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SPACE SHUTTLE STAGING SIMULATION

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16. ABSTRACT

This document describes and delineates the overall capability of a new digital computer program for simulation of space shuttle vehicle staging maneuvers. It is not intended as a detailed user's manual for the program. The formal documentation and users manual are currently being prepared for publication. The important distinctive feature of the program is that it enables simulation of linkage-type separation devices (as well as all the more usual types) and includes the effects of interference aerodynamics and thrust plume impingement.

A general flow description and a moderately detailed description of the major simulation components are presented in Sections II and III. Some typical simulation results are shown in Section IV, and the flexibility and growth potential of the basic simulation are discussed in Section V.

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SPACE SHUTTLE STAGING SIMULATION

SUMMARY

This document describes and delineates the overall capability of a new digital computer program for simulation of space shuttle vehicle staging maneuvers. It is not intended as a detailed user's manual for the program. The formal documentation and user's manual are currently being prepared for publication. The important distinctive feature of the program is that it enables simulation of linkage-type separation devices (as well as all the more usual types) and includes the effects of interference aerodynamics and thrust plume impingement.

A general flow description and a moderately detailed description of the major simulation components are presented in Sections II and III. Some typical simulation results are shown in Section IV, and the flexibility and growth potential of the basic simulation are discussed in Section V.

I. INTRODUCTION

The separation maneuver performed by the space shuttle is critically important to the feasibility of the shuttle concept. The system must function flawlessly in abort as well as nominal conditions to ensure a safe return for the crew(s) and vehicles. Thus, an accurate and complete simulation of the separation mechanism and the vehicle dynamics is imperative. For several years, Marshall Space Flight Center (MSFC) has successfully analyzed and designed tandem staging configurations. The space shuttle dictates that the techniques used in this analysis be updated in order to adequately analyze a parallel (piggy-back) staging maneuver. These new problems prompted the development of a new simulation called ASET (Ascent and Staging Evaluation Technique), the pertinent features of which are presented in this report.

PERTINENT FEATURES OF THE SIMULATION

ASET is capable of treating a wide variety of both nominal and abort staging conditions. Although the terms "Booster" and "Orbiter" are used to denote lower and upper stages, the simulation is general and applicable to tandem or parallel staging, as well as hybrid schemes such as external tank jettison. It is also applicable to cargo deployment. The following list outlines a few of the features available in ASET.

- Analyzes two rigid bodies with six degrees of freedom.

- Simulates the dynamics of both vehicles during three phases of flight:

  (1) The mated ascent portion of flight, in which the orbiter is secured to the booster through four tie-points.

  (2) Articulation or staging, in which the orbiter is still connected by the separation mechanism to the booster but is moving with respect to it.

  (3) Free and independent flight, in which the bodies are not physically connected but may be coupled through interference aerodynamics and thrust plume impingement effects.

- Accommodates various separation schemes, including passive reverse trapeze, passive forward trapeze, rocket, hot gas ram, and active linkage arrangements.

- Determines instantaneous forces in the vehicle interface components

- Computes the instantaneous state of deployment for each separation link: trapeze and the hot gas ram

- Simulates off-nominal thrust conditions for any or all of the engines on the booster and orbiter

- Has three-axis thrust vector control (TVC) for both vehicles

- Engine deflections include second-order actuator dynamics and are rate and position limited.

ASET is designed for the complete analysis of a five-to-ten-second flight interim, which makes the use of the program as an entire-mission analysis tool impractical though not impossible. Since the simulated time period is relatively short, the mass and inertia properties are assumed to be constant, although these properties can be time-varying with simple modification to the program.

USES FOR ASET

Some typical applications for which ASET can be used are as follows:

- Weigh the relative merits of the various separation concepts.

- Determine the effect of tie-point and linkage design changes on the separation maneuver.

- Determine interface loads experienced during mated ascent.
- Simulate the effects of various release criteria.
- Monitor the effect of thrust dispersions on staging.
- Determine the effect of engine gimbal and rate limits on staging.
- Simulate the effect of TVC malfunctions on staging.
- Determine the effectiveness of control laws and gains during staging.
- Determine the effect of staging sequence on the post separation flight of both shuttle vehicles.
- Determine the extent of catapult thrust degradation due to side loads.

Through investigations like these, staging envelopes wherein successful staging is assured can be identified.

II. GENERAL SIMULATION FLOW

ASET computes the six-degree-of-freedom, rigid body motion of two powered vehicles. A simplified flowchart appears in Figures 1 and 2. The major portions of this flowchart are discussed in greater detail in Section III.

Initially, all data are read into the program. These data include :

- The initial state of each vehicle (stage)
- The linkage and tie-point geometry
- The linkage and tie-point structural characteristics
- Thrust profiles for each engine
- Tabulated gain schedules for use in attitude control of each vehicle

After reading these data, the initial conditions are computed. The simulation enters the integration loop by computing the initial transformation matrices. These matrices enable the simulation to express any vector in any or all of three coordinate systems: (1) booster body, c.g.-centered, (2) orbiter body, c.g.-centered; and (3) earth-centered inertial.

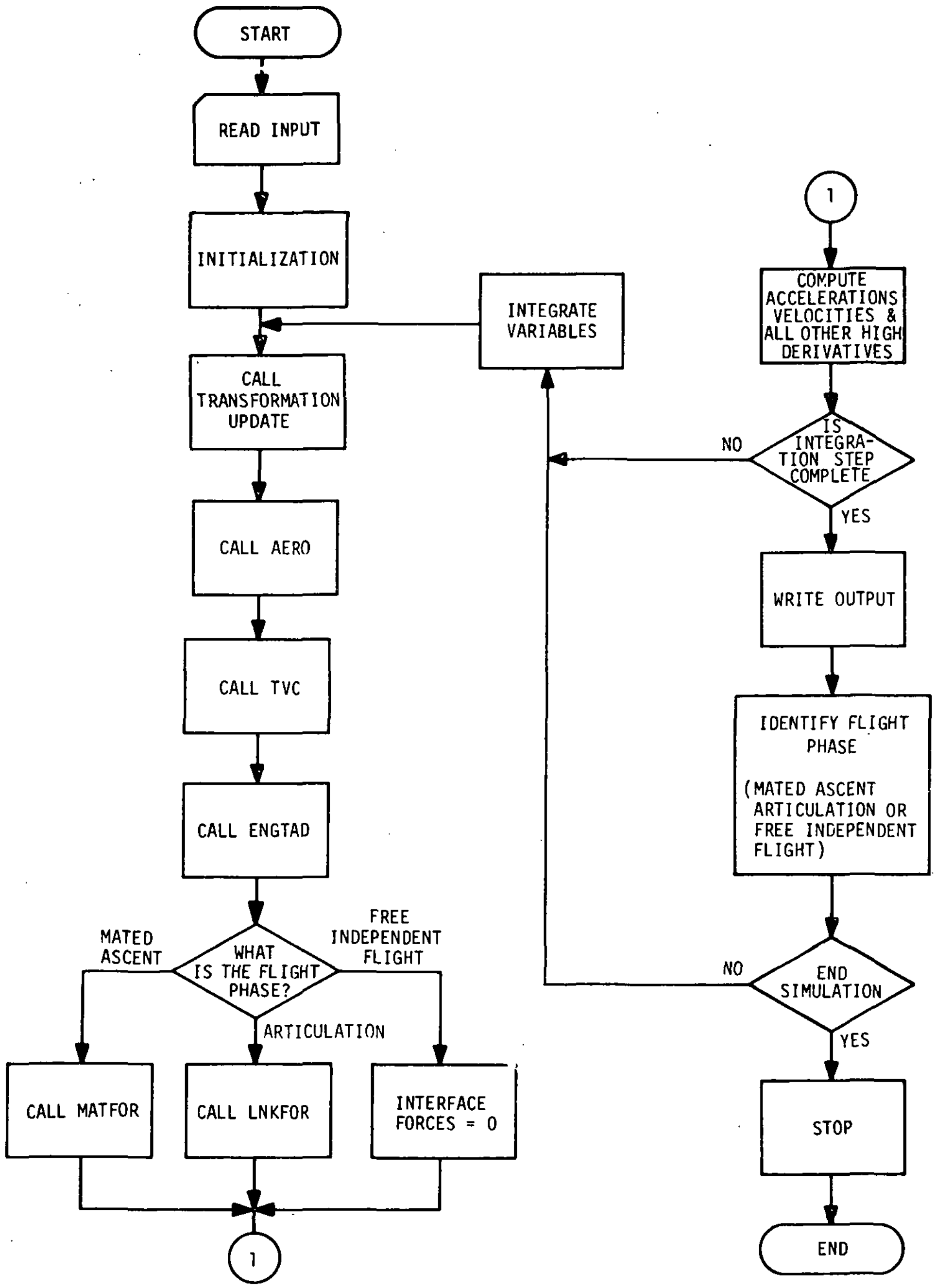


FIGURE 1: SIMULATION FLOW

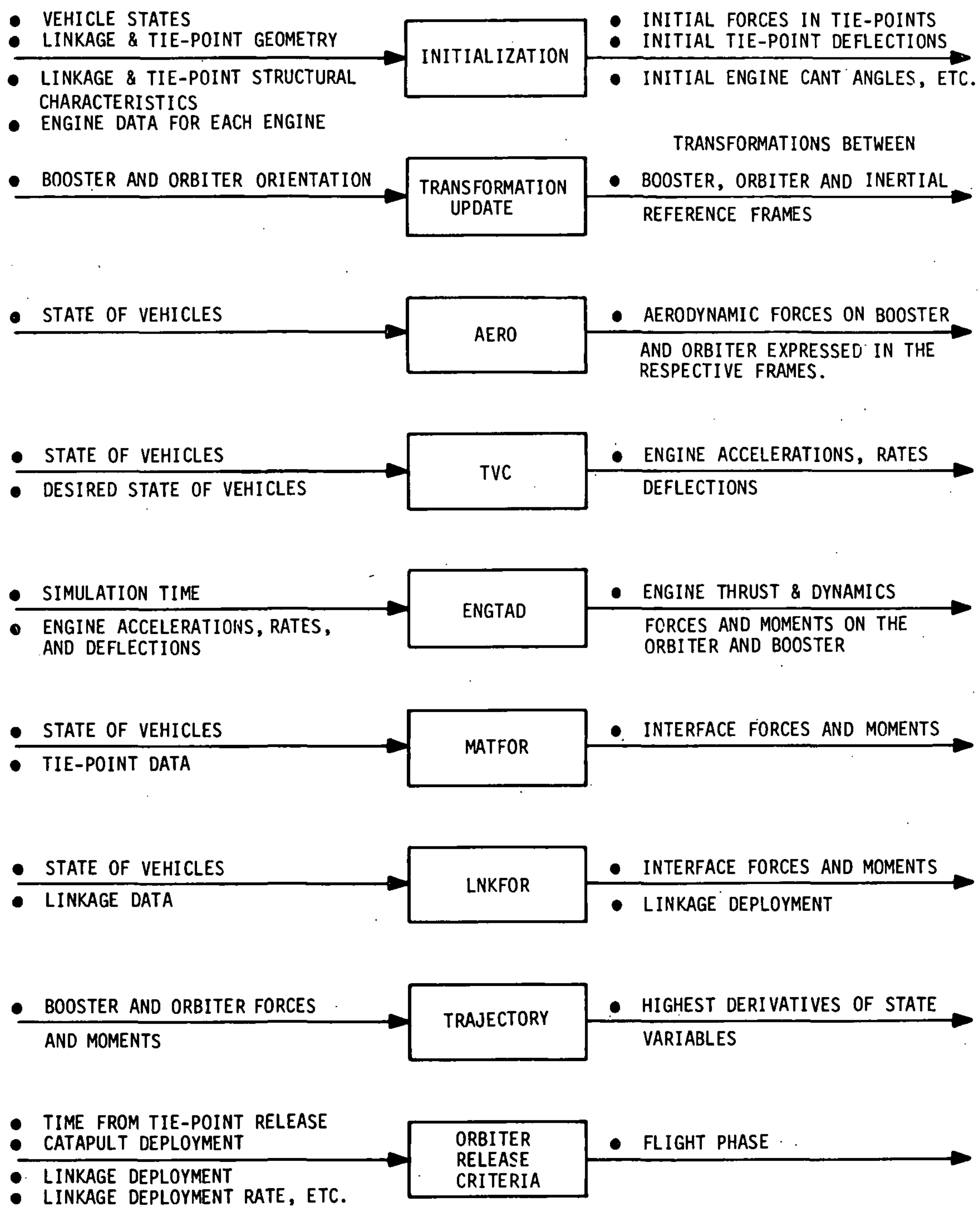


FIGURE 2: MODULE FUNCTIONS

Control is then passed to the aerodynamics module which computes forces and moments on both the booster and orbiter including interference aerodynamics and thrust plume impingement effects. This module permits the analysis of the separation maneuver under off-nominal and abort conditions. The interference aerodynamics are supplied by a four-dimensional table of total pitch-plane force and moment coefficients. Principally through lack of data, the lateral directional aerodynamics analysis comprises the conventional stability derivative approach and does not include the effects of aerodynamic interference and thrust plume impingement.

The state of each vehicle is then compared to the desired state, and control acceleration commands are computed in the TVC routine. These accelerations are then integrated to find the engine gimbal rates and deflections. The accelerations, rates, and deflections for each booster and orbiter engine are then supplied to the engine thrust and dynamics module. The engine dynamics and thrust forces and moments on each vehicle are computed within this routine.

The routine MATFOR is called when the ascent vehicle is in the mated configuration. This module computes the interface forces from the tie-point locations, tie-point structural characteristics, and the relative states of the two vehicles. While the vehicles are articulating, the forces in the connecting mechanisms are computed in the LNKFOR routine, which is very similar to the MATFOR module and uses similar data. The output from LNKFOR is the same form as that from MATFOR since in each case, the interface forces and moments on both vehicles are computed.

The central routine in the simulation is the trajectory module. In this module, aerodynamic and control forces and moments from above are employed to determine each vehicle's translational and rotational accelerations. These accelerations are then integrated by a fourth-order Runge Kutta integration scheme. After each integration step, the state of the analysis is checked to see if the flight phase should be changed, permitting the simulation of various orbiter release criteria and allowing the investigator to determine the most advantageous release scheme.

III. MAJOR SIMULATION COMPONENTS

INTERFACE SIMULATION (TIE-POINTS)

ASET is capable of simulating the tie-point arrangement which holds the orbiter to the booster during mated ascent. Each tie-point is represented by a 3 x 3 stiffness matrix and a 3 x 3 damping matrix expressed in booster body coordinates. The tie-point deflection and deflection rates are used to compute the forces on the booster and orbiter. These tie-point forces are then translated to the vehicle center-of-gravity and the corresponding moments are computed. A block diagram of the interface force and moment loop employed during mated ascent is shown in Figure 3.

This method of analysis supplies the cyclic, peak, and average loading for each tie-point.

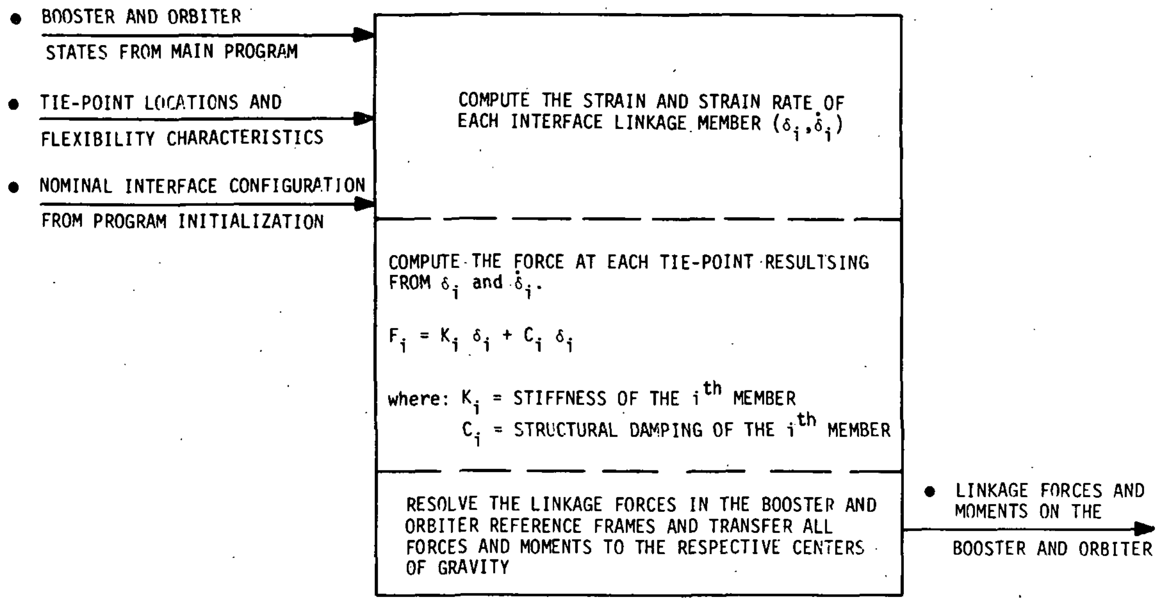


FIGURE 3: STRUCTURAL INTERFACE FORCE COMPUTATION

INTERFACE SIMULATION (LINKAGES)

The analysis of the separation linkage is quite similar to the tie-point analysis discussed above. The simulation can analyze up to fifteen connecting members with no program modification required. Each member undergoes elastic deformation along its longitudinal axis allowing the investigator to determine the compression and tension forces in each member. The effect of hinge, ball joint, or cantilever attachment is then added to this elastic effect. Figure 4 depicts a typical linkage member. Three of the attachment mechanisms which can be simulated are shown in Figure 5.

The separation linkage loop is the same as that shown in Figure 3 except the method of computing the forces in the interface differs as discussed above. The hot gas ram is simulated by an expandable linkage member that is cantilevered to the booster. The orbiter attachment is a ball joint connection.

By using the method of analysis described above, the simulation can analyze the effect of tie-point release criteria on staging. For example, a proposal by MDAC allows release of the aft tie at catapult initiation;

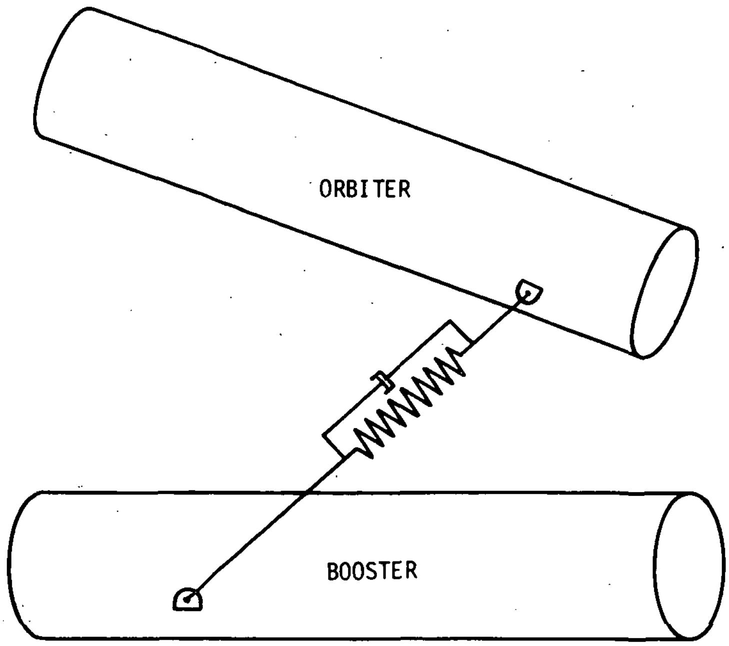


FIGURE 4: LINKAGE MODEL

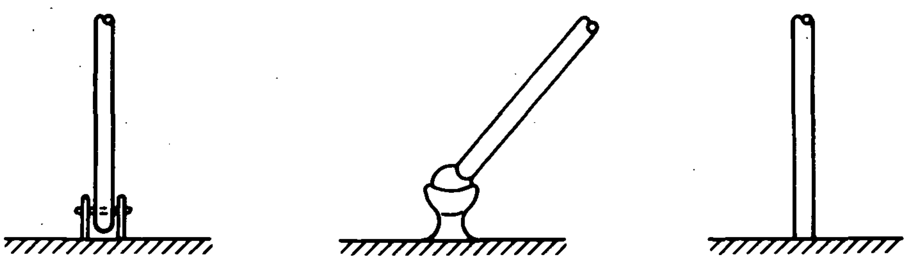


FIGURE 5: TYPICAL ATTACHMENT MECHANISMS

however, the tie is intact as long as it is in compression. The advantages and disadvantages of this type of release can be studied through the simulation. Linkage release criteria can also be varied to find the most advantageous scheme. One method, proposed by GDC, calls for orbiter release 0.5 seconds after the tie-points are severed. This logic can be tested under various abort conditions to determine its advantages and disadvantages. These schemes are illustrated in Figures 6 and 7.

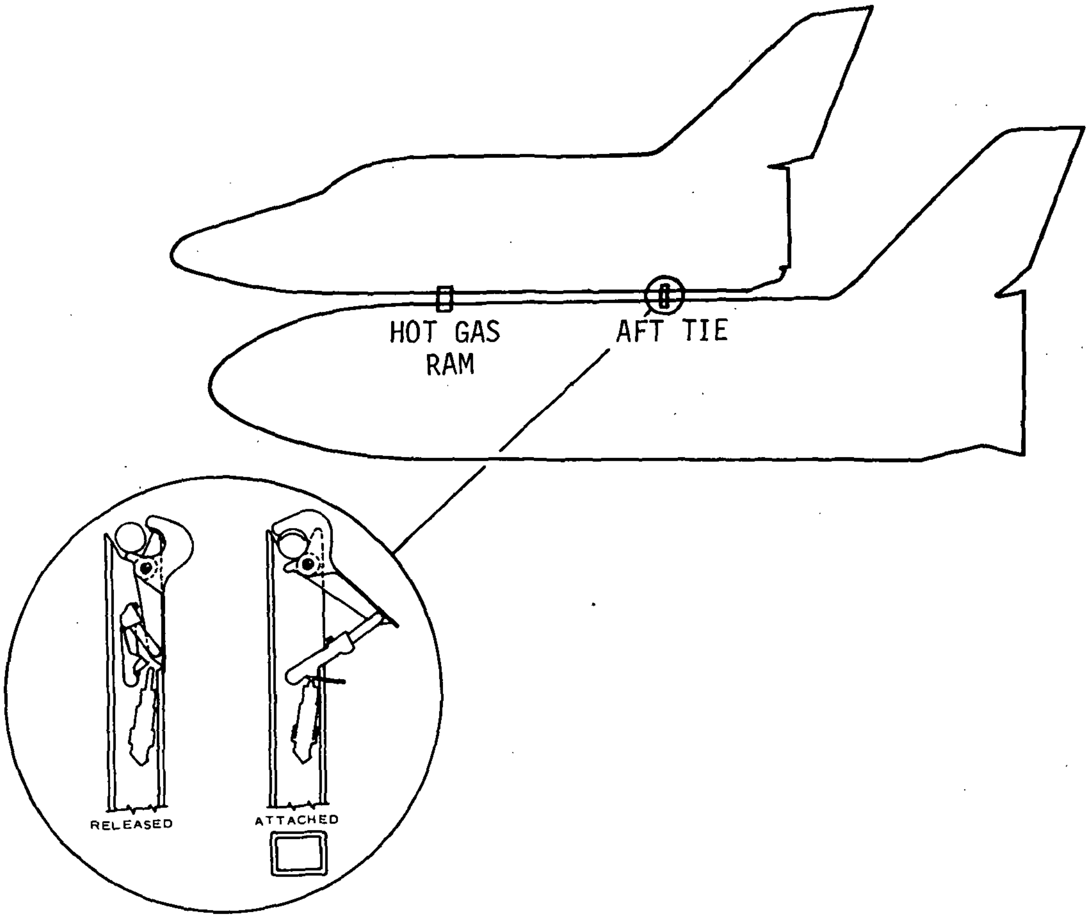


FIGURE 6: HOT GAS RAM CONCEPT

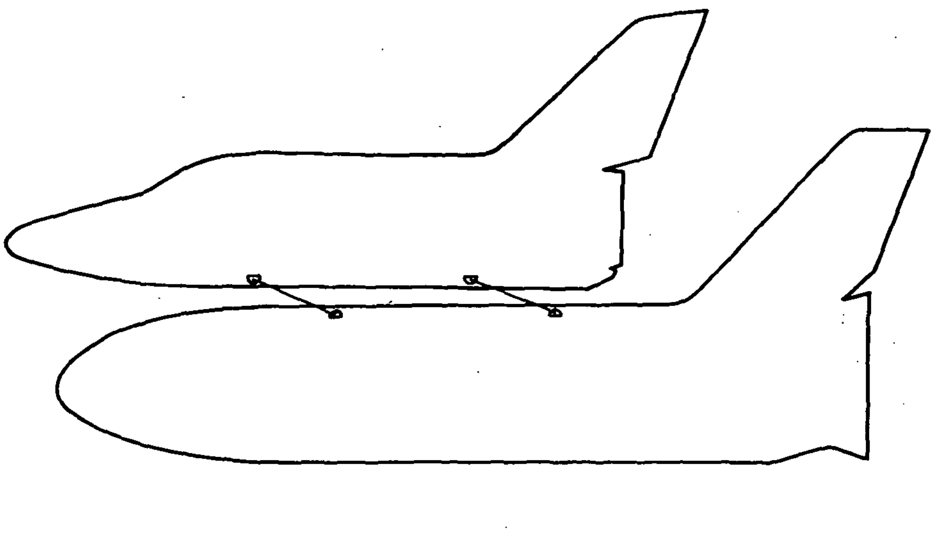


FIGURE 7: REVERSE TRAPEZE SCHEME

The capability of the simulation to compute the tie-point forces enables the investigator to determine the magnitude of the linkage forces encountered, the initial conditions before tie-point release, and the consequence of premature or delayed tie-point release.

ENGINE SIMULATION

The engine thrust and dynamics model has been kept as general as possible so as to simulate the various conditions that merit investigation. Two methods of calculating the thrust transients are available to the user. The most general method is a conventional table lookup with linear interpolation. A second option computes the thrust profiles as a series of linear and quadratic line segments. In the second option, the thrust transients of the shuttle engines currently under consideration can be closely approximated by varying the input thrust levels and event times. Since each booster engine and each orbiter engine has its individual thrust profile, the simulation is flexible enough to analyze many off-nominal conditions for all, or any combination, of the engines. A partial list of possible off-nominal conditions includes:

Partial thrust build-up

Slow build-up, decay

Rapid build-up, decay

Premature booster engine cut-off

The engine thrust and dynamics calculations also account for the forces and moments resulting from the engine gimbal accelerations, known as the tail-wags-dog effect.

GUIDANCE AND CONTROL CALCULATIONS

At this stage in the program development, the guidance and control calculation consists of thrust vector control (TVC) about three axes. The control laws utilized in the orbiter and booster are shown in Figure 8. The roll angle command is added to the pitch or yaw command depending on the location of the engine in the array.

After computing the engine command pitch and yaw angles, for each engine, the simulation responds with a second order lag. The result is then rate- and position-limited as shown in Figure 9.

The gains employed by the TVC system are scheduled with respect to flight time. The above treatment of the engine commands and response enables the investigator to simulate the effects of different control schemes on the separation maneuvers. The capability of analyzing the

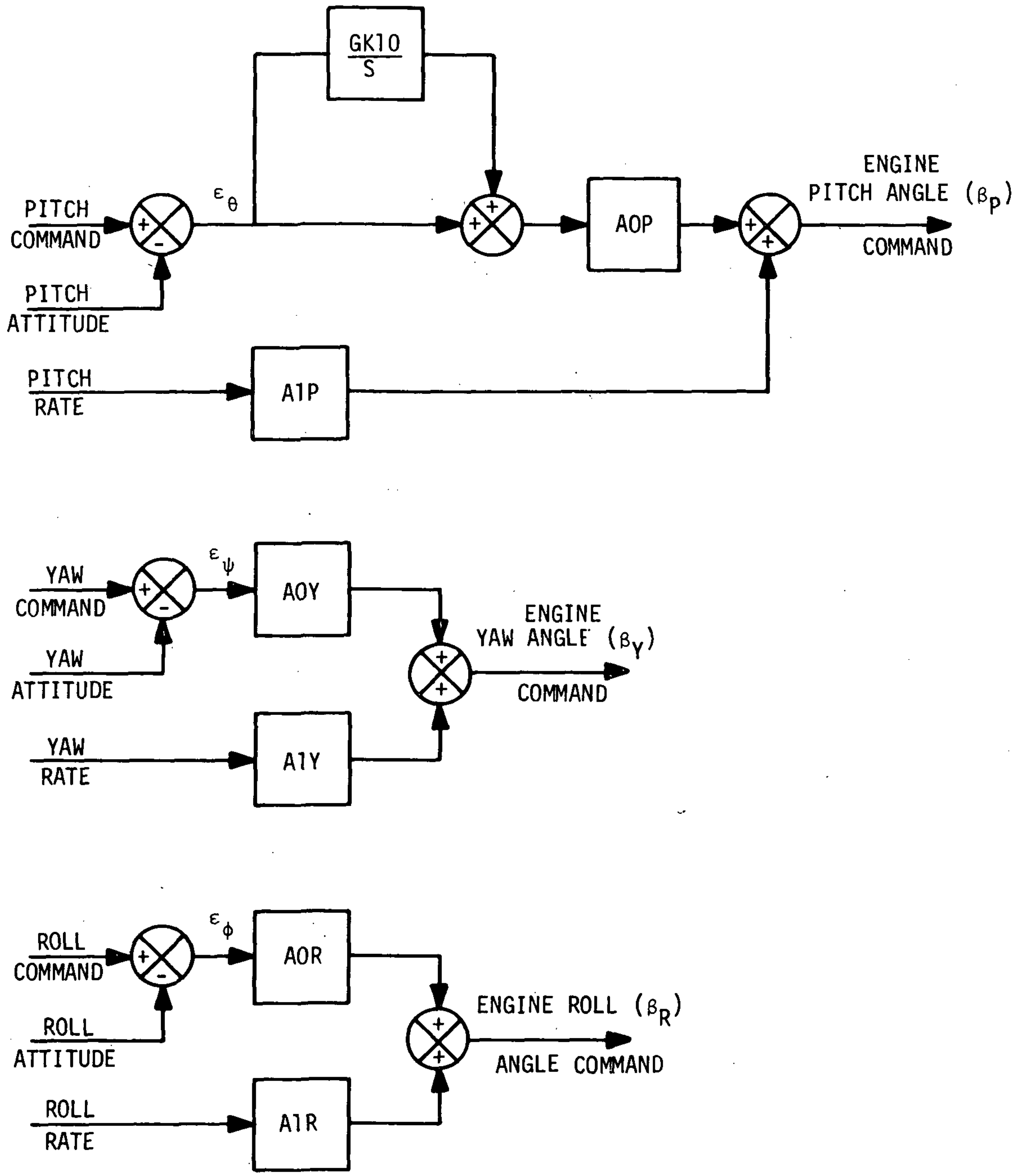


FIGURE 8: BOOSTER AND ORBITER CONTROL DIAGRAM

seriousness of a TVC failure is an added bonus gained from the approach described above.

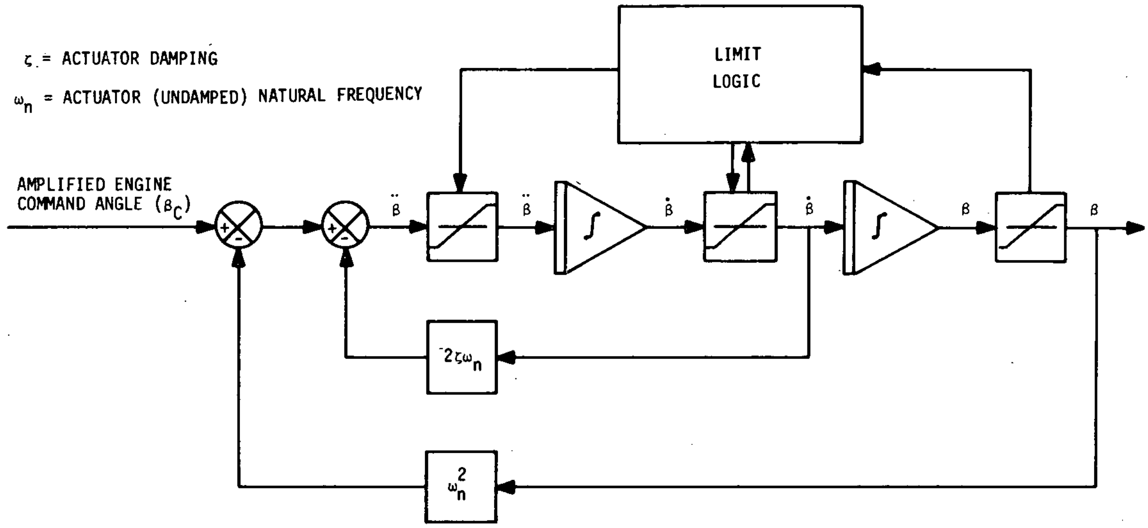
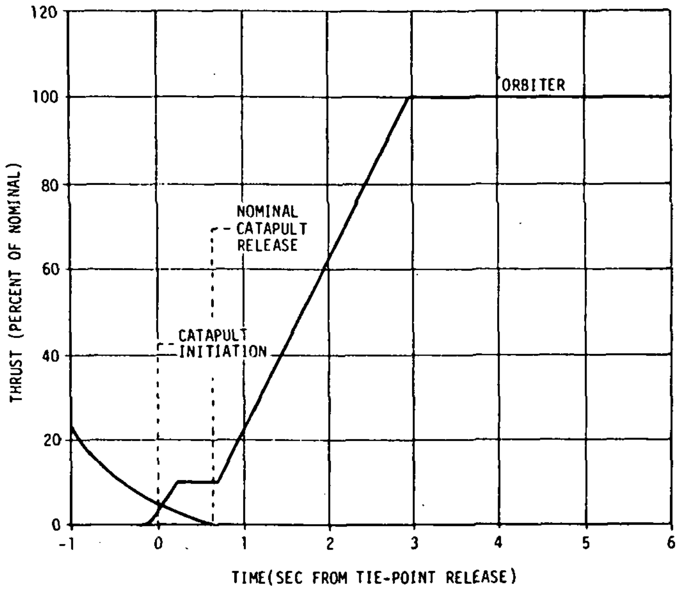


FIGURE 9: ENGINE RESPONSE MODEL

IV. TYPICAL NUMERICAL RESULTS

Several studies have been conducted on shuttle configurations proposed by McDonnell-Douglas (MDAC) and General Dynamics (GDC) teams. In each case, the simulation was run at nominal staging conditions with the aerodynamic and thrust impingement effects assumed negligible. Pictorial results of some of these studies are shown in Figures 10 through 14.

The nominal MDAC separation is shown in Figure 10. The times indicated on the figure are in seconds elapsed from tie-point release. The aft tie is released when it first experiences tension, occurring at 0.008 second after tie-point release. The catapult provides 72,000 pounds of thrust until it is extended .61 meters (2 feet). At nominal conditions, this occurs 0.65 seconds after aft tie release. Figure 11 depicts the staging of an off-loaded MDAC orbiter at nominal conditions. The off-loaded orbiter has approximately half the mass of the fully loaded orbiter with orbiter center-of-gravity approximately 9.8 meters aft of the nominal staging c.g. The pitch inertia of the off-loaded orbiter is approximately 1/3 that of the nominal orbiter. A comparison of Figures 10 and 11 shows that decreased mass enables the orbiter to stage faster and



NOMINAL STAGING

AFT TIE RELEASE AT .008 sec
CATAPULT RELEASE AT .65 sec
TIE-POINT RELEASE AT 0.000 sec

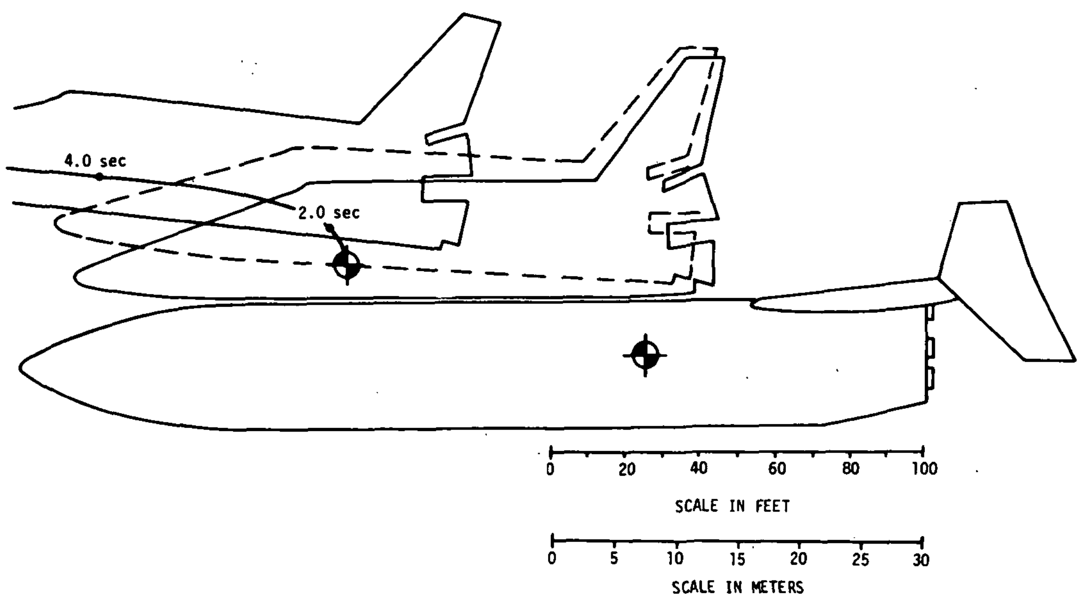
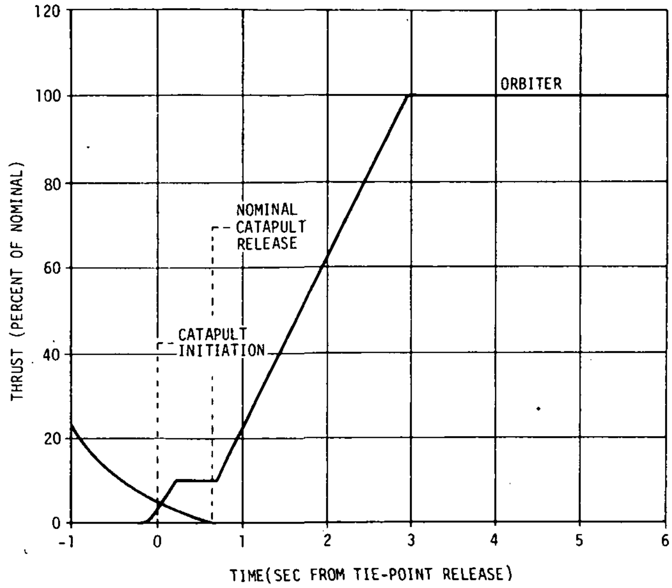


FIGURE 10: CATAPULT STAGING



OFF-LOADED ORBITER

AFT TIME RELEASE AT .039 sec
CATAPULT RELEASE AT .448 sec
TIE-POINT RELEASE AT 0.000 sec

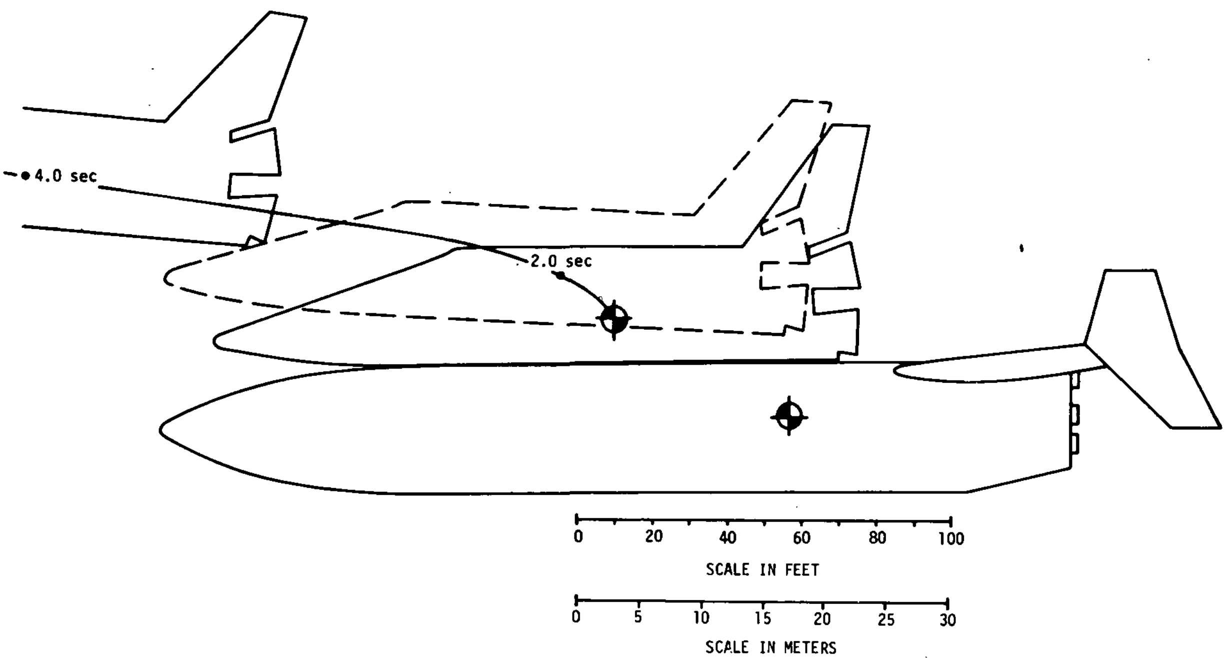
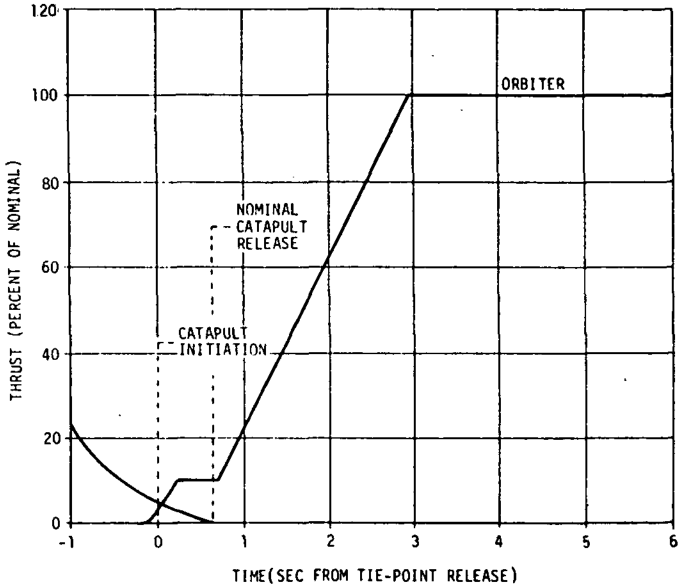


FIGURE 11: CATAPULT STAGING - OFF-LOADED ORBITER



NOMINAL WEIGHT

AFT TIE RELEASE AT .008 sec
CATAPULT RELEASE AT .65 sec

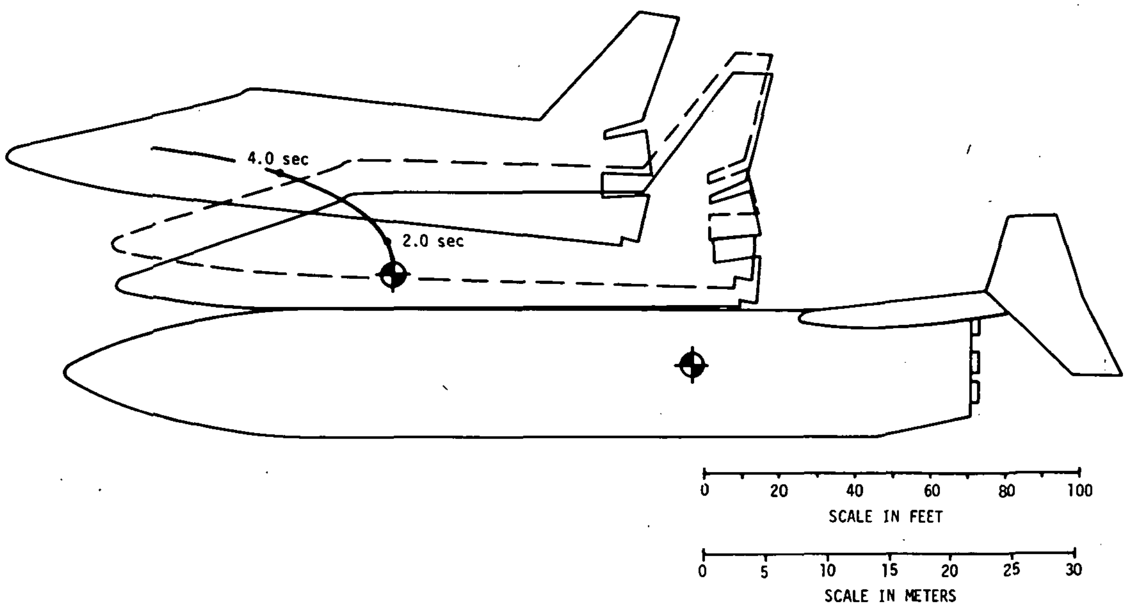
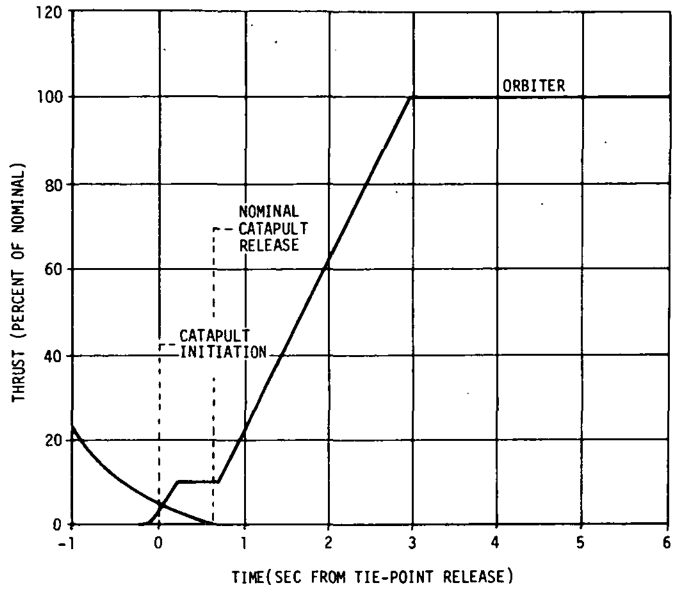


FIGURE 12: CATAPULT STAGING - ENGINE FAILURE



OFF-LOADED ORBITER

AFT TIE RELEASE AT .031 sec
CATAPULT RELEASE AT .430 sec

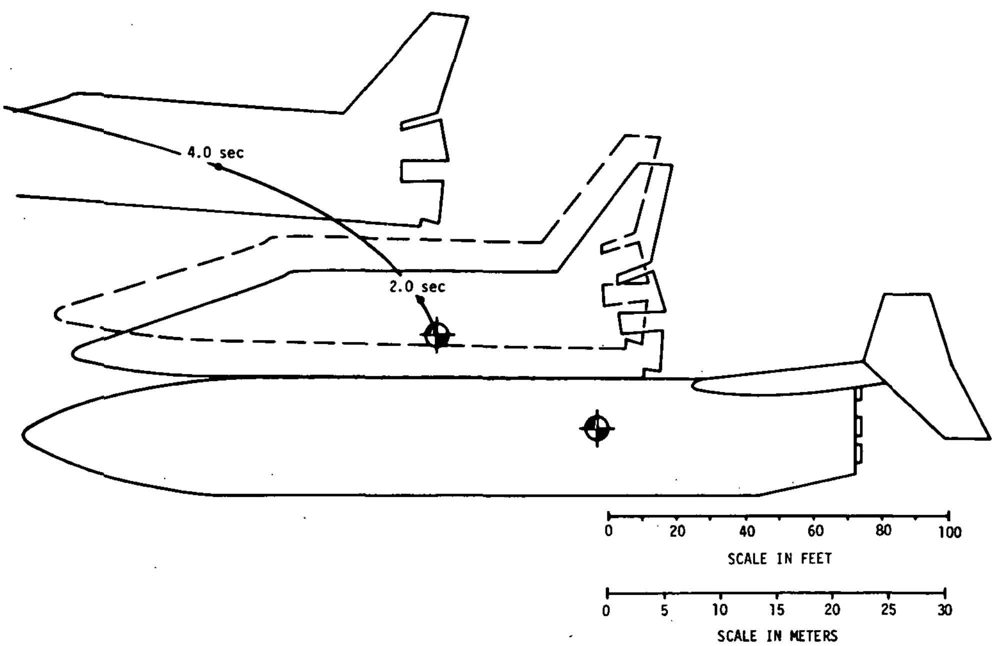


FIGURE 13: CATAPULT STAGING - OFF-LOAD ORBITER ENGINE FAILURE

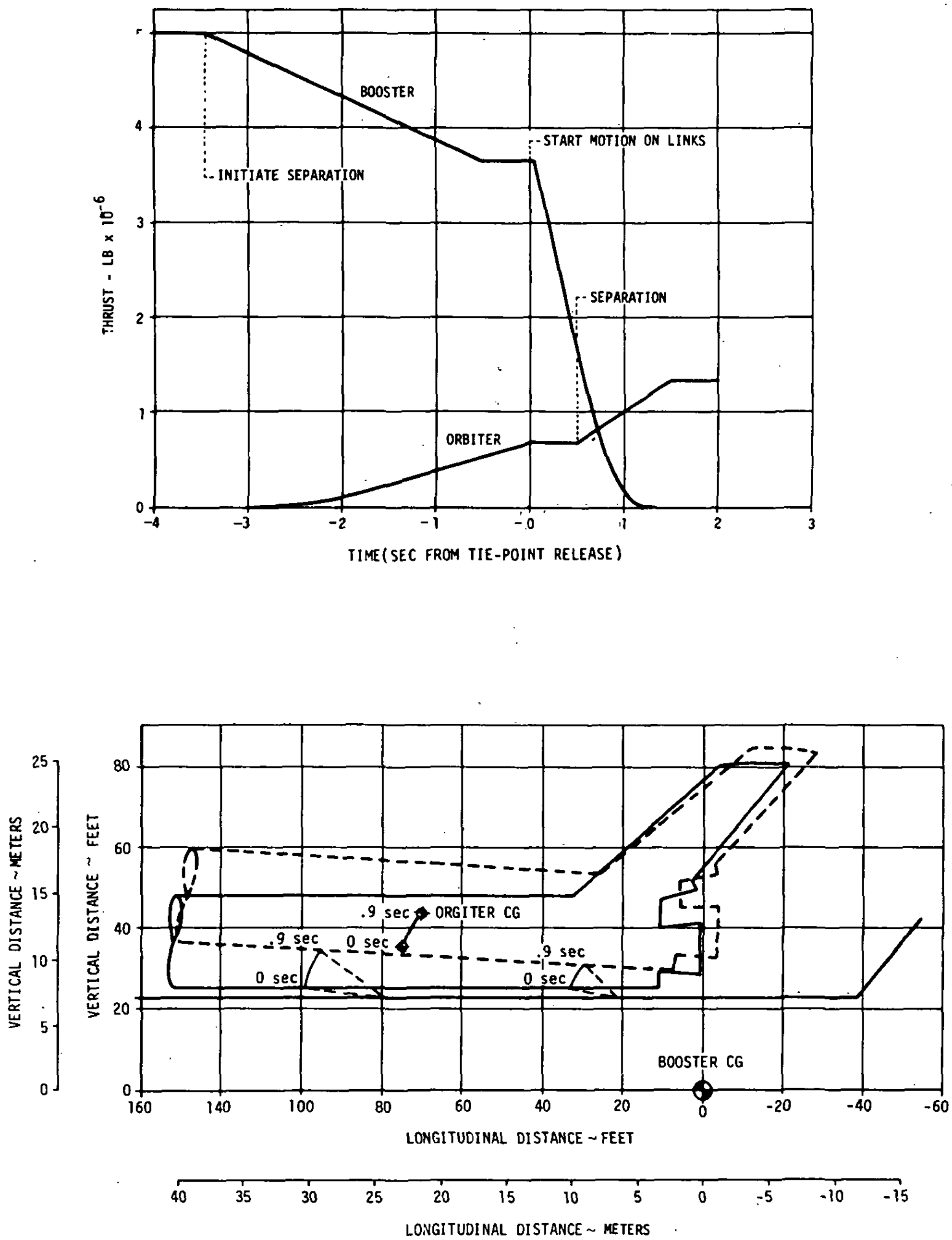


FIGURE 14: REVERSE LINKAGE STAGING

cleaner. The catapult is released approximately 0.2 seconds faster in the off-loaded orbiter configuration. The effect of the increased catapult moment arm and the decreased pitch inertia is shown in the aft tie release time. In this case, the aft tie point stays in compression for 0.039 second. The same two cases are shown in Figures 12 and 13, except in these cases the top orbiter engine failed to ignite. A comparison of these figures with the corresponding full thrust separations shows that the lighter orbiter translates vertically away from the booster before the rotation causes impingement on the booster stern. The thrust build-up and decay profiles used in the above analysis are shown in these figures.

A reverse linkage separation is depicted in Figure 14. This is a passive scheme proposed by GDC and uses no linkage actuation devices. The motion on the links, which is induced by the booster acceleration, starts at time zero. As shown in Figure 14 the linkage has deployed nearly 1 meter at 0.5 seconds. The thrust profile used in this analysis is inset in Figure 14. These results illustrate typical outputs available from the program.

V. GROWTH CAPABILITY

Several features will be added to the simulation to increase analysis capabilities and efficiency. Additional control capabilities will be required if the simulation is to be used as a detailed design tool. Under some conditions, a low orbiter or booster thrust level may be required for successful staging; however, this requirement limits the available TVC. Therefore, the ability to simulate other control schemes must be available for the vehicle with low thrust. These control schemes may be either aerodynamic surface control or reaction jet control (RCS). These capabilities will aid the analysis of various post separation maneuvers and the capability of the vehicle to perform these maneuvers.

A two-dimensional plot routine will be incorporated into the simulation to enable the investigator to more quickly and accurately determine the dynamic effects of a separation scheme. A "jump start" capability will also enable the investigator to look at longer time intervals with more efficiency. This "jump start" permits the simulation to be stopped at any flight time and restarted at exactly the same states that previously existed.

It is also planned to expand the simulation capability to include the effects of time varying mass and inertia properties. This feature will allow the analysis of longer pre-separation and post-separation flight intervals.

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by Charles E. Hall and Rex D. Agler

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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