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THE EVOLUTION OF THE VIKING LANDING GEAR[a]

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ABSTRACT

The primary function of the landing gear is to dissipate touchdown energy in a controlled fashion that minimizes the landing shock for onboard components while maximizing ground clearance and the probability of landing stability over the range of possible surface and touchdown parameter variations. Many other mission requirements and constraints were translated into the evolving Viking landing gear design as they arose. Hence, design considerations included such factors as prelaunch heat sterilization and non-contamination of the Martian landing site, gear stowage and deployment, terminal descent engine shutdown initiation, structural load attenuation, hard/soft landing surface capability, reliability, weight, and post-landed stability.

The landing gear, which was selected on the basis of proposal-phase trade studies, consisted of three inverted-tripod legs with crushable honeycomb elements in the main struts and omnidirectional crushable footpads, both for energy absorption and strut load attenuation. The gear design evolved through several intermediate configurations during early analytical studies and development test programs as the functional specifications for the landing gear were definitized. The final flight-design landing gear consists of three inverted-tripod landing legs, with optimized crushable honeycomb elements having return-stroke load capability in the main struts, deformable load limiters for the attachment of the split bipod struts to the lander body, and a footpad having both hard surface capability and soft surface bearing load enhancement.

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INTRODUCTION

The configuration of the Viking landing gear at the time of contract award in May 1969 was conceptually similar to the Surveyor gear. A crushable/shearable footpad was fastened to the end of the tripod. The original footpad is shown in Figure 1. The main strut for Viking utilized crushable honeycomb with multiple force levels instead of the pressurized oleo strut of Surveyor. Component footpad, attenuator and limiter development tests, vehicle stability analyses, and sub-scale model tests were conducted through 1970, '71, and '72 with full scale vehicle structural model drop tests in 1973 and three system-level vehicle drop tests on a "flight type" lander in 1974. The flight gear, following one of these drop tests, is pictured in Figure 2. The requirements which were imposed on the landing system during the course of the program are listed in Table 1.

Table 1. Viking Landing Gear Design Criteria

Parameter	Contract Go Ahead	As Flown
Vertical Velocity	3 ± 1.5 m/sec (10 ± 5 fps)	2.44 ± .9 m/sec (8 ± 3 fps)
Horizontal Velocity	± 1.8 m/sec (± 6 fps)	± 1.22 m/sec (± 4 fps)
Engine Cut-Off Altitude	3 ± 1.5 m (10 ± 5 feet)	at touchdown
Engine Cut-Off Sensor	by Radar	switches in legs
Stability	all 19° slopes	99.7% stable
Package Loads	80 g's	30 g's
Clearance	22 cm (8.66 in.)	22 cm (8.66 in.)
Coeff. of Friction	1.0 for stability 0.2 for clearance	1.0 for stability 0.2 for clearance

FOOTPAD/LOAD LIMITER DESIGN

The primary function of the crushable footpad employed in the original gear design (circa 1969) was to limit the lateral loads applied to the lander. This design concept relied on the fact that the shear strength of the pad honeycomb is less than the longitudinal crush strength. The footpad was fastened to the inverted tripodal gear by means of a "U" joint to prevent bending moments in the main strut and the secondary bipods, in the event that the pad hit an uneven surface. A footpad rollover problem was uncovered early (1970) in testing conducted at Langley Research Center. The problem shown in the photo of Figure 1, was especially evident when landing on a hard, high-friction surface. These tests showed that the crushing force dropped drastically for loads applied at angles to the honeycomb cell axes, so that the omnidirectional capability of the crushable honeycomb footpad was very poor and unpredictable. Also, sharp or protruding immovable rocks easily penetrated the honeycomb while providing little or no energy absorption. These results led to the deletion of the crushable rotating footpad and prompted the development of a fixed conical footpad design. A solid spherical nosecap was selected to keep high load, hard surface landings from "dumping" high moments into the bipods. The soil penetration tests pictured in Figure 3 dictated the addition of an integral reverse flange skirt on the cone. This thin flange could not carry point loads, and therefore could not cause excessive moments in the bipods. The impact velocity for all the tests shown in Figure 3 was 2.5 m/sec. The soil density was 1.4 g/cm^3 for a and b (sand), 1.45 g/cm^3 for c and d (lunar nominal), and 1.6 g/cm^3 for e and f (also lunar nominal). Drops pictured in a, c, and e were conducted with a bare conical pad, while b, d, and f had the reverse flange. The final flight design is shown in Figure 2.

At the time that the conical pad was implemented, the secondary struts (bipods) were conceived to be telescoping members, permitting both tension and compression stroke and having load limiting capability while carrying significant moment and axial loads. Another haunting requirement, that of post-landed stability, stood a chance of loosing ground. While yet in the paper phase of the above nightmare, the project "invented" the idea of fastening a load limiter to the body of the lander. A very simple H-beam type bipod could be fastened to this and when the axial load in the bipod member exceeded the bending capability of the limiter, it "stroked." A significant analytical and development test program took place to get the actual limiter performance characteristics now employed on the lander. At about the time the initial limiter hardware was being delivered, significant site alteration test results allowed the lander to be flown all the way to the surface. This change reduced the maximum touchdown kinetic energy by a factor of four. As a result, the load limiter design went from the one pictured at the top of Figure 4, which weighed 1.5 kg , to that of the other three limiters shown in the same figure with a weight of 0.45 kg. The limiter on the right is shown as-built with the center one tested and exhibiting approximately 2 cm of stroke and the limiter on the left has been stroked 6.0 cm. The flight configuration limiter design fabricated from fully annealed stainless steel had load requirements shown in Figure 5, with typical test performance as shown.

MAIN STRUT ATTENUATOR DESIGN

The primary strut transmits the majority of the vertical load to the lander body, and hence, the landing deceleration applied to on-board components is controlled by the selection of attenuator crushing force levels. More importantly, the main strut attenuator must dissipate most of the touchdown energy, particularly in the event that the footpad can slide out across the landing surface with little frictional resistance. The force levels carried in each of the strut members, and the changing gear geometry during landing determine the stabilizing (and destabilizing) moments which act about the lander center of gravity.

Crushable aluminum honeycomb (H/C) tubecore was selected at the outset to provide the necessary landing energy absorption for several reasons: the desired crushing force levels can be obtained by varying the core cross-sectional area and the skin thicknesses; the core is very lightweight; the core can be stroked over 80% of its initial length before bottoming; and the crushing behavior is unaffected by long-term exposure to the interplanetary thermal/vacuum environment. These performance advantages were demonstrated on the Apollo project, where crushable H/C tubecore and hexagonal cell H/C elements were used in the primary and secondary struts, respectively, of the Lunar Excursion Module landing gear.

Tubecore attenuator elements are formed by wrapping alternating layers of corrugated skin and face-sheet skin on a circular mandrel to obtain the desired ID/OD dimensions. The initial elements which were built and tested as part of the attenuator development program were fabricated in this manner from sheets of corrugated/flat skins, where the corrugated skin was brazed at each "wavelength" to the face sheet. The layers were not able to be brazed together during wrapping. This all-metal attenuator was designed to meet the requirement that the landing site not be contaminated with any organic compounds. At that point in time, the primary strut attenuator was composed of five separate stages of tubecore, which were to crush at prescribed step-wise increasing force levels. The attenuator was assembled by bonding a spacer disc between each stage; the entire assembly was about 40.6 cm long (four 1 in. stages and one high-force 12 in. stage). Crushing force of the stages increased progressively from 8230 nt. (1850 lbs) to 21360 nt. (4800 lbs).

These initial H/C attenuators, and several early variants, exhibited column instability problems during static and dynamic testing due to the absence of brazing between wrapped layers. This behavior caused very erratic fluctuations in the crushing strength and unpredictable energy absorption capability.

On the basis of subsequent testing, it was concluded that a fully-bonded tubecore attenuator design would perform properly. At about the same time, site alteration testing indicated that descent engine shutoff at touchdown was feasible. Extensive "worst-case" and statistical landing dynamics studies, similar to those conducted earlier, provided new H/C attenuator design requirements which optimized the trade-offs between landing stability, shock, and post-landed ground clearance. These new design requirements called for attenuators whose crushing load-vs-stroke characteristics would follow a ramped curve for the first 8.9 cm (3.5 in) of stroke, initially crushing at 4448 nt. (1000#), and then crushing at a constant 11200 nt. (2500#) force level for at least another 21.6 cm (8.5 in.); these requirements are depicted in Figure 6. The tubecore vendor (Hexcel Corp.) was able to supply attenuators whose static and dynamic crushing performance (also depicted in Figure 6) satisfied these design requirements. These attenuators were fabricated from fully bonded tubecore cylinders whose cross-section was tapered for 8.9 cm (3.5 inches) by machining; the elements were slightly pre-crushed, and then bonded to machined end-fittings for installation in the primary strut. The final flight-design attenuator assembly is about 53 cm (21 in.) long. These flight attenuators also have limited return-stroke capability to resist tension loads up to about 445 nt. (100 lbs). Figure 7 is a photo of flight-type attenuators; the upper assembly is shown compressed approximately 18 cm.

To conform with site non-contamination requirements, it was necessary to completely enclose these organically-bonded H/C attenuators. A laminate Kapton cloth contamination fairing, identified on Figure 2, was used for this purpose. An O-ring was used to seal off the enclosed attenuator as the primary strut strokes; in addition, a microfilter was fitted to the top of the primary strut housing to provide venting during launch and landing. A long spring in the main strut tube is used to deploy the leg from its stowed configuration (Figure 8) after a pyrotechnic pin-puller releases the leg about fifteen seconds following aeroshell jettison. The main strut tube is treated with a Tufram coating to minimize deployment friction. A terminal engine shutdown switch (TESS) was fitted to each leg to provide shutdown commands to the lander computer. These switches are activated on touchdown as the leg compresses a weak spring a distance of 1.3 cm (1/2 in.) before any attenuator stroking has occurred.

CONCLUSIONS

The final flight-design Viking landing gear geometry is shown in Figure 8. The evolution of this gear design has been described in terms of functional requirements defined primarily from analytical studies, and in terms of hardware performance (and problems) determined from test programs. The more innovative features of this design are the footpad, the honeycomb main strut attenuators and the secondary strut load limiters. Their consistent performance, demonstrated in component development tests and in lander verification drop tests, permitted landing dynamics analyses to be conducted with certainty.

The stringent and challenging mission requirements imposed on the landing gear have been satisfied by this design.

In particular:

--- Probability of stability exceeds 99.7% ;
--- Statistical ground clearance exceeds 22 cm;
--- Three-sigma component landing shock is less than 30 g;
--- The energy absorption capability of the gear elements permits landings at greater than three-sigma velocities;
--- Site non-contamination and engine-shutdown requirements have been satisfied; and
--- The footpad design permits landing on surfaces ranging from impenetrable to very soft soils.

Furthermore, the total landing gear has evolved from an early design weighing over 45 kg (100 lbs) to the flight-design, which weighs only 20 kg (44 lbs), less than 3.5% of the lander touchdown weight.

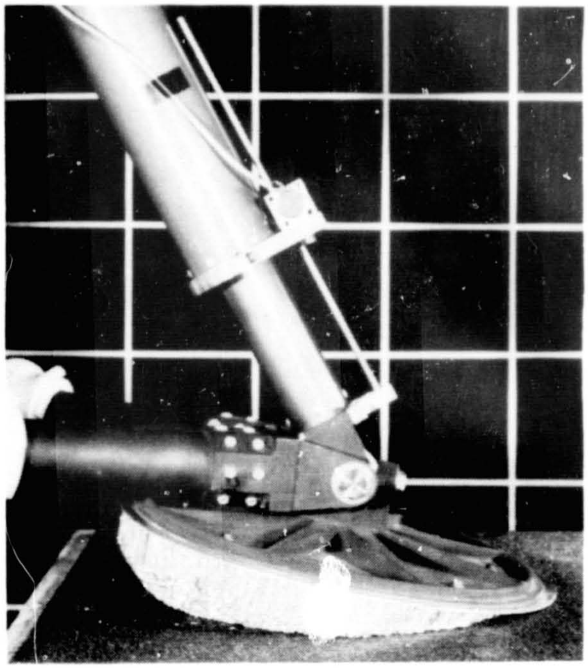

Figure 1 - Original Gear Design

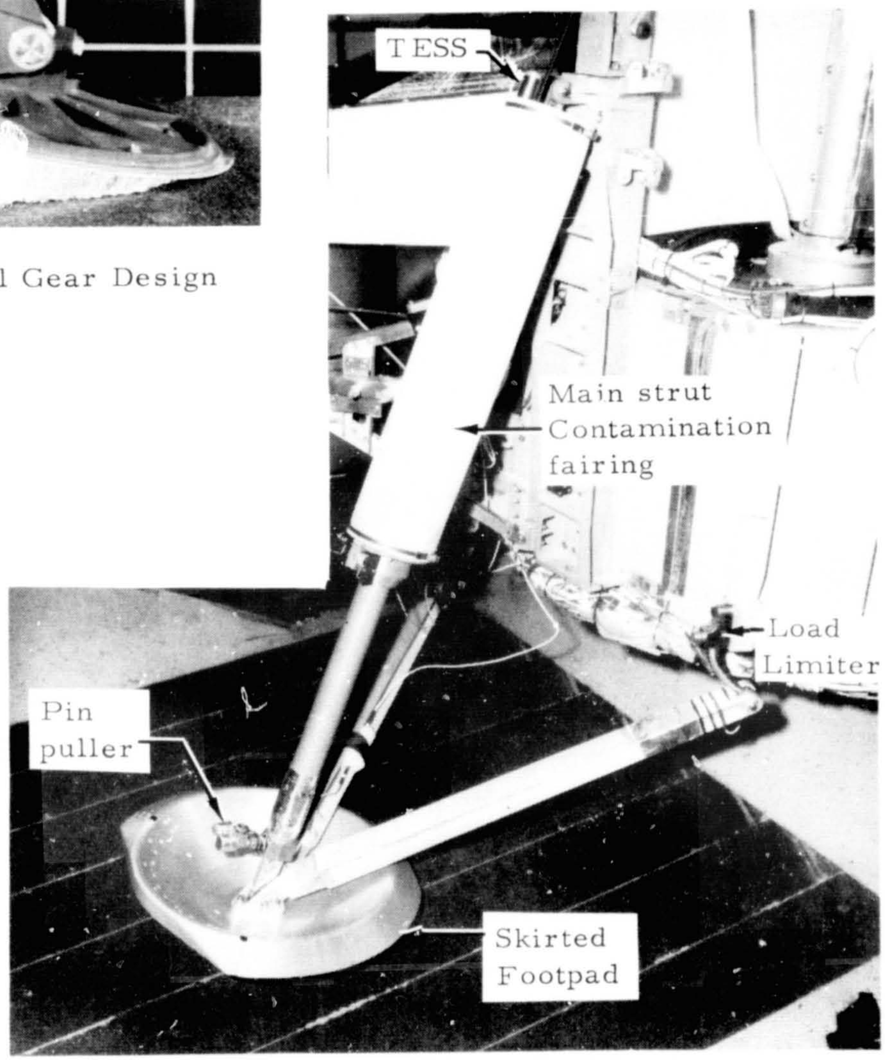

Figure 2 - Final Flight Gear

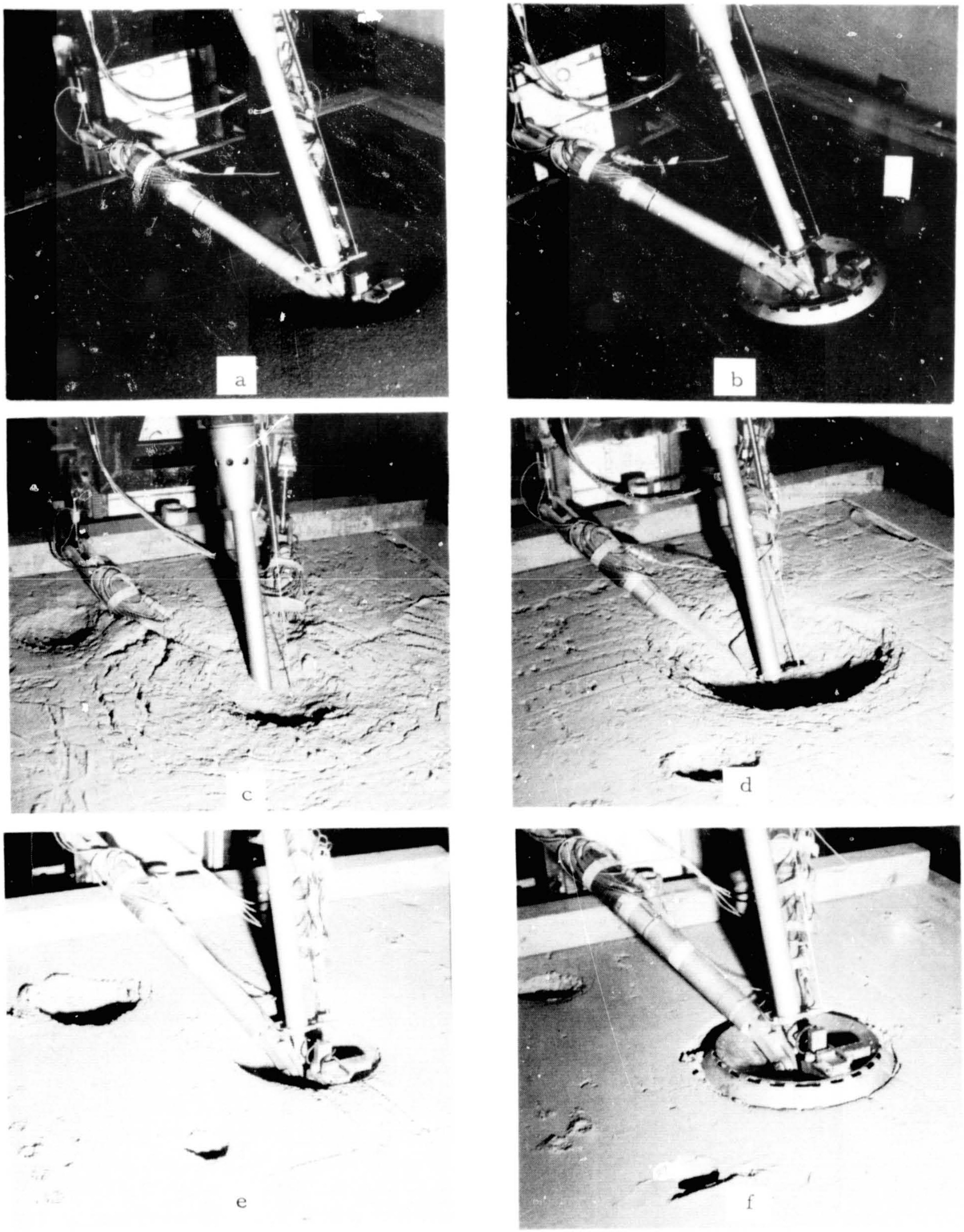

Figure 3 - Footpad Soil Penetration Tests

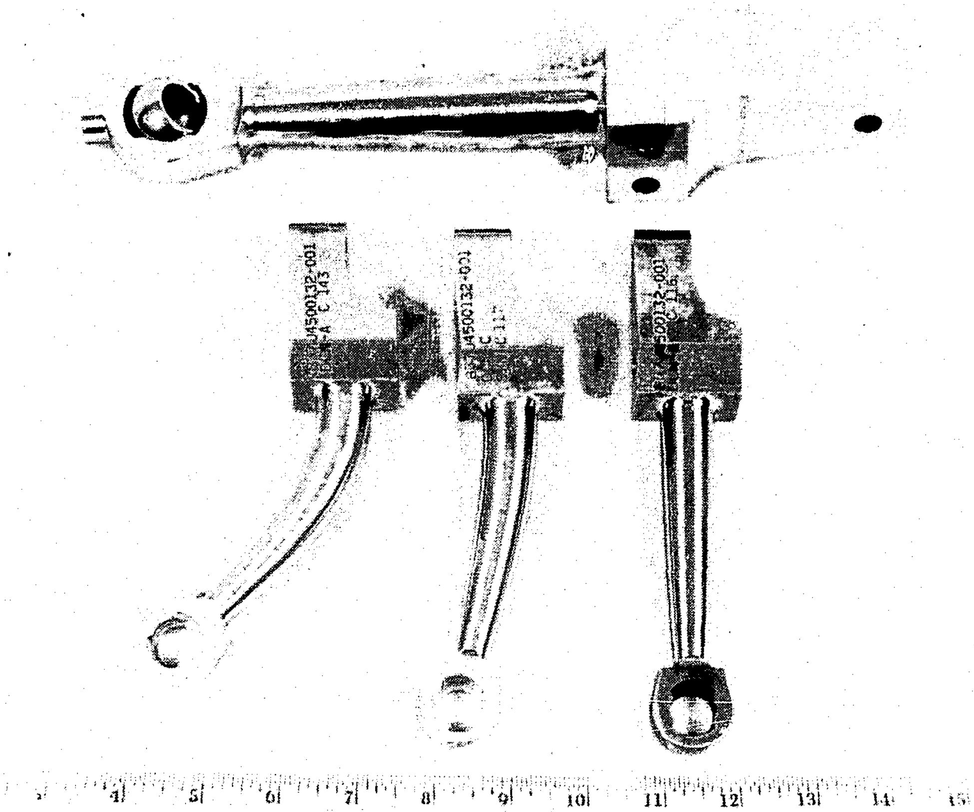

Figure 4 - Load Limiters

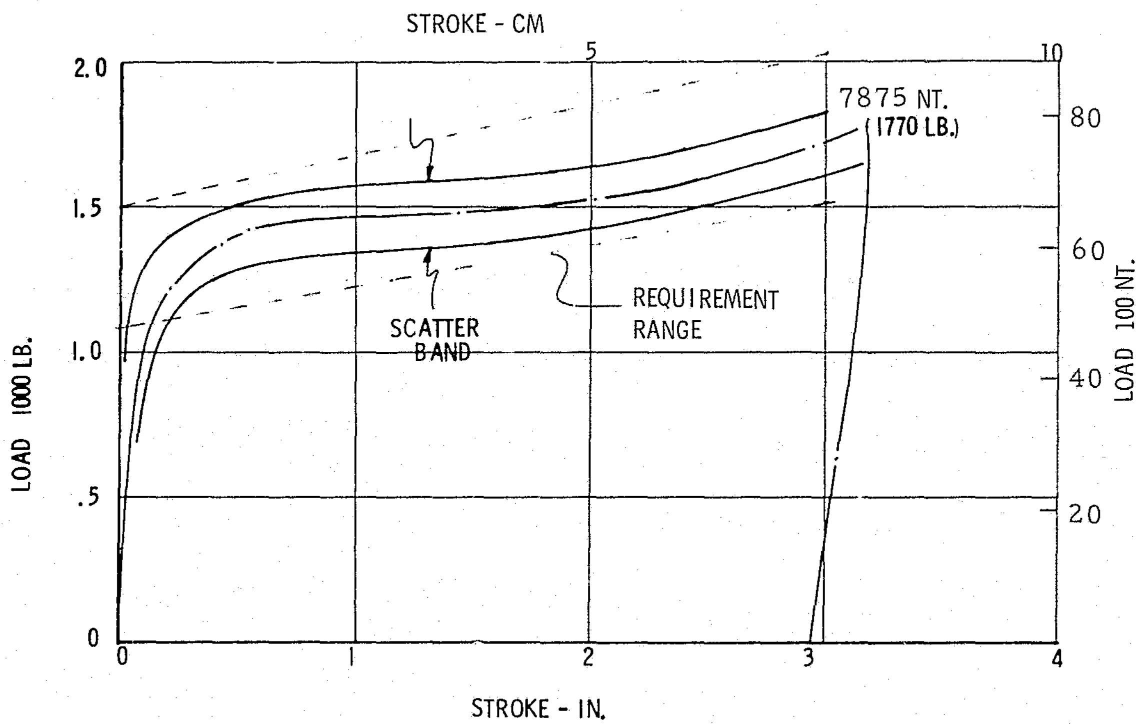

Figure 5 - Load Limiter Requirement and Test Data

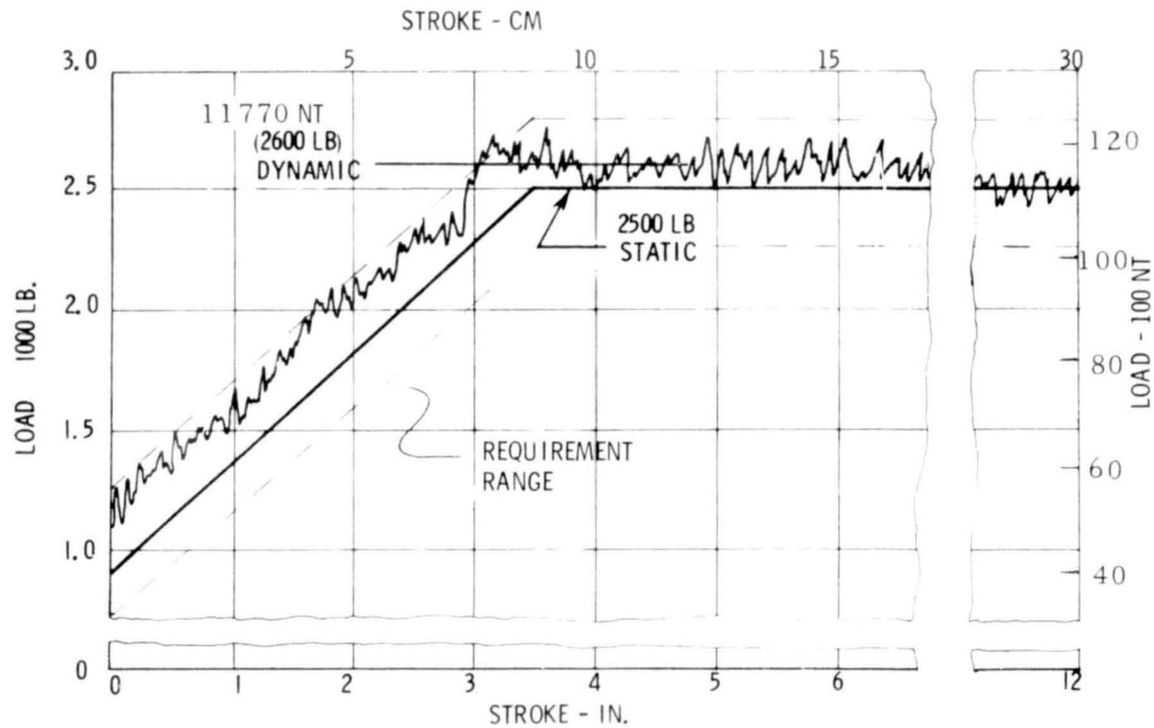

Figure 6 - Attenuator Requirement and Test Data

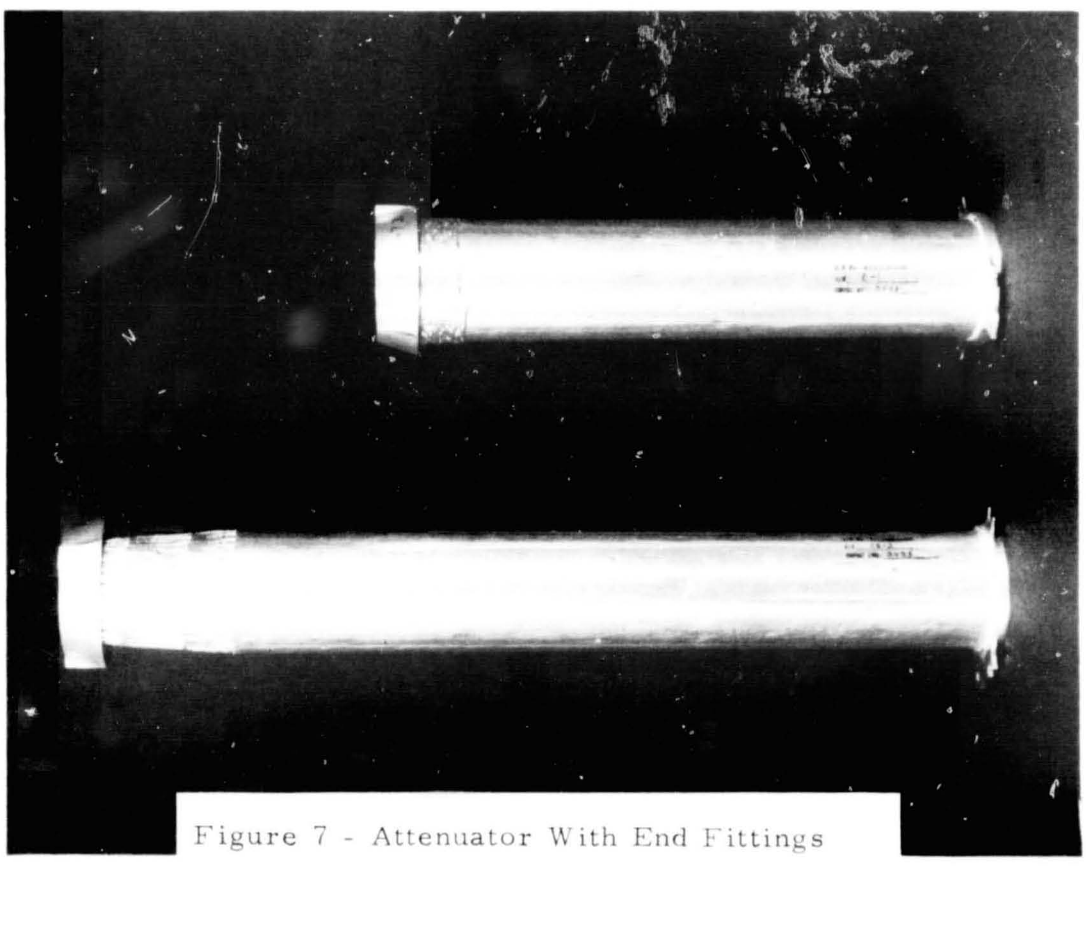

Figure 7 - Attenuator With End Fittings

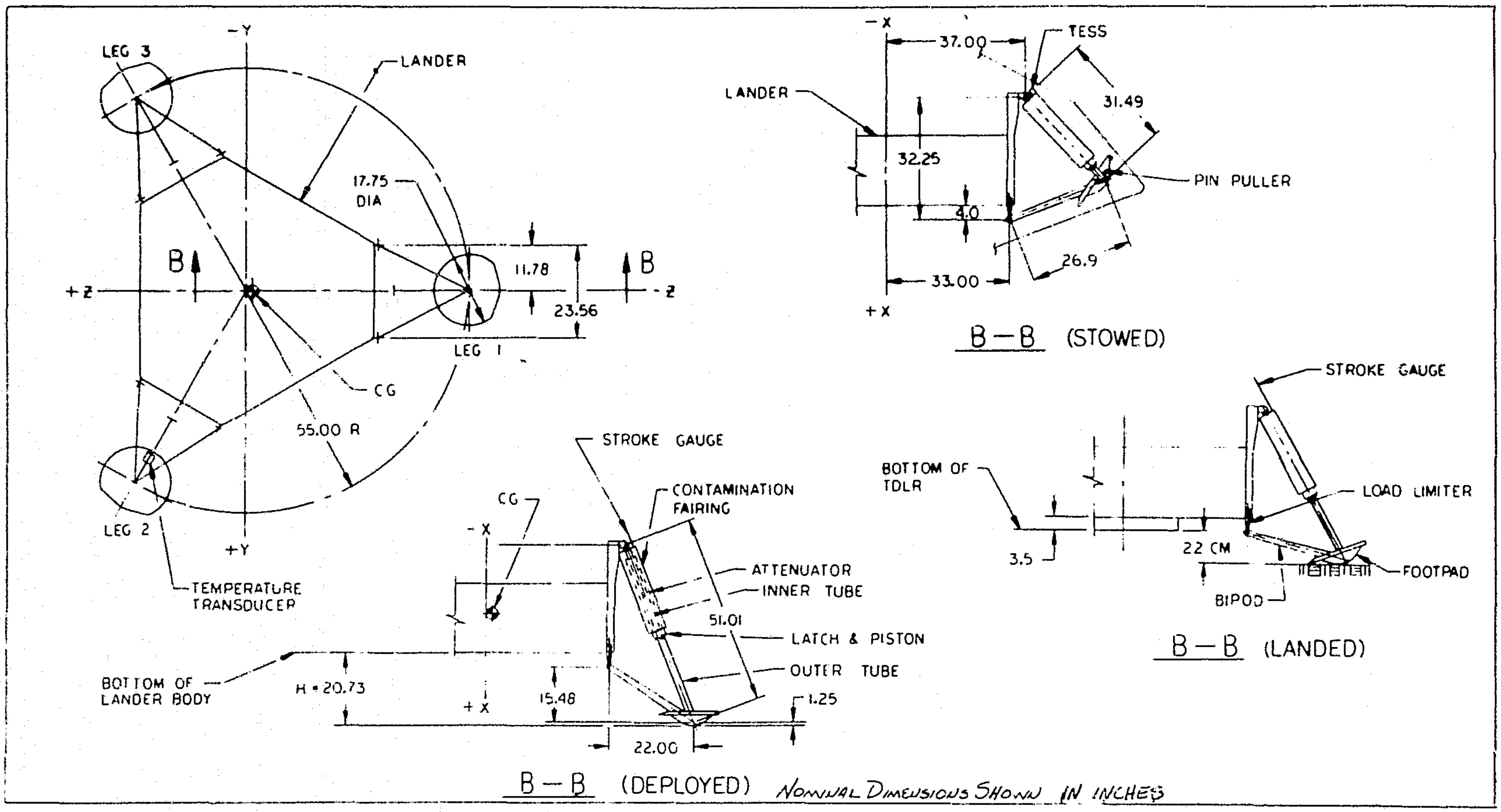

Figure 8 - Flight Design Configuration