system:

1. If the landing gear absorbs 35 percent of the energy, it will do better than that required for 20 fps. The fuselage will absorb 65 percent, which is better than that required for a 30 fps impact.

2. If the gear absorbs 50 percent and the fuselage 50 percent, the 20 fps and 30 fps conditions for landing gear and frame are still satisfied.

3. If the gear absorbs 65 percent of the energy, equivalent to 33.8 fps sink speed, and the frame absorbs 35 percent or equivalent of 25 fps, then the fuselage will not fulfill the specification requirement and the landing gear will be overdesigned.

4. For a 42 fps condition, if the fuselage is designed for the 30 fps impact (51 percent) and if the landing gear is designed for 20 fps impact (22.7 percent), both combined will not satisfy the needs of the 42 fps impact.

By studying the needs of the fuselage, it was found that the minimum level of energy to be absorbed will be 38 percent which is based on the requirement of the fuselage frequency for an effective High Harmonics Control System. Therefore, the gear must be designed for 62 percent of the energy of a 42 fps vertical impact.

A simple linear representation of system weight is shown in the second right-hand graph in Figure 51. In evaluating the relative weight of the landing gear on the fuselage (systems) in relation to the energy level absorbed in Figure 51,

COMPARISON ENERGY
AT DIFF LEVELS

% ENERGY/SINK SPEED

SPEED FPS	ENERGY FT LB	% OF 100%	GEAR % E	FRAME % E
10	13199	5 7	100	θ
12 25	19806	8 5	100	θ
13 28	23282	10 0	θ	θ
13 8	25145	10 8	θ	θ
18 78	46565	20 0	θ	θ
20	52795	22 7	100	θ
23	69847	30 0	θ	θ
26	89223	38 3	θ	100
26 56	93130	40 0	θ	θ
29 69	116413	50 0	50	50
30	118788	51 0	θ	100
32 5	139695	60 0	θ	θ
35	161685	70 0	θ	θ
37 5	185607	80 0	θ	θ
40	211180	90 0	θ	θ
41	221871	95 0	θ	θ
42	232826	100 0	61 7*	38 3*
42	232826	100 0	49**	51**

* BASED UPON 28 FPS COND
** BASED UPON 30 FPS COND

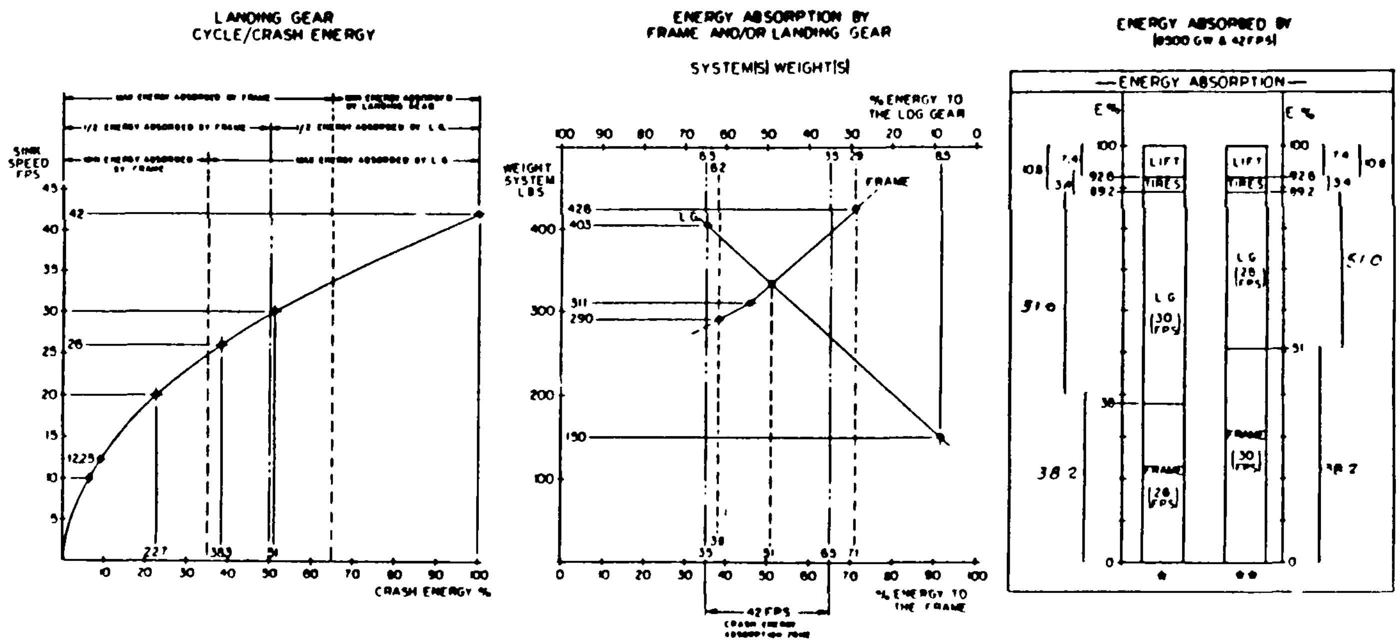


Figure 51. Energy/weight trade-off analyses for landing gears.

the fuselage weighs 290 pounds at 38 percent energy absorption and 426 pounds at 71 percent energy absorption. The landing gear weighs 150 pounds at 8.5 percent energy absorption (12.25 fps, noncrashworthy) and 403 pounds at 65 percent energy absorption (does not include the controls weight). At the intersection of the plots, or at about 51 percent of the energy, each system will weigh about 325 pounds.

On the extreme right-side graph in Figure 51, the variation in energy absorption is shown. In increasing the fuselage capability from 26 to 30 fps, the energy absorption capability of the fuselage increases from 38 to 51 percent while correspondingly decreasing the capability of the landing gear. In this plot it is assumed that the energy absorbed by the tires and lift remains constant.

6.3 ENERGY TRADE-OFF ANALYSIS USING 'KRASH'

The trade-off study for three ratios of the energies absorbed by the landing gear and the fuselage from a 42 fps level impact are presented here. The trade-off study is for the landing gear absorbing 37, 50 and 60 percent of the energy under level impact. The remaining energy for each case was absorbed by the fuselage. The weight sensitivity of the landing gear and airframe is evaluated with respect to the current helicopter, which absorbs energy from a 42 fps impact at ±10-degree roll and -5/+15-degree pitch. The weight for the three cases under level impact will be a reduction from that of the current helicopter, which is designed to impact under roll and pitch conditions. The reduction will be in (a) the shock strut, (b) the trailing arm, (c) the fuselage and (d) the support structure. In this simplified study, it was assumed that the weight of the support structure will be the same for the three impact conditions, and the kinematics and configuration of the landing gear remain unaffected.

6.3.1 Shock Strut

The difference in the incremental weight for the three impact conditions was calculated on the required length of the shock strut. The length of the strut depends on the stroke of the strut. The stroke was calculated from the energy absorbed in each of the three cases for the same axial strut force. The energy absorbed is determined from the load-stroke curve obtained from program KRASH. In addition to the calculated stroke, an additional 1 inch of stroke was added for design safety. On the basis of the design of the shock strut, it was determined that the length of the inner cylinder and the piston can be reduced to accommodate reduction in the strut stroke. The weight reduction in the strut from the current helicopter is given in Table 22.

6.3.2 Trailing Arm

The weight reduction in the trailing arm depends on the reduction in its length, which in turn is proportional to the reduced strut stroke. From the kinematics of the landing gear, the reductions in trailing arm length and weight were calculated. The reduced weights are given in Table 23.

6.3.3 Fuselage

The crushable fuselage was shown in Figure 4. The lower fuselage consists of two major keel beams along Stations ±16.1 and two supplemental keel beams along

TABLE 22. REDUCTION IN WEIGHT OF THE SHOCK STRUT

Energy Ratio L.G. vs. Fuselage	Strut Required (in.)	Stroke Reduced (in.)	Weight Saved (lb)
60 vs. 40	11.39	1.02	1.14
50 vs. 50	9.70	2.71	3.04
37 vs. 63	6.54	5.87	6.57

NOTES:

1. 'Stroke Reduced' is based on 12.41 inches stroke of current strut.
2. 'Weight Saved' is with respect to the strut designed for 10° roll and -5°/+15° pitch impact.

TABLE 23. REDUCTION IN WEIGHT OF THE TRAILING ARM

Energy Ratio L.G. vs. Fuselage	Strut Stroke Reduced (in.)	Stroke Reduced (in.)	Weight Saved (lb)
60 vs. 40	1.02	1.00	0.43
50 vs. 50	2.71	2.71	1.13
37 vs. 63	5.87	5.78	2.49

NOTES:

The 'Weight Saved' is with respect to the trailing arm designed for 10° roll and -5°/+15° pitch impact.

Stations $\pm$32.2. In addition, there are five bulkheads. Two bulkheads, at Stations 152.8 and 228.9, extend from the upper roof beam to full depth below the floor. The keel beams and bulkheads are reinforced with stiffeners to absorb the crash-impact energy. The number of stiffeners required depends on the energy to be absorbed by the fuselage. The estimated weight of the lower fuselage is given below:

Weight of stiffeners	=	3.48 lb
Weight of keel beam and bulkhead webbing	=	40.00 lb
Weight of ribs and longerons	=	17.35 lb
Weight of skin	=	19.60 lb

The total weight of the crushable lower fuselage is 80.4 pounds. Since the floor is 10 inches deep, the weight per inch depth is 8.04 pounds.

The lower fuselage was divided into three sections: forward section from Station 41.1 to Station 91.7, mid-section from Station 113.3 to Station 228.9, and aft section from Station 266.7 to Station 298.9. The division was made in

order to achieve a more realistic estimate of the reduction in weight because all sections of the fuselage do not deform uniformly. The maximum deformation for each section was taken to calculate the maximum allowable fuselage depth, from which the weight savings were estimated. The maximum allowable fuselage depth was calculated as the depth crushed from program KRASH plus 2.5 inches, the minimum depth of the fuselage required to route hydraulic and electrical lines, control rods, etc. The weights of the three fuselage sections are apportioned as 25, 60 and 15 percent of the total crushable weight. The reduction in fuselage weight is given in Table 24.

TABLE 24. REDUCTION IN WEIGHT OF THE CRUSHABLE FUSELAGE

Energy Ratio L.G. vs. Fuselage	Fuselage Depth Saved			Fuselage Weight Saved			Weight Saved (lb)
	Fwd (in.)	Mid (in.)	Aft (in.)	Fwd (lb)	Mid (lb)	Aft (lb)	
60 vs. 40	3.54	3.83	5.91	7.18	18.48	7.13	32.78
50 vs. 50	3.43	3.50	3.84	6.89	16.88	4.63	28.40
37 vs. 63	3.24	1.70	1.17	6.51	8.16	1.41	16.08

NOTES:
The 'Weight Saved' is with respect to the fuselage designed for 10° roll and -5°/+15° pitch impact.

6.3.4 Total Weight Saved

The total weight saved for each of the three crashworthy systems for level impact is the sum of twice the weight for each of the shock struts shown in Table 22, twice the weight for each of the trailing arms shown in Table 23, and the weight of the crushable fuselage shown in Table 24. These are summarized in Table 25 and illustrated in Figure 52.

6.3.5 Discussion

From the energy trade-off analysis, the helicopter weight is a minimum when the landing gear absorbs 53 percent of the total energy for level impact. The weight of this landing gear, designed to absorb 60 percent of the impact energy, increases a marginal 0.82 pound. Since the weight saved decreases as the energy-absorbing capability of the landing gear is increased above 53 percent, for this configuration the landing gear should be limited to absorb no more than 60 percent of the impact energy.

For this configuration, crashworthiness can be incorporated into a low-weight design of a helicopter by designing a landing gear which absorbs a greater percentage of the impact energy than the fuselage. The fuselage absorbs kinetic energy by deforming over a limited area, the location of which depends on the impacting attitude. Since the location of the "limited area" is never known and

TABLE 25. TOTAL WEIGHT SAVED FOR THE THREE CRASHWORTHY SYSTEMS

Energy Ratio L.G. vs. Fuselage	Shock Strut Weight (lb)	Trailing Arm Weight (lb)	Fuselage Weight (lb	Total Weight (lb)
60 vs. 40	2.28	0.86	32.78	35.92
50 vs. 50	6.08	2.26	28.40	36.74
37 vs. 63	13.14	4.92	16.08	34.14

NOTES:

The total 'Weight Saved' is for level impact with respect to the weight of the helicopter designed for 10° roll and -5°/+15° pitch impact.

since it can be anywhere over the wider area of the fuselage underbelly, the entire underbelly is reinforced. In contrast, the landing gear is subjected to point loading. The location of the 'reinforcement' in the landing gear is, therefore, exactly known.

However, the optimum percentages of the energies absorbed by the landing gear and the fuselage for a low-weight design depend on the configuration and on the design requirements. Some of the configuration factors that affect this issue are: (1) the path in the fuselage taken by the landing gear loads, (2) the type of landing gear system, and (3) the separation between the gears. Design requirements which may affect the "optimum percentages" are those of the impact condition, such as the nature of the impacting surface and the impact attitude. Furthermore, if the landing gear is already being designed to a requirement of absorbing a minimum amount of energy (e.g., from a 20 fps level impact) to protect the hardware, how much more capability would be an optimum condition?

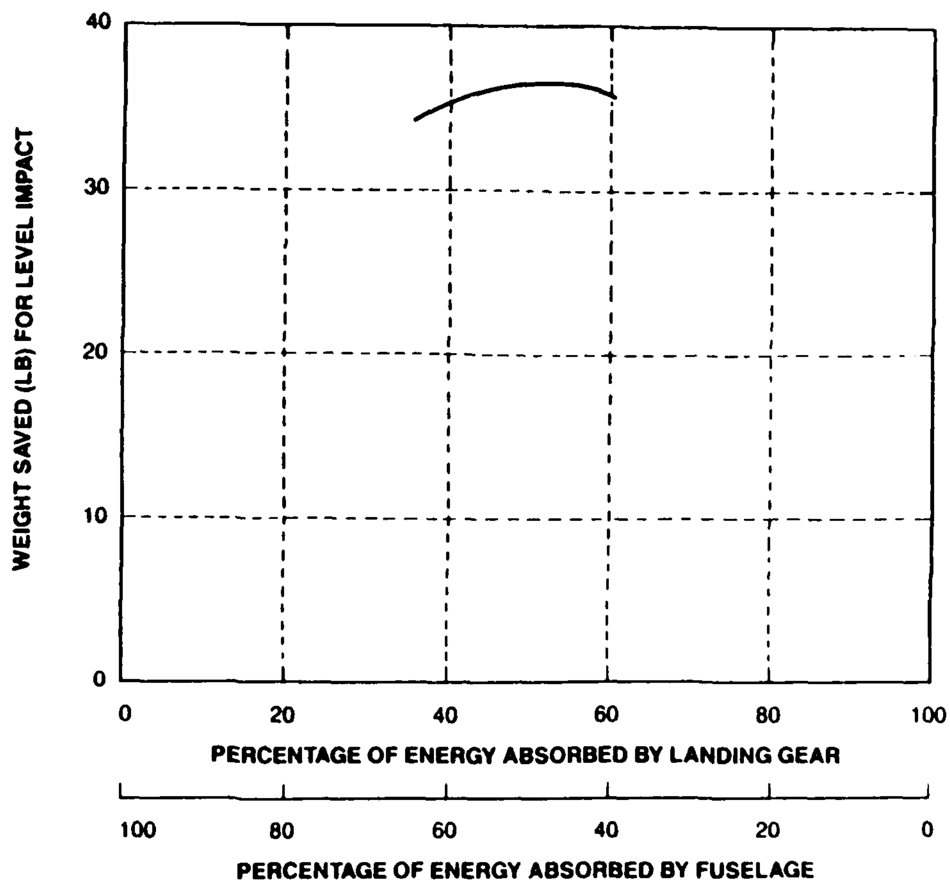


Figure 52. Influence on helicopter weight of the ratio percentage of energies absorbed by the landing gear and fuselage.

7.0 CRASHWORTHINESS ANALYSIS

7.1 GENERAL

The preliminary design analysis for crashworthiness was conducted with a simple five-mass model, shown in Figure 17. The analysis was conducted to determine the load factors desired to meet the design requirements and to conduct trade-off analysis to identify the optimum ratio of the energies to be absorbed by the landing gear and fuselage. This ratio was based on a level crash condition at an impact velocity of 42 fps.

Following the preliminary analysis, two KRASH models were developed. The first model was that of the detailed helicopter. The second model was a six-mass model of the iron-bird test fixture. The detailed helicopter KRASH model was used to predict the crash-impact behavior of the helicopter. The six-mass KRASH model was used to correlate the crash-impact response of the iron-bird test results with the results from the detailed helicopter model. The six-mass KRASH model was necessary because the iron-bird test fixture did not simulate the moments of inertia of the helicopter exactly.

In this section, the two KRASH models will be described and the results from the detailed model discussed. In addition, the six-mass model will be correlated with the detailed model for the same moments of inertias. Because of the correlation between the six-mass and detailed models, it would be reasonable to assume that the detail model accurately predicts the results of crash-impact behavior of a helicopter.

7.2 PROGRAM KRASH

The crashworthiness analysis of the ATLG was conducted using Program KRASH ('85 version). Program KRASH utilizes nonlinear spring and beam elements and lumped masses arranged in a three-dimensional framework to simulate the major fuselage structural elements. The nonlinear characteristics needed to describe the structural elements are derived from component testing and other analyses. Program KRASH formulation solves coupled Euler equations of motion for inter-connected lumped masses. The equations of motion are explicitly integrated to obtain the velocities, displacements, and rotations of lumped masses under the influence of external forces such as gravity, aerodynamic and impact forces, as well as internal structural loads.

A summary of major features of Program KRASH is as follows:

- Aircraft major mass items and occupants are modeled as lumped masses.
- Nonlinear external spring elements are used to model crushable subfloor structure, landing gear, soil, and friction forces.
- Nonlinear beam elements are used to model the airframe structure. Stiffness reduction factors are used to represent the nonlinear properties.

- Initial conditions of linear and angular velocities about three axes and impact into horizontal ground and/or inclined slope can be specified.

- Large structural displacements and rotations can be simulated.

- Mathematical model can contain up to 80 lumped masses, 50 massless node points, and 180 nonlinear degrees of freedom.

Major output parameters available from Program KRASH are as follows:

- Mass point response time histories (displacement, velocity, and acceleration).

- Distribution of kinetic and potential energy by mass item, strain and damping energy by beam element, and crushing and sliding friction energy associated with each external spring.

- Internal loads and deformations for structural elements.

- Occupant survival indicators including probability of injury indicated by Dynamic Response Index (DRI).

- Overall vehicle center-of-gravity translation velocity.

7.3 DETAIL KRASH MODEL

A schematic view of the 8500 lb utility helicopter is shown in Figure 1. A detailed KRASH model of the helicopter (Figure 53) was first developed to evaluate the effect of the ATLG design on the overall helicopter crash dynamics as well as energy absorption trade-off studies.

The detailed KRASH model consists of 53 lumped masses, 14 massless nodes, 39 crushable spring elements and 105 beam elements. The model has nine nonlinear degrees of freedom. These nonlinear beam elements are limited to landing gear shock struts and crashworthy seats. The landing gear shock strut load-stroke characteristics were obtained from single gear dynamic tests shown schematically in Figure 42. The crushable lower fuselage was also modeled by nonlinear springs.

The total weight, moments of inertia, and center of gravity location of the detailed model are the same as those of the helicopter's. The weight and mass properties of major mass items and their locations are given in Table 1. The properties of the remaining structural elements of the helicopter were initially scaled from the KRASH model of the AH-64 helicopter. The spring rates for the tires in the main and nose gears were obtained from manufacturers' data.

The key crashworthiness parameters of the detailed model, including load factors and maximum available strokes, were as follows:

- Landing gear stroke available = 29 inches (or 33 inches with 4 inch tire deformation).

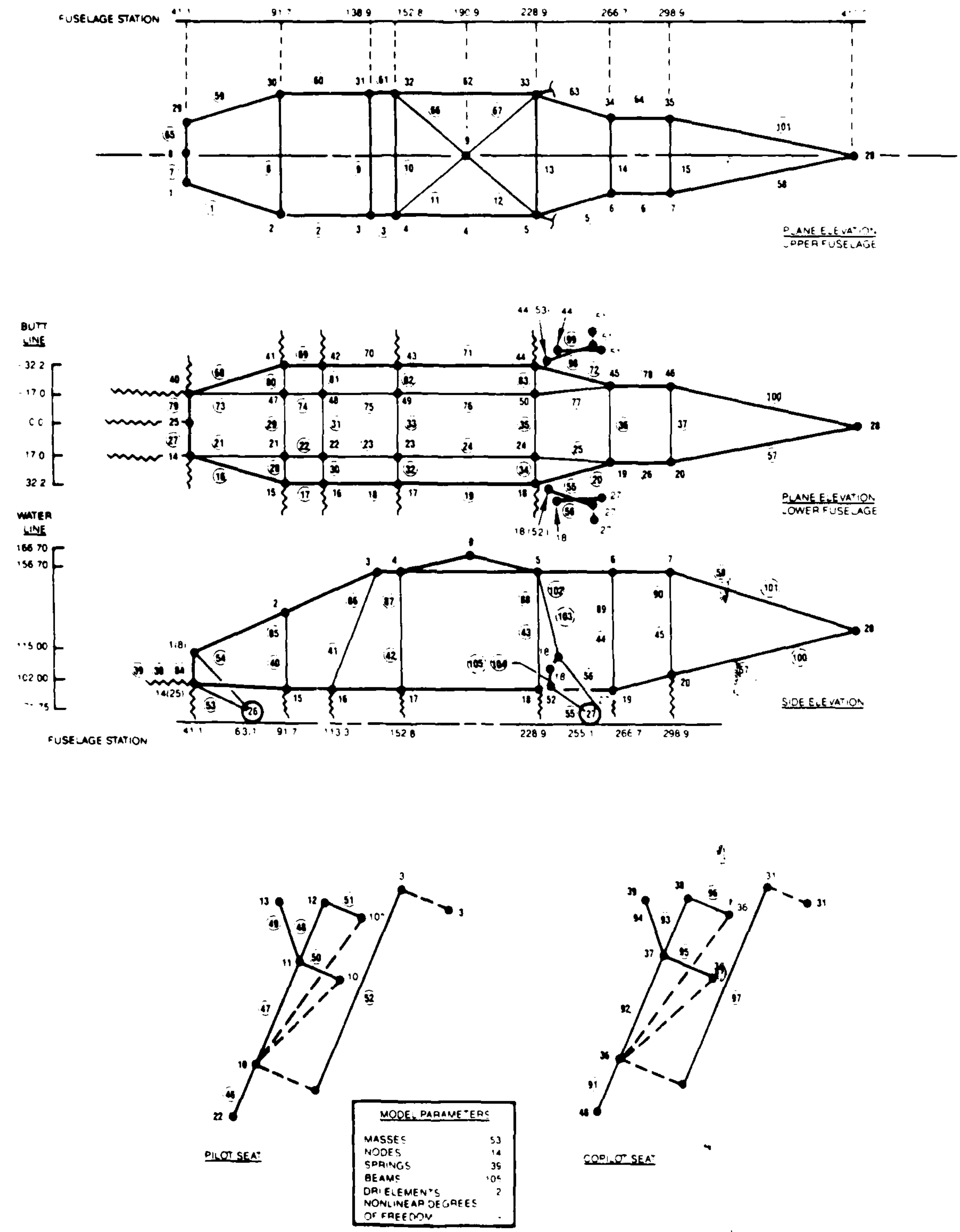


Figure 53. KRASH model of the detailed helicopter.

- Fuselage load factor = 32g
- Fuselage crushable stroke available = 7.5 inches
- Crew seat load factor = 14.5g (50th percentile occupant)
- Crew seat stroke available = 12 inches

The load factor of the landing gear varies with impact velocity since the shock strut load is velocity sensitive. However, the landing gear load factor is 8g for level impact at 42 fps.

The fuselage springs were designed to absorb the impact energy after the initial kinetic energy is absorbed by the landing gear. Since the fuselage absorbs 40 percent of the energy from a 42 fps level impact, the fuselage spring was initially designed to absorb this equivalent energy: 1,125,962 in.-lb. However, the crash conditions include roll and pitch impact conditions which require higher energy absorption capability locally. For example, under level impact conditions the crushing of the fuselage is mainly between Stations 91.7 and 228.9, and ranges between 2.3 and 3.9 inches. Under 10 degrees roll and +15 degrees pitch impact conditions, the maximum crushing of 6.10 inches of the fuselage occurs at Station 298.9, after which the fuselage rotates and impacts the forward fuselage at Station 41.1, where the fuselage is crushed 3.21 inches. Under this roll and pitch condition, the mid-section of the fuselage is barely crushed. To account for the local crushing of the fuselage, the fuselage springs must be designed accordingly to optimize weight. The present fuselage springs are designed to absorb a total of 550.0 in.-kips in the forward and aft sections of the fuselage and 982.0 in.-kips in the mid-section of the fuselage.

The detail structural properties of the main landing gear components were initially sized by apportioning the correct percentage of the impact energy to be absorbed. The main landing gear model included the trailing arm and the retraction actuator. The attachment to the bulkhead was modeled as a rigid member with no energy-absorbing capability. The nose landing gear, which is not part of this program, was designed to the same energy absorption characteristics as the individual main gears.

The detail KRASH model was conducted for gross weights of 8,500 and 10,625 pounds at 10 to 42 fps impact velocities, 0 to 10 degrees roll and -5/+15 degrees pitch impact attitudes. The crash-impact analyses envelope is shown in Figure 54. The ratio of crash-impact energies absorbed by the landing gear and the fuselage was 60:40 for 42 fps level impact condition. The analysis time required by this model was 16 to 22 CPU hours on a MicroVAX-II computer using an integration time step of 0.00001 sec. The integration time step was governed by the natural frequencies of the beam elements. In general, the time step was chosen such that the product of the maximum beam frequency and the time step was less than 0.01.

7.4 SIX-MASS KRASH MODEL

Dynamic tests were conducted using the iron-bird test fixture with two main landing gears and a nose gear that simulate the utility helicopter. The iron-bird fixture was designed to be dropped repeatedly at impact speeds up to 42 fps without any structural failures. The weight and center of gravity of the iron-

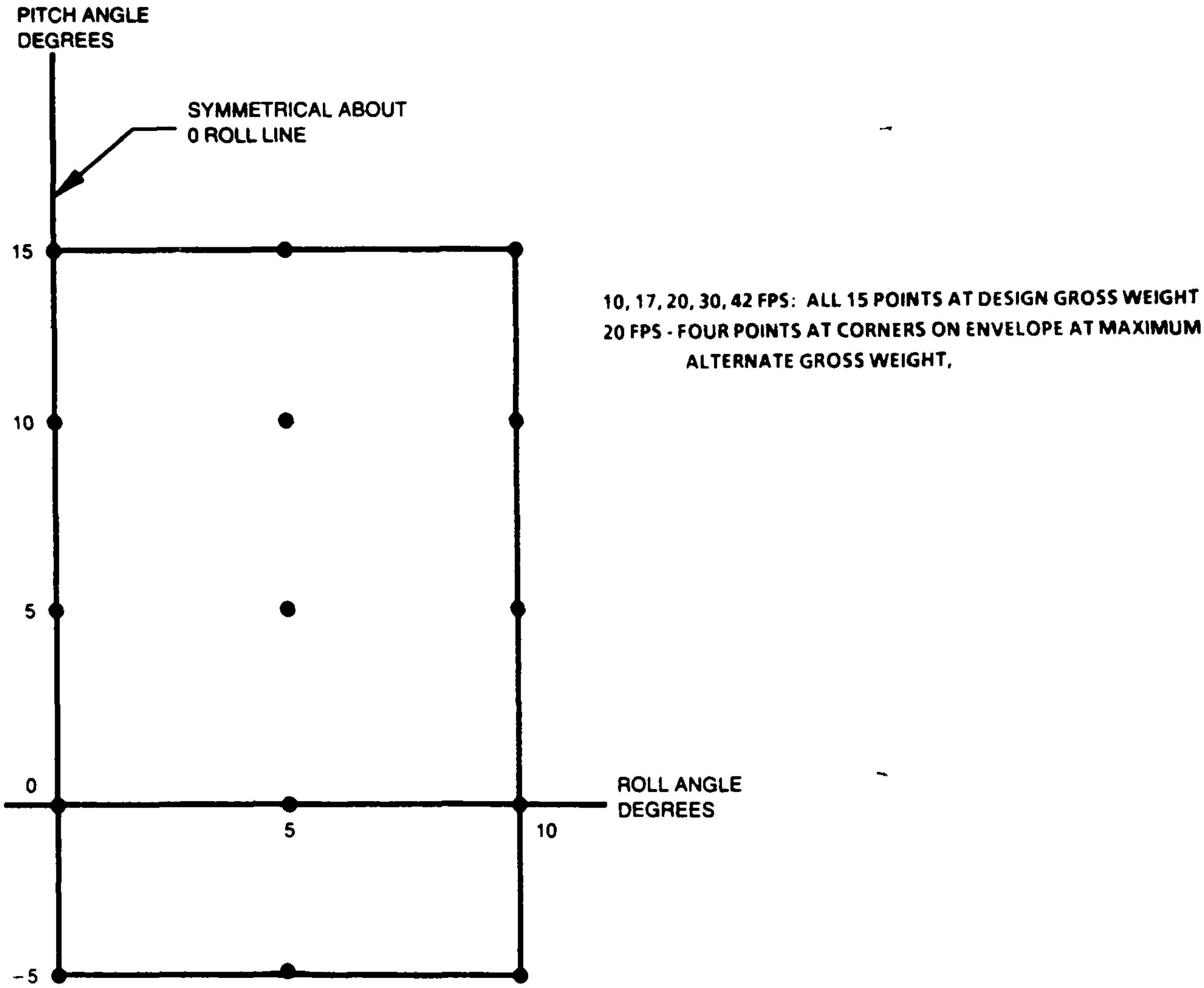


Figure 54. Crash-impact envelope for KRASH analyses.

bird closely matched those of the helicopter. The moments of inertia of the iron-bird, however, are different due to the physical constraints of the test drop tower. In order to correlate with the drop test results, a simple six-mass RASH model of the iron-bird fixture was developed. This model allowed lumping of all weights and moments of inertia to the center of gravity of the iron-bird fixture. All other model parameters, including landing gears and fuselage crushing spring rates, were identical to the detailed KRASH model. The springs in this model, however, were attached to massless node points that were rigidly connected to the mass concentrated at the center of gravity location. This modeling technique allowed the moments of inertia of the iron-bird fixture to be accurately modeled, and resulted in considerable savings in program execution time: 1 CPU hour compared to 16 to 22 CPU hours for the detail model. The six-mass KRASH model is shown in Figure 55.

The six-mass KRASH model was the link between the iron-bird test fixture and the helicopter. Since the iron-bird fixture and the helicopter differed in mass and inertias, the six-mass KRASH model was used to correlate both the results from the iron-bird drop tests and the KRASH results from the detail model. To correlate the iron-bird test results, the six-mass KRASH model simulated the mass and inertias of the iron-bird fixture. Similarly, to correlate the detail

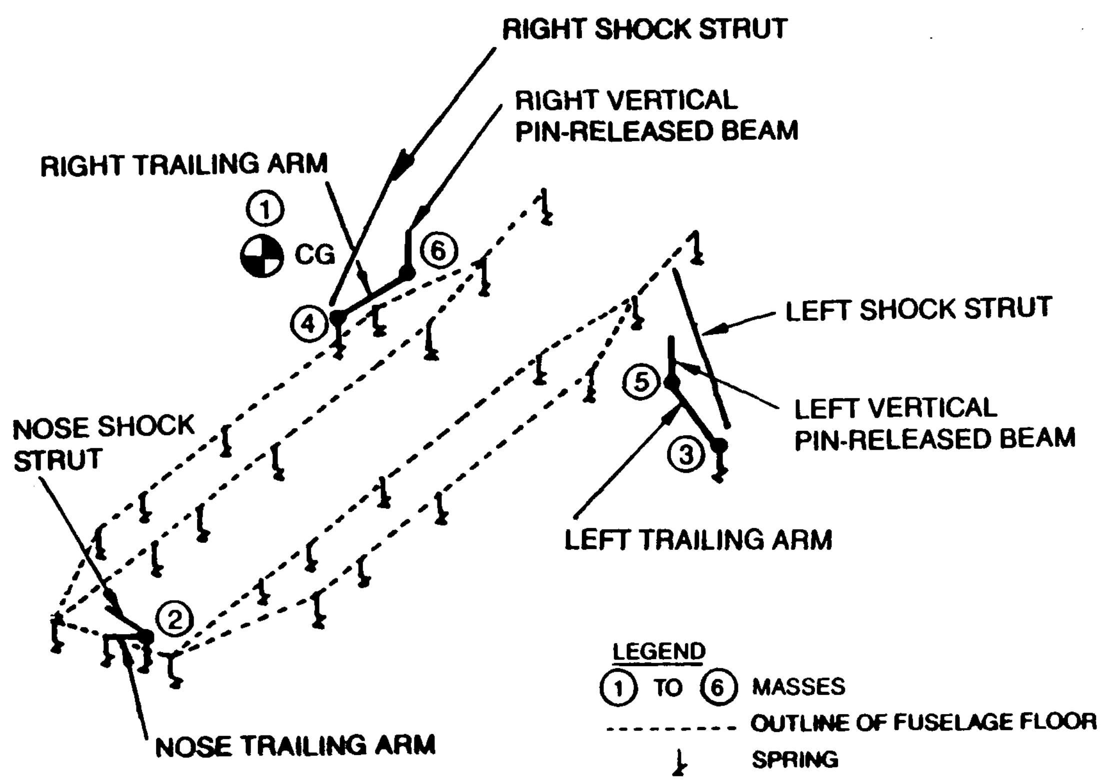


Figure 55. Six-mass KRASH model of the iron-bird test fixture.

model, the six-mass KRASH model simulated the mass and inertias of the helicopter. The six-mass model was correlated with the detail model of the helicopter by lumping the masses and inertias to those of the helicopter. The correlation with the detail model for the 42 fps level impact condition is very good, as seen in Table 26. The ratio of the crash-impact energies absorbed by the landing gear and the fuselage was 58:42, which closely correlated with the distribution in the detail KRASH model.

TABLE 26. CORRELATION OF FUSELAGE AND SHOCK STRUT BEHAVIOR OF DETAIL AND SIX-MASS KRASH MODELS

Vertical Velocity fps	Impact		Max. Fuselage Crush			Oleo Stroke in.	
	Roll degree	Pitch degree	Fwd. in.	Mid in.	Aft in.	Left	Right
Detail KRASH Model							
42	0	0	3.9	3.8	2.3	10.3	10.3
Six-Mass KRASH Model							
42	0	0	4.0	3.8	2.3	9.4	9.4

7.5 KRASH RESULTS

The KRASH analyses for all impact conditions shown in Figure 54 were conducted in addition to five analyses to evaluate the results with reduced strut loads. The reduced strut load analyses were conducted to simulate the response of the actual shock strut more accurately because KRASH models the shock strut as a nonlinear beam. The results presented below are from 104 KRASH analy.es.

All the impact conditions studied were survivable, as evidenced by the occupants' DRI data and by comparing the accelerations of the occupant seatpan, lower torso and upper torso with the acceptable human tolerance limits given by the Eiband human tolerance curves in Reference 6. All the inputs tested were considered successful using (1) the occupant response as the indicator of a survivable impact, and (2) the close correlation with the test data, discussed in Volume II of this report, as a second indicator.

7.5.1 Fuselage Deformation

Contact of the fuselage with the ground occurred only at impact velocities of 30 and 42 fps. Fuselage contact did not occur for impact velocities of 20 fps and less at the basic structural design gross weight of 8,500 pounds. The fuselage deformations at the alternate gross weight of 10,625 pounds and impact velocity of 20 fps are negligible. The deformations occur in the forward or aft sections depending on whether the impact attitude was a nose-down or nose-up condition.

The deformation of the fuselage at 30 fps was localized mainly in the forward fuselage between Stations 41.1 and 91.7 for all fifteen conditions investigated. Deformation of the mid-section of the fuselage, between Stations just aft of 91.7 and 228.9, occurred only for pitch conditions of -5 degrees and 0 degree. The results of the deformations at 30 fps, 10-degree roll and all five pitch conditions are shown in Figure 56.

For impacts at 42 fps, the fuselage deformations generally occurred throughout. The results of the deformations at 42 fps, 10 degree roll and all five pitch conditions are shown in Figure 57. In the nose-down (-5° pitch) condition, there was no deformation of the aft fuselage, and the energics were absorbed by the forward and mid-sections of the fuselage. In the +15° nose-up condition, most of the fuselage deformations occurred in the forward and aft sections. This indicates the "slap-down" behavior of the helicopter as it pivots about the landing gear following crushing of the aft fuselage.

7.5.2 Shock Strut

The shock strut strokes increased with increased impact velocity. The stroke of the down-side strut was always greater than that of the up-side strut. The difference between the struts on the two sides can be seen by comparinq Figures 58 and 59. The strut strokes for all impact velocities and pitch attitudes for 10-degree roll condition are shown in Figure 58 for the down-side gear and in Figure 59 for the up-side gear.

At a given impact velocity, the strut stroke increases more rapidly at the lower pitch impact angles (-5° to +5°) than at the higher pitch impact angles (+5° to +15°). This typical behavior for all roll angles is shown in Figure 60.

7.5.3 Occupant DRI

The occupant DRI generally increases with speed. This is true for the occupant on the down-side and the up-side. The differences between the DRIs for 17 and 20 fps impacts are negligible, however. The DRIs for 5° roll and for all impact speeds and attitudes are shown in Figure 61 for the down-side occupant, and in Figure 62 for the up-side occupant. The figures also indicate that the DRIs at lower pitch angles (-5°, 0°, +5°) are greater than at +10° and +15°, for which two conditions the DRIs are almost identical. The effect of different roll angles on the DRI is shown in Figure 63. The DRI is dramatically affected by the roll angle. At 5° roll, the DRI remains almost constant between +10° and +15° pitch. But at 10° roll, there is a dramatic increase in the DRI from +10° to +15° pitch.

7.5.4 Seat Stroke

The seat stroke increases with the impact velocity with the highest stroke being at -5° pitch angle. However, the increase in the stroke from 30 to 42 fps is dramatic. In several cases, and especially for -5° pitch and +10° roll, the seat stroke is greater on the up-side than on the down-side. This indicates that the pulse is distinctly greater (time, peak, rate) on the up-side than on the down-side. This is another demonstration of the "slap-down" behavior occurring in an impact condition. These effects are seen in Figures 64, 65, and 66.

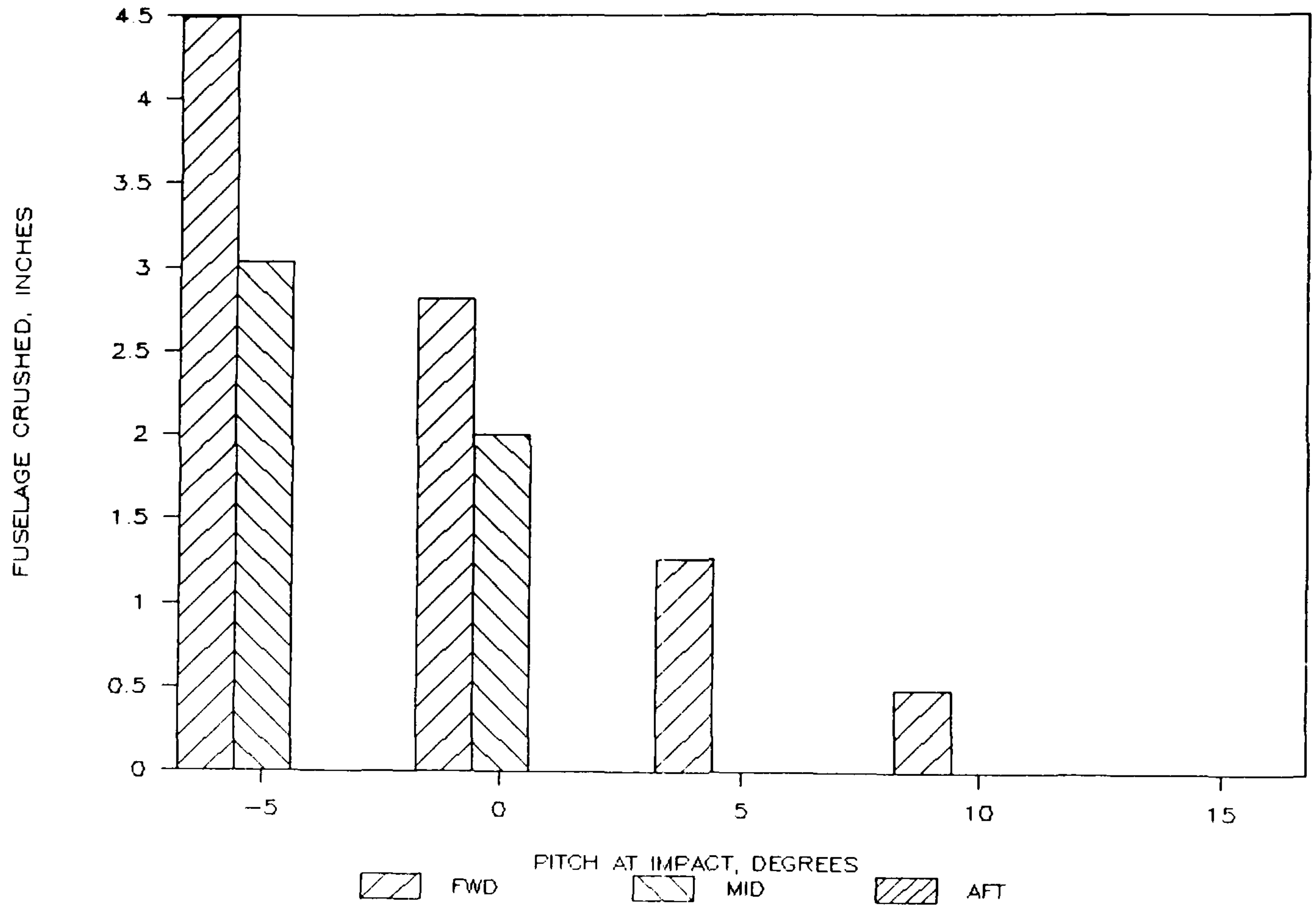


Figure 56. Fuselage deformations at 30 fps and 10° roll.

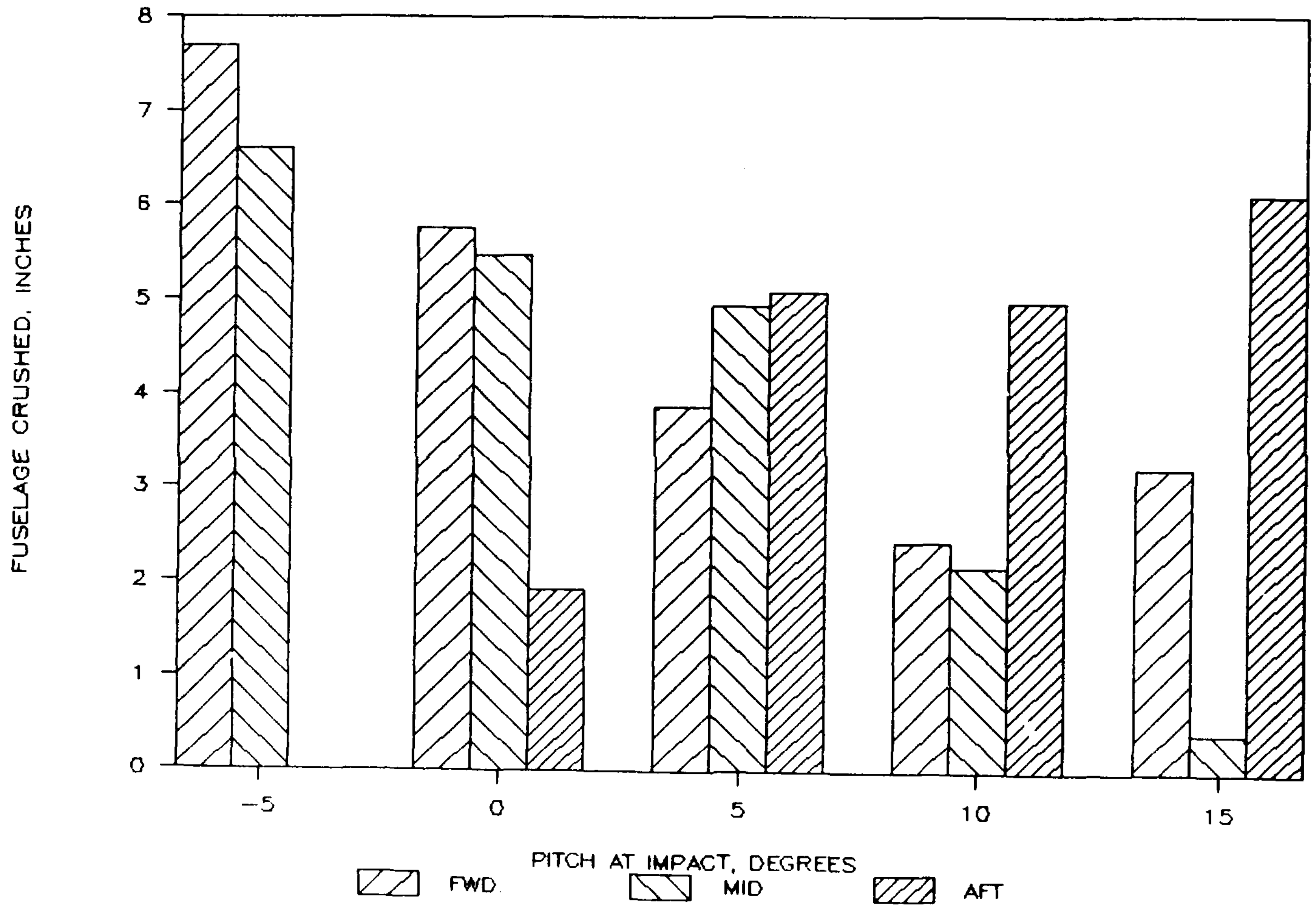


Figure 57. Fuselage deformations at 42 fps and 10° roll.

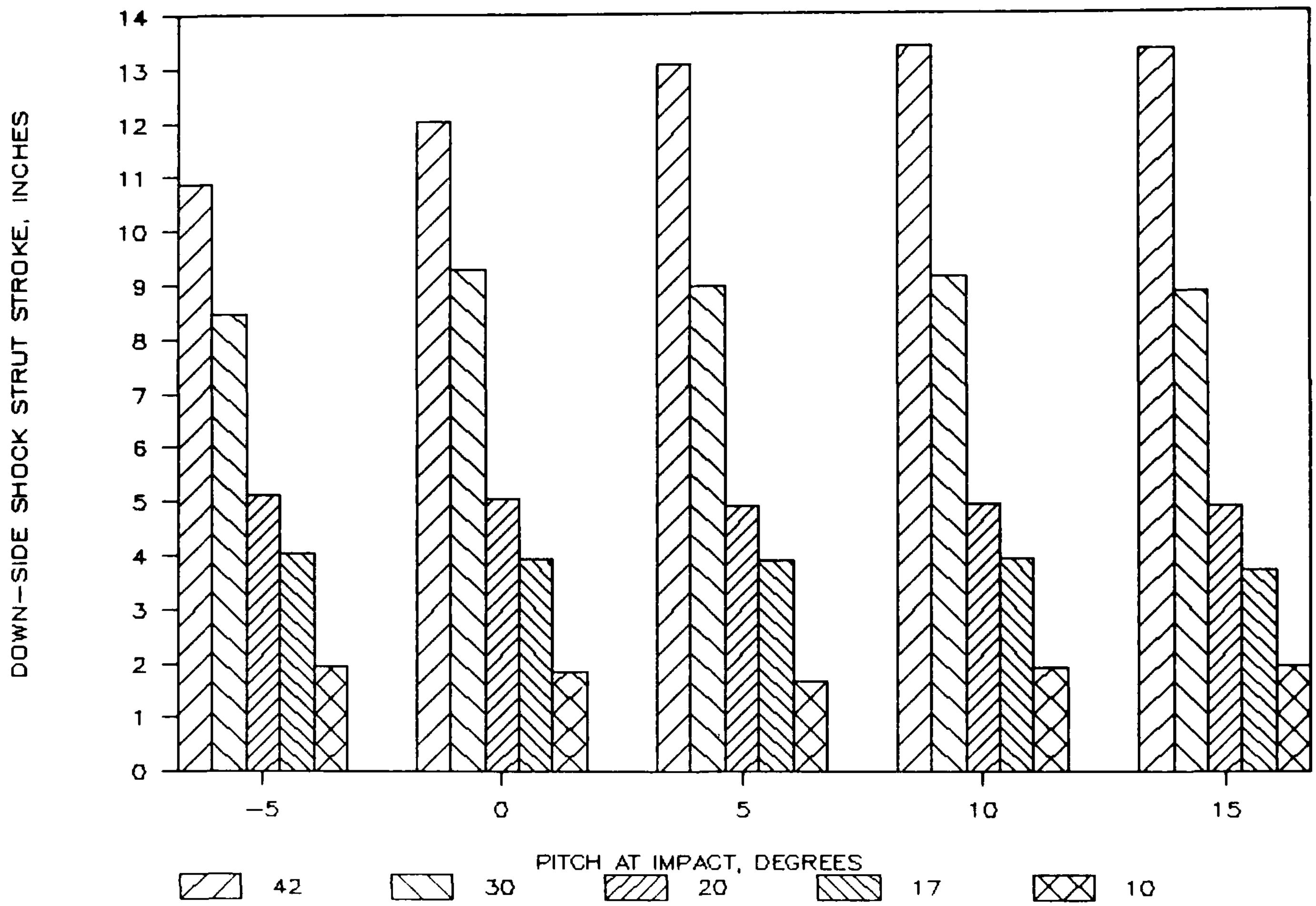


Figure 58. Comparison of down-side strut strokes at 10° roll.

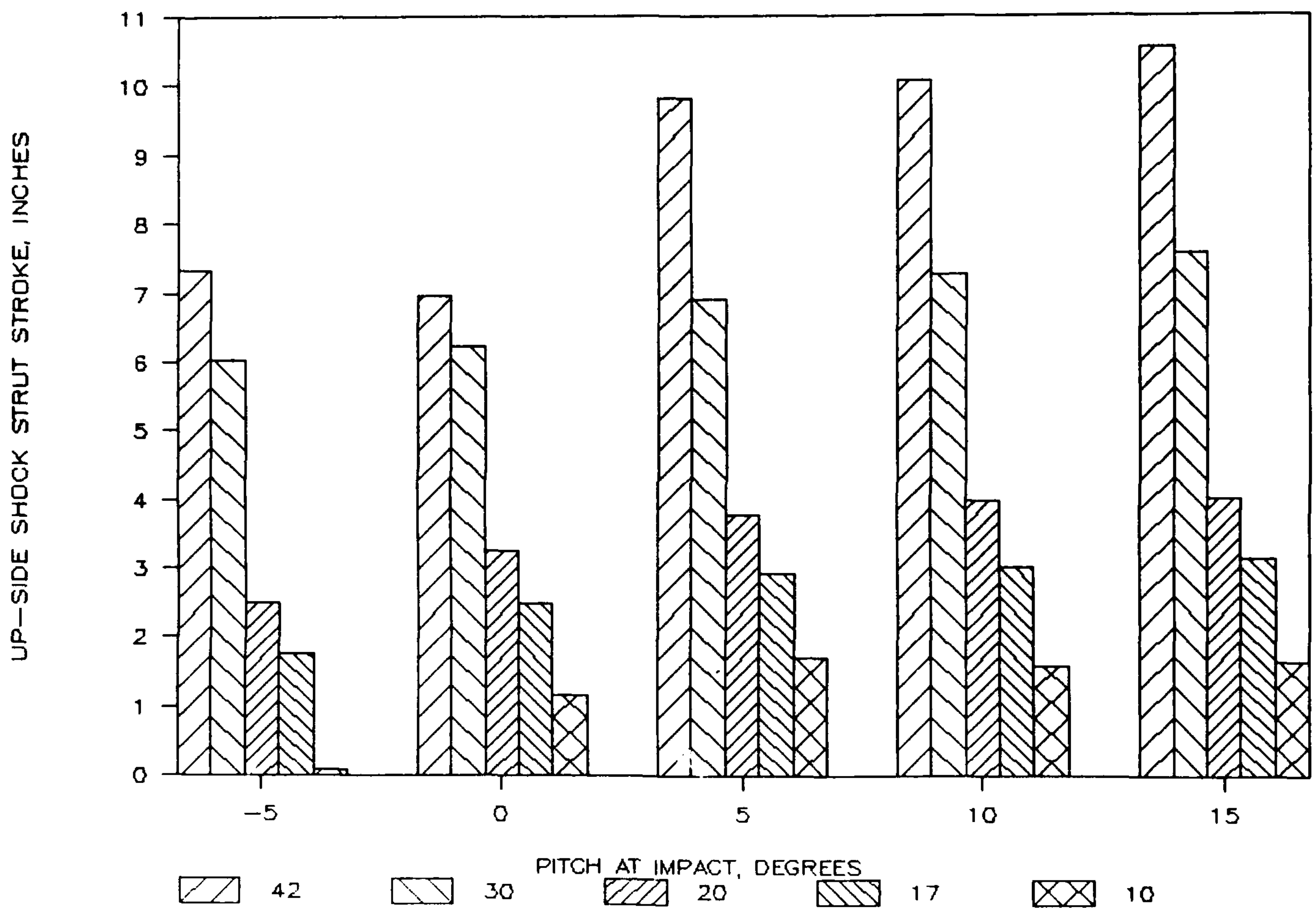


Figure 59. Comparison of up-side strut strokes at 10° roll.

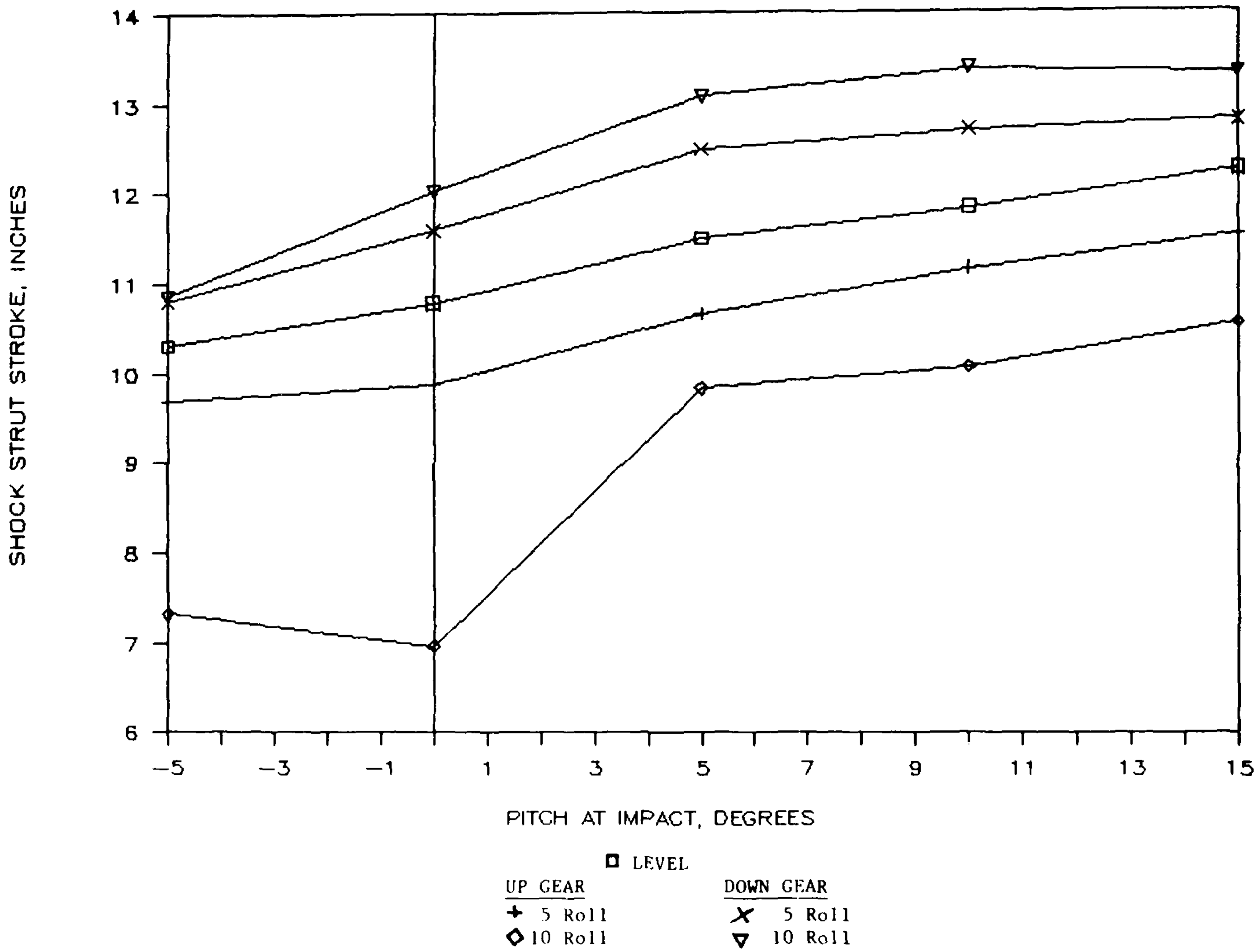


Figure 60. Behavior of strut strokes for all pitch and roll angles at 42 fps.

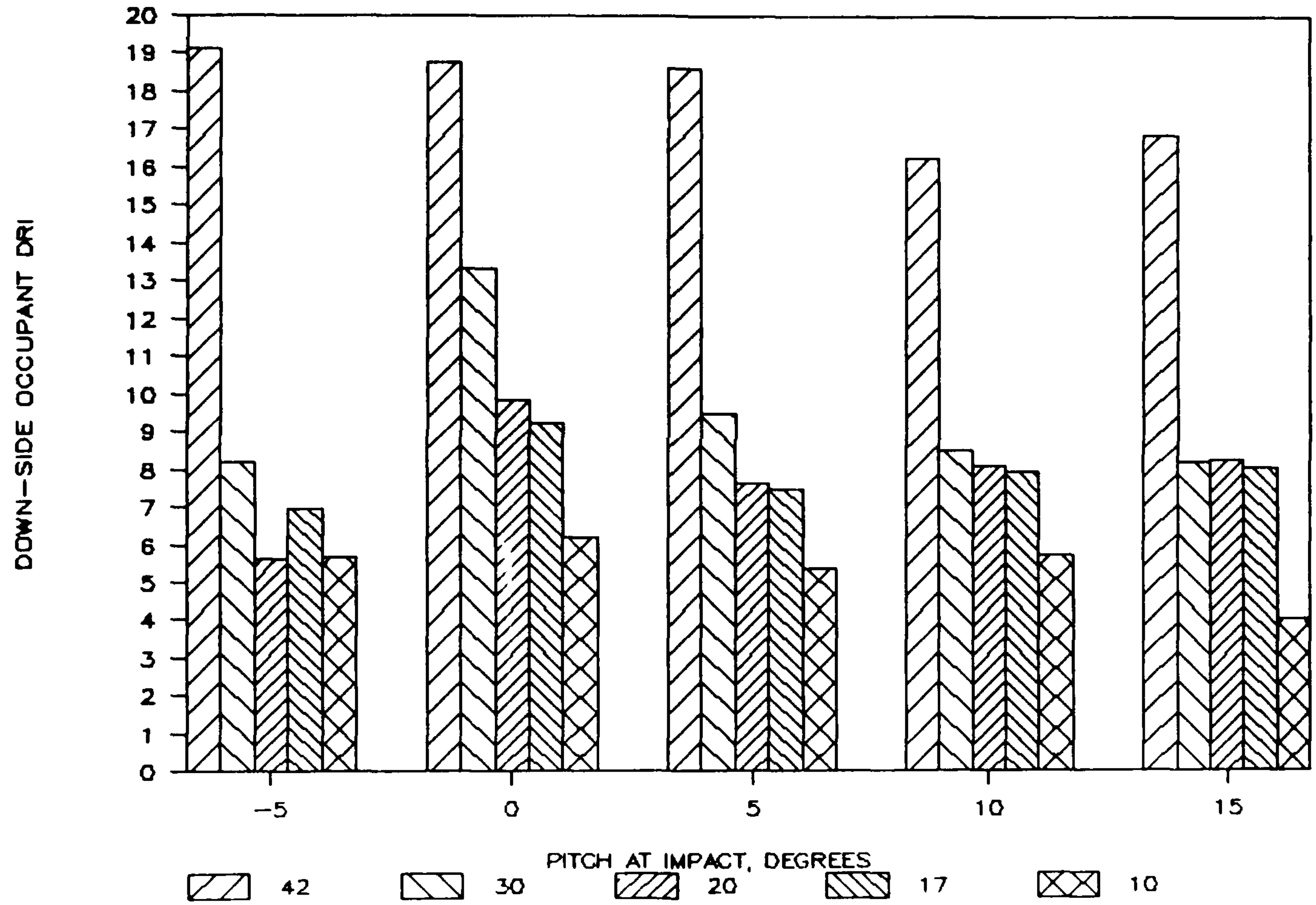


Figure 61. DRIs for down-side occupant for all speeds and pitch angles investigated for 5° roll.

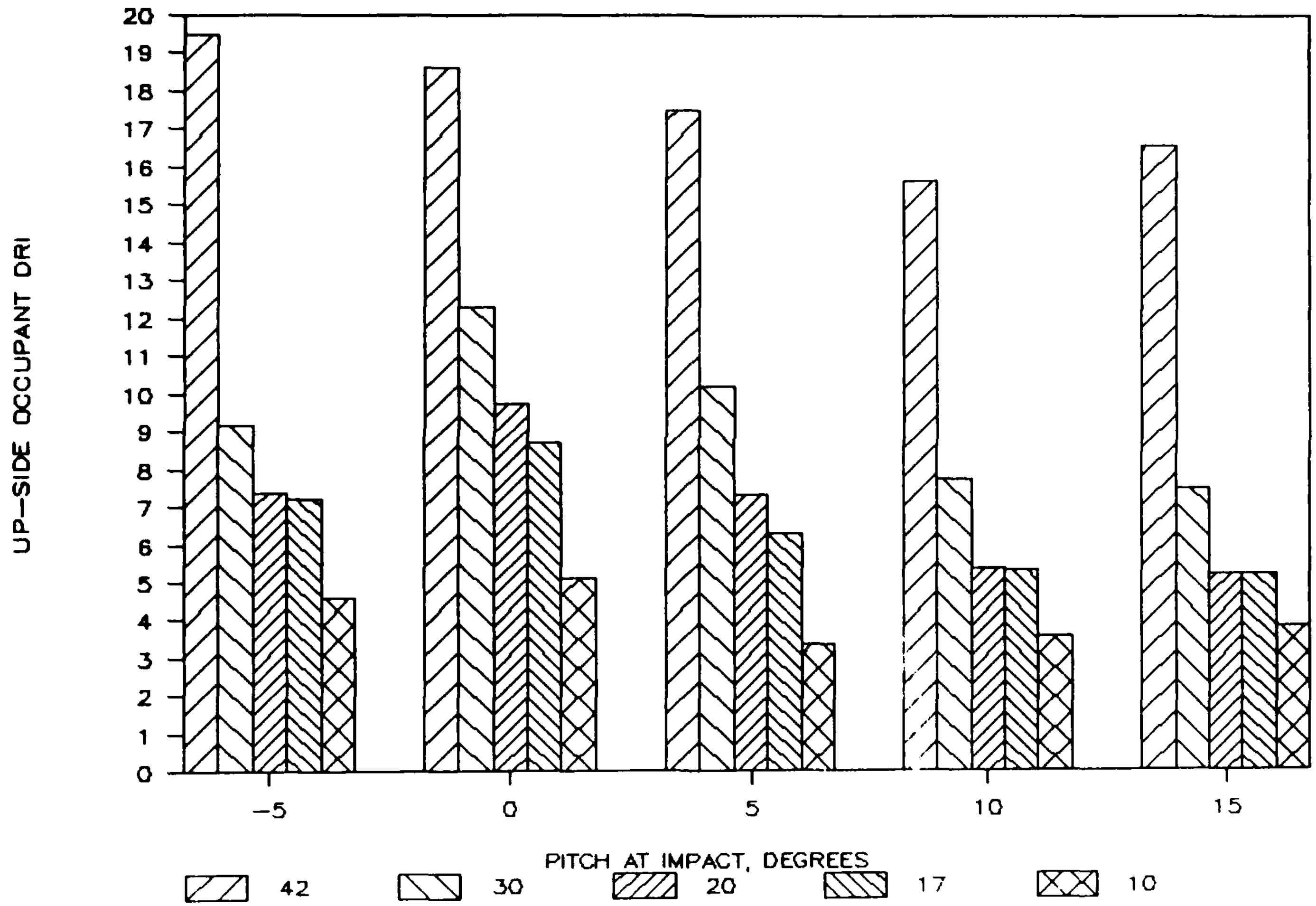


Figure 62. DRIs for up-side occupant for all speeds and pitch angles investigated for 5° roll.

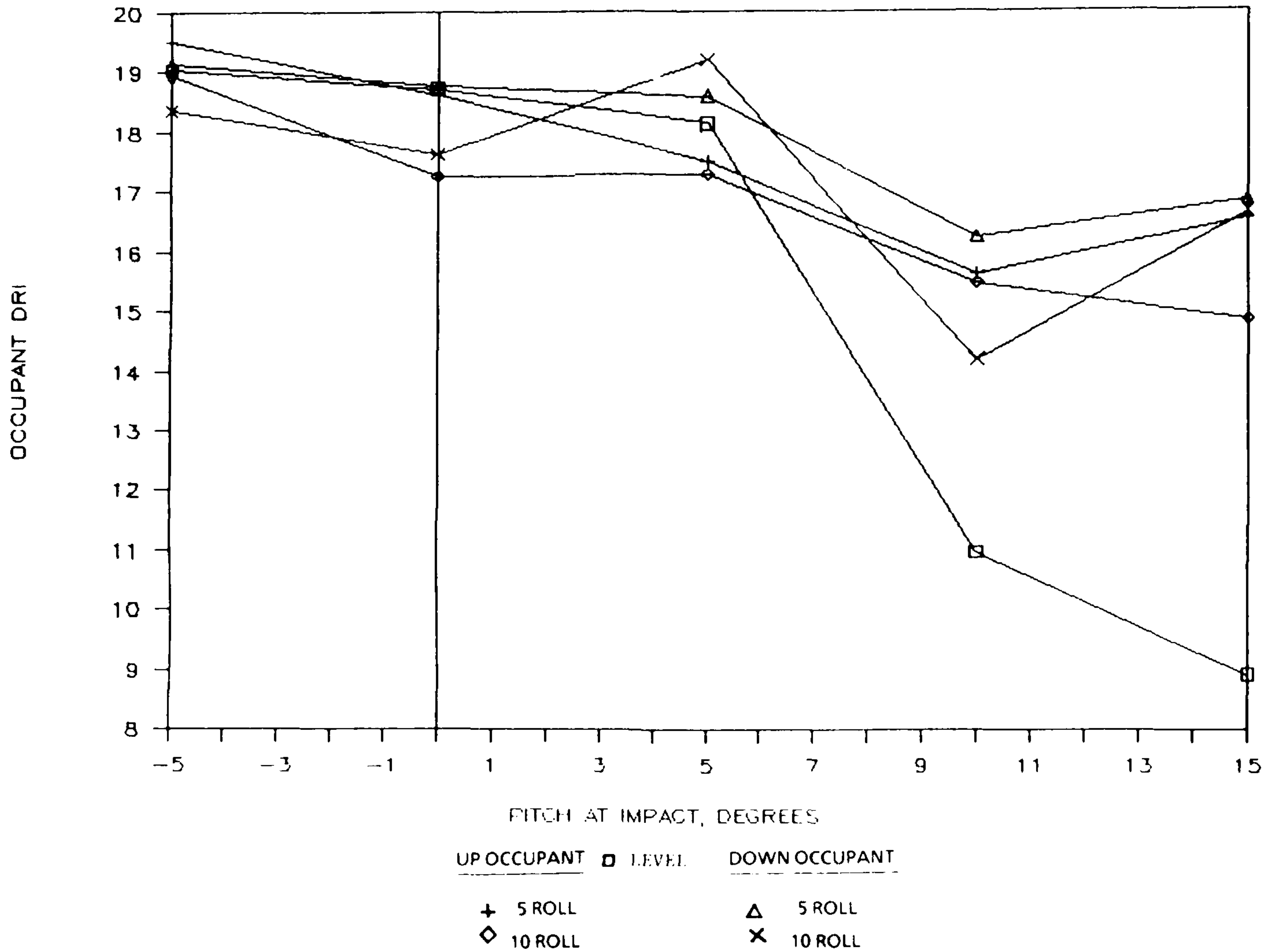


Figure 63. Effect of roll and pitch angles on DRI at 42 fps.

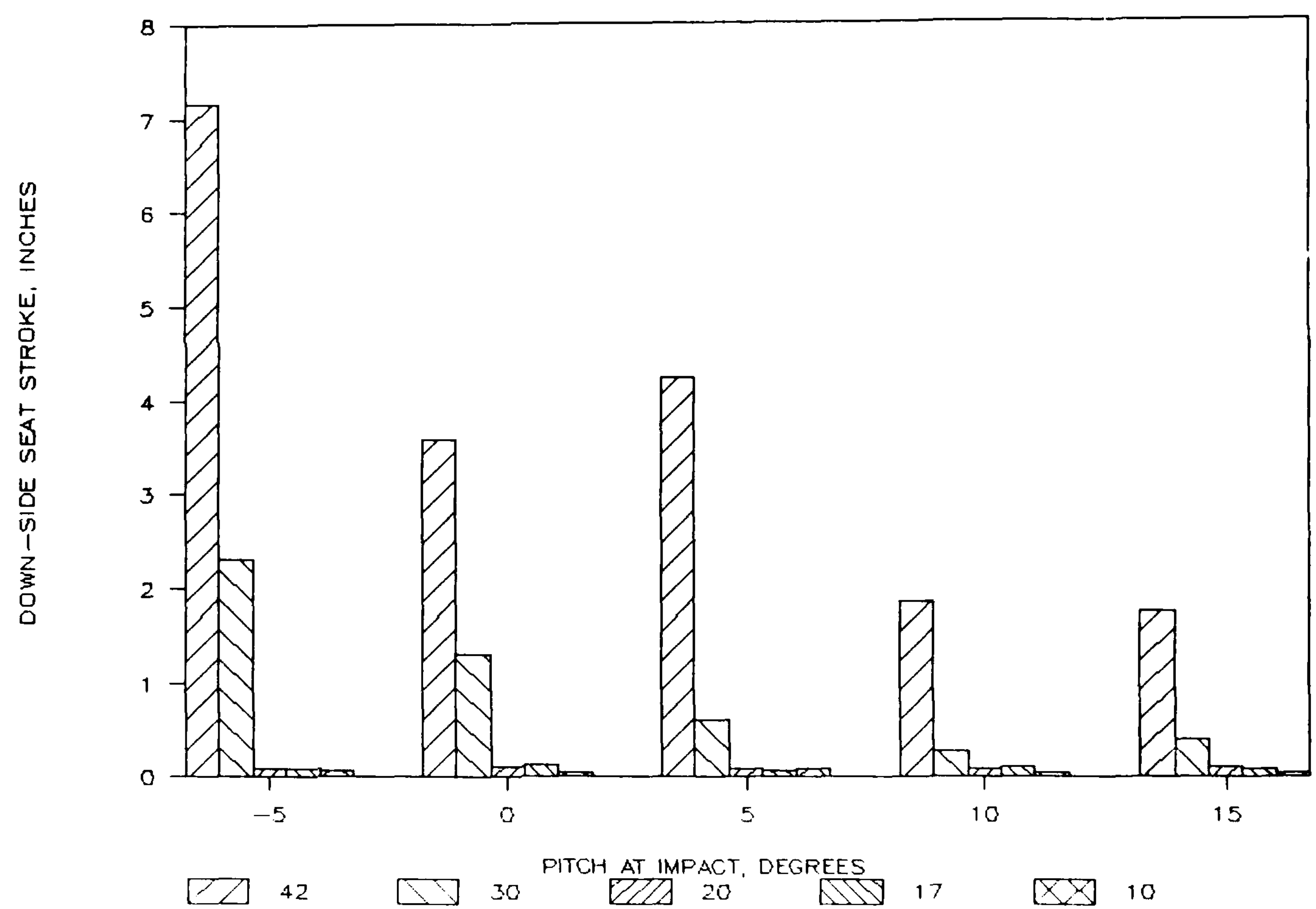


Figure 64. Down-side seat stroke for all speeds and pitch angles investigated for 10° roll.

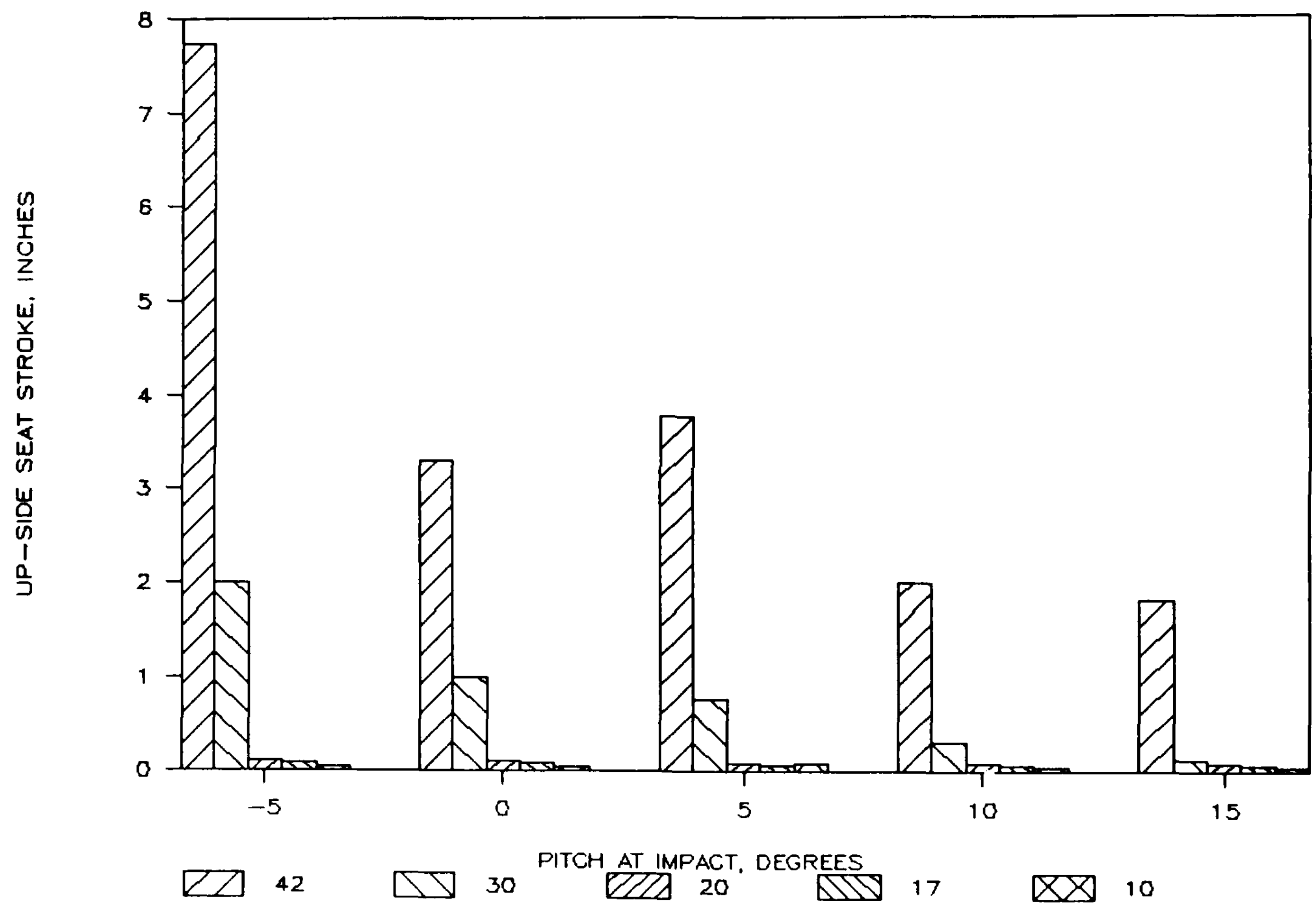


Figure 65. Up-side seat stroke for all speeds and pitch angles investigated for 10° roll.

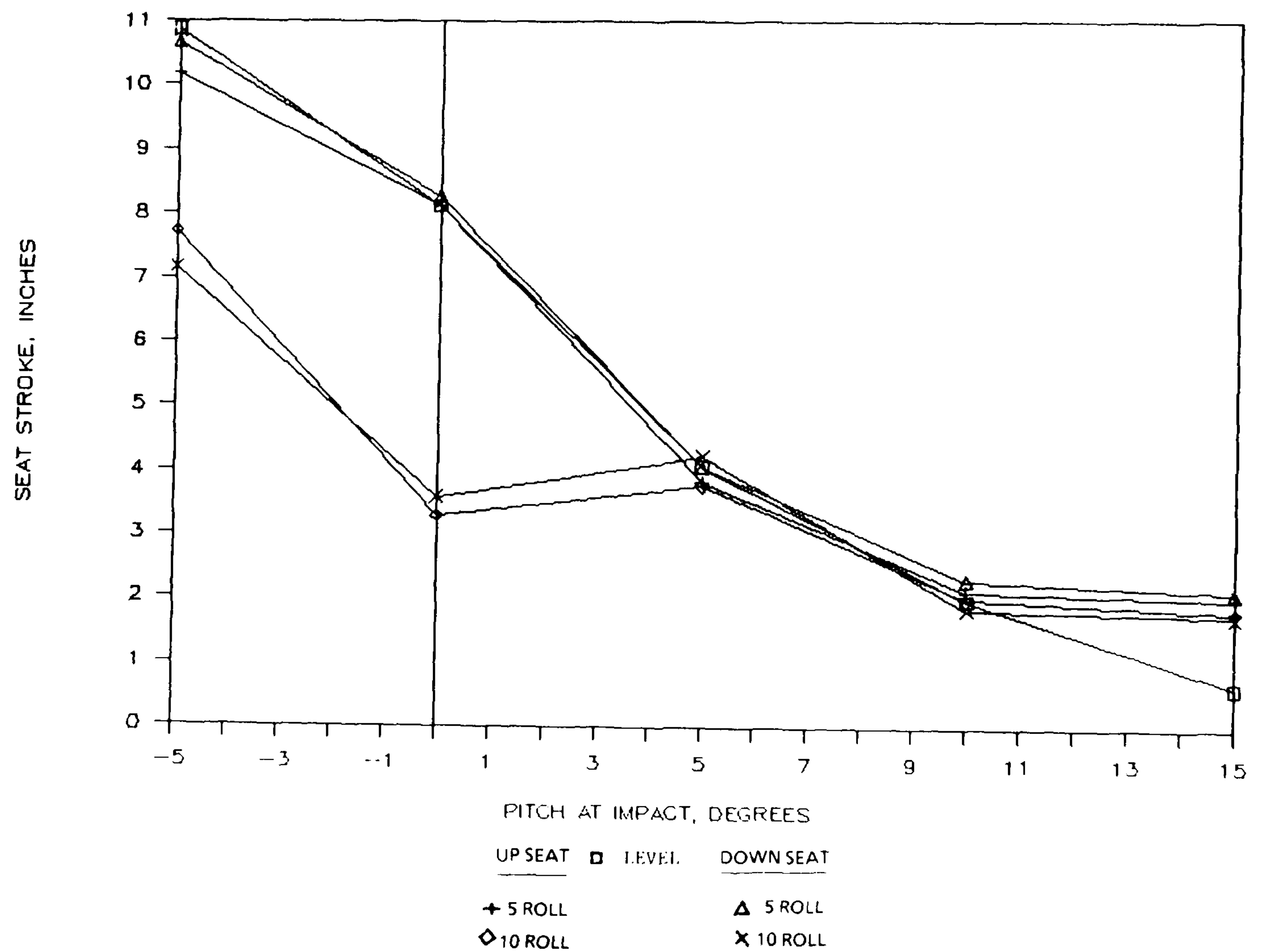


Figure 66. Effect of roll and pitch angles on seat stroke at 42 fps.

8.0 MATERIAL ANALYSIS

8.1 MATERIAL TRADE-OFF ANALYSIS

Advanced material systems were investigated for use in the landing gear components. The potential advantages of substituting advanced materials for conventional materials are:

- Lighter weight
- Reduced volume and drag area
- Lower acquisition and life-cycle costs
- Applicability of design details

The landing gear components which would have been potential candidates for design with advanced material systems are:

- Trailing Arm
- Shock Strut
- Retraction Actuator and Linkage System
- Pivot Crank
- Attachment Bracket

The advanced material components designs were studied as interchangeable units with components designed of the baseline material. Volume and size of the components were important criteria because of restrictions on increasing the drag area and the limitation of the available internal space.

The candidate components were selected for redesign with advanced material systems because design requirements indicated potential advantages. The choices of the various material systems for applicability to a given component were first weighted and ranked with respect to size, weight and cost. Following this evaluation, the requirements of detail design were given particular emphasis. Some of the areas which required definition were joints, bearing surfaces and attachment lugs which apply significant out-of-plane loads on the components. A preliminary evaluation of the anticipated advanced materials and processes is given in Table 27.

Metal matrix composites (MMC) are used where their high specific mechanical properties, low coefficient of thermal expansion, and stability of the mechanical properties at high temperatures can be best utilized. The aluminum matrix composites generally provide higher longitudinal strengths, whereas titanium matrix composites provide higher transverse strengths and higher longitudinal stiffnesses, and are suitable for higher temperature applications. As with all fiber-reinforced materials, MMC can be tailored for a given application by varying the fiber, matrix, and fiber volume. An additional advantage of MMC is that conventional metal design considerations are generally

TABLE 27. SUMMARY OF ADVANCED MATRIALS AND PROCESSES FOR HELICOPTER LANDING GEARS

Property and/or Behavior	Organic Matrix		Advanced Process	Metal Matrix			
	C/Ep (vf = 0.6)	B/EP (vf = 0.5)	6-4-Ti SPF/DB	B/Al (v/o = 0.45)	C/Al (v/o = 0.3)	FP/Al (v/o = 0.3)	B4 C(b)/Ti (v/o = 0.38)
Specific Tensile (0°) Strength, 10^6 LBF-Inch/LBM	4.15	2.20	0.862	2.21	1.06	0.56	1.73
Specific ±45° Shear Strength, 10^6 LBF-Inch/LBM	0.70	-	0.51	0.95	0.53	0.28	-
Specific Modulus (0°), 10^6 LBF-Inch/LBM	301.89	414.67	100.0	326.32	235.29	229.51	246.15
Cost, $/Pounds (1984)	40	200	25	500	1200	-	1500
Fabrication or Machining	Simple	Difficult	Simple	Difficult	Same as Aluminum	Casting	Difficult
Resistance to Foreign Object Damage	Poor	Poor	Good	Poor	Poor	Poor	Good

Legend for terms: vf = fiber volume fraction, v/o = filament volume fraction

applicable. The biggest drawback of these materials at this time is the poor potential for low-cost fabrication in large quantities. The cost of metal matrix materials, as shown in Table 27, is 1150 to 3650 percent higher than carbon-epoxy composite material. In terms of conventional steel and aluminum alloys, MMC are even less cost efficient. The poor machinability of these materials further increases the cost of design and tooling in comparison to conventional and organic composite materials.

In designing with organic composite materials, conventional design methods have to be reevaluated to achieve the potential of weight savings that these materials offer. Careful consideration must be given to joining techniques, methods of load transfer from and into composite structures, and impact damage from stones and debris to vulnerable areas of the landing gear. The advantages of organic composites are the very high specific strength and stiffness of the lamina, the ability to optimize the design by tailoring the constituent materials and by selectively using hybrids for specific requirements, and the ease of repairability. The biggest disadvantage of organic composite materials in their application to landing gears is their very low shear strength, which reflects on their response to torsional loads. The trailing arm of the landing gear is best suited for a composite design. However, the torsional load on the arm under crash-impact conditions is very high, the result of which is to increase the polar moment of inertia in order to remain within the given stress allowable. This requirement automatically increases the volume of the component. The design of the landing gear in Reference 7 addresses successfully a composite trailing arm for the same design criteria as those for the AH-64A helicopter landing gear. By comparing the volumes of the trailing arms of the existing landing gear of the AH-64A helicopter and of the design in Reference 7, a one-to-one comparison is possible. The volume of the 300M alloy steel trailing arm of the existing AH-64 landing gear is approximately 1161 cubic inches and that of the carbon-epoxy trailing arm is approximately 7890 cubic inches. The volume increase is of the order of 580 percent. Thus, a composite trailing arm design, though lighter and less expensive, is impractical at this stage when designed for retractable landing gears with limited stowing volume available.

8.2 MATERIALS FOR LANDING GEAR COMPONENTS

Based on the material trade-off analysis during preliminary design, it was apparent that only the retraction actuator itself lends to advanced composite materials. The remaining components must be designed with conventional materials. The design of the retraction actuator, however, was changed to include a linkage system and a combination of steel and aluminum alloys, resulting in the most efficient design.

The selection of conventional materials for the landing gear components was based on specific strength, ease of fabrication, quality of available material, cost and availability. A summary of the mechanical properties of conventional materials, normalized with respect to the properties of 300M alloy steel, is given in Table 28. The materials used in the landing gear components and the rationale for their selection are given in Table 29.

TABLE 28. SUMMARY OF 300M-NORMALIZED PROPERTIES OF CONVENTIONAL MATERIALS

Alloy	Material	Condition	FTU/d	K_{Ic}	Fatigue	Shear/d	FTY/d	FTY/d
Steels	300M	Q & T	1	1	1	1	1	1
	4340	Q & T	0.71	0.47	0.92	0.70	0.64	0.78
	4330V	Q & T	0.76	0.60	0.69	0.77	0.69	0.84
Aluminum	7075 T73	Hand	0.60	0.58	0.23	0.65	0.64	0.62
		Die	0.60	0.47	0.23	0.68	0.64	0.65
	7040 T73652	Hand	0.66	0.60	0.36	0.68	0.70	0.68
		Die	0.66	0.60	--	0.69	0.70	0.71
	7049 T73	Hand	0.57	0.55	0.44	0.66	0.70	0.68
		Die	0.59	0.57	--	0.68	0.72	0.68
	7175 T736	Hand	0.72	0.60	0.23	0.68	0.76	0.75
		Die	0.67	0.53	--	0.72	0.83	--
Titanium	Ti6A14V	A	0.78	1.24	0.71	0.88	0.88	--
		STA	0.89	0.71	1.02	0.83	1.02	--
	Ti7A14V	A	0.82	--	0.99	--	0.94	--
		STA	1.0	--	--	--	1.08	--
	Ti8A11Mo1V	DA	0.86	1.0	0.93	--	0.90	--
	Ti10V2Fe3A1	STA	1.05	0.92	1.43	1.13	1.21	1.28
		STOA	0.81	1.82	--	--	0.95	--
Aluminum	Al/Li 2090	Extrusion	0.93	0.35	--	0.77	1.12	1.07
		Plate	0.87	0.50	--	0.82	1.0	0.87

TABLE 29. MATERIALS OF LANDING GEAR COMPONENTS

Major Item	Material	Strength/ Wt.	Ease of Fabrication	Available Data	Cost	Quality	Availability	Remarks
Trailing Arm	7175 AL-Alloy	Good	Very Good	Excellent	Fairly Low	Good	Good	High Strength, Stress Corrosion Resistant
Shock Strut Outer Cyl.	7175 AL-Alloy	Good	Very Good	Excellent	Fairly Low	Good	Good	(Same as Trailing Arm)
Shock Strut Inner Cylinder	7175 AL-Alloy	Good	Very Good	Excellent	Fairly Low	Good	Good	(Same as Trailing Arm)
Shock Strut Piston	4340 Steel	Fairly High	Very Good	Excellent	Low	Very Good	Good	HighStrength, Vacuum Remelted Clean
Axle	4330V Steel	Fairly High	Very Good	Excellent	Low	Very Good	Good	(Same as shock strut piston)
Ret Act'r Piston	4340 Steel	Fairly High	Very Good	Excellent	Low	Very Good	Good	(Same as shock strut piston)
Upper and Lower Links	7075 AL-Alloy	Good	Very Good	Excellent	Fairly Low	Good	Good	High Strength, Stress Corrosion Resistant
Attachment Pins	300M Steel	High	Fair	Good	High	Very Good	Long Lead Time	HighStrength, Vacuum Remelted Clean
Pivot Crank	7175 AL-Alloy	Good	Very Good	Excellent	High	Very Good	Good	(Same as Trailing Arm)

9.0 WEIGHT ANALYSIS

9.1 GENERAL

The weight sensitivity analysis for the ATLG and the crashworthy helicopter includes calculations of incremental weights from the landing gear, fuselage and crew seats to satisfy the design requirements for the maximum crash-impact condition at a vertical speed of 42 fps, 10 degrees roll and 15 degrees pitch. The ATLG system was sized to absorb 60 percent of the energy from a 42 fps level impact. The crash-impact behavior is based on loads from KRASH and static structural analyses to size the components. The weight sensitivity analysis includes the calculated weights of the crashworthy and standard (noncrashworthy) landing gears and helicopters.

9.2 LANDING GEAR WEIGHTS

The components of the landing gear which are affected by changes in the load are the trailing arm, shock strut, retraction actuator and fuselage fittings. The incremental weights are calculated by sizing the components for the applied load. Typically, the shock strut is an axially loaded member which varies in weight as a function of impact velocity, gross weight, pitch/roll angles, and critical load. The wall thicknesses of the pistons and cylinders, and the stroke required, become the weight driver which affects many internal components of the shock strut assembly including end caps, seals, and bearings. The weight of the fittings is proportional to that of the shock strut load.

The actual weight of the ATLG system is summarized in Table 30. The weight of a typical standard landing gear is also given in the table. The weight of the ATLG system is 373 pounds in comparison to the standard landing gear weight of 243.9 pounds. The ATLG crashworthy retractable gear is 53 percent heavier.

The weight of the standard (noncrashworthy) landing gear was determined from energy absorption requirements for a vertical impact speed of 12.5 fps, 0 degree roll and 0 degree pitch. The shock strut is designed for 3.5g and absorbs all the energy. The weight of the standard landing gear is lower because of lower loads on the trailing arm and axle, shock strut, retraction actuator, attachment fittings and assembly hardware. The mass fractions of current main landing gears and of the ATLG are compared in Figure 67. A summary of the weight history is given in Figure 68. The group weight statements for a crashworthy helicopter with the ATLG system and for a noncrashworthy standard helicopter are given in Table 31.

TABLE 30. COMPARISON OF THE WEIGHTS OF THE ATLG AND THE STANDARD NONCRASHWORTHY LANDING GEAR

Item	ATLG Weight (lb)	Standard Noncrashworthy Landing Gear Weight (lb)
Running Gear*	62.0	54
Trailing Arm and Axle*	79.3	53
Shock Strut and Retraction Actuator*	109.3	64
Fuselage Attachment Fittings/Crank*	66.2	32
Pins, Bolts, Nuts, misc.**	35.3	20
Controls**	20.9	20.9
Total Main Landing Gear	373.0	243.9

*Actual weight
**Estimated weight

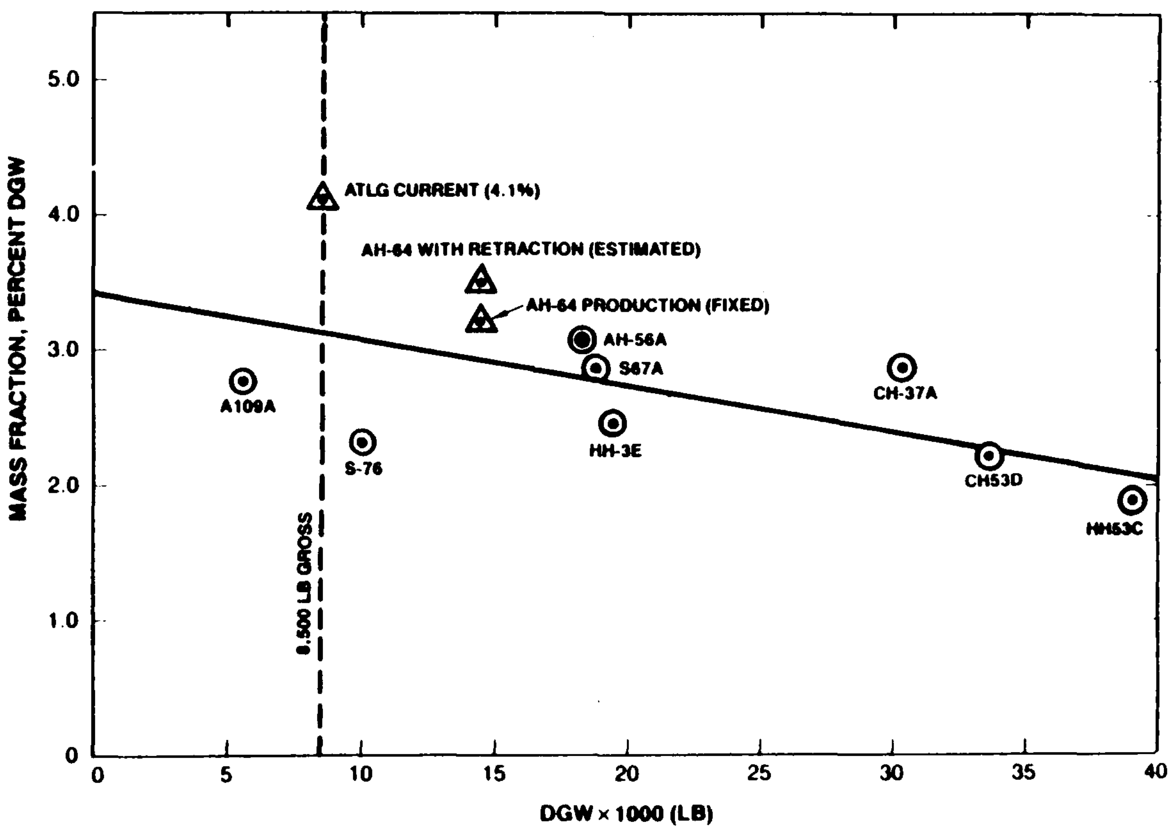


Figure 67. Mass fractions of main landing gear systems.

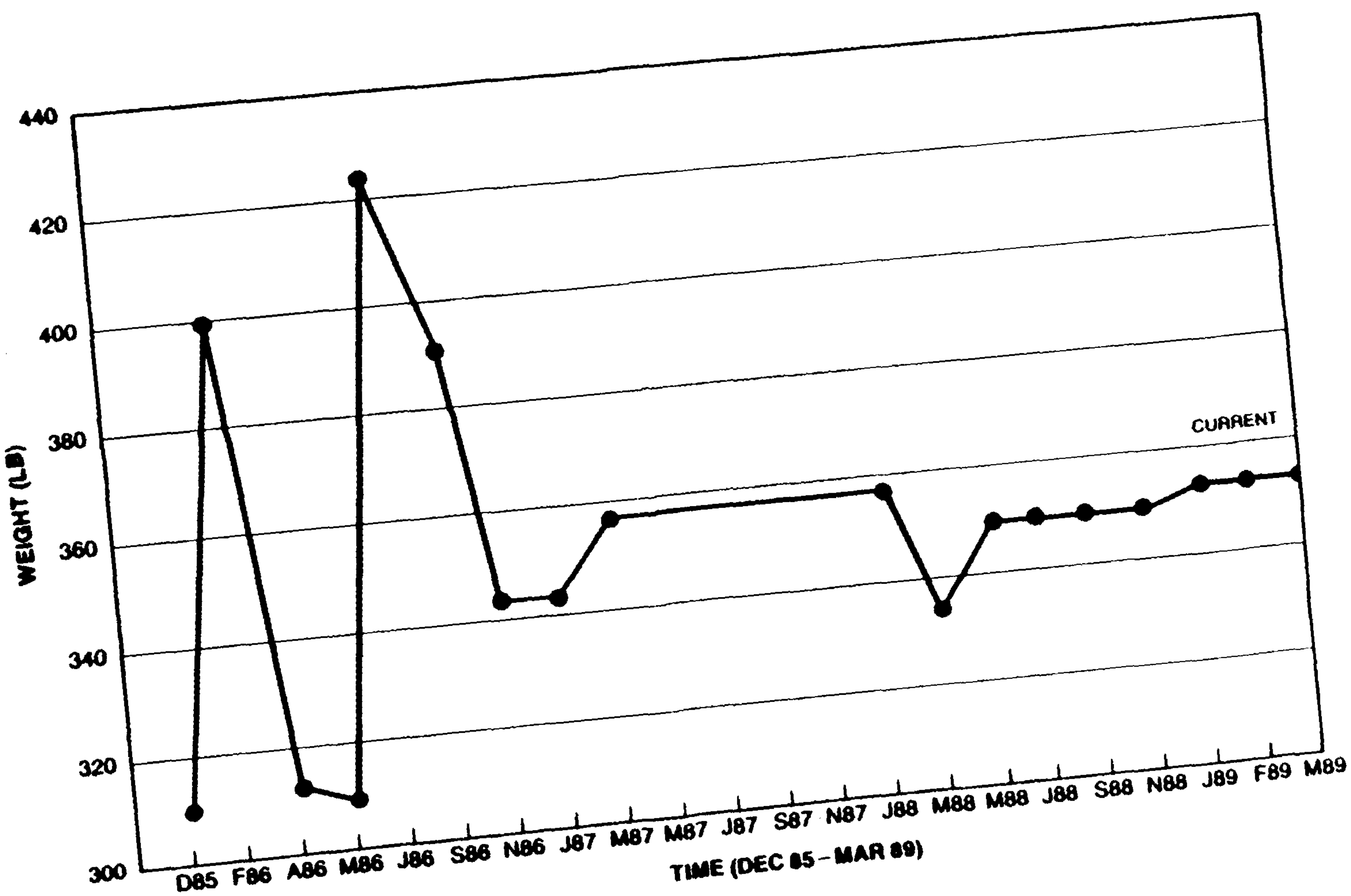


Figure 68. ATLG weight history.

TABLE 31. GROUP WEIGHT STATEMENT OF ATLG UTILITY AND NONCRASHWORTHY HELICOPTERS

Item	ATLG Crashworthy Weight (lb)	Noncrashworthy Standard Weight (lb)
Main Rotor Group	668	668
Tail Group	190	190
Body Group	922	876
Alighting Gear Group	417	287
Nacelle	120	120
Air Induction	27	27
Propulsion	1443	1379
Flight Controls	422	422
Auxiliary Power Plant	60	60
Instruments	91	91
Hydraulics and Pneumatics	215	215
Electrical	229	229
Avionics	270	270
Armament	457	457
Furnishing and Equipment	372	214
Air Conditioning	180	180
Anti-Ice	16	16
Loading and Handling	5	5
Weight Empty	6104	5706
Crew	235	235
Unusable Fuel	18	18
Engine Oil	25	25
Fuel	776	776
Payload (6 Troops)	1342	1342
Gross Weight	8500	8102

10.0 MAINTAINABILITY AND RELIABILITY ANALYSES

10.1 ALLOCATED MAINTAINABILITY REQUIREMENTS

The maintainability guidelines and preliminary analysis were presented in Section 2.6. Following the completion of fabrication and test of the ATLG, the preliminary maintainability analysis was further verified. The allocated requirements for maintainability were based on the analysis of the LHX requirements. The requirements for the full landing gear system (main and nose gears) are given below:

MTBF	=	180 Hrs
MTBMA	=	108.11 Hrs
MTTR	=	0.5475 Hrs
MMH/FH	=	0.04700

10.2 MAINTAINABILITY EVALUATION

The ATLG system is a modular (LRU) design such that all components except the trailing arm and pivot crank are interchangeable. The entire landing gear, or any major component of the landing gear, can be removed by releasing only two pins or bolts. The system thus permits ease of accessibility and two-level maintenance with easily replaceable modules in the field. Downtime is considerably reduced with this concept and without the requirement for alignment with special tools.

The design of the landing gear system was optimized to further improve maintainability. The materials and fabrication processes selected for the landing gear components were designed to reduce stress corrosion and fatigue failures, and improve fracture toughness. The design was evaluated for full extension and retraction without interference when components are worn to their maximum possible limits. Provisions were made to prevent cross-connection of hydraulic fittings and to provide lubrication points where needed.

The reliability and maintainability (RAM) evaluation for the ATLG results in an MTBF = 417.29 hours, MTBMA = 170.32 hours, MTTR = 0.6281 hour, MMH = 0.7233 hour and MMH/FH = 0.00350. This result is shown on Table 32.

In comparing with the allocated requirements for the full landing gear system, the RAM analysis provides favorable results for the ATLG. The MTBF of 417.29 hours is high and will possibly reduce following the introduction of the failure-prone switches and other components of the full landing gear system.

Similarly, an MTBMA of 170.32 hours has considerable latitude before the allocated requirement of 108.11 hours is reached. The MMH/FH of 0.00350 is low enough for growth to the allocated requirement of 0.04700.

TABLE 32. ATLG RAM ANALYSIS

ATLG	MTBF	MTBMA	MTTR	MMH	MMH/FH
Shock Strut (2)	8,710.80	3,288.50	1.0000	1.4000	0.00043
Trailing Arm (2)	138,888.89	58,987.50	0.5000	0.7400	0.00001
Wheel (2)	12,019.23	5,104.69	0.4000	0.4000	0.00008
Tire (2)	1,030.08	437.49	0.4000	0.4000	0.00091
Disk Brake (2)	4,184.10	1,875.75	0.5000	0.5000	0.00027
Actuator (2)	3,125.00	1,179.75	1.2000	1.6000	0.00136
Crank (2)	3,551.14	1,340.63	0.6000	0.6000	0.00045
Bracket (2)	4,599.82	1,953.59	0.6000	0.7000	0.00036
Act. Linkage (2)	6,157.64	2,324.63	0.8000	0.9000	0.00039
SUBTOTAL	417.29	170.32	0.6281	0.7233	0.00350

10.3 RELIABILITY ANALYSIS

Reliability considerations were incorporated early in the program in order to substantiate that the reliability requirements were reflected properly in the landing gear design. During the detailed design phase, the reliabilities of the system and the components were established by using the FARADA (Weapons Failure Rate Data Program) and RADC (Reliability Central) data base. A reliability block model of the design is shown in Figure 69. Based upon the current design, the MTBF is 417.29 hours.

The potential failure modes were listed in the FMECA (Failure Mode, Effects and Criticality Analysis) for the shock strut and the retraction linkage. These are given in Tables 33 and 34. The potential failures were utilized as a checklist during the detail design phase.

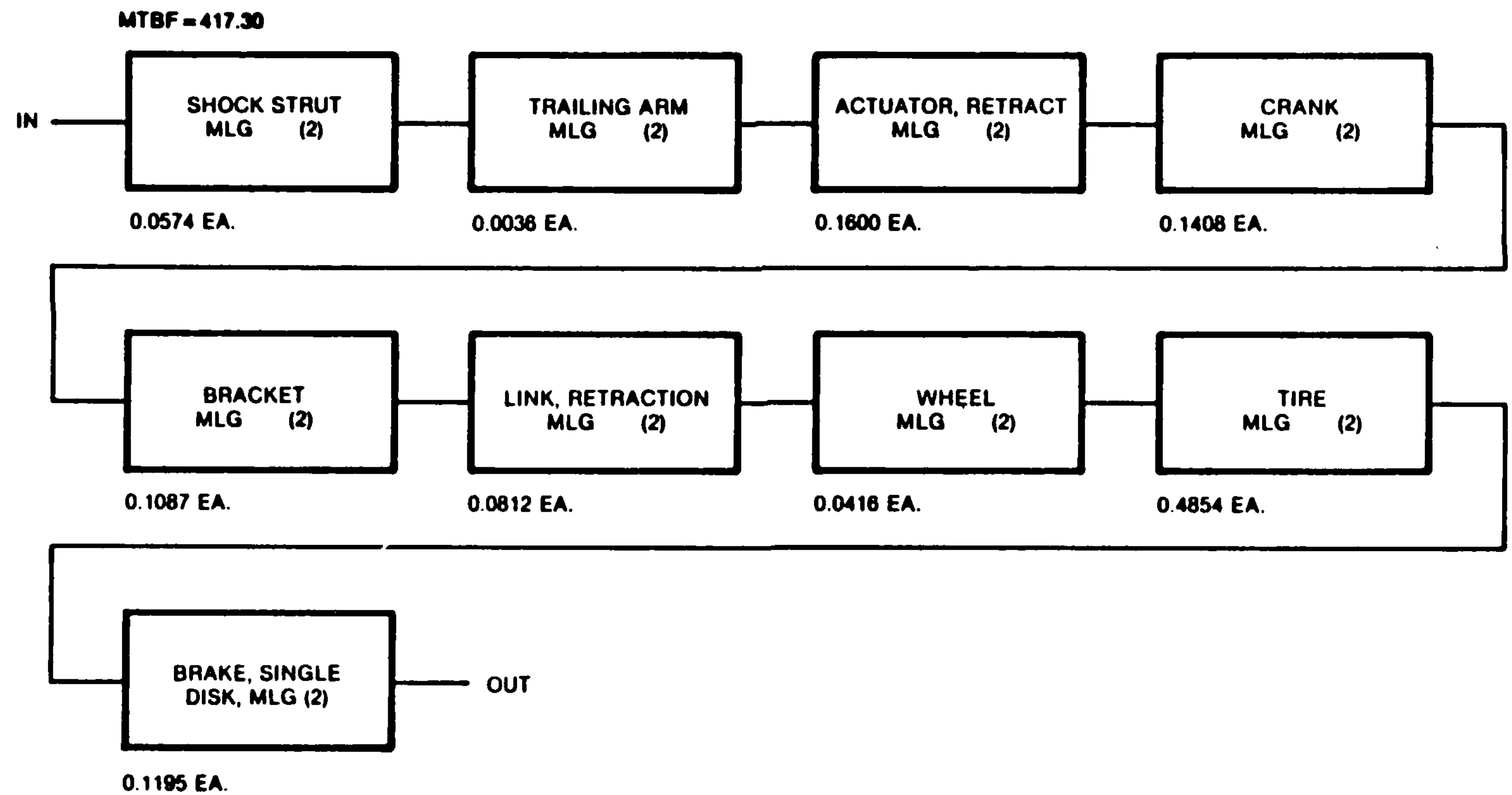


Figure 69. Reliability block model of ATLG system.

TABLE 33. FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) OF THE SHOCK STRUT ASSEMBLY

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

4340 V/R STL.

SUBSYSTEM: MAIN LANDING GEAR (ATLG) W.B.S. NO. 7-11 PRELIMINARY PREPARED BY: J. WILLIAMS SHEET: ____ OF ____ REV NEW DATE: 6-25-86

REF NO. (1)	ITEM NOMENCLATURE & FUNCTION (2)	FAILURE MODE/S (3)	METHOD OF DETECTION (4)	FAILURE EFFECT SUBSYSTEM (5)	FAILURE EFFECT AIR VEHICLE (6)	TOTAL UNSCHED MAINT ACTNS (7) UMA 1000 HR	SOURCE	QTY (8)	TIME (9)	α (10)	MODE (11)	COMMENTS/COMPENSATING PROVISIONS (12)
1252100	SHOCK STRUT ASSY, MLG, ATLG - MDHC The shock strut works as a shock absorber for normal takeoff, landing and taxiing. Nitrogen compressed by hydraulic fluid in the upper piston serves to cushion landings.					.0574	RADC & ENG. EST.	1	1.0			The Main Landing Gear design includes three Major Components per gear which are a Shock Strut, Extension/Retraction Actuator and a Trailing Arm. The Shock Strut is designed with an attached pressurized component, which allows for the Strut's hard landing capabilities. The design will also have provisions for an Emergency System to aid the Extension/Retraction Actuator in case of failure. These components are attached to the airframe through a fixture having four rotating points of contact.
		(a) External Leakage	Visually inspect for fluid loss and/or improper strut extension	Strut could collapse, and cause damage to other components in the landing gear system	Mission abort and/or potential safety of flight if this failure mode goes undetected.					109 010 001	S M FS	
		(b) Internal Leakage	Visually inspect for improper strut extension and/or loss of ability to properly service the strut	Strut could collapse, and cause damage to other components in the landing gear system	Mission abort and/or potential safety of flight if this failure mode goes undetected.					009 010 001	S M FS	
		(c) Excessively scored Piston Assy.	Visually inspect for fluid loss and/or erratic system response.	Loss of fluid could result in the collapse of the strut and damage to other components in the landing gear system.	Mission abort and/or potential safety of flight if this failure mode goes undetected.					140 010	S M	
		(d) Structural Failure of the Assembly.	Visually inspect for cracks and/or other degradation.	Complete loss of function and/or possible damage to the aircraft.	Possible loss of aircraft and/or possible loss of life if this failure mode goes undetected.					090 010	S M	
		(e) Strut stuck in the extended or retracted position	System response and/or during operation.	Possible total loss of of function.	Mission abort and/or safety of flight.					110 030 010	S M FS	
		(f) Corrosion	Visual inspection	Degraded Material	None					300	S	

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TABLE 34. FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) OF THE RETRACTION LINKAGE ASSEMBLY

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

SHEET: ____ OF ____

SUBSYSTEM: MAIN LANDING GEAR (ATLG) W.B.S. NO. 7-11 PRELIMINARY PREPARED BY: J WILLIAMS REV: NEW DATE: 6-25-

REF NO. (1)	ITEM NOMENCLATURE & FUNCTION (2)	FAILURE MODE/S (3)	METHOD OF DETECTION (4)	FAILURE EFFECT SUBSYSTEM (5)	FAILURE EFFECT AIR VEHICLE (6)	TOTAL UNSCHED MAINT ACTNS (7) MMA 1000 HR	SOURCE	QTY (8)	TIME (9)	α (10)	MODEL (11)	COMMENTS/COMPENSATING PROVISIONS (12)
1252300	LINKAGE, RETRACTION ASSY, ATLG MDHC MLG					.0812	RADC & ENG. EST.	1	1.0			
	Provides the means for retracting and lowering the Main Landing Gear.	(a) Cracked/Broken	Visual inspection and/or system response	Possible loss of ability to retract and/or lower the landing gear.	Mission abort and/or potential safety of flight if this failure goes undetected.					089 010 001	S M FS	
		(b) Linkage stuck in the extended or retracted position	System Response	System could become totally inoperative	Mission abort and/or potential safety of flight.					100 020 030	S M FS	
		(c) Inoperative Microswitch	System Response	Loss of gear position indication.	Possible mission abort if pilot or copilot are unable to determine gear position.					300 040 010	S M FS	Ref. RM Level FMECA
		(d) Corrosion	Visual, Inspection	Degraded Material	None					400	S	

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11.0 MANUFACTURING COSTS

11.1 GENERAL

The elements of cost address a crashworthy, retractable landing gear for an LHX-size utility helicopter. The components include the trailing arm, shock strut, retraction actuator with linkage assembly, the pivot crank and the running gear. The objective was to estimate the Cumulative Average Cost (CAC) of producing 5000 landing gear shipsets in a 13-year production cycle. The resultant estimated costs are presented in a Flyway Cost format as specified in "Instructions for Reformatting the BCE/ICE," DCA-P-92(R). The cost elements addressed are given in a Work Breakdown Structure (WBS) format. The WBS elements, used in the estimates and in the flyaway cost tables, are given below.

1. Recurring Production

   a. Engineering
   b. Tooling
   c. Manufacturing
   d. Quality Control
   e. Integration and Test
   f. G&A
   g. Profit

2. Engineering Changes

   a. Nonrecurring Production, Initial Production Facilities (IPF) and Tooling
   b. System/Project Management

3. Exclusions

   a. Government Furnished Equipment
   b. System Test and Evaluation

11.2 SYSTEM DESCRIPTION

The system addressed in this analysis is a crashworthy, retractable landing gear. The main landing gear shipset without the controls, as shown in Table 30, weighs 352 pounds. It has been designed with high strength aluminum and steel alloys. The major components of the landing gear system are the trailing arm and axle; the piston, and inner and outer cylinders of the shock strut; the retraction actuator and linkage assembly; the pivot crank; and the running gear. The ATLG system for the cost analysis is defined in accordance with the Manufacturing Methods Report and the December 1988 Weight Control Status Report of the program.

11.3 GROUND RULES AND ASSUMPTIONS

1. Costs are reported in economic base year 1988 dollars.

2. Escalation Indices:

   AFR Regulation 173-13 (1988 Revision), USAF weighted inflation indicies on OSD raw inflation and outlay rates and the USAF raw inflation indicies. (See Appendices A to C.)

3. Development and production quantities and rates:

   a. Five main landing gears including two pivot cranks were used as prototype quantities to calibrate the parametric model for the development to production transition.

   b. Ten thousand main landing gears constituting 5000 shipsets are to be manufactured during the investment phase. The production rate buildup was allocated based on a previously proposed LHX production rate for a 13-year production cycle. The production rate buildup is as follows:

Production Rate Buildup

Fiscal Year	90	91	93	93	94	95	96	97	98	99	00	01	02
Quantity (S/S)	76	184	343	440	440	440	440	440	440	440	440	440	437

Total: 5000

4. Schedule:

	Start	First-Item	Completion
Development	Nov 86	Nov 87	Jan 89
Production	Mar 89	Mar 90	Mar 01

5. Production costs were based upon a parametrically derived 90.1 percent learning curve.

6. Burden rates were supplied by MDHC Pricing and Estimating Department via the 1988 Rates Package - Number 4, TWS/RS 2320-088. General and Administrative (G&A) rate was applied at 12.99 percent. Profit at 15 percent was assumed to be reasonable for relative purposes.

7. Baseline System:

Nomenclature	Quantity	Weight (lbs)	
Trailing Arm	2		66.0
Shock Strut/Actuator			109.3
- Strut	2	97.2	
- Oil		12.1	
Axle	2		13.3
Main Running Gear	2		62.0
- Wheels		24.0	
- Tires		24.5	
- Brakes		12.0	
- Air		1.5	
Steps/Fairings			3.0
- Steps		1.6	
Fairings		1.4	
Pins, Bolts, Nuts, Etc.			32.3
Pivot Crank	2		66.2
TOTAL WEIGHT			352.1

8. Exclusions/Inclusions:

a. The cost of two pivot cranks at approximately $26K each was added to the development cost. This was necessary for implementing the PRICE Model calibration process. A required cost of five complete gears was necessary to transition from the development phase into production.

b. Systems test and evaluation was assumed to occur at the next higher assembly, i.e., at the aircraft level.

11.4 COST SUMMARIES

The cost summaries shown in Tables 35 and 36 are the results of the sensitivity analysis. In performing this analysis, costs were calculated based on varied manufacturing processes. The least likely case, shown in Table 35, yielded a total program cost of $275 million at an average unit cost of $55-thousand per shipset. The most likely case, shown in Table 36, yielded a total program cost of $303 million at an average unit cost of $61-thousand a shipset.

These costs represent the nominal values for each case. They are presented in economic base year 1988 dollars. The cost elements addressed represent flyaway cost.

BASE YEAR 1988 DOLLARS
COST/THOUSAND

TABLE 35. FLYAWAY COST ESTIMATE FOR LEAST LIKELY CASE

FISCAL YEAR	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97	FY98	FY99	FY00	FY01	FY02	TOTAL
LOT QUANTITY/(S/S)	76	184	343	440	440	440	440	440	440	440	440	440	437	5000
RECURRING PRODUCTION														
ENGINEERING	38	14	10	10	10	10	10	10	10	10	10	10	10	162
TOOLING & TEST EQ	533	100	138	160	159	159	159	159	158	158	158	158	157	2356
MFG HDWR	4932	9443	15559	18127	16875	16034	15403	14899	14480	14122	13809	13533	13190	180406
INTEG & TEST	508	1227	1551	1650	1608	1509	1368	1241	1114	973	790	494	71	14104
G&A (12.99%)	781	1401	2242	2591	2423	2301	2201	2119	2048	1983	1918	1844	1744	25594
PROFIT (15%)	1019	1828	2925	3381	3161	3002	2871	2764	2672	2587	2503	2406	2276	33393
TOTAL DESIGN-TO-PROD	7810	14012	22425	25918	24236	23015	22012	21192	20482	19833	19188	18444	17448	256016
ENGR CHANGE PROP (ECP)	301	539	518	598	373	354	0	0	0	0	0	0	0	2683
TOTAL HARDWARE COST	8111	14551	22943	26517	24609	23369	22012	21192	20482	19833	19188	18444	17448	258699
NONRECURRING PRODUCTION														
IPF/TOOLING	1441	269	372	431	431	430	430	429	429	429	428	427	425	6371
SYSTEM PROJ MANAGEMENT	520	548	741	821	769	742	721	705	691	679	668	659	648	8912
SYS TEST & EVAL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL FLYAWAY (BY88$)	10072	15369	24056	27769	25809	24541	23163	22326	21601	20941	20284	19530	18521	273981
ESCALATION/DISCOUNT FACTORS:														
ESCALATION RATES	1.082	1.116	1.147	1.173	1.200	1.227	1.256	1.285	1.314	1.344	1.375	1.407	1.439	
DISCOUNT RATES (10%)	0.826	0.751	0.683	0.621	0.564	0.513	0.467	0.424	0.386	0.350	0.319	0.290	0.263	
THEN YEAR (TY$) DOLLARS	10898	17151	27592	32573	30971	30112	29092	28689	28384	28145	27890	27479	26651	345628
PRESENT VALUE DOLLARS	9005	12886	18846	20228	17492	15452	13572	12167	10943	9864	8887	7960	7018	164309
UNIT COST FAF	133	84	70	63	59	56	53	51	49	48	46	44	42	55

TABLE 36. FLYAWAY COST ESTIMATE FOR MOST LIKELY CASE

BASE YEAR 1988 DOLLARS
COST THOUSAND

FISCAL YEAR	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97	FY98	FY99	FY00	FY01	FY02	TOTAL
LOT QUANTITY/(S/S)	76	184	343	440	440	440	440	440	440	440	440	440	437	5000
RECURRING PRODUCTION														
ENGINEERING	43	16	12	12	12	12	12	12	12	12	12	12	12	191
TOOLING & TEST EQ	610	118	163	188	188	188	188	187	187	187	187	187	185	2763
MFG HDWR	5478	10473	17199	19999	18598	17658	16953	16389	15920	15520	15171	14862	14481	198701
INTEG & TEST	565	1365	1726	1836	1789	1679	1522	1381	1240	1083	879	549	78	15690
G&A (12.99%)	870	1555	2481	2862	2674	2538	2426	2334	2255	2183	2111	2020	1917	28233
PROFIT (15%)	1135	2029	3237	3735	3489	3311	3165	3045	2942	2848	2754	2646	2501	36837
TOTAL DESIGN-TO-PROD	8700	15556	24818	28632	26750	25386	24265	23349	22556	21832	21113	20283	19175	282415
ENGR CHANGE PROP (ECP)	335	599	573	661	412	391	0	0	0	0	0	0	0	2970
TOTAL HARDWARE COST	9035	16154	25391	29293	27162	25776	24265	23349	22556	21832	21113	20283	19175	285385
NONRECURRING PRODUCTION														
IPF/TOOLING	1649	318	440	510	509	508	507	507	506	506	505	504	502	7471
SYSTEM/PROJ MANAGEMENT	591	599	809	883	839	808	785	767	752	738	727	717	704	9709
SYS TEST & EVAL	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL FLYAWAY (BY88$)	11265	17072	26640	30686	28510	27093	25558	24622	23813	23076	22345	21504	20380	302565
ESCALATION/DISCOUNT FACTORS:														
ESCALATION RATES	1.082	1.116	1.147	1.173	1.200	1.227	1.256	1.285	1.314	1.344	1.375	1.407	1.439	
DISCOUNT RATES (10%)	0.826	0.751	0.683	0.621	0.564	0.513	0.467	0.424	0.386	0.350	0.319	0.290	0.263	
THEN YEAR (TY$) DOLLARS	12189	19052	30556	35994	34212	33243	32101	31640	31291	31014	30725	30257	29327	381600
PRESENT VALUE DOLLARS	10074	14314	20870	22350	19312	17059	14975	13418	12064	10870	9790	8764	7723	181583
UNIT COST BY$	148	93	78	70	65	62	58	56	54	52	51	49	47	61

11.5 SPECIFIC METHODOLOGIES

The object of this section is to establish an audit trail for the analysis. This is accomplisihed through the documentation of the methods, reference data sources, normalization processes, data modification procedures, Cost Estimating Relationships (CER) and cost factors.

11.5.1 PRICE System Model

A parametic approach employing the General Electric PRICE system models was used in deriving the flyaway cost of the ATLG. PRICE (Parametric Review of Information for Costing and Evaluation) is a computerized model that parametrically derives cost estimates of electronic and mechanical hardware assemblies and systems. With PRICE the current product based on actual data can be fingerprinted and the organizational habits captured by means of a calibration process. Thus, the actual program performance can be emulated.

The approach taken was to calibrate the model to the actual costs of the ATLG development phase. The process was synonymous to a least squares linear regression fit. After calibration, the model was used to transition from the development phase to the production phase. The elements of costs addressed by PRICE include design, drafting, project management, documentation, manufacturing, and special tools and test equipment. Excluded are costs associated with field testing, site activation/construction and software development. The process documentation is described below.

11.5.2 Model Calibration

The model was calibrated using the program Cost/Schedule Status Report for the October 1988 reporting period. The budgeted Cost-At-Completion was used, less Cost of Money (COM), General and Administrative (G&A), and Management Reserves (MR) to calibrate the PRICE model.

TOTAL (88 $)		$2575.1
Less:	COM	$ 30.7
	G&A	$ 268.6
	MR	$ 34.7
CALIBRATION SUBTOTAL		$2241.1

Since the development program included only 5 prototypes and 2 pivot cranks, an additional cost for three pivot cranks was added to the Phase II at $26K per crank.

CALIBRATION SUBTOTAL	$2241.1
PIVOT CRANKS (3) @ $26k ea.	$ 78.0
	$2319.1

The calibration process is called the ECIRP mode of operation. A copy of the output is given in Appendix D. The results are as follows:

Manufacturing Complexities

From	6.279
Center	6.376
To	6.474

The model was executed using manufacturing complexities 6.376 and 6.474 to establish sensitivity limits. Input files are given in Appendix E and the output files in Appendces F and G.

The model was calculated based on a unit learning curve of 90.1 percent for both manufacturing complexities.

11.5.3 Integration and Test (I&T)

Integration and test costs incorporate those efforts associated with perfecting electrical and structural interfaces, and the verification of specification compliance. It also encompasses costs for system-oriented tasks such as acceptance test procedures, top assembly drawings, field installation drawings, the design of shipping containers, and the performance of final acceptance test.

The integration and test costs for the ATLG have been allocated by year based on a 65%/35% frequency distribution. The choice of a 65/35 ratio was made assuming the majority of funds would be required in the early stages of the production process. The PRICE A distribution analysis program, for projecting and evaluating time-dependent resource requirements, was used in distributing the I&T funds by year. The details are given in Appendix H.

11.5.4 Engineering Change Proposals (ECP)

The Delphi analysis approach was used in determining allocations for the ECP effort. The consensus was that very few, if any, changes would occur in a manufacturing program at this level. The assumptions made in this analysis are given below.

1. No changes would occur after the manufacture of approximately 2000 shipsets.

2. Change requirements demand would decrease gradually.

3. ECP allocations are based on a percentage of the recurring production cost less G&A and profit.

4. The assumed allocations are:

   Lots 1 & 2 at 5 percent of recurring production cost
   Lots 3 & 4 at 3 percent of recurring production cost
   Lots 5 & 6 at 2 percent of recurring production cost.

11.6 MANUFACTURING SENSITIVITY ANALYSIS

In conducting the manufacturing sensitivity analysis, uncertainty was addressed by evaluating the cost based on varied manufacturing complexities. The manufacturing complexities (MCPLXS) were parametrically derived. The results of the calibration process yielded manufacturing complexities ranging from

MCPLXS = 6.279 to MCPLXS = 6.474.

The model was executed using an MCPLXS of 6.376 as the least likely case and an MCPLXS of 6.474 as the most likely case. The nominal value of the "most likely" case is presented as the ATLG Program Cost.

Unit Cost (000)	Low	Nominal	High
Least Likely MCPLXS = 6.376	49	55	62
Most Likely MCPLXS = 6.474	55	61	68

Total Cost (Millions)	Low	Nominal	High
Least Likely MCPLXS = 6.376	246	274	308
Most Likely MCPLXS = 6.474	272	303	339

11.7 COMPARATIVE ANALYSIS WITH HISTORICAL DATA

A comparative analysis with the landing gear of the AH-64A Apache helicopter was performed to further validate and verify the parametric analysis. Since Menasco, the manufacturer of the ATLG landing gear, is also the manufacturer of the main landing gear of the Apache and since cost data are readily available, the Apache main landing gear was chosen as the candidate for comparison.

11.7.1 Considerations for Comparison

1. Weight of AH-64 main landing gear is 456 lbs/shipset.
2. The AH-64A main landing gear is nonretractable.
3. Apache gear was designed to survive a 42 fps level drop.

The Apache cost data used was the negotiated purchase order cost for Lots 1-4. The costs were escalated to 1988 dollars and a least squares linear regression exercise performed to determine the associated slope and first unit cost. (See Appendix I.)

Based on the Apache first unit cost of $109,928 dollars and a learning slope of 94%, the costs of the Apache main landing gear were estimated for a quantity of 5000 shipsets over a 13 year production cycle. The cumulative learning curve was applied against the ATLG production rate delivery schedule.

11.7.2 Fiscal Year Cost Comparison

The Apache landing gear was compared against the nominal value of the "least likely" and "most likely" cases of the ATLG landing gear. The cost of the Apache gear is expected to exceed the least likely case by 1994 and the most likely case by the year 2000. The graph illustrating the cost comparison by yearly expenditures of the fiscal year is shown in Figure 70.

11.7.3 Delta Lot Cost Comparison

The 'Delta Cost Comparison' is the differences between the ATLG landing gear and the Apache landing gear for each of the "least likely" and "most likely" cases. This comparison is presented as bar graphs in Figure 71. The bar graphs, which extend below zero, the "$0" level, show the yearly expenditure for the Apache gear exceeding that of the ATLG gear. This first happens for the least likely case in 1993, and for the most likely case in the year 2000.

11.7.4 Cumulative Average Unit Cost Comparison

The 'Cumulative Average Unit Cost' of the ATLG landing gear and the Apache landing gear were also compared against estimated midpoints. Two conditions of the "least likely" and "most likely" costs of the ATLG landing gear were examined against the nominal cost of the apache landing gear. In the first case, the nominal costs of these two "likely" cases were compared against the nominal cost of the Apache gear and, in the second case, the extreme costs of the same two "likely" cases were similarly compared.

The comparison of the cumulative average unit cost of the nominal values, using the nominal costs for the least likely and most likely cases of the ATLG gear, is presented in Figure 72. Both costs of the ATLG gear drop quickly below the nominal cost of the Apache gear: after 431 and 1263 ATLG shipsets for the nominal values of the least and most likely costs, respectively.

The comparisons of the cumulative average unit cost of the extreme values, using the low range of the least likely cost and the high range of the most likely cost of the ATLG gear, is presented in Figure 73. The low range of the least likely cost of the ATLG gear and the high range of the most likely cost of the ATLG gear will be less than the nominal cost of the Apache gear when 168 and 3023 ATLG shipsets, respectively, are delivered.

11.8 COST SUMMARY

The estimated production cost of 5000 shipsets of the advanced technology landing gear has been established as a cumulative average unit cost of $61,000 based on a total flyaway cost of $303 million. In analyzing, with respect to historical data from the AH-64A Apache helicopter, the cost of the ATLG landing gear is comparable to that of the Apache landing gear even though the ATLG gear is designed to be retractable and has crashworthiness capability in excess of that of the Apache gear.

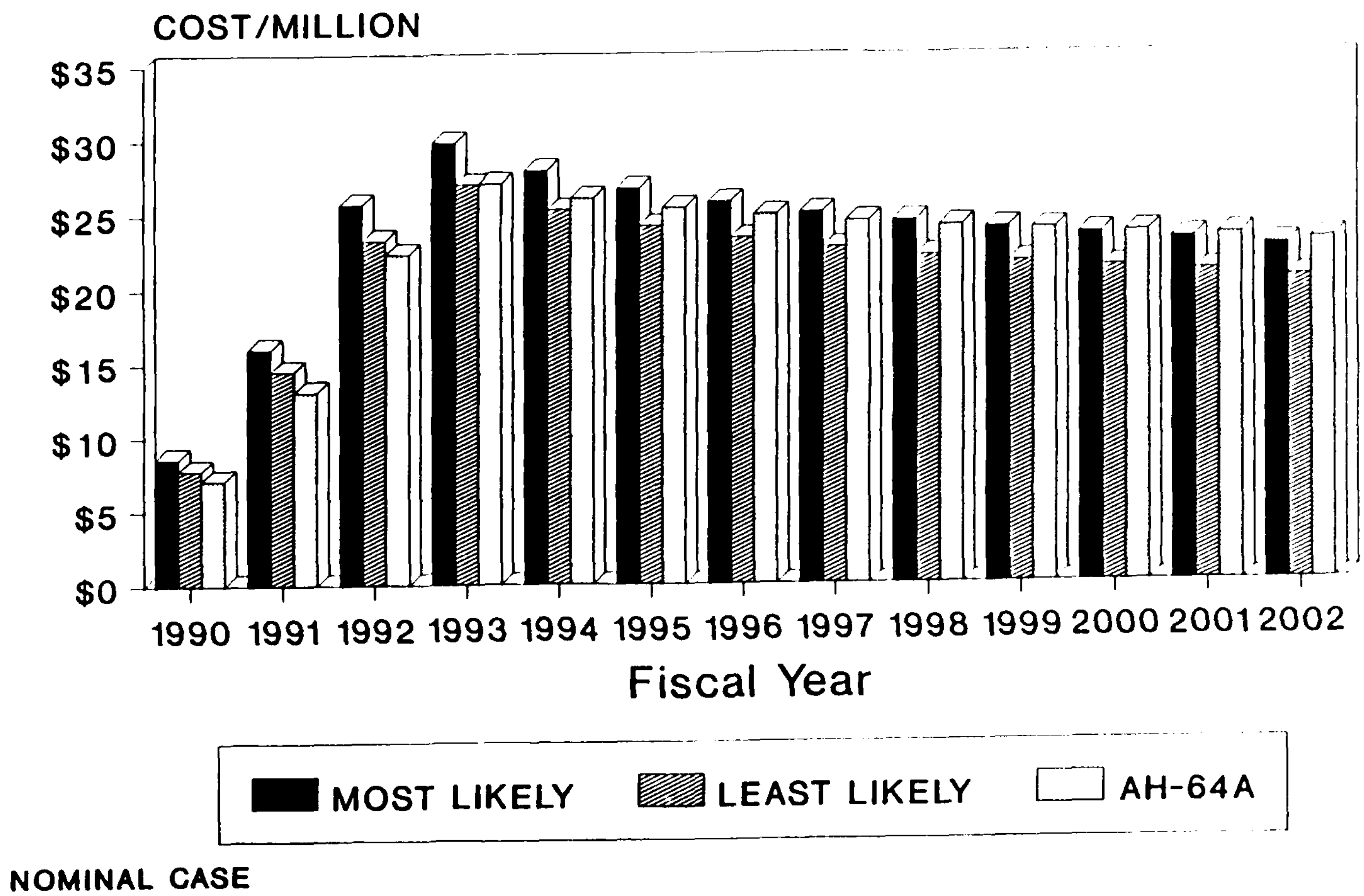

Figure 70. Comparison of fiscal year costs of ATLG and Apache landing gears.

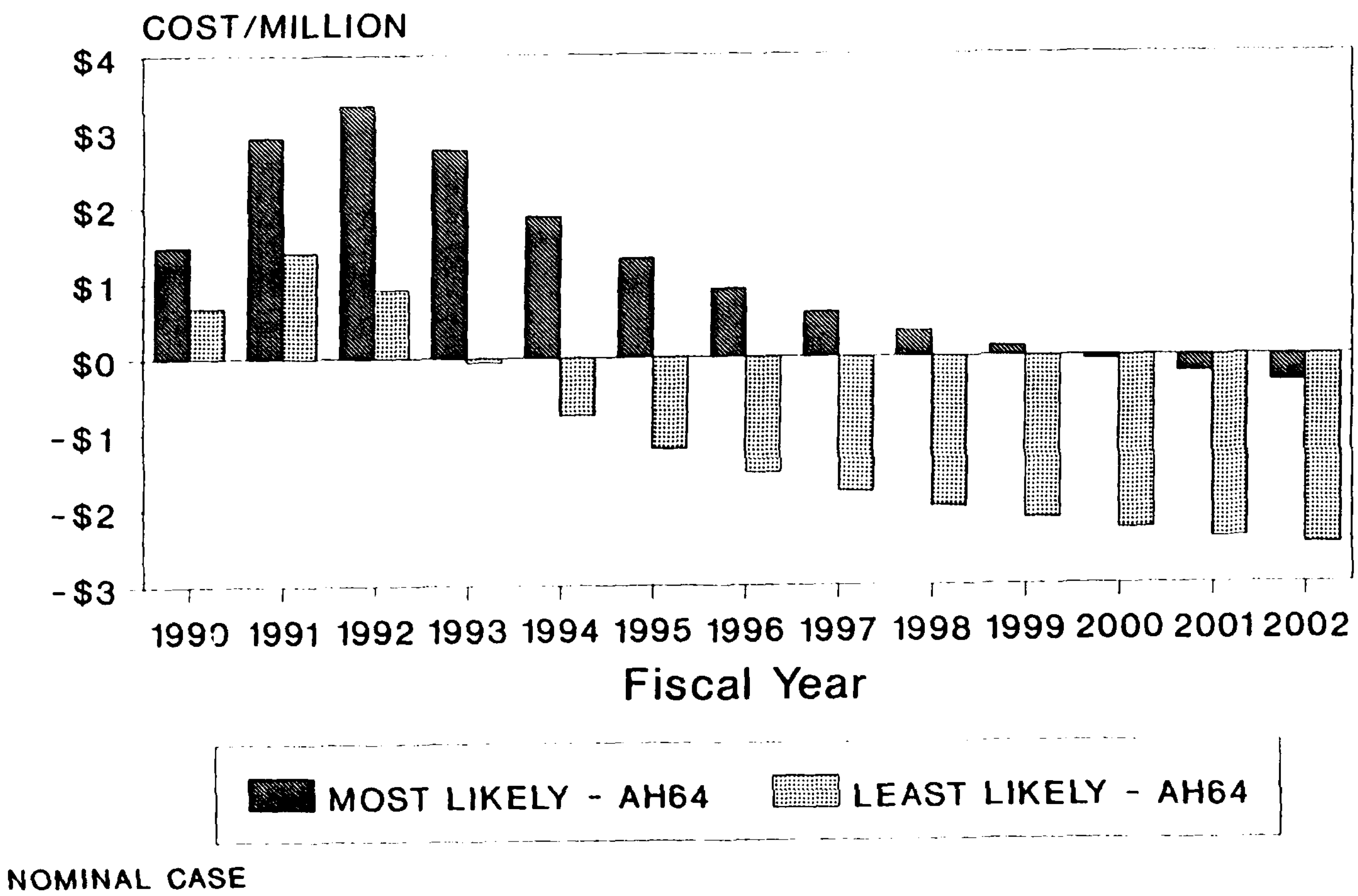

Figure 71. Comparison of Delta lot costs of ATLG and Apache landing gears.

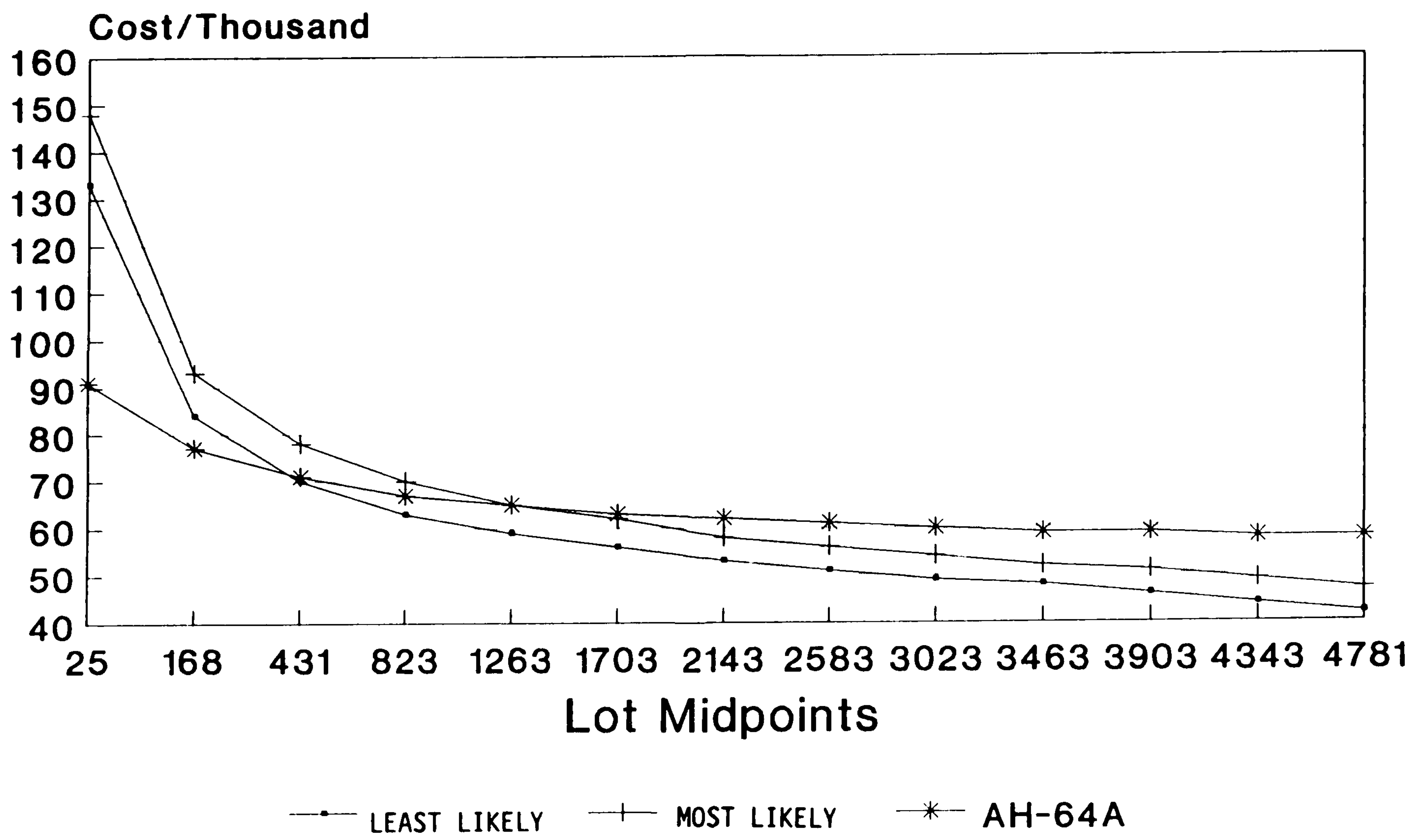

Figure 72. Cumulative average nominal unit costs of ATLG and Apache landing gears.

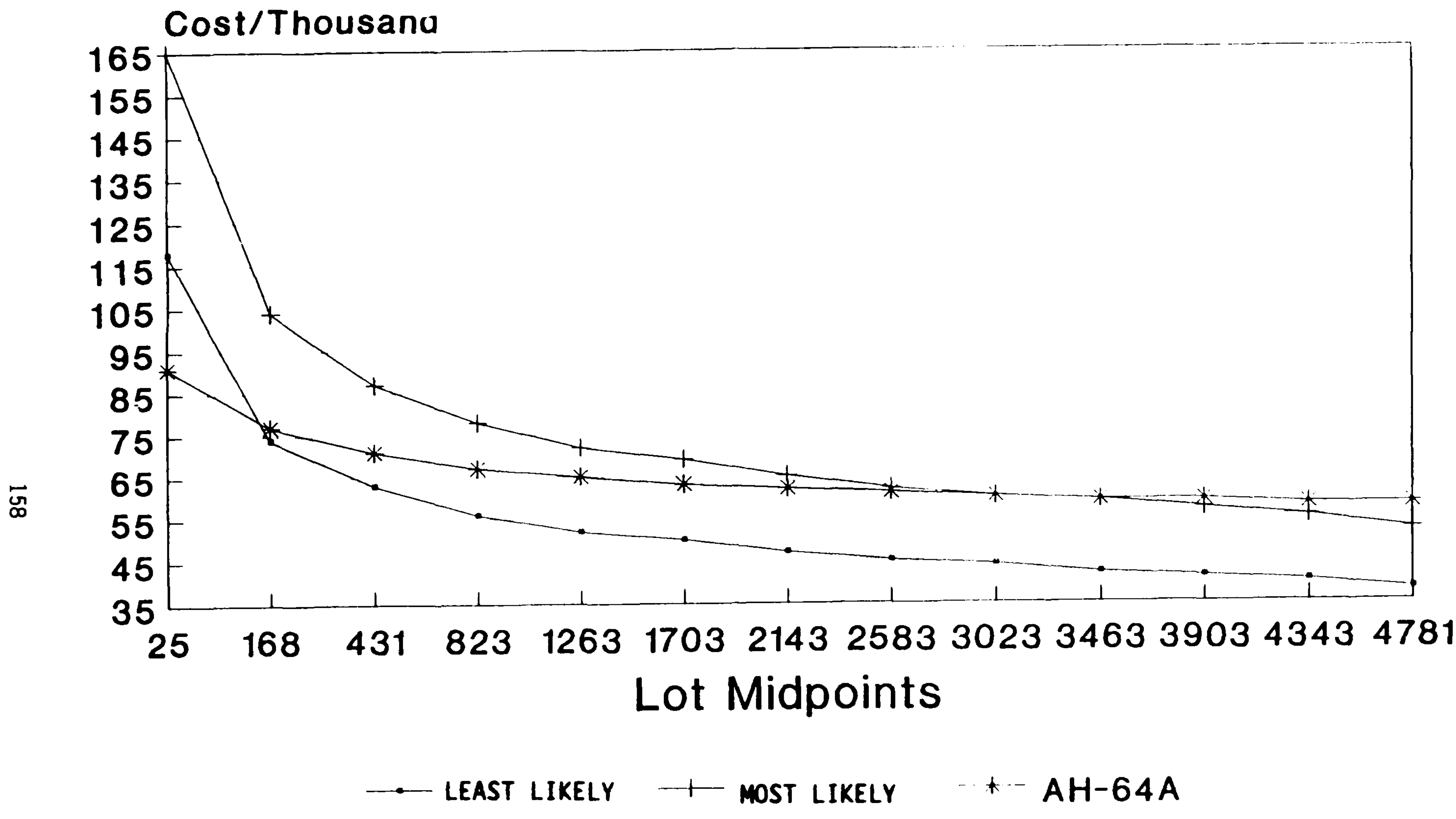

Figure 73. Cumulative average extreme unit costs of ATLG and nominal unit costs of Apache landing gears

REFERENCES

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NOMENCLATURE

F_{BU} = Bending ultimate stress

F_{BY} = Bending yield stress

F_{BRU} = Bearing ultimate stress

F_{BRY} = Bearing yield stress

F_{CU} = Compression ultimate stress

F_{CY} = Compression yield stress

F_{HT} = Hoop tension stress

F_{SU} = Shear ultimate stress

F_{SY} = Shear yield stress

F_{STU} = Torsional ultimate stress

F_{SUN} = Shear ultimate stress at the neutral axis

F_{TU} = Tension ultimate stress

F_{TY} = Tension yield stress

F_{TRU} = Transverse tensile ultimate stress

APPENDIX A
OSD ESCALATION TABLE-1

NOTE: 'SPECIAL' APPROPRIATI REFER TO PROGRAMS CLASSIFIED AS SECRET.

AFR 173-13 Attachment 5 *1988 Revision

*Table A5-2. Continued.

OPR: SAF/ACCE

DATE OF OSD INFLATION RATES: 26 JANUARY 1988

DATE OF OSD OUTLAY RATES : 31 MAY 1987

DATE OF ACC ISSUE : 1 FEBRUARY 1988

USAF WEIGHTED INFLATION INDICES
BASED ON OSD RAW INFLATION AND OUTLAY RATES
BASE YEAR FY 1988

FISCAL YEAR	OPERA-TIONS & MAINTEN-ANCE (3400)	RESEARCH DEVELOP-MENT, TESTING & EVALUA-TION (3600)	MILITARY CONSTR-UCTION: AF (3300)	MILITARY CONSTR-UCTION: GUARD (3830)	MILITARY CONSTR-UCTION: RESERVE (3730)	AIRCRAFT PROCURE-MENT SPECIAL 3010.000	AIRCRAFT PROCURE-MENT OTHER 3010.000	MISSILE PROCURE-MENT SPECIAL (3020)	MISSILE PROCURE-MENT OTHER (3020)	OTHER PROCURE-MENT SPECIAL (3080)	OTHER PROCURE-MENT OTHER (3080)
1973	0.381	0.395	0.411	0.411	0.411	0.402	0.395	0.376	0.390	0.390	0.418
1974	0.413	0.427	0.447	0.447	0.447	0.436	0.437	0.410	0.425	0.422	0.476
1975	0.454	0.468	0.485	0.485	0.485	0.466	0.474	0.439	0.461	0.461	0.517
1976	0.486	0.508	0.519	0.519	0.519	0.498	0.523	0.482	0.511	0.494	0.584
1977	0.520	0.539	0.558	0.558	0.558	0.538	0.541	0.507	0.535	0.527	0.590
1978	0.562	0.584	0.606	0.606	0.606	0.587	0.589	0.580	0.573	0.563	0.644
1979	0.613	0.630	0.716	0.716	0.716	0.602	0.655	0.607	0.633	0.608	0.707
1980	0.675	0.701	0.754	0.772	0.745	0.616	0.734	0.670	0.722	0.677	0.781
1981	0.753	0.776	0.816	0.816	0.807	0.703	0.799	0.744	0.792	0.750	0.836
1982	0.824	0.829	0.872	0.864	0.863	0.753	0.841	0.792	0.847	0.819	0.866
1983	0.862	0.868	0.906	0.913	0.890	0.826	0.891	0.847	0.893	0.860	0.900
1984	0.896	0.901	0.932	0.936	0.924	0.889	0.929	0.899	0.935	0.890	0.927
1985	0.925	0.929	0.955	0.956	0.952	0.918	0.958	0.926	0.960	0.917	0.958
1986	0.951	0.953	0.984	0.983	0.978	0.943	0.990	0.950	0.994	0.942	0.987
1987	0.979	0.985	1.019	1.018	1.013	0.970	1.026	0.980	1.030	0.969	1.023
1988	1.016	1.022	1.056	1.055	1.051	1.007	1.063	1.016	1.067	1.005	1.060
1989	1.054	1.059	1.092	1.091	1.087	1.044	1.099	1.054	1.107	1.043	1.095
1990	1.090	1.095	1.125	1.125	1.121	1.082	1.131	1.090	1.134	1.080	1.128
1991	1.124	1.128	1.155	1.155	1.151	1.116	1.160	1.124	1.163	1.115	1.158
1992	1.153	1.157	1.183	1.182	1.178	1.147	1.188	1.153	1.190	1.146	1.186
1993	1.180	1.184	1.210	1.209	1.205	1.173	1.215	1.180	1.217	1.172	1.213
1994	1.207	1.211	1.238	1.237	1.233	1.200	1.243	1.207	1.245	1.199	1.241
1995	1.235	1.239	1.266	1.265	1.261	1.227	1.271	1.235	1.274	1.227	1.269
1996	1.263	1.267	1.29[illegible]	1.295	1.290	1.256	1.301	1.263	1.303	1.255	1.298
1997	1.292	1.297	1.325	1.324	1.320	1.285	1.331	1.292	1.333	1.284	1.328
1998	1.322	1.326	1.356	1.355	1.350	1.314	1.361	1.322	1.364	1.313	1.359
1999	1.352	1.357	1.387	1.386	1.381	1.344	1.393	1.352	1.395	1.343	1.390
2000	1.383	1.388	1.419	1.418	1.413	1.375	1.425	1.383	1.427	1.374	1.422
2001	1.415	1.420	1.451	1.450	1.446	1.407	1.457	1.415	1.460	1.406	1.455
2002	1.448	1.453	1.485	1.484	1.479	1.439	1.491	1.448	1.494	1.438	1.488

APPENDIX B
OSD ESCALATION TABLE-2

AFR 173-13 Attachment 5 *1988 Revision
*Table A5-1. Contd.
OPR: SAF/ACCE
DATE OF OSD INFLATION RATES FOR PERSONNEL : 13 JANUARY 1988
DATE OF OSD INFLATION RATES FOR NON-PERSONNEL: 26 JANUARY 1988
DATE OF ACC ISSUE : 1 FEBRUARY 1988

USAF RAW INFLATION INDICES
BASE YEAR FY 1988

	MILITARY COMPENSATION										
FISCAL YEAR	PAY BASE (3500)	OTHER EXPENSES (3500)	TOTAL (3500)	RETIR. PAY (3500)	GENERAL SERVICE & WAGE BOARD PAY (3400)	OPERATIONS & MAINTENANCE: NON-PAY, NON-POL (3400)	RESEARCH DEVELOPMENT, TESTING EVAL. (3600)	MILITARY CONSTRUCTION (3300)	AIRCRAFT AND MISSILE PROCUREMENT (150.5)	OTHER PROCUREMENT (3080)	FUEL
1973	0.408	0.397	0.408	0.357	0.388	0.377	0.384	0.377	0.352	0.382	0.540
1974	0.436	0.441	0.437	0.392	0.423	0.406	0.414	0.406	0.380	0.412	0.572
1975	0.464	0.467	0.465	0.447	0.457	0.450	0.459	0.450	0.421	0.457	0.658
1976	0.488	0.493	0.489	0.496	0.495	0.481	0.491	0.481	0.450	0.488	0.707
197Q	0.502	0.506	0.503	0.510	0.517	0.497	0.507	0.497	0.465	0.504	0.736
1977	0.516	0.519	0.517	0.525	0.539	0.514	0.524	0.514	0.480	0.521	0.765
1978	0.552	0.549	0.552	0.565	0.581	0.555	0.560	0.549	0.513	0.557	0.820
1979	0.585	0.592	0.587	0.612	0.616	0.605	0.607	0.601	0.558	0.605	0.947
1980	0.627	0.636	0.629	0.685	0.65[illegible]	0.664	0.664	0.664	0.612	0.664	1.711
1981	0.726	0.789	0.735	0.762	0.715	0.743	0.743	0.743	0.685	0.743	2.026
1982	0.826	0.837	0.827	0.812	0.755	0.811	0.811	0.811	0.750	0.811	1.993
1983	0.859	0.871	0.861	0.859	0.791	0.851	0.851	0.851	0.818	0.851	1.790
1984	0.884	0.900	0.887	0.889	0.815	0.883	0.883	0.883	0.883	0.883	1.625
1985	0.920	0.926	0.920	0.920	0.861	0.913	0.913	0.913	0.913	0.913	1.555
1986	0.956	0.948	0.956	0.956	0.870	0.939	0.939	0.939	0.939	0.939	1.215
1987	0.978	0.969	0.977	0.978	0.917	0.964	0.964	0.964	0.964	0.964	0.890
1988	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1989	1.037	1.032	1.037	1.037	1.021	1.038	1.038	1.038	1.038	1.038	1.039
1990	1.084	1.064	1.082	1.084	1.049	1.075	1.075	1.075	1.075	1.075	1.077
1991	1.133	1.094	1.130	1.133	1.081	1.111	1.111	1.111	1.111	1.111	1.124
1992	1.182	1.120	1.176	1.182	1.114	1.142	1.142	1.142	1.142	1.142	1.186
1993	1.231	1.142	1.223	1.231	1.148	1.168	1.168	1.168	1.168	1.168	1.248
1994	1.283	1.164	1.272	1.283	1.184	1.195	1.195	1.195	1.195	1.195	1.315
1995	1.337	1.187	1.324	1.337	1.220	1.223	1.223	1.223	1.223	1.223	1.384
1996	1.393	1.210	1.377	1.393	1.258	1.251	1.251	1.251	1.251	1.251	1.458
1997	1.452	1.234	1.432	1.452	1.296	1.279	1.279	1.279	1.279	1.279	1.535
1998	1.513	1.258	1.489	1.513	1.336	1.309	1.309	1.309	1.309	1.309	1.616
1999	1.576	1.283	1.549	1.576	1.377	1.339	1.339	1.339	1.339	1.339	1.702
2000	1.642	1.308	1.611	1.642	1.419	1.370	1.370	1.370	1.370	1.370	1.792
2001	1.711	1.334	1.676	1.711	1.463	1.401	1.401	1.401	1.401	1.401	1.887
2002	1.783	1.360	1.743	1.783	1.508	1.434	1.434	1.434	1.434	1.434	1.987

APPENDIX C
OSD ESCALATION TABLE-3

AFR 173-13 Attachment 5 *1988 Revision

*Table A5-1. Contd.
OPR: SAF/ACCE
DATE OF OSD INFLATION RATES FOR PERSONNEL : 13 JANUARY 1988
DATE OF OSD INFLATION RATES FOR NON-PERSONNEL: 26 JANUARY 1988
DATE OF ACC ISSUE : 1 FEBRUARY 1988

USAF RAW INFLATION INDICES
BASE YEAR FY 1985

FISCAL YEAR	MILITARY COMPENSATION: PAY BASE (3500)	MILITARY COMPENSATION: OTHER EXPENSES (3500)	MILITARY COMPENSATION: TOTAL (3500)	MILITARY COMPENSATION: RETIR. PAY (3500)	GENERAL SERVICE & WAGE BOARD PAY (3400)	OPERATIONS & MAINTENANCE: NON-PAY, NON-POL (3400)	RESEARCH DEVELOPMENT, TESTING EVAL. (3600)	MILITARY CONSTRUCTION (3300)	AIRCRAFT AND MISSILE PROCUREMENT (150.5)	OTHER PROCUREMENT (3080)	FUEL
1973	0.444	0.429	0.443	0.388	0.451	0.413	0.421	0.412	0.386	0.419	0.347
1974	0.474	0.476	0.475	0.426	0.491	0.445	0.454	0.445	0.416	0.451	0.368
1975	0.505	0.504	0.506	0.486	0.531	0.493	0.503	0.493	0.461	0.500	0.423
1976	0.531	0.533	0.532	0.539	0.575	0.527	0.537	0.527	0.493	0.534	0.455
197Q	0.546	0.547	0.547	0.555	0.600	0.545	0.555	0.544	0.509	0.552	0.473
1977	0.561	0.561	0.562	0.571	0.626	0.563	0.574	0.562	0.526	0.571	0.492
1978	0.600	0.593	0.600	0.614	0.675	0.607	0.613	0.601	0.562	0.610	0.527
1979	0.635	0.640	0.638	0.665	0.715	0.663	0.664	0.658	0.611	0.663	0.609
1980	0.681	0.687	0.683	0.745	0.764	0.727	0.727	0.727	0.670	0.727	1.100
1981	0.789	0.852	0.799	0.829	0.831	0.813	0.813	0.813	0.750	0.813	1.302
1982	0.898	0.904	0.899	0.883	0.877	0.888	0.888	0.888	0.822	0.888	1.282
1983	0.934	0.941	0.935	0.934	0.918	0.932	0.932	0.932	0.895	0.932	1.151
1984	0.962	0.972	0.964	0.966	0.947	0.967	0.967	0.967	0.967	0.967	1.045
1985	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1986	1.040	1.024	1.038	1.040	1.010	1.028	1.028	1.028	1.028	1.028	0.781
1987	1.063	1.047	1.062	1.063	1.065	1.056	1.056	1.056	1.056	1.056	0.572
1988	1.087	1.080	1.087	1.087	1.161	1.095	1.095	1.095	1.095	1.095	0.643
1989	1.128	1.115	1.127	1.128	1.186	1.136	1.136	1.136	1.136	1.136	0.668
1990	1.179	1.149	1.176	1.179	1.218	1.177	1.177	1.177	1.177	1.177	0.693
1991	1.232	1.182	1.228	1.232	1.256	1.216	1.216	1.216	1.216	1.216	0.722
1992	1.285	1.210	1.278	1.285	1.294	1.250	1.250	1.250	1.250	1.250	0.762
1993	1.339	1.233	1.330	1.339	1.334	1.279	1.279	1.279	1.279	1.279	0.803
1994	1.395	1.258	1.383	1.395	1.375	1.308	1.308	1.308	1.308	1.308	0.845
1995	1.454	1.282	1.438	1.454	1.417	1.339	1.339	1.339	1.339	1.339	0.890
1996	1.515	1.307	1.496	1.515	1.461	1.369	1.369	1.369	1.369	1.369	0.937
1997	1.578	1.333	1.556	1.578	1.505	1.401	1.401	1.401	1.401	1.401	0.987
1998	1.645	1.359	1.618	1.645	1.552	1.433	1.433	1.433	1.433	1.433	1.039
1999	1.714	1.386	1.683	1.714	1.599	1.466	1.466	1.466	1.466	1.466	1.094
2000	1.786	1.413	1.751	1.786	1.648	1.500	1.500	1.500	1.500	1.500	1.152
2001	1.861	1.441	1.821	1.861	1.699	1.534	1.534	1.534	1.534	1.534	1.213
2002	1.939	1.469	1.894	1.939	1.751	1.569	1.569	1.569	1.569	1.569	1.277

APPENDIX D
PRICE CALIBRATION RESULTS
"ECIRP"

- - - PRICE HARDWARE MODEL - - -
ECIRP

INPUT FILENAME: DMATLG	18-JAN-89 11:48 (18825)	GLOBAL FILENAME: ESCALATION FILENAME:

ATLG

	UNIT WEIGHT	176.00	MODE	7
PROTOTYPE QUANTITY 5.000	UNIT VOLUME	0.98	QUANTITY/NHA	0

ACTUAL COST DATA

AV UNIT	0.00	PRODUCTION	0.	PROTOTYPES	0.	DEVELOPMENT	23190

PROGRAM COST ($ 1000)	DEVELOPMENT	PRODUCTION
ENGINEERING		
SUBTOTAL (ENG)	1650.	-
MANUFACTURING		
PRODUCTION	-	-
PROTOTYPE	618.	-
TOOL-TEST EQ	51.	-
SUBTOTAL (MFG)	669.	-
TOTAL COST	2319.	-

DESIGN FACTORS	MECHANICAL	PRODUCTION DESCRIPTORS	
WEIGHT	176.000	ENGINEERING COMPLEXITY	1.200
DENSITY	179.592*	PROTOTYPE SUPPORT	1.0
MFG. COMPLEXITY	6.376*	PROTO SCHEDULE FACTOR	0.250*
NEW DESIGN	0.600	PLATFORM	1.800
DESIGN REPEAT	0.000	YEAR OF TECHNOLOGY	1986
INTEGRATION LEVEL	0.000	RELIABILITY FACTOR	1.0
		MTB (FIELD)	6465

SCHEDULE	START		FIRST ITEM		FINISH	
DEVELOPMENT	NOV 86	(13)	NOV 87	(14)	JAN 89	(27)

SUPPLEMENTAL INFORMATION		TOOLING & PROCESS FACTORS	
ECONOMIC BASE	188		
ESCALATION	0.00	DEVELOPMENT TOOLING	1.00*
DEV COST MULTIPLIER	1.00*		

MCPLX RANGES	MCPLXS
FROM	6.279
CENTER	6.376
TO	6.474

APPENDIX E

PRICE INPUT FILES - LEAST LIKELY CASE

```
LG89     WED, 18 JAN 1989     12:00:56

00001:ATLG
00002:  152 5 176 .98 2
00003:  1 0 1.2 1.8 1988 0
00004:  176 6.376 .6
00005:  1186 1187 189 1.4 0 0
00006:  389 390 391 .89 0 0
00007:LOT 2
00008:  368 291 391 192 9 0
00009:LOT 3
00010:  686 1291 192 1192 9 0
00011:LOT 4
00012:  880 1092 1192 993 9 0
00013:LOT 5
00014:  880 893 993 794 9 0
00015:LOT 6
00016:  880 694 794 595 9 0
00017:LOT 7
00018:  880 495 595 396 9 0
00019:LOT 8
00020:  880 296 396 197 9 0
00021:LOT 9
00022:  880 1296 197 1197 9 0
00023:LOT 10
00024:  880 1097 1197 998 9
00025:LOT 11
00026:  880 898 998 799 9 0
00027:LOT 12
00028:  680 699 799 500 9 0
00029:LOT 13
00030:  874 400 500 301 9 0
00031:ATLG INTEG & TEST
00032:10000 5 0 .5 5
00033:0 0 0 1.8 1988
00034:1186 1187 189 389 391
END-OF-DATA
```

APPENDIX E

PRICE INPUT FILES - MOST LIKELY CASE

```
LIST

LG89     WED, 18 JAN 1989     12:00:24

00001:ATLG
00002:  152 5 176 .98 2
00003:  1 0 1.2 1.8 1988 0
00004:  176 6.474 .6
00005:  1186 1187 189 1.4 0 0
00006:  389 390 391 .89 0 0
00007:LOT 2
00008:  368 291 391 192 9 0
00009:LOT 3
00010:  686 1291 192 1192 9 0
00011:LOT 4
00012:  880 1092 1192 993 9 0
00013:LOT 5
00014:  880 893 993 794 9 0
00015:LOT 6
00016:  880 694 794 595 9 0
00017:LOT 7
00018:  880 495 595 396 9 0
00019:LOT 8
00020:  880 296 396 197 9 0
00021:LOT 9
00022:  880 1296 197 1197 9 0
00023:LOT 10
00024:  880 1097 1197 998 9
00025:LOT 11
00026:  880 898 998 799 9 0
00027:LOT 12
00028:  680 699 799 500 9 0
00029:LOT 13
00030:  874 400 500 301 9 0
00031:ATLG INTEG & TEST
00032:10000 5 0 .5 5
00033:0 0 0 1.8 1988
00034:1186 1187 189 389 391
END-OF-DATA
LIST
```

APPENDIX F

PRICE DETAILS OF OUTPUTS FILES - LEAST LIKELY CASE

- - - PRICE HARDWARE MODEL - - -
ECIRP

INPUT FILENAME: LG89 | 19-JAN-89 13:02 (188225) | GLOBAL FILENAME: ESCALATION FILENAME:

TOTAL COST FOR ALL LOTS

PROGRAM COST ($ 1000)	DEVELOPMENT	PRODUCTION	TOTAL COST
ENGINEERING			
DRAFTING	323.	39.	363.
DESIGN	1212.	131.	1343.
SYSTEMS	255.	-	255.
PROJ MGMT	345.	9572.	9917.
DATA	112.	3317.	3429.
SUBTOTAL (ENG)	247.	13059.	15306.
MANUFACTURING			
PRODUCTION	-	193109.	193109.
PROTOTYPE	717.	-	717.
TOOL-TEST EQ	64.	9223.	9287.
PURCH ITEMS	0.	0.	0.
SUBTOTAL (MFG)	3028.	215391.	218419.
TOTAL COST	3028.	215391.	218419.

COST RANGES	DEVELOPMENT	PRODUCTION	TOTAL COST
FROM	2717.	192943.	195660.
CENTER	3038.	215391.	218419.
TO	3446.	241771.	245217.

APPENDIX F

PRICE DETAILS OF OUTPUTS FILES - MOST LIKELY CASE

--- PRICE HARDWARE MODEL ---

SYSTEM COST SUMMARY

INPUT FILENAME: LG89B   19-JAN-89 13:11 (188225)   GLOBAL FILENAME:
ESCALATION FILENAME:

TOTAL COST FOR ALL LOTS

PROGRAM COST ($ 1000)	DEVELOPMENT	PRODUCTION	TOTAL COST
ENGINEERING			
DRAFTING	343.	44.	387.
DESIGN	1294.	148.	1441.
SYSTEMS	268.	-	268.
PROJ MGMT	368.	10451.	10820.
DATA	118.	3620.	3738.
SUBTOTAL (ENG)	2392.	14262.	16655.
MANUFACTURING			
PRODUCTION	-	212810.	212810.
PROTOTYPE	795.	-	795.
TOOL-TEST EQ	71.	10810.	10881.
PURCH ITEMS	0.	0.	0.
SUBTOTAL (MFG)	866.	223620.	224486.
TOTAL COST	3259.	237882.	241141.

COST RANGES	DEVELOPMENT	PRODUCTION	TOTAL COST
FROM	2927.	213223.	216150.
CENTER	3259.	237882.	241141.
TO	3701.	266377.	270078.

DATA INPUT SECTION:
BASE YEAR 1988 DOLLARS
COST/THOUSAND

APPENDIX G
PRICE SUMMARY OF OUTPUTS FILES

MCPLXS=6.376 W/ RATOOL

LOT NUMBER	I&T	DRAFT	DESIGN	S/PM	DATA	HDWR	T&TEQ	TOTAL	TOTAL (W/I&T)
LOT 1	14093	9	29	520	185	4932	1974	7649	21742
LOT 2	0	3	11	548	191	9443	369	10565	10565
LOT 3	2	2	8	741	256	15559	510	17076	17078
LOT 4	0	2	8	821	279	18127	591	19828	19828
LOT 5	1	2	8	769	266	16875	590	18510	18511
LOT 6	2	2	8	742	256	16034	589	17631	17633
LOT 7	1	2	8	721	249	15403	589	16972	16973
LOT 8	0	2	8	705	244	14899	588	16446	16446
LOT 9	1	2	8	691	239	14480	587	16007	16008
LOT 10	0	2	8	679	235	14122	587	15633	15633
LOT 11	2	2	8	668	231	13809	586	15304	15306
LOT 12	1	2	8	659	228	13533	585	15015	15016
LOT 13	1	2	8	648	224	13190	582	14654	14655
INTEG & TEST		1	3	670	233	12702	495	14104	14104
TOTAL W/I&T	14104	35	131	9582	3316	193108	9222	215394	215394
TOTAL W/O I&T	14104	34	128	8912	3083	180406	8727	201290	215394

BASE YEAR 1988 DOLLARS PRICE REFERENCE FILENAME: LG89B
COST/THOUSAND

MCPLXS=6.474 W/ RATOOL

LOT NUMBER	I&T	DRAFT	DESIGN	S/PM	DATA	HDWR	T&TEQ	TOTAL	TOTAL (W/I&T)
LOT 1	15689	10	33	581	206	5478	2259	8567	24256
LOT 2	0	4	12	599	209	10473	436	11733	11733
LOT 3	0	3	9	809	280	17199	603	18903	18903
LOT 4	0	3	9	803	305	19999	698	21097	21097
LOT 5	0	3	9	839	289	18598	697	20435	20435
LOT 6	1	3	9	808	279	17658	696	19453	19454
LOT 7	0	3	9	785	271	16953	695	18716	18716
LOT 8	0	3	9	767	265	16389	694	18127	18127
LOT 9	0	3	9	752	260	15920	693	17637	17637
LOT 10	0	3	9	738	255	15520	693	17218	17218
LOT 11	0	3	9	727	251	15171	692	16853	16853
LOT 12	0	3	9	717	248	14862	691	16530	16530
LOT 13	0	3	9	704	244	14481	687	16128	16128
INTEG & TEST		1	3	743	258	14111	574	15690	15690
TOTAL W/I&T	15690	48	147	10452	3620	212812	10808	237887	237887
TOTAL W/O I&T	15690	47	144	9709	3362	198701	10234	222197	237887

APPENDIX H

PRICE A - ACTIVITY DISTRIBUTION ANALYSIS MODEL

- - - PRICE SYSTEMS SERVICES - - -

ACTIVITY DISTRIBUTION ANALYSIS MODEL

DATE 31-JAN-89	TIME 12:06 (188204)	FILENAME NOT USED

ACTIVITY 1	ADVANCED TECHNOLOGY LANDING GEAR			
SCHEDULE MILESTONES	START:	1 APR 89	END:	30 APR 01
PROFILE SHAPE	LEAD:	0.65	LAG:	0.35
START AND END LEVELS	SLEVEL:	0.30	ELEVEL:	0.10
REFERENCE COST	AMOUNT:	303077.0	AS OF:	1 APR 89
REFERENCE ECONOMICS	RTABLE:	PRESET	BY START:	JANUARY
REPORT REQUESTED	PERIOD:	YEARS	AS OF:	1 APR 89

ADVANCED TECHNOLOGY LANDING GEAR

UNINFLATED EXPENDITURE PROFILE	PEAK/AVERAGE RATE	=	1.42
LEAD = 0.65	LAG	=	0.35
STARTING LEVEL = 0.30	ENDING LEVEL	=	0.10

ADVANCED TECHNOLOGY LANDING GEAR

YEARLY EXPENDITURE SUMMARY

COST IN COST/THOUSAND 1 APR 89 UNITS

PERIOD ENDING	PER CENT COMPLETE	EXPENDITURES FOR PERIOD TOTAL	%	CUMULATIVE EXPENDITURES TOTAL	%
DEC 89	3.6	10884.6	3.6	10884.6	3.6
DEC 90	12.3	26293.7	8.7	37178.3	12.3
DEC 91	23.3	33306.4	11.0	70484.7	23.3
DEC 92	35.0	35462.3	11.7	105947.0	35.0
DEC 93	46.4	34658.0	11.4	140604.9	46.4
DEC 94	57.1	32338.6	10.7	172943.3	57.1
DEC 95	66.8	29496.9	9.7	202439.9	66.8
DEC 96	75.6	26674.2	8.8	229113.9	75.6
DEC 97	83.5	23959.9	7.9	253073.7	83.5
DEC 98	90.4	20991.6	6.9	274065.1	90.4
DEC 99	96.0	16955.3	5.6	291020.0	96.0
DEC 00	99.5	10584.8	3.5	301604.5	99.5
APR 01	100.0	1470.4	0.5	303074.8	100.0

APPENDIX I

APACHE MAIN LANDING GEAR HISTORICAL DATA

LEAST SQUARES LINEAR REGRESSION

AH-64A MAIN LANDING GEAR
HISTORICAL DATA FILE
VENDOR: MENASCO
FILENAME: ATLG189
JANUARY 19, 1989

HISTORICAL DATA: NEGOTIATED P.O. DATA		BASE YEAR 1985 DOLLARS			
NOMENCLATURE		LOT 1	LOT 2	LOT 3	LOT 4
LOT QTY	(ESC88$)	11	50	112	144
MAIN LANDING GEAR-LH		45026	36237	33523	31050
(7-311210100-1)	1.095	49303	39680	36708	34000
MAIN LANDING GEAR-RH		45026	36237	33523	31050
(7-311210100-2)	1.095	49303	39680	36708	34000
TOTAL S/S COST (BY85$)		90052	72474	67046	62100
TOTAL S/S COST (BY88$)		98607	79359	73415	68000

LEAST SQUARES LINEAR REGRESSION: BASE YEAR 1988 DOLLARS

	QTY	AUC	CUM QTY	LOT MIDPT	PLOT(X)	LN(X)	LN(Y)	LN(X*Y)	LN(X 2)
1	11	98607	11	4	4	1.299	11.499	14.940	1.688
2	50	79359	61	25	36	3.584	11.282	40.428	12.842
3	112	73415	173	56	117	4.762	11.204	53.355	22.678
4	144	68000	317	72	245	5.501	11.127	61.214	30.264
SUM	317	319381	317	157	402	15.146	45.112	169.937	67.472

Y=AX b OR LN(Y) = LN(A) + bLN(X)

b = -0.08705
LN(A) = 11.60758
SLOPE = 94%
FIRST UNIT (A) = $109,928

☆U.S. GOVERNMENT PRINTING OFFICE: 1990 - 727-075/01376