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THRUST VECTOR CONTROL
GROUND TEST LIMITS TRADE STUDY

NERVA Program

Contract SNP-1

December 1970

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I. INTRODUCTION

This trade study presents results of a gimbal limits investigation conducted for verification of the NERVA engine gimbaling requirements during ground firing. A solution was necessary due to a known incompatibility during engine ground firing between the magnitude of the gimbaling requirements to be verified and the lesser amplitude capability allocated in the test facility exhaust duct design.

Possible safety problems arising from gimbaling operations were also of concern. These problems are identified and various possible solutions are discussed.

Since test cell "C" does not have the duct constraint, this facility was considered as a possible alternate to test facilities ETS-1 and E/STS-2. Considered as a supporting study to the main subject, the results of this investigation are presented in Appendix A.

Early in the study the cost trade parameter indicated that alternate means of verification would be necessary for large gimbal amplitude requirements. Results of a supporting investigation to study various methods are presented in Appendix B.

This document establishes a reference in support of the engine and applicable subordinate specifications, planning documents for verification, reliability, test operations, facility utilization and the long range program, and facilities engineering criteria considerations.

The effect of gimbaling is but one of several factors affecting the facility exhaust duct inlet sizing. Misalignment of the thrust vector relative
to the duct centerline can occur from such "non-gimbaling" causes as mechanical assembly tolerance stackup, engine static compliance, thermal growth and bending, gas dynamics and structural vibration. A study to evaluate significant contributing parameters is in process. Secondly, operation of the duct and shape of the engine nozzle exhaust plume is unknown for a condition of off-center firing into the duct. Duct scale model testing is planned for later in this contract year to investigate this problem area. Based on some preliminary results of the former study, these related studies are expected to have a significant impact on the trade-off cost and schedule parameters.
II. **SUMMARY**

The engine Thrust Vector Control (TVC) requirements include capabilities of 3 degrees of amplitude and gimbaling rates of 0.25 deg/sec (minimum) to 0.75 deg/sec (design). An angular acceleration capability of 0.50 deg/sec$^2$ is required for the rate response of 0.25 deg/sec. The design criteria for the ETS-1 exhaust duct presently specify an inlet diameter of 64-inches. When the engine uses a nozzle with an exit area ratio of 24:1, this inlet diameter allocates $\pm 1/2$ degree physical capability (as opposed to functional) for gimbaling.

To investigate this incompatibility an option approach was selected for trade-off analysis. Verification goals based on TVC requirements were chosen, and the related gimbal amplitudes were determined. These goals were the flight system capability, rates of 0.75, 0.50, 0.25 deg/sec and a "no response" case. For the rate goal options, gimbal amplitudes were estimated for two cases of varying verification quality level: "target" and "minimum acceptable". The former provides for demonstration of the acceleration ramp, rate overshoot characteristics and "steady state" rate response. The latter deletes the "steady state" rate response portion of the former and is the minimum acceptable response capability for servo analysis correlation. Test stand facilities considered available for gimbaling during ground firing were ETS-1 and E/STS-2.

Parameters of evaluation, which were found sensitive to the TVC function, were performance in the sense of verification quality, reliability including the effect on trend data development, safety in ground test operation, potential growth related to possible future requirements and flexibility for analytical estimate uncertainties, cost as affected by facility criteria changes and program power test series start schedule as affected by test facility activation.
The following conclusions were reached:

1. An engine ground firing evaluation of the flight system actuator option was not economically feasible. The "no response" option was determined to be unacceptable due to inadequate performance and reliability verification quality. Verification of a rate goal was found to be a satisfactory compromise.

2. Within certain limited restrictions on the assumed nozzle exhaust plume and control on the gimbaling amplitude vector sum, the \( \pm 1 \) degree gimbal amplitude can be provided by the 64-inch diameter exhaust duct inlet as planned for ETS-1. However, the allowance for thrust vector misalignment due to "non-gimbaling" causes was found to be effectively zero, which is unrealistic. Removal of these restrictions was found to incur a delta cost increase to modify the duct diameter to allow for the \( \pm 1 \) degree gimbal amplitude.

3. Provided the gimbaling amplitude vector sum is restricted to a circular pattern, the present engine specification rate of 0.25 deg/sec can be verified with the 64-inch duct inlet diameter. The gimbal amplitude required for this rate is estimated to be between 0.52 and 0.62 degrees. Allowable lateral displacement for thrust vector misalignment relative to the duct centerline for "non-gimbaling" causes was estimated to vary from 0.33 inches to 2.52 inches depending on the nozzle exhaust plume assumptions and option case amplitude.

The following recommendations are made:

1. A minimum gimbal amplitude capability of \( \pm 1.0 \) degree is recommended for TVC verification during engine ground testing. This capability provides for a potential 0.50 deg/sec rate requirement in which the acceleration ramp, rate overshoot characteristics and "steady-state" rate response can be demonstrated and for some uncertainty in the preliminary basis of the amplitude requirement estimates. Verification quality was also considered superior to that which would be attained with the slower rate of 0.25 deg/sec.
2. Based on a possible one-year delay in duct availability, a change to the 64-inch duct inlet diameter at ETS-1 on the basis of accommodating a ± 1 degree TVC amplitude capability alone is questioned. Results from the related problem area studies may have more bearing on this trade-off. It is recommended that this capability be programmed for E/STS-2 where slack time is apparently available prior to the PQE and QE power test series.

3. Restriction of the gimbal amplitude vector sum to a circular path is recommended with the safety means provided by the facility command-control electronic system. External mechanical measures were found to adversely affect rate verification. If an electronic safety system is found unacceptable, amplitude requirements must be increased by a factor of $\sqrt{2}$ on this basis and neglecting "non-gimbaling" misalignment, verification of the 0.25 deg/sec rate may be marginal for a 64-inch duct inlet diameter.
III. **SCOPE**

A. **OBJECTIVES**

The overall objective of this trade study is to determine the TVC gimbal limits for ground testing of the NERVA engine in test facilities ETS-1 and E/STS-2.

Specific objectives are:

1. To determine the gimbal actuator stroke limits, including provision for snubbing, required to achieve verification of TVC response requirements,
2. To investigate test facility capability relative to TVC response verification requirements and estimate allowance available for thrust vector misalignment due to non-gimbaling causes,
3. To establish a minimum acceptable TVC response verification requirement to be demonstrated during engine ground testing, and
4. To recommend alternate test facility criteria for those parameters which provide a constraint to achieving verification of the minimum acceptable TVC response requirement.

Two peripheral studies are included in the Appendices in support of this trade study. The objectives are:

1. To investigate the use of Test Cell "C" as an alternate facility to verify TVC response requirements during engine ground testing (Appendix A),
2. To investigate possible supplementary means of functional demonstration for those engine TVC response requirements which will exceed the demonstration capability during engine firing within either of the two test facilities (Appendix B).

B. **FUNCTIONAL AND TECHNICAL REQUIREMENTS**

1. **Thrust Vector Control Function**

   In accordance with SNPO-NPRD-1 (Reference 1), the NERVA 75K Full Flow Engine shall provide a capability for TVC, and this shall be accomplished
by means of gimbaling the engine. The purpose of the engine TVC function is to provide the following nuclear powered vehicle capabilities:

a. A means of nulling the pitching (or yawing) moment due to misalignment of the engine thrust about the vehicle center of gravity, and

b. A means of vehicle attitude control about a nominal flight trajectory during engine operation.

For the engine concept shown on ANSC drawing 1137400C, the gimbal center is located on the engine longitudinal axis at station 23.0. To provide a controlled angular motion, one each linear electro-mechanical servo actuator is located parallel to the engine longitudinal axis and 25 inches radial about the pitch ($\theta = 90^\circ$) and yaw ($\theta = 180^\circ$) axes. These features are presented in a view of the engine in Figure 1.

As specified in the engine specification (Reference 2), the gimbal system shall provide the following TVC capabilities in all directions:

<table>
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<th>Equivalent Gimbal Actuator Linear Motion (1)(2)</th>
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<tr>
<td>Angle from null</td>
<td>0 - 3.0 degrees</td>
<td>± 1.31 inches</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>0 - 0.25 deg/sec</td>
<td>± 0.11 in./sec</td>
</tr>
<tr>
<td>Angular acceleration</td>
<td>0 - 0.50 deg/sec$^2$</td>
<td>± 0.22 in./sec$^2$</td>
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Approximately ± 1.5 degrees of the 3-degree amplitude is presently allocated for vehicle system thrust misalignment correction function (Reference 3). The remaining amplitude is available for attitude control function.

(1) Linear motion associated with the upper limit capability shown for gimbaled engine motion.

(2) Assumes a structural compliance equal to zero.
To provide a common understanding of the rate and acceleration requirements as considered within this report, the following interpretations are presented:

**0.25 deg/sec rate:** ... that the engine shall be capable of responding to a rate (ramp) command of 0.25 deg/sec within the limits defined in Figure 2.

**0.50 deg/sec² acceleration:** ... that the engine shall ramp from rest at a minimum acceleration of 0.50 deg/sec² during a rate command of 0.25 deg/sec (Figure 2).

The design angular rate (or response to a ramp command) is to be at 0.75 deg/sec(1) rather than 0.25 deg/sec (Reference 4).

Based on these engine TVC requirements, the following command-response conditions have been used for actuator servo system concept design:

a. Step command up to 3 degrees.

b. Ramp command at 0.75 deg/sec.

c. Ramp command at 0.25 deg/sec.

These criteria apply commanding both from an initial null position and from a 3-degree position returning to the null position (References 5 and 6). Intermediate conditions occur for the step and ramp commands initiated from the allocated thrust misalignment amplitude of 1.5 degrees. Since the actuators are energized during normal engine operation (Reference 7), a minimum cumulative life of 10 hours is required (Reference 2). In one limiting case, duty life cycle conditions are to be considered for amplitudes varying from threshold to 3 degrees. The distribution of amplitude versus number of cycles remains to be determined. In another limiting case the actuator must hold a static position representing the

---

(1) Equivalent gimbal actuator (GA) linear rate is 0.33 in./sec.
thrust misalignment correction function. Although the cumulative life is 10 hours, any single test will not exceed 60 minutes.\(^{(1)}\)

In the course of performing the static and dynamic position requirements during engine operations, the GA's are energized to oppose moments which react across the gimbal plane. The two GA's and gimbal pivot, together, provide a moment couple about any angular vector relative to the pitch and yaw axes. Mechanical loads result from:

a. Engine mass moment of inertia about the gimbal center,
b. An inertia moment of the gimbaled engine based on angular acceleration about the vehicle center of gravity,
c. Spring rates for the gimbal pivot assembly, lines that cross the gimbal plane and the electrical wiring harness,
d. Thrust misalignment about the gimbal center, and
e. Static unbalances about the gimbal center such as due to single turbopump operation.

Item a. applies to dynamic conditions only and is a dominant factor at the null position. Items b. and c. apply to both static and dynamic conditions. In flight, Item b. is a back-driving load tending to produce an unstable condition and is linear with the magnitude of thrust misalignment about the vehicle center of gravity. Based on presently assumed A-L-M vehicle properties (Reference 7), this loading is dominant at the greater gimbal amplitudes. Items d. and e. are dependent upon engine operating conditions, rather than the gimbaling position.

The actuators must be able to satisfy both the manned (with an engine external shield) and unmanned (without an engine external shield) nuclear stage loading conditions within their respective nuclear induced radiation and

\(^{(1)}\) Represents design operating time associated with 300,000 lb hydrogen capacity nuclear stage.
thermal environments. Thermal loads due to differential expansion (or contraction) between the gimbal loop and engine lines crossing the gimbal plane will occur during the engine firings. The magnitude of this loading is time variant relative to the duration and thrust level of the engine firing and thermal environmental factors. An additional environment during TVC operations occurs as the result of engine induced vibration. The amplitude magnitude and frequency distribution environment for the gimbal system will depend upon the source excitation and the means of transmission from the source to the TVC components. Some likely sources are the turbopump and nozzle exhaust.

Maximum amplitude and decelerating capability are two flight safety requirements placed upon the gimbal system. The maximum gimbaling amplitude is controlled by the mechanical stops within the actuators which restrict the extend or retract stroke. Since the restriction occurs only in the two orthogonal axes, the maximum thrust vector gimbaling pattern is shown as a square (Figure 3). In the plane of the actuators a maximum gimbaling amplitude of ± 4 degrees (± 1.70 inches actuator stroke) has been specified to account for response overshoot beyond 3 degrees and for snubber displacement (Reference 5). At 45 degrees to the actuator axes it is then possible to have a maximum gimbaled amplitude of ± 5.66 degrees.

With respect to the deceleration design condition, a conventional practice is to use snubbers, which in most cases are non-linear springs similar to Belleville washers. Present requirements specify contact with the snubber nominally at an actuator amplitude of ± 1.57 inches (Reference 8). A nominal spring displacement of 0.11 inch provides a gimbaling amplitude of about 0.25 degrees. In a recent preliminary design analysis (Reference 9), it was found that additional displacement was needed to preclude undue impact loading
which exceeds the 30,000 lb structural limit of the actuator(1). A linear snubbing amplitude of about 0.22 inches (0.50 degrees of gimbaling motion) has been estimated to absorb the kinetic energy based on an actuator linear velocity of about 1.10 in./sec (2.5 deg/sec)(2).

2. Verification Test Program

The verification program for the NERVA engine, including lower tiers for the gimbal system and gimbal actuator, is covered by the NERVA Verification Plan (Reference 10). Discussion on non-firing TVC verification of response requirements is presented in Appendix B.

The NERVA engine ground testing program presently consists of three series: Development (DE-1 and 2), Preliminary Qualification (PQE-1 and 2), and Qualification (QE-1, 2, and 3). Each Series represents an increased phase of the engine verification. Both "gimbaled" and "non-gimbaled" engines will be tested. The "gimbaled" engine uses a nozzle configuration with an exit area ratio ($e$) of 24:1 (exit plane for the cryogenically cooled nozzle). These engine assemblies are used when TVC demonstration is scheduled to occur during some of the experimental plan (EP) test runs. For the "non-gimbaled" engines, two nozzle area ratios are being considered. For the normal ground test configuration, a short graphite extension is attached to the nozzle flange for the purpose of demonstrating the integrity of the nozzle to extension joint. The exit area ratio is close to 29:1 (60.0-inch inside diameter). A tentative plan is to test one engine with the 100:1 area ratio flight nozzle extension. Gimbaling operations are not planned during these ground firings (29:1 and 100:1) due to facility operational and safety limitations.

(1) Criteria for the GA concept ANSC Dwg. 1138420B, which is shown on the engine layout, ANSC Dwg. 1137300C.

(2) The analytical model was based on a 3-degree saturated (step) command in which the operating electrical channel failed at the time of achieving linear amplifier control (maximum velocity). Contact with and depression of the snubber was assumed to occur prior to completion of malfunction detection and electrical channel switching process.
During the tests of the "gimbaled" engines, EP's will be conducted both with and without the external nuclear radiation shield to simulate loads and environment conditions for the two cases. As specified in the verification portion of the engine specification, a nozzle extension inertia simulator is to be installed to compensate for the lack of a nozzle extension from 24:1 to 100:1. A comparison of mass properties for the flight and ground test (assuming no inertia simulator) configurations of the engine, with and without an external shield, are shown in Table 1.

3. Engine to Facility Interfaces

The engine/facility interface dimensional control is provided by ANSC Dwg. 1137421. A schematic arrangement is presented in Figure 4 to show the inter-relationships which are associated with gimbaling the engine. These are the interfaces with the test stand adapter, the test stand intermediate shield, and the NERVA Altitude Simulation System (NASS) exhaust duct.

a. Test Stand Adapter

The function of this interface is to provide a means of structural support for the engine and to transmit thrust and inertia forces and moments which may occur while the engine is installed within the test facility. As it applies to the scope of this study, the stiffness simulation of the nuclear stage interface affects load distribution at the engine/adapter interface, in particular at the actuator/UTS support. Variance in the compliance characteristics may affect the TVC response results. Due to facility space limitations in ETS-1, stiffness simulation is considered less likely to occur compared to the capability planned for E/STS-2.

b. Intermediate Facility Shield

The function of the intermediate facility shield in ETS-1 and E/STS-2 is to minimize radiation streaming to engine components forward
of the engine inner shield. Component heating results from radiation streaming. As shown in Figure 5, interface dimensions remain to be determined. Recent radiation shielding analysis locates the bottom of this facility shield in-plane with the bottom of the engine inner nuclear radiation shield (Reference 12). Tentatively a 2-inch gap is being planned between the engine and the shield to allow for lateral displacement due to engine installation misalignment, engine structural dynamics during firing and the currently allocated ± 1/2 degree gimbaling motion.

c. NASS Exhaust Duct

The function of the duct during engine ground tests at ETS-1 and E/STS-2 is to provide safe disposal of the hydrogen gas, exclusion of air in the Engine Test Compartment (ETC) and limited space altitude (vacuum) simulation. Primary performance characteristics for the duct, when installed in ETS-1, are presented in Reference 13.

Based on a NASS guideline provided by SNPO-N, the inlet diameter of the primary ejector is to be 64 inches to permit testing of a 60.0-inch inside diameter (approximately 29:1 area ratio) nozzle with no gimbaling nor misalignment (Reference 14). With the use of a longer collar, testing of a 24:1 area ratio nozzle with plus or minus one-half degree of engine gimbal movement from the nominal centerline would be permitted.

The interfaces between the engine and the duct, as presently defined, are shown in Figure 6. Although lateral alignment on the engine/test facility interface drawing tolerances remain to be determined, the duct design has proceeded on a criteria assumption of a zero engine-to-primary ejector centerline misalignment during all phases of engine operation (Reference 13). Basis for this assumption was that satisfactory duct performance could only be assured when the nozzle exhaust was directed concentric with the duct opening.
C. RESTRICTIONS

1. Programmatic and Schedular

Engine power series shall be as shown on NRTO Milestone Network dated 10-27-70. Power start dates for ETS-1 and E/STS-2 which establish initial readiness constraints are:

ETS-1 DE-1 Jan 1975 $\epsilon = 29:1$

E/STS-2 PQE-2 Apr 1977 $\epsilon = 100:1$

The initial gimbaled engine shall be considered as DE-2. In event the PQE-2 assembly does not use the flight nozzle extension, use of a 24:1 area ratio configuration will be considered for E/STS-2.

NASS exhaust duct activity schedules for both ETS-1 and E/STS-2 shall be as shown on the Engine/Stage Testing Complex Program IB network, dated 9-22-70, prepared under the direction of SNPO-N*. To meet the ETS-1 readiness data consistent with the above DE-1 power start date, a critical path is shown on the network for the duct activity: A summary of major ETS-1 duct milestone events are:

- NASS Final Design Review (FDR) Feb 1971
- Start NASS Procurement and Fab Apr 1971
- Duct Beneficial Occupancy Date (BOD) Jan 1973
- Complete NASS Qual Tests Nov 1973
- ETS-1 Ready for DE-1 Nov 1974

Any change in the inlet diameter from the present 64-inch design criteria is anticipated to delay about one year the availability of the duct for engine firing. Previous duct experience has shown that a certain ratio of inlet diameter to primary ejector throat diameter must be maintained for maximum efficiency of duct

* NASS duct activity time spans are not under ANSC control.
operation. Additional redesign and scale model testing would be required for an inlet diameter change. A summary of major milestone events for the E/STS-2 flight duct are:

- Start Procurement: Oct 1973
- Complete Installation: Mar 1975
- Complete FNTF Qual Tests: Jul 1975
- E/STS-2 Ready for PQE-2: Jun 1976

Slack time is shown from engine PDR to start of preliminary design. The start power test for PQE-2 is shown about 8 months early on the IB program network compared to the NRTO milestone network.

The configuration of the NASS duct installed in ETS-1 for DE-1 will remain throughout the NERVA engine ground firings. As presently planned, E/STS-2 will initially have a flight area ratio-type duct. Upon completion of the PQE-2 power test series, the E/STS-2 flight system duct will be removed and replaced with another capable of accepting a gimbaled engine with a 24:1 area ratio nozzle.

2. Assumptions

This study initially assumes a zero misalignment criterion between the nozzle thrust vector and the duct inlet centerline during non-gimbaling operations. The magnitude of thrust vector lateral offset due to static compliance, mechanical misalignment, thermal deformation and gas dynamics uncertainties remain to be determined (1).

The shape of the exhaust plume between the nozzle exit plane and the duct inlet plane shall be assumed to fall between the two following projections:

(1) A related study is in process to investigate these unknown quantities.
1. In the radial direction of gimbaling, the gas exhaust remains within the projection of the nozzle exit plane diameter extended perpendicular to the exit plane (Figure 7a).

2. In the radial direction of gimbaling, the gas exhaust remains within the projection of the cone angle of the nozzle exit plane extended from the exit plane (Figure 7b).

Basis for the first is the tendency for the nozzle plume to stay within the duct. The second assumption is based on a more conservative spill-over safety criterion. The shape of the exhaust plume is an unknown quantity when the thrust vector is offset. It is considered to be influenced by the combination of back pressure and position of the thrust vector relative to the duct opening.

It is assumed that the design criteria for the E/STS-2 facility provides for simulation of the nuclear stage stiffness characteristics at the engine/stage interface (Station zero).

D. PARAMETERS FOR EVALUATION

As related to the scope of this report, the tradeoff parameters are associated either with TVC function verification requirements or verification capability constraints. On the one hand, known performance and reliability requirements represent the former. Growth potential/flexibility for increased requirements and uncertainties also falls into this category. On the other hand, cost and schedule represent constraint conditions. Assumed safety criteria provide a means of comparing needed capability for verification versus available capability for a particular constraint. Maintainability, a parameter often

(1) As provided in the Project 224 Work Statement for Contract Year 1971, scale model duct testing is to be initiated to investigate this problem. An offset of 1/2-degree, representing the allowed gimbal angle, has been tentatively selected.
considered in these trade study reports, was found to be an insensitive parameter within the report scope.
IV. TECHNICAL DISCUSSION

A. AVAILABLE OPTIONS

The following options apply to TVC response verification engine ground testing. The options may be categorized into two groups: (a) ground firing verification goals related to TVC response requirements (para. III.B.1) and (b) test stand facilities planned to be available for ground firing a "gimbaled" engine. Each of the verification goals represents a maximum capability as controlled by the actuator stroke limit. The goals are shown in a descending order from the full flight actuator stroke to some minimal stroke.

1. Ground Firing Verification Goals
   a. Demonstrate all position control and life cycle requirements (flight system)
   b. Demonstrate response to design rate command (0.75 deg/sec)
   c. Demonstrate response to an intermediate rate command (0.50 deg/sec)
   d. Demonstrate response to engine minimum rate command (0.25 deg/sec)
   e. Demonstrate null position hold (zero response).

2. Test Stand Facilities and Variations
   a. ETS-1 configured for 24:1 and 29:1 area ratios
   b. E/STS-2 configured for 24:1 and 29:1 area ratios
   c. E/STS-2 configured for 100:1 and 24:1 area ratios.

During the investigation for this study the command rate of 0.50 deg/sec was found to be a satisfactory compromise for response quality and minimum stroke requirements when comparing the design and minimum rates.
B. CRITERIA

An ideal verification test series to demonstrate the engine thrust vector position control capabilities under simulated flight operative conditions would include:

1. Proper stiffness, mass properties and structural connection characteristics representative of the engine and of components crossing the gimbal plane,
2. Proper stiffness representation of the stage/engine interface,
3. Applied mechanical design loads for the flight case consistent with gimbaled amplitude,
4. Cryogenically applied thermal loadings, and
5. Operating environment for induced vibration, induced nuclear radiation and thermal conditions.

Due to the complex nature of items 4 and 5, the ground test firing provides the best "ground oriented" means of combining these conditions with TVC response tests.

Due to the severity of the cost constraint, a compromise of TVC verification test conditions during ground testing was clearly indicated early in the study. A problem arose as to what forms an acceptable criterion for evaluating the TVC function while these engine operating conditions were occurring. A solution is to conduct a standardized time response test common to all TVC oriented verification tests. The response test can be used to interpret change in characteristics as a function of either condition or time. For example, the response test would be performed as a pretest and posttest checkout operation in addition to being conducted at selected periods during engine operational runs. The same test would apply to TVC function verification with non-firing engine assemblies and
gimbal actuator verification. Correlation with analytical servo model results would apply in each case.

Safety is a necessary criterion due to potential effects on the engine, on the facility and more ultimately, the engine development program. For this study it shall be considered a safety criterion that the assumed exhaust plume (cylindrical and conic) remains within the NASS duct opening. Also, undue contact impact loads of unpredictable magnitude are considered to be a hazard condition and should be avoided.

C. METHOD OF EVALUATION

A quantitative approach was used in discussing each of the trade parameters whenever technical status permitted. In some cases the data are preliminary as the analyses were based on simplified analytical models. In a number of other instances a subjective approach was found necessary since analytical effort was premature at this stage of the actuator program.

The evaluation was conducted for the various options using the parameters listed in para. III.D. Discussion for each parameter is presented within the following scope.

1. Performance
   a. Actuator stroke limits related to a specific verification goal.
   b. Effect of actuator stroke limits on verification quality.
   c. Effect of test facility constraints on verification quality.
2. Reliability
   a. Effect of stroke limits on providing actuator data in support of design reliability analysis.
   b. Effect of stroke limits on developing TVC trend data analysis parameters for flight.

3. Safety
   a. Identify safety hazards to the engine and facility resulting from engine gimbaling.
   b. Discuss safety precautions.
   c. Relate to constraints on gimbaling amplitude.

4. Growth Potential/Flexibility
   a. Effect of changing TVC requirements on verification.
   b. Contingency to account for preliminary nature of estimates.

5. Cost
   a. Facility delta costs for duct size increase from present criteria.

6. Schedule
   a. Effect of duct size change on availability of ETS-1 and E/STS-2 for initial power tests.

D. EVALUATION RESULTS

1. Performance
   a. Actuator Stroke Related to Goal Option
      Using source data presented in Appendix C as a guide, preliminary estimates for the undisturbed gimbal amplitude\(^{(1)}\) for each of the

\(^{(1)}\) The "snubbing" amplitude must be added to this amplitude to obtain the total gimbal amplitude about either the pitch or yaw axis. See discussion under "Safety".
verification goal options listed in para. IV.A.1 have been made. The values represent requirements for single actuator response about either the pitch or yaw axis.

<table>
<thead>
<tr>
<th>GOAL OPTION</th>
<th>GIMBAL AMPLITUDE&lt;sup&gt;(1)&lt;/sup&gt;</th>
<th>EQUIVALENT GA LINEAR STROKE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight System</td>
<td>± 3.5 degrees</td>
<td>± 1.53 inches</td>
</tr>
<tr>
<td>0.75 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>± 0.93</td>
<td>± 0.41</td>
</tr>
<tr>
<td>Min Accept</td>
<td>± 0.70</td>
<td>± 0.31</td>
</tr>
<tr>
<td>0.50 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>± 0.60</td>
<td>± 0.27</td>
</tr>
<tr>
<td>Min Accept</td>
<td>± 0.45</td>
<td>± 0.20</td>
</tr>
<tr>
<td>0.25 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>± 0.33</td>
<td>± 0.15</td>
</tr>
<tr>
<td>Min Accept</td>
<td>± 0.25</td>
<td>± 0.11</td>
</tr>
<tr>
<td>&quot;No Response&quot;</td>
<td>≤ (+ 0.25)</td>
<td>≤ (+ 0.11)</td>
</tr>
</tbody>
</table>

For the rate command options two cases are provided to represent both a "target" capability (Case 1) and a "minimum acceptable" capability (Case 2). For Case 1 stroke is provided for take-up in the system at the initiation of the command, an acceleration ramp, some rate overshoot, a period to settle at and maintain a "rate steady state error". Case 2 is the same as Case 1 up to maintaining the steady rate. The difference represents about 30 percent in stroke requirements.

The estimate for the "Flight System" option represents the use of the flight actuators. The estimates for the rate options were based on simplified GA servo analyses using data parameters representing GA concepts.

<sup>(1)</sup>The maximum gimbal amplitude based on vector sum of both actuators operating is discussed under "Safety".

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1138345 and 1138420 for the ground test cases. A summary analysis for these estimates, including position and rate versus time response curves, is shown in Appendix C. It should be noted that some uncertainties exist due to the analysis assumptions and subsequent engine load changes. These uncertainties could be reduced by upgrading the analysis to include:

(1) Incorporate engine compliance into the servo model system equations.

(2) Update to latest engine loads.

(3) Inclusion of the flight engine thrust misalignment loads into the motor drive horsepower requirement\(^{(1)}\).

b. Verification Limits Related to Gimbaling Amplitude Limits

The engine TVC requirement verification capability as a function of the gimbaling amplitude limits determined for each goal option are presented in Table 2. Although the Flight System option presents no amplitude limitations relative to verification during the ground firing, it will be shown later that the cost of providing a NASS exhaust duct capability for the + 4 degrees of maximum gimbaling amplitude\(^{(2)}\) is difficult to justify. A similar problem occurred during the altitude qualification testing of the Apollo SPS engine at the Arnold Flight Test Center, Tullahoma, Tennessee (Reference 15). In this case, a precedence for demonstrating gimbaling response to the specification ramp command was provided. The Apollo gimbal actuators are also electromechanical in design, and were man-rated qualified for space flight. Increased confidence in the gimbaling system was gained as a result of performing control dynamic response tests under the combined

\(^{(1)}\) Misalignment loading is presently under investigation in a separate study.

\(^{(2)}\) Includes amplitude for overtravel, position error and snubbing (para. III.B.1).
conditions of an actual flight engine hardware and an induced engine operating environment.

For rate demonstration the "Target" case capability is preferred since rate stability is defined. In achieving this boundary condition interpretation of the data and correlation with analytical model results is made easier. It also provides some contingency for uncertainties in response prediction, non-linearities and variations between engine gimbal systems. As a fallback position, the "Minimum Acceptable" case capability provides for checking the acceleration ramp and the "rate overshoot" and approximating the "steady-state rate error".

The limits for these two cases were based on performing the response tests by one of the two techniques. For a rate command initiated from the null position "steady-state rate error" is considered to occur just prior to contact with the snubber (Figure 8). Both the servo motor and the snubber are used to decelerate the engine mass. Position feedback from the actuator is provided to the command system so that the rate input can be changed at the approximate snubber contact amplitude. To reduce the quantity of deceleration "g's" on the engine, a saw-tooth position command can be given whereby the engine gimbals from side-to-side without hitting the snubbers. A square wave position command technique could provide a similar gimbaling rate with less stroke requirement; however, this presents a non-linear saturated amplifier operating condition. Within the present design intent, the rate requirements discussed in this study are considered to occur under linear amplifier control to the specified ramp.

The quality of response verification is considered better with the higher rates. With larger amplitudes, the magnitude of data values should provide for better accuracy in estimating response characteristics. Also, system threshold about null would be less sensitive. As indicated by the rate response curves in Appendix C, definition of the acceleration ramp improves with
increased rate. Since the minimum rate for the flight engine is 0.25 deg/sec, it is felt that this rate should also represent the minimum acceptable rate response capability for verification during engine ground testing.

The "no response" option is considered unacceptable since dynamic response characteristics would remain unknown both during the runs and between runs during the system checkouts. It does provide feedback on the actuators' ability to hold a null position under misalignment and unbalanced moments in the engine induced environment. As will be discussed under "reliability", the trend data analysis method is reduced severely in capability with this option.

c. Test Stand Facility

The stage/engine interface, loads and environmental simulation as a function of test stand facility is presented in Table 3. The effect of test facility option simulation on TVC verification is the same for all test characteristics excepting the stage/engine interface.

2. Reliability

a. Support of Reliability Design Analyses

Since the engine induced environmental and thermal load conditions are coupled with the TVC functional response tests, this "new" data will help evaluate the failure modes established by the failure modes analysis (FMA) and will add confidence to the reliability design analyses. By "new" it is implied that this data is not available from earlier gimbal actuator and non-firing engine TVC response tests. Only by these tests will this information be gained. As for all NERVA engine components, the gimbal system reliability allocation\(^{(1)}\) is high compared to similar systems of earlier rocket engines. Data accuracy is necessary to minimize variances which tend to impede confidence gain in the design capability. Although a

\(^{(1)}\) The TVC reliability allocation is presently 0.999984 as shown in the gimbal system specification (Reference 5).
quantitative analysis on the variance effect is not presented, it is felt that the
greater rate capability would provide a more beneficial effect on this parameter.

b. Trend Data Analysis

A capability to analyze gimbal system trends during the
power test phase of ground tests serves two purposes. It provides feedback of
potential undesirable or hazardous conditions during ground test operations. Both
cases during power tests and checkouts would be considered. If deemed necessary,
alternate courses of action may then be taken. It also provides a training phase
for developing a realistic flight trend data system relative to the TVC function.
In this latter case, the ground testing experience would supplement the non-firing
test analysis training gained for large amplitude TVC requirements.

To be an effective part in the engine trend data analysis
development, the gimbal actuators require sufficient stroke capability during
ground firings to result in a meaningful dynamic response. This applies to evalua-
tions conducted both during the firing and during the pre-test and post-test check-
outs. The standardized rate response test previously specified (para. IV.B) should
be of sufficient magnitude that parameter measurements will indicate any degradation
trends in time response or parameter ratio characteristics. Although the definition
of the engine trend data analysis system is undergoing study, it would seem
that several levels of trend significance should be determined: (1) warning of
a potential problem, (2) level at which the crew (or operational personnel) may
option an alternate course of action, and (3) level at which automatic change
occurs. Preliminary GA parameter measurements for trend data analysis are presented
in Table 4. Upon concept selection and power optimization of the GA servo system,
a detailed analysis of interpreting these trend parameters (or parameter ratios)
will be warranted. One case can be illustrated comparing motor current and
acceleration for different rate responses.
As presented in Appendix C, ground firing rate response cases were conducted for a d.c. torque motor GA servo system. Based on a motor maximum current capability of about 51.5 amps for this concept, the following maximum operating currents were shown for each rate response. The associated angular acceleration which occurred coincidently is also provided.

<table>
<thead>
<tr>
<th>RATE</th>
<th>MAX ACCELERATION</th>
<th>MAX OPERATING CURRENT</th>
<th>RATIO TO PEAK MOTOR CURRENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 deg/sec</td>
<td>0.84 deg/sec^2</td>
<td>2.89 amps</td>
<td>5.6%</td>
</tr>
<tr>
<td>0.50</td>
<td>1.67</td>
<td>5.77</td>
<td>11.2</td>
</tr>
<tr>
<td>0.75</td>
<td>2.51</td>
<td>8.67</td>
<td>16.8</td>
</tr>
</tbody>
</table>

It is readily seen that the greater rate response tests provide more significant parameters for comparing characteristic changes during the power test series.

3. Safety

Consideration must be provided to the following potential problems associated with TVC during engine ground testing:

(a) GA failure
(b) Overtravel deceleration impact loads
(c) Intermediate facility shield contact loads
(d) Nozzle exhaust plume exceeding NASS exhaust duct inlet diameter.

The assumed safety criteria were previously presented in para. IV.B.

a. GA Failure

The two failure modes which would produce a potential safety hazard during the ground power tests are:

(1) Inability to transmit load, and
(2) Loss of position control.
The effect produced by one of the above failure modes would be a thrust vector location based on the rotation with respect to the gimbal center from the following moment equilibrium balance:

\[ I\ddot{\theta} + W\dot{\theta} + K\theta - M = 0 \]

where
- \( I \) = mass moment of inertia of the gimbaled engine about the gimbal center
- \( W \) = weight of the gimbaled engine
- \( \varepsilon \) = distance between gimbal center and c.g. of the gimbaled engine
- \( K \) = composite spring rate of the gimbal pivot assembly, lines and electrical harness resisting the engine gimbal rotation
- \( M \) = moment due to thrust misalignment and other unbalanced forces
- \( \theta \) = amplitude of engine gimbal rotation

In most cases, the extreme limits of angular motion would be represented by the included angle between the actuator mechanical stops. For failures between the internal stops and actuator/thrust structure interfaces (i.e., part of the housing or rod end bearings) the upper limit would be controlled by the equilibrium balance. For nozzle-down firing in ETS-1 and E/STS-2, gravity provides a strong stabilizing condition.

Considering the present engine layout GA concept, ANSC 1138420, certain failure mechanisms within the mechanical portion of the assembly contribute to these two modes. Since the electrical system has redundant features, switching from the operating channel to the standby channel can be commanded upon
detection, evaluation and energizing. For failure mode (1) (i.e., inability to transmit load) the cause would most likely be the result of a stress failure. However, the estimated operating loads of the ground engine reduced stroke actuators will be less than for flight (0 - 5000 lbs range compared with 0 - 12,000 lbs, respectively). The structural limit design load is 30,000 lbs based on motor maximum stall (peak) torque. Only under the following situations during ground firing would the loading normally come close to this limit:

(1) For about 10-20 milliseconds during the startup of a saturated (step) command,

(2) Stall of the operating motor, and

(3) Full speed deceleration into the snubbers.

It is assumed that condition (2) would occur only momentarily due to detection by the malfunction and detection system and switching to the standby channel. (Note: Since full amplitude is achieved within one (1) sec, the detection and switching system must be automatic. A manual over-ride capability is optional). The loading of Item (3) would be dependent on the combination of a saturated command, an operating channel servo failure occurrence at the maximum gimbaling velocity and the design of the snubbers.

In addition to the above failure cause, the "loss of position control" failure mode could occur as a result of excessive binding within the bearings or transmission. A possible cause would be the result of inexact predictably temperature gradients on the close tolerance parts or an obstruction caused by some foreign object. The thrust vector would be retained in a fixed position resulting from these latter causes. The actuator electrical system was not considered a possible source due to the standby channel redundancy. It does
assume, as in the flight case, that the command-control systems and power supplies for the two channels of each actuator be independent of one another, such that failure of one will not contribute to the failure of the other.

An inability to transmit load during actuator operation is considered as very unlikely due to:

(1) High margins of safety during ground test operations,
(2) Thorough structural and operational component test program including margin testing prior to DE-2, and
(3) Proof test demonstration as part of the hardware component acceptance.

As an additional precautionary measure, it is suggested that those factors which contribute to the moment "M" be controlled such that the exhaust for angle $\Theta$ is maintained within the duct safety limits (para. IV.B). At present, the possible temperature conditions in the test stand are undefined and, therefore, the severity of this potential problem can not be evaluated. Use of thermocouples should be considered for diagnostics on these tests. Also, an actuator design alternate for ground testing should be considered which will permit both de-activating the actuators and retaining the capability to transmit load at a fixed command position. An electro-mechanical locking device is suggested. A more thorough discussion on failure mode analysis and redundancy of the GA is presented in Trade Study Report S054-031 (Reference 18).

b. Impact from Deceleration Conditions

For reasons of simplicity and predictability, the primary means of providing mechanical deceleration resulting from overtravel should be with snubbers located in the actuators. This conventional method has
been selected for use on the flight engine gimbal actuators. As shown in Figure 10, the snubbers are located between the ball screw shaft and the mechanical stops. The speed of the shaft is reduced based on a balance of the kinetic energy of the moving mass, any external work done during the spring displacement, and the potential energy of the snubber. The potential energy is a function of the spring geometry and the material selection. A typical load displacement curve showing the 30,000 lb load limit is presented in Figure 11. Based on a criterion similar to the flight case (para. III.B.1), the preliminary estimates for actuator snubbing amplitude are presented below corresponding to the TVC stroke amplitudes shown for the goal options listed in para. IV.D.1. A single equivalent GA linear stroke is shown for the rate target and minimum acceptable cases due to the effect of numerical rounding. A summary of individual TVC and snubbing gimbal amplitudes are shown in Table 5. Amplitudes for both in-plane-of, and midway between, the pitch and yaw axes are considered. A summary of equivalent actuator linear stroke as related to these goal options is shown in Table 6.

<table>
<thead>
<tr>
<th>GOAL OPTION(1)</th>
<th>GIMBAL AMPLITUDE(2)</th>
<th>EQUIVALENT GA LINEAR STROKE(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight System</td>
<td>± 0.50 degrees</td>
<td>± 0.22 inches</td>
</tr>
<tr>
<td>0.75 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>± 0.35</td>
<td></td>
</tr>
<tr>
<td>Min Accept</td>
<td>± 0.33</td>
<td>± 0.15</td>
</tr>
<tr>
<td>0.50 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>± 0.32</td>
<td></td>
</tr>
<tr>
<td>Min Accept</td>
<td>± 0.31</td>
<td>± 0.14</td>
</tr>
<tr>
<td>0.25 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>± 0.29</td>
<td></td>
</tr>
<tr>
<td>Min Accept</td>
<td>± 0.27</td>
<td>± 0.12</td>
</tr>
<tr>
<td>&quot;No Response&quot;</td>
<td>≤ (+ 0.27)</td>
<td>≤ (+ 0.12)</td>
</tr>
</tbody>
</table>

(1) See para. IV.D.1 for discussion on "target" and "minimum acceptable" terms.
(2) Based on summary analysis in Appendix D.
c. Contact With the Intermediate Shield

During gimbaling the engine moves laterally toward the intermediate facility shield. A plot of the displacement both in-the-plane of and midway between the two actuator axes as a function of gimbal amplitude is shown in Figure 12. The displacements were based on an engine inner shield aft plane considered at Station 122.28 (para. III.B.3.b). Adequate clearance within the tentative 2-inch gap allowance is provided for target and minimum acceptable cases for this 0.25 deg/sec rate goal option. Contact is indicated for the 0.50 deg/sec rate goal option if both actuators are commanded hardover to the mechanical stops. The flight system option requires gaps of 6.92 and 9.80 inches for in-the-plane of and midway between the actuators, respectively, for hardover conditions.

Contact between the rigid intermediate shield and the engine would introduce impact loads of unpredictable magnitudes. For this reason, any such contact should be avoided. For a given gimbal lateral displacement, some gap allowance is required; however, some radiation streaming does occur causing higher heating rates for engine components in the forward area. Predicted gamma dose rates for various engine locations forward of the shield are shown in Tables 7 and 8 for zero and 24-inch gaps, respectively. The former represents a simplified theoretical optimum, and the latter represents the case where no intermediate shield is installed. The increase in gamma heating for the 24-inch gap is shown to be 2 to 3 times that for the assumed zero gap. Although intermediate gap data points are not available, the gap requirement for flight system gimbal amplitude simulation is considered unacceptable from a radiation streaming condition. To allow full gimbaling motion in any direction for the 0.50 deg/sec and the 0.75 deg/sec rate options, the gap dimension should be a minimum of about 3 and 4 inches, respectively. It is felt that the increase in radiation
level for the additional inch or two gap should be tolerable. For confirmation, in any case, a nuclear analysis for this gap should be conducted for whatever gap size is selected.

d. Position of the Nozzle Exit Plane Relative to the NASS Duct

During gimbaling the nozzle exit plane moves laterally with respect to the NASS exhaust duct inlet. Estimated lateral displacements of the thrust vector at the nozzle exit plane and the duct opening, located 4.5 inches further aft, are presented in Table 9. Further estimates have been made based on the assumed cylindrical and conic expansion shaped plumes (para. III.C.2) for the outermost location at the duct opening plane (Table 12). The data in both tables are presented for the cases in-the-plane of and midway between the actuators.

Based on the assumed safety criteria of retaining the exhaust projections within the duct opening, safe-unsafe conditions have been determined for the planned 64-inch diameter duct in ETS-1 as related to goal options(1). If the vector sum is restricted to a circular pattern related to the in-the-plane gimbal amplitude, the results for the two exhaust projections are:

<table>
<thead>
<tr>
<th>GOAL OPTION</th>
<th>SAFE-UNSAFE CONDITION</th>
<th>ASSUMED CYLINDER PROJECTION</th>
<th>ASSUMED CONE PROJECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight System</td>
<td>unsafe</td>
<td>unsafe</td>
<td></td>
</tr>
<tr>
<td>0.75 deg/sec rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>unsafe</td>
<td>unsafe</td>
<td></td>
</tr>
<tr>
<td>Min Accept</td>
<td>safe</td>
<td>unsafe</td>
<td></td>
</tr>
<tr>
<td>0.50 deg/sec rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>safe</td>
<td>unsafe</td>
<td></td>
</tr>
<tr>
<td>Min Accept</td>
<td>safe</td>
<td>unsafe</td>
<td></td>
</tr>
<tr>
<td>0.25 deg/sec rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>safe</td>
<td>safe</td>
<td></td>
</tr>
<tr>
<td>Min Accept</td>
<td>safe</td>
<td>safe</td>
<td></td>
</tr>
</tbody>
</table>

(1) Lateral displacements resulting from thrust vector misalignment due to non-gimbaling causes has been neglected.
It shows that the 0.25 deg/sec rate goal option is safe for each of the considerations. At the higher rates, the safety condition is sensitive to the assumed conditions.

If the vector sum is allowed to be unrestricted, the resultant pattern is a square pattern and is related to the data midway between the actuators:

<table>
<thead>
<tr>
<th>GOAL OPTION</th>
<th>SAFE-UNSAFE CONDITION</th>
<th>ASSUMED CYLINDER PROJECTION</th>
<th>ASSUMED CONE PROJECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight System</td>
<td>unsafe</td>
<td>unsafe</td>
<td></td>
</tr>
<tr>
<td>0.75 deg/sec rate</td>
<td>unsafe</td>
<td>unsafe</td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>unsafe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min Accept</td>
<td>unsafe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50 deg/sec rate</td>
<td>unsafe</td>
<td>unsafe</td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>unsafe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min Accept</td>
<td>safe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25 deg/sec rate</td>
<td>safe</td>
<td>unsafe</td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td>safe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min Accept</td>
<td>safe</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As can be seen, none of the goals can be met for the cone projection assumption. A limited capability is shown for the cylinder projection assumption.

As related to the goal options, lateral displacements available for non-gimbaling thrust vector misalignment with the 64-inch duct centerline have been determined (Table 11). The data generated are based on the assumed safety criteria and the exhaust projection data presented in Table 10. Within the planned duct inlet diameter constraint, the upper limit for this allowance is 2.52 inches. This limit is based on a cylinder exhaust projection for the "minimum acceptable" case at the minimum gimbaling rate of 0.25 deg/sec and with the gimbaling amplitude restricted to a circular vector sum pattern. This allowance diminishes to zero as influenced by either increased goal option rates or the analysis assumptions.
Possible means of restricting the engine gimbaling motion to a circular pattern are: 1) the use of safety devices in the facility command electronic system, and 2) the use of secondary mechanical snubbers located for contact at other points of the engine. Since this topic is a study within itself, discussion will pertain to presenting some considerations with each approach.

Electronic control can be provided by a combination of key control and logic circuitry within the command system. Key control has been previously used on the NERVA technology engine to activate the control drum actuator. As an example method for the gimbal system, a three-key approach could be used: one for each actuator (A and B) and the third (C) for vector sums limiting control. With the keys inserted only the null position command is provided. For full stroke gimbaling in the plane of an actuator, a single key is removed to allow the command position voltage to increase. If both keys A and B are coincidently removed, the interlocking system would automatically command a null position for both actuators until the key control was corrected. For vector sum gimbaling removal of the third key would limit the command position voltage to .707 of full stroke range for each actuator. In this manner, the circular pattern is not violated. Redundant position feedback is provided within the actuator for visual (CRT or osillographic) and automatic diagnostics analysis.

The secondary snubbers operate on the same principle of spring displacement as the actuator snubbers. Some possible locations are at the intermediate facility shield for radial contact and across the gimbal plane in the thrust structure. For the former, effects of nuclear heating on suitable contact materials and sufficient tolerance control are possible problems. For the latter, some space envelope limitations with the propellant feed system may
occur. To restrict motion mechanically within the circular pattern, contact with the secondary snubber would occur within the unrestricted TVC amplitude for single actuator operation. The external loading resulting from this secondary snubber deceleration would interfere with the rate response verification. Therefore an increase in stroke requirements would result eliminating any gain by restricting the square pattern to a circular pattern by mechanical means. If the electronic safety feature control is objectionable, it is recommended that the allowance for gimbaling within the duct be based on a square gimbaling pattern for the thrust vector.

4. Potential Growth/Flexibility

As applied to this study, test stand facility growth or flexibility is primarily intended to provide contingency for possible increase in the engine TVC requirements. Results of various nuclear stage studies on TVC requirements are presented in Table 12. Although reasonable consistency is shown for amplitude, recent contacts with MSFC at Huntsville, Alabama indicate that higher amplitudes are being evaluated. Based on discussion under "Performance", "Safety" and "Cost", full amplitude testing during engine ground firings is neither considered desirable nor feasible.

More scatter is shown for the rate requirement. The SNPO requirement presently coincides with the lowest value: 0.25 deg/sec. The LMSC rate of 0.75 deg/sec was determined for stability reasons associated with an earlier sub-orbital start requirement. The MDAC value of 0.50 deg/sec appears to provide a reasonable growth capability in rate verification.

The total actuator amplitude about either of the axes for 0.50 deg/sec ramp response and snubbing is only about 50 percent more than required for 0.25 deg/sec rate verification (Table 5). In terms of lateral
motion at the nozzle exit plane the higher rate represents an additional 1.0 to 1.25 inches of displacement in-the-plane of the actuator axis (Table 9). As shown in Figure 12, the difference in the gap requirement between the engine and the facility intermediate shield appears to be less than 1/2-inch.

As previously stated in this study, the estimates for the required gimbal amplitudes to achieve the various goals were based on simplified analytical models using preliminary loads data. For the original intent of evaluating the d.c. motor drive for the actuator servo system, the math model results were quite helpful. The extension to use it for this study may be limited; however, the math model was the best available at that time. Engine flexibility data is now available and indicates that compliance in the gimbal loop vicinity is not a negligible factor as was previously assumed in the simplified model. Engine mass properties have since been upgraded and a sizable change is shown\(^1\). A major uncertainty is the selection of the nuclear stage configuration. The configuration mass properties have a dominant influence in the actuator loads during flight TVC.

The response characteristics have been determined for a d.c. motor drive servo system which was sized to operate in a linear amplifier mode at a 0.75 deg/sec rate. Selection of this drive concept is only tentative (Reference 18). Further study has been recommended to include the a.c. induction motor and the stepping motor drive concepts. Response characteristics for these approaches are presently unknown. If motor power sizing is reduced to provide linear amplifier control up to a rate of 0.25 deg/sec rather than 0.75 deg/sec, a change in response characteristics is to be expected.

\(^{(1)}\) The recent data is presented in Table 1. The data used in the analysis is shown in Appendix C.
It is recommended that a gimbal amplitude of about ± 1 degree be allocated in the test facility to provide a contingency for rate verification growth and actuator response uncertainties. This amplitude includes the provision for snubbing. The amplitude of ± 0.92 degrees for "target" case at the 0.50 deg/sec rate is considered as the growth goal. The remainder provides additional flexibility for the actuator uncertainties. Estimated lateral motions at the intermediate facility shield (at Station 122.28) and nozzle exit plane for the ± 1 degree amplitude are ± 1.73 inches and ± 4.10 inches, respectively.

5. Cost

Cost estimates have been prepared for NASS duct inlet diameters varying with gimbal angle capability from ± 1/2 degree to ± 4 degrees (Table 13). The diameter/gimbal angle relationships shown are based on the assumed zero misalignment between the thrust vector and the duct centerline. The cost data is presented as delta costs with the "existing" 64-inch inlet diameter as the reference. Two cases are shown. In Case A the ETS-1 inlet diameter remains at 64 inches and the E/STS-2 inlet diameter is increased to allow for greater gimbal angles. In Case B both facility ducts grow in diameter according to the gimbal angle but are maintained equal in configuration with one another. A comparison of these two cases shows that there is very little cost savings in retaining the ETS-1 duct at 64 inches if the duct diameter of the second must be increased. A plot of the data in Figure 13 shows that the cost is proportionately higher for the greater gimbal angles (3 to 4 degrees).

The delta costs for these two facility options, as related to the TVC ground firing goal options, are presented in Table 14. Data are

(1) Equivalent actuator linear stroke is ± 0.44 inch.
(2) Misalignment due to "non-gimbaling" causes.
shown for both exhaust plume assumptions to indicate the sensitivity of this unknown quantity. A capability for the full flight gimbal amplitude is clearly too expensive. All rate response options can be accommodated at delta facility costs of $6 million or less based on the cylindrical plume assumption and $8 million or less based on the assumed conic expansion safety criteria\(^{(1)}\). The upper limits allow for unrestricted TVC motion resulting in a square thrust vector pattern. For the recommended $\pm 1$ degree growth gimbal amplitude the estimated delta costs are zero for the cylindrical exhaust plume and about $3 - 4$ million for the conic exhaust plume. Restriction to a circular vector sum pattern is assumed. For the same restriction assumption, no facility delta cost is incurred for either the "target" case or the "minimum acceptable" case at a rate of 0.25 deg/sec.

6. **Schedule**

Based on the NASS exhaust duct critical path and the DE-1 power test date restrictions, the ETS-1 facility option limits TVC testing to verification of the 0.25 deg/sec rate response requirement goal option. The growth rate option of 0.50 deg/sec is marginal, dependent upon the exhaust plume shape. Note also that these conclusions are contingent on the thrust vector to duct centerline zero misalignment restriction. As previously specified under the "restrictions" of this report, any increase in duct inlet diameter will effect a one-year slip in the duct readiness, which similarly affects the DE-1 power test date.

According to the IB Program Network logic, sufficient slack time is available for design and scale model testing of a larger duct size in E/STS-2 independent of nozzle extension area ratio selection for PQE-2.

\(^{(1)}\) Costs to provide allowance for thrust vector misalignment due to "non-gimbaling" causes must be added to these figures.
This approach provides additional time for the following:

a. Evaluation of duct operation and plume shape results from duct scale model tests as affected by non-concentric firing and other duct operating variables.
b. Evaluation of engine and facility characteristics as related to the zero misalignment restriction.
c. Further updating of TVC requirements from continuing MSFC and stage contractor studies.
d. Updating gimbaling ground firing verification requirements based on updated engine configuration and GA servo analytical model.

Assuming PQE-2 does have the flight nozzle extension, one additional engine, a gimballed QE engine, is programmed for this facility. In view of the ETS-1 constraints, it is considered essential that the gimbaling during qualification be as free of restrictions as possible to satisfy the verification goals in support of the TVC performance and reliability effort.
V. CONCLUSIONS AND RECOMMENDATIONS

It was concluded that gimbaling verification for the +3 degree amplitude requirement during engine ground firing was not feasible. The dominant factor was excessive cost; however, a significant increase in expected gamma heating of the components forward of the inner shield resulting from the large size gap between the engine and facility intermediate shield was also considered as undesirable.

The "no response" option was determined to be unacceptable due to an inadequate performance and reliability verification quality.

It is recommended that TVC verification during ground firing center about rate response demonstration. The acceleration requirement is demonstrated during the response ramp to follow the commanded rate. Use of a non-firing simulated or prototype inert engine assembly is recommended for those TVC requirements needing a larger gimbal amplitude.

A minimum gimbal amplitude of ±1.0 degree (actuator linear stroke of ±0.44 inch) is recommended for TVC verification during engine ground testing. This amplitude includes snubbing within the actuator as a safety provision. The gain in performance and reliability verification capability, provision for a growth capability to verify a 0.50 deg/sec rate and uncertainty of the requirement estimates were considered to outweigh the possible test facility delta costs.

A gimbal amplitude of ±1 degree can be provided with the 64-inch diameter exhaust duct inlet planned for ETS-1 if (1) the exhaust plume retains the cylindrical projection of the nozzle exit plane diameter, and (2) the gimbaling amplitude vector sum is restricted to a circular pattern. However, the allowance available for thrust vector misalignment due to non-gimbaling causes was found to be effectively zero, which is unrealistic.
If instead the nozzle exhaust plume has a projected cone shape relative to the nozzle exit plane, the duct inlet must be increased at least 2.6 inches in diameter to allow for this +1 degree amplitude. Neglecting any allowance for "non-gimbaling" influenced thrust vector misalignment, the facility delta cost was estimated at about $3 - $4 million.

Provided the gimbaling amplitude vector sum is restricted to a circular pattern, the present engine specification rate of 0.25 deg/sec can be verified with the use of the 64-inch duct opening independent of the two assumed exhaust plume projections. This rate represents the minimum acceptable dynamic response case for TVC verification during ground firing. Allowable lateral displacements for thrust vector misalignment in relation to the duct centerline for "non-gimbaling" causes were estimated to be:

<table>
<thead>
<tr>
<th>0.25 deg/sec Rate Case</th>
<th>Assumed Cylinder Projection (Table 11)</th>
<th>Assumed Cone Projection (Table 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Amplitude (+0.62 deg)</td>
<td>2.10 inches</td>
<td>0.33 inches</td>
</tr>
<tr>
<td>Minimum Acceptable Amplitude (+0.52 deg)</td>
<td>2.52</td>
<td>0.76</td>
</tr>
</tbody>
</table>

For any given rate verification, the "target" case amplitude is recommended since provision has been made in the estimate for "steady-state" rate response demonstration. The "minimum acceptable" case amplitude is intended for an exhaust duct marginal condition consideration, where some compromise in performance and reliability verification quality is accepted.

Based on a possible one year delay in duct availability, a change to the 64-inch duct inlet diameter at ETS-1 on the basis of accommodating a ±1 degree TVC amplitude capability alone is questioned. Slack time was shown to be available for completion of the related problem area studies and to provide a
larger duct size for a $\pm 1$ degree gimbal amplitude capability in E/STS-2 prior to the PQE and QE power test series.

Restriction of the gimbal amplitude vector sum to a circular path is recommended and the safety means should be provided by electronic measures within the test facility command-control electronic system. Mechanical measures to restrict the vector sum from a square pattern to a circular path based on maximum actuator stroke were found to interfere with the TVC verification. If electronic means are considered as unacceptable, the TVC gimbaling amplitude allocation must then be based on a factor $\sqrt{2}$ applied to the previously stated amplitude requirements. Neglecting any consideration for thrust vector misalignment due to "non-gimbaling" causes, a capability for minimum acceptable TVC verification with a square pattern may be marginal with the 64-inch diameter duct inlet.

For the 0.25 deg/sec rate case gimbal amplitudes, the estimated lateral displacements of the engine at the facility intermediate shield remain within the 2-inch allowable gap tentatively planned. For the recommended $\pm 1$ degree gimbal amplitude capability, an increase to about 3 inches may be necessary.
LIST OF REFERENCES


5. ANSC Detail Specification EC-90244, Gimbal Assembly Subsystem
   a. Preliminary Submittal Issue, 23 April 1970
   b. Basic Issue, 17 July 1970


14. Minutes of NASS Program Review Meeting #5, convened in Las Vegas, Nevada, on 26 November 1969 between SNPO-N and AGC-NRO.


18. ANSC Report S054-031, Gimbal Actuator Trade Study
   (to be published)

19. LMSC Report 682562, Modular Nuclear Vehicle Study Phase IV
    Final Report - NERVA Thrust Vector Control Requirements,
    17 March 1969.

20. IBM Report 69-K44-006E, Astrionic Systems Optimization and
    Modular Astrionics for NASA Missions after 1974 - Progress
    Report February 16, 1970 to April 15, 1970, Appendix B,
    5 May 1970.

21. MDAC Report G0585, Nuclear Flight System Definition Study Final
    Report, Volume II RNS System Definition, Part 2 Single Module
    Concept Definition, May 1970.

22. ANSC Memorandum 7270:0470, R. L. Murray to L. D. Johnson,
    dated 22 June 1970, Subject: "NASS ROM Cost Estimate Input for
    Gimbal Trade Study"
FIGURE 1
NERVA 75K FULL FLOW ENGINE

GIMBAL PIVOT ASSEMBLY
WITH GIMBAL CENTER
AT ENGINE STA 23.0

\( \theta = 90^\circ \) (PITCH AXIS)

\( \theta = 180^\circ \) (YAW AXIS)

NOZZLE EXIT PLANE
\( \varepsilon = 24:1 \)

FLIGHT NOZZLE
EXTENSION EXIT PLANE
\( \varepsilon = 100:1 \)
FIGURE 2
RESPONSE CRITERION FOR A 0.25 DEG/SEC RATE COMMAND

- RATE OVERSUCHT (TBD) DEG/SEC
- RATE ERROR \pm (TBD) DEG/SEC
- EXAMPLE RESPONSE
- LIMITS
- ACCELERATION RAMP 0.5 DEG/SEC MINIMUM

\( T_s^* \), (TBD) SEC

* DENOTES RATE SETTLING TIME

- 48 -
FIGURE 3

GIMBAL AMPLITUDE PATTERN ABOUT THE PITCH AND YAW AXES*

- SNUBBER CONTACT + 3 1/2 DEG
- MAXIMUM AMPLITUDE + 4 DEG
- REQUIRED GIMBAL AMPLITUDE ± 3 DEG
- LIMTS DEFINED BY MECHANICAL STOPS IN GIMBAL ACTUATORS
- SNUBBER DISPLACEMENT IN ACTUATOR OCCURS
- AVAILABLE FOR RESPONSE OVERSHOOT AND POSITION ERROR

* BASED ON FLIGHT CONCEPT GIMBAL ACTUATORS
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>W/External Shield</th>
<th>W/O External Shield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/Nozzle Ext</td>
<td>w/o Nozzle Ext</td>
</tr>
<tr>
<td>Weight, K lbs</td>
<td>35.4</td>
<td>34.8</td>
</tr>
<tr>
<td>Pitching mass moment of inertia, slug-ft^2</td>
<td>90,726</td>
<td>77,900</td>
</tr>
<tr>
<td>Longitudinal c.g., inches from Engine Station 0.0</td>
<td>114.1</td>
<td>110.4</td>
</tr>
</tbody>
</table>

NOTES: (1) Reference 12 for source data.
(2) Gimbal center at Engine Station 23.0
FIGURE 5
ENGINE/FACILITY INTERMEDIATE SHIELD INTERFACE

STA 79.33
ELEV TBD
TBD DIA
TBD DIA
ENGINE EXTERNAL SHIELD
STA 69.33
ELEV TBD

ENGINE
INTERMEDIATE SHIELD

ELEV TBD
TBD DIA
TBD DIA
TBD DIA

REF 1137421
FIGURE 6
ENGINE/NASS EXHAUST DUCT INTERFACE

ENGINE

TEST STAND

TBD MAX RADIAL MISALIGNMENT

ELEV 3812'-5" ± .50
STA 258.19

TBD MAX ALLOWABLE MISALIGNMENT

TBD DIA MAX NON GIMBALLING & GIMBALED

64.00 DIA MIN AMBIENT & OPERATING

4.00 ± .50 AMBIENT & OPERATING

SIDE SHIELD

BOTTOM SHIELD

ELEV 3811'-0"

82.00 DIA

NOZZLE EXIT RATIO 24:1
GIMBALED ENGINE TESTS

REF 1137421
FIGURE 7

ASSUMED NOZZLE EXHAUST PLUME SHAPES DURING GIMBALING

CASE a. CYLINDRICAL

CASE b. CONIC EXPANSION

\[ \varepsilon = 24:1 \]

CONE HALF ANGLE
\[ 20^\circ 55' \]
<table>
<thead>
<tr>
<th>Test Requirement</th>
<th>Allowable Gimbaling Amplitude, degrees&lt;sup&gt;(1)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+ 3.5</td>
</tr>
<tr>
<td>1. Response to step command</td>
<td></td>
</tr>
<tr>
<td>a. 3 deg from null position</td>
<td>Yes</td>
</tr>
<tr>
<td>b. 1.5 deg from 1.5 deg position</td>
<td>Yes</td>
</tr>
<tr>
<td>2. Response to ramp command from null position</td>
<td></td>
</tr>
<tr>
<td>a. 0.75 deg/sec</td>
<td>Yes</td>
</tr>
<tr>
<td>b. 0.25 deg/sec</td>
<td>Yes</td>
</tr>
<tr>
<td>3. Response to ramp command from either 1.5 deg or 3.0 deg position</td>
<td></td>
</tr>
<tr>
<td>a. 0.75 deg/sec</td>
<td>Yes</td>
</tr>
<tr>
<td>b. 0.25 deg/sec</td>
<td>Yes</td>
</tr>
<tr>
<td>4. Position hold - long duration</td>
<td></td>
</tr>
<tr>
<td>a. 1.5 deg position</td>
<td>Yes</td>
</tr>
<tr>
<td>b. Null position</td>
<td>Yes</td>
</tr>
<tr>
<td>5. Life cycle (see Note 2)</td>
<td>Yes</td>
</tr>
<tr>
<td>6. Deceleration (see Note 2)</td>
<td>Yes</td>
</tr>
<tr>
<td>7. Malfunction - channel switching</td>
<td>Yes</td>
</tr>
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NOTES: (1) Correlation with goal option and actuator linear stroke is shown in para. IV.D.1.
(2) These tests can be performed with lesser amplitude; however, at design levels the full amplitude is needed.
TABLE 2

TVC REQUIREMENT VERIFICATION CAPABILITY
AS RELATED TO
ALLOWABLE GIMBALING AMPLITUDE

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NOTES: (1) Correlation with goal option and actuator linear stroke is shown in para. IV.D.1.
(2) These tests can be performed with lesser amplitude; however, at design levels the full amplitude is needed.
EXAMPLE RESPONSE TO A RATE COMMAND FROM NULL UNDER LIMITED ACTUATOR STROKE

ACTUATOR POSITION

FULL COMPRESSION OF SNUBBER, MECHANICAL STOPS

STEP COMMAND AS SHOWN BASED ON PREDETERMINED POSITION FEEDBACK SIGNAL

DIFFERENCE = POSITION TRACKING ERROR

POSITION RESPONSE

COMMAND POSITION

ACTUATOR RATE

COMMANDED RATE

RANGE OVERSHOOT

VERIFICATION RATE

APPROX RATE TRACKING ERROR

NEGATIVE RATE RESPONSE DUE TO SPRING FORCE AND SERVO NEGATIVE ERROR SIGNAL

TIME

TIME
FIGURE 9

EXAMPLE RESPONSE TO A SAW-TOOTH COMMAND PROCEDURE UNDER LIMITED ACTUATOR STROKE

+ Full Compression of Snubber; Mechanical Stops

- COMMAND RATE

+ ACTUATOR RATE

- COMMAND RATE

FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

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POSITION RESPONSE

TIME

COMMAND POSITION

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COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

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POSITION TRACKING ERROR

POSITION RESPONSE

TIME

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POSITION TRACKING ERROR

POSITION RESPONSE

TIME

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POSITION RESPONSE

TIME

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POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

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TIME

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POSITION RESPONSE

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TIME

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TIME

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POSITION RESPONSE

TIME

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SNubby DISPLACEMENT

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POSITION RESPONSE

TIME

COMMAND POSITION

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SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

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POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

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TIME

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- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

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POSITION TRACKING ERROR

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TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

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POSITION RESPONSE

TIME

COMMAND POSITION

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SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION

- FULL COMPRESSION OF SNUBBER; MECHANICAL STOPS

SNubby DISPLACEMENT

POSITION TRACKING ERROR

POSITION RESPONSE

TIME

COMMAND POSITION
### TABLE 3

**INTERFACE, LOADS AND ENVIRONMENTAL SIMULATION AS RELATED TO TEST STAND FACILITY**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Test Stand Facility</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stage/engine interface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Mechanical loads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Thrust</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Thrust load misalignment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Vehicle pitching motion moment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d. Spring rates of gimbaled components</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e. Single turbopump</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Thermal loads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Cryogenic filling PIL's</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Fluids in other lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Induced vibration from engine operations (turbopumps, nozzle exhaust)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Induced nuclear radiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Thermal conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Nuclear induced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Solar soak</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Cold soak</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d. Heat sink conditions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTES:**

1. Based on restriction assumption, para. III.C.2.
2. Reduction due to lower thrust and possible engine tolerance stackup correction procedures.
3. Inertia moment due to gravity is in opposite direction.
4. Spring rate on ground will be higher as a result of emergency cooldown line and more electrical wiring (harness).
5. Assumes that single pump operation is performed
6. Expect higher rates as a result of facility ETC structure.
7. The ETC will have gas purge of TBD pressure and wall temperature between 100°F at beginning to some temperature less than 200°F at end of the run.
TABLE 4

GIMBAL ACTUATOR COMMAND, CONTROL AND TREND DATA MEASUREMENTS

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Functional Use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Command</td>
</tr>
<tr>
<td>Position input</td>
<td>x</td>
</tr>
<tr>
<td>Linear position feedback</td>
<td></td>
</tr>
<tr>
<td>Rate feedback</td>
<td></td>
</tr>
<tr>
<td>Motor current</td>
<td></td>
</tr>
<tr>
<td>Shaft load cell</td>
<td></td>
</tr>
<tr>
<td>Housing pressure</td>
<td></td>
</tr>
<tr>
<td>Clutch solenoids</td>
<td>x</td>
</tr>
<tr>
<td>Clutch position proximity indicator</td>
<td></td>
</tr>
</tbody>
</table>

NOTES: (1) All command, control and data measurements (or signals) are redundant with separate power supply for primary and standby channels.
(2) Based on use of GA Concept 1138420B shown on engine layout 1137500C.
(3) Command measurements are related to inputs initiated by the guidance system (flight) or test facility operations (ground test).
(4) Control measurements are related to actuator transducer outputs used for servo system stability and error signal comparison.
(5) Any of the trend data measurements may be used by the Malfunction-Detection System.
(6) From References 16 (Flight MDRL) and 17 (DE-1 MDRL).
(7) Reference 18 (Redundancy Section).
FIGURE 11

TYPICAL SNUBBER LOAD - DISPLACEMENT CURVES

NOTE: FOR GA CONCEPT 1138420 100% LOAD = 30,000 LBS
### TABLE 5

**SUMMARY OF GIMBAL AMPLITUDE LIMITS AS RELATED TO GROUND FIRING VERIFICATION GOAL**

<table>
<thead>
<tr>
<th>Goal Option(1)</th>
<th>Flight system</th>
<th>0.75 deg/sec rate</th>
<th>0.50 deg/sec rate</th>
<th>0.25 deg/sec rate</th>
<th>&quot;No response&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TVC Verification(2)</td>
<td>Snubbing(3)</td>
<td>Total</td>
<td>Midway between Axes(4)</td>
</tr>
<tr>
<td>Flight system</td>
<td>± 3.5</td>
<td>± 0.93</td>
<td>± 0.35</td>
<td>± 1.28</td>
<td>± 5.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 0.70</td>
<td>± 0.33</td>
<td>± 1.03</td>
<td>± 1.81</td>
</tr>
<tr>
<td>0.75 deg/sec rate</td>
<td>target</td>
<td>± 0.93</td>
<td>± 0.35</td>
<td>± 1.28</td>
<td>± 1.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 0.70</td>
<td>± 0.33</td>
<td>± 1.03</td>
<td>± 1.46</td>
</tr>
<tr>
<td></td>
<td>min accept</td>
<td>± 0.93</td>
<td>± 0.35</td>
<td>± 1.28</td>
<td>± 1.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 0.70</td>
<td>± 0.33</td>
<td>± 1.03</td>
<td>± 1.46</td>
</tr>
<tr>
<td>0.50 deg/sec rate</td>
<td>target</td>
<td>± 0.60</td>
<td>± 0.32</td>
<td>± 0.92</td>
<td>± 1.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 0.45</td>
<td>± 0.31</td>
<td>± 0.76</td>
<td>± 1.08</td>
</tr>
<tr>
<td></td>
<td>min accept</td>
<td>± 0.60</td>
<td>± 0.32</td>
<td>± 0.92</td>
<td>± 1.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 0.45</td>
<td>± 0.31</td>
<td>± 0.76</td>
<td>± 1.08</td>
</tr>
<tr>
<td>0.25 deg/sec rate</td>
<td>target</td>
<td>± 0.33</td>
<td>± 0.29</td>
<td>± 0.62</td>
<td>± 0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 0.25</td>
<td>± 0.27</td>
<td>± 0.52</td>
<td>± 0.74</td>
</tr>
<tr>
<td></td>
<td>min accept</td>
<td>± 0.33</td>
<td>± 0.29</td>
<td>± 0.62</td>
<td>± 0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 0.25</td>
<td>± 0.27</td>
<td>± 0.52</td>
<td>± 0.74</td>
</tr>
<tr>
<td>&quot;No response&quot;</td>
<td>&lt;(± 0.25)</td>
<td>&lt;(± 0.27)</td>
<td>&lt;(± 0.52)</td>
<td>&lt;(± 0.74)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;(± 0.25)</td>
<td>&lt;(± 0.27)</td>
<td>&lt;(± 0.52)</td>
<td></td>
</tr>
</tbody>
</table>

**NOTES:**

1. See para IV.D.1 for discussion on "target" and "minimum acceptable" case terms.
2. Data analysis in Appendix C.
3. Data analysis in Appendix D.
4. Assumes no restriction.
<table>
<thead>
<tr>
<th>Goal Option</th>
<th>TVC Verification</th>
<th>Snubbing</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight system</td>
<td>± 1.53</td>
<td>± 0.22</td>
<td>± 1.75</td>
</tr>
<tr>
<td>0.75 deg/sec rate</td>
<td>± 0.41</td>
<td>± 0.15</td>
<td>± 0.56</td>
</tr>
<tr>
<td>target</td>
<td>+ 0.31</td>
<td>+ 0.15</td>
<td>+ 0.46</td>
</tr>
<tr>
<td>min accept</td>
<td>± 0.31</td>
<td>+ 0.15</td>
<td>+ 0.46</td>
</tr>
<tr>
<td>0.50 deg/sec rate</td>
<td>± 0.27</td>
<td>± 0.14</td>
<td>± 0.41</td>
</tr>
<tr>
<td>target</td>
<td>± 0.20</td>
<td>± 0.14</td>
<td>± 0.34</td>
</tr>
<tr>
<td>min accept</td>
<td>± 0.20</td>
<td>± 0.14</td>
<td>± 0.34</td>
</tr>
<tr>
<td>0.25 deg/sec rate</td>
<td>± 0.15</td>
<td>± 0.12</td>
<td>± 0.27</td>
</tr>
<tr>
<td>target</td>
<td>± 0.11</td>
<td>± 0.12</td>
<td>± 0.23</td>
</tr>
<tr>
<td>min accept</td>
<td>± 0.11</td>
<td>± 0.12</td>
<td>± 0.23</td>
</tr>
<tr>
<td>&quot;no response&quot;</td>
<td>≤ (+ 0.11)</td>
<td>≤ (+ 0.12)</td>
<td>≤ (+ 0.23)</td>
</tr>
</tbody>
</table>

NOTES: (1) Reference Table 5 for in-plane gimbal amplitudes.
(2) Based on actuator lever arm of 25 inches and assumption of a structural compliance equal to zero.
ENGINE LATERAL DISPLACEMENT AT FACILITY INTERMEDIATE SHIELD AS RELATED TO TOTAL GIMBALING AMPLITUDE

FIGURE 12

ENGINE LATERAL DISPLACEMENT AT STA 122.28, INCHES

NOTE: DOES NOT INCLUDE LATERAL DISPLACEMENT DUE TO "NON-GIMBALING" CAUSES
<table>
<thead>
<tr>
<th>LOCATION R (in.)</th>
<th>LOCATION Z ABOVE CORE CENTER (in.)</th>
<th>FLIGHT(^{(2)}) ENVIRONMENT GAMMA DOSE RATE RAD(c)/HR</th>
<th>FACILITY CAPTURE GAMMA DOSE RATE RAD(c)/HR</th>
<th>FACILITY SCATTER DOSE RATE RAD(c)/HR</th>
<th>TOTAL GAMMA DOSE RATE RAD(c)/HR</th>
<th>RATIO TOTAL/FLIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>81.0</td>
<td>5.97 + 6(^{(3)})</td>
<td>7.39 + 6</td>
<td>2.75 + 6</td>
<td>1.61 + 7</td>
<td>2.70</td>
</tr>
<tr>
<td>7.87</td>
<td>81.0</td>
<td>5.70 + 6</td>
<td>7.27 + 6</td>
<td>2.98 + 6</td>
<td>1.60 + 7</td>
<td>2.80</td>
</tr>
<tr>
<td>15.74</td>
<td>81.0</td>
<td>4.95 + 6</td>
<td>7.41 + 6</td>
<td>2.94 + 6</td>
<td>1.53 + 7</td>
<td>3.09</td>
</tr>
<tr>
<td>25.98</td>
<td>81.0</td>
<td>3.77 + 6</td>
<td>8.09 + 6</td>
<td>3.21 + 6</td>
<td>1.51 + 7</td>
<td>4.00</td>
</tr>
<tr>
<td>31.49</td>
<td>81.0</td>
<td>6.25 + 6</td>
<td>7.90 + 6</td>
<td>3.37 + 6</td>
<td>1.75 + 7</td>
<td>2.80</td>
</tr>
<tr>
<td>39.37</td>
<td>81.0</td>
<td>1.07 + 7</td>
<td>7.30 + 6</td>
<td>3.88 + 6</td>
<td>2.19 + 7</td>
<td>2.04</td>
</tr>
<tr>
<td>50.00</td>
<td>81.0</td>
<td>2.29 + 7</td>
<td>5.44 + 6</td>
<td>5.22 + 6</td>
<td>3.36 + 7</td>
<td>1.47</td>
</tr>
<tr>
<td>35.10</td>
<td>64.4</td>
<td>1.75 + 7</td>
<td>1.22 + 7</td>
<td>4.40 + 6</td>
<td>3.41 + 7</td>
<td>1.95</td>
</tr>
<tr>
<td>0.00</td>
<td>107.0</td>
<td>3.07 + 6</td>
<td>4.61 + 6</td>
<td>2.34 + 6</td>
<td>1.00 + 7</td>
<td>3.26</td>
</tr>
<tr>
<td>7.87</td>
<td>107.0</td>
<td>2.99 + 6</td>
<td>4.74 + 6</td>
<td>2.28 + 6</td>
<td>1.00 + 7</td>
<td>3.35</td>
</tr>
<tr>
<td>15.74</td>
<td>107.0</td>
<td>2.78 + 6</td>
<td>4.93 + 6</td>
<td>2.36 + 6</td>
<td>1.01 + 7</td>
<td>3.62</td>
</tr>
<tr>
<td>25.98</td>
<td>107.0</td>
<td>3.02 + 6</td>
<td>5.11 + 6</td>
<td>2.48 + 6</td>
<td>1.06 + 7</td>
<td>3.51</td>
</tr>
<tr>
<td>31.49</td>
<td>107.0</td>
<td>4.01 + 6</td>
<td>4.98 + 6</td>
<td>2.50 + 6</td>
<td>1.15 + 7</td>
<td>2.86</td>
</tr>
<tr>
<td>39.37</td>
<td>107.0</td>
<td>4.98 + 6</td>
<td>4.72 + 6</td>
<td>2.60 + 6</td>
<td>1.23 + 7</td>
<td>2.47</td>
</tr>
<tr>
<td>50.00</td>
<td>107.0</td>
<td>8.12 + 6</td>
<td>3.88 + 6</td>
<td>2.51 + 6</td>
<td>1.45 + 7</td>
<td>1.79</td>
</tr>
</tbody>
</table>

**NOTES:**

(1) Reference 11
(2) No engine external shield
(3) 5.97 + 6 means 5.97 x 10^6
## Table 8

**Gamma Dose Rates at Selected Critical Engine Locations with 75K NERVA in ETS-1 and No Intermediate Shield in Place**

<table>
<thead>
<tr>
<th>Location R (in.)</th>
<th>Location Z Above Core Center (in.)</th>
<th>Flight Environment Gamma Dose Rate (rad(c)/hr)</th>
<th>Facility Capture Gamma Dose Rate (rad(c)/hr)</th>
<th>Facility Scatter Gamma Dose Rate (rad(c)/hr)</th>
<th>Total Gamma Dose Rate (rad(c)/hr)</th>
<th>Ratio Total/Flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>81.0</td>
<td>$5.97 \pm 6^{(4)}$</td>
<td>$2.46 + 7$</td>
<td>$6.18 + 6$</td>
<td>$3.68 + 7$</td>
<td>6.16</td>
</tr>
<tr>
<td>7.87</td>
<td>81.0</td>
<td>$5.70 + 6$</td>
<td>$2.47 + 7$</td>
<td>$6.25 + 6$</td>
<td>$3.66 + 7$</td>
<td>6.43</td>
</tr>
<tr>
<td>15.74</td>
<td>81.0</td>
<td>$4.95 + 6$</td>
<td>$2.53 + 7$</td>
<td>$6.28 + 6$</td>
<td>$3.65 + 7$</td>
<td>7.37</td>
</tr>
<tr>
<td>25.98</td>
<td>81.0</td>
<td>$3.77 + 6$</td>
<td>$2.74 + 7$</td>
<td>$6.46 + 6$</td>
<td>$3.76 + 7$</td>
<td>9.98</td>
</tr>
<tr>
<td>31.49</td>
<td>81.0</td>
<td>$6.25 + 6$</td>
<td>$2.81 + 7$</td>
<td>$6.63 + 6$</td>
<td>$4.10 + 7$</td>
<td>6.56</td>
</tr>
<tr>
<td>39.37</td>
<td>81.0</td>
<td>$1.07 + 7$</td>
<td>$2.93 + 7$</td>
<td>$6.83 + 6$</td>
<td>$4.68 + 7$</td>
<td>4.38</td>
</tr>
<tr>
<td>50.00</td>
<td>81.0</td>
<td>$2.29 + 7$</td>
<td>$3.03 + 7$</td>
<td>$7.21 + 6$</td>
<td>$6.04 + 7$</td>
<td>2.64</td>
</tr>
<tr>
<td>0.00</td>
<td>107.0</td>
<td>$3.07 + 6$</td>
<td>$2.29 + 7$</td>
<td>$6.01 + 6$</td>
<td>$3.20 + 7$</td>
<td>10.4</td>
</tr>
<tr>
<td>7.87</td>
<td>107.0</td>
<td>$2.99 + 6$</td>
<td>$2.32 + 7$</td>
<td>$6.02 + 6$</td>
<td>$3.22 + 7$</td>
<td>10.8</td>
</tr>
<tr>
<td>15.74</td>
<td>107.0</td>
<td>$2.78 + 6$</td>
<td>$2.36 + 7$</td>
<td>$6.05 + 6$</td>
<td>$3.24 + 7$</td>
<td>11.7</td>
</tr>
<tr>
<td>25.98</td>
<td>107.0</td>
<td>$3.02 + 6$</td>
<td>$2.42 + 7$</td>
<td>$6.16 + 6$</td>
<td>$3.34 + 7$</td>
<td>11.0</td>
</tr>
<tr>
<td>31.49</td>
<td>107.0</td>
<td>$4.01 + 6$</td>
<td>$2.44 + 7$</td>
<td>$6.20 + 6$</td>
<td>$3.46 + 7$</td>
<td>8.63</td>
</tr>
<tr>
<td>39.37</td>
<td>107.0</td>
<td>$4.98 + 6$</td>
<td>$2.48 + 7$</td>
<td>$6.32 + 6$</td>
<td>$3.61 + 7$</td>
<td>7.25</td>
</tr>
<tr>
<td>50.00</td>
<td>107.0</td>
<td>$8.12 + 6$</td>
<td>$2.51 + 7$</td>
<td>$6.48 + 6$</td>
<td>$3.97 + 7$</td>
<td>4.89</td>
</tr>
<tr>
<td>35.10</td>
<td>64.4</td>
<td>$1.75 + 7$</td>
<td>$3.10 + 7$</td>
<td>$6.74 + 6$</td>
<td>$5.52 + 7$</td>
<td>3.16</td>
</tr>
</tbody>
</table>

**Notes:**

1. Reference 11
2. Provides 24-inch gap when engine is at the null gimbal position
3. No engine external shield
4. $5.97 + 6$ means $5.97 \times 10^6$
### TABLE 9

THRUST VECTOR LATERAL DISPLACEMENT AT THE NOZZLE EXIT PLANE AND NASS DUCT OPENING AS A FUNCTION OF GOAL OPTION MAXIMUM GIMBAL AMPLITUDE

<table>
<thead>
<tr>
<th>Goal Option(1)</th>
<th>Nozzle Exit Plane(2)</th>
<th>Duct Opening(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight system</td>
<td>In-Plane of Actuators</td>
<td>In-Plane of Actuators</td>
</tr>
<tr>
<td></td>
<td>Midway between Actuators</td>
<td>Midway between Actuators</td>
</tr>
<tr>
<td>Flight system</td>
<td>16.4 inches</td>
<td>16.7 inches</td>
</tr>
<tr>
<td></td>
<td>23.2 inches</td>
<td>23.6 inches</td>
</tr>
<tr>
<td>0.75 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>5.26</td>
<td>7.45</td>
</tr>
<tr>
<td>min accept</td>
<td>4.23</td>
<td>5.99</td>
</tr>
<tr>
<td>0.50 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>3.76</td>
<td>5.32</td>
</tr>
<tr>
<td>min accept</td>
<td>3.12</td>
<td>4.41</td>
</tr>
<tr>
<td>0.25 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>2.54</td>
<td>3.59</td>
</tr>
<tr>
<td>min accept</td>
<td>2.13</td>
<td>3.02</td>
</tr>
<tr>
<td>&quot;no response&quot;</td>
<td>≤2.13</td>
<td>≤3.02</td>
</tr>
</tbody>
</table>

NOTES:  
(1) See para IV.D.1 for discussion on "target" and "minimum acceptable" case terms.  
(2) Based on 24:1 area ratio nozzle with exit plane at Station 258.19.  
(3) Clearance between exit plane and duct opening assumed at 4.5 inches per ANSC 1137421 (ICD).
TABLE 10

ESTIMATE EXHAUST PLUME PROJECTION IN RADIAL DIRECTION AT NASS DUCT OPENING
AS A FUNCTION OF
GOAL OPTION MAXIMUM GIMBAL AMPLITUDE

<table>
<thead>
<tr>
<th>Goal Option (1)</th>
<th>Assumed Cylinder Projection (2)</th>
<th>Assumed Cone Projection (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In-Plane of Actuators</td>
<td>Midway between Actuators</td>
</tr>
<tr>
<td>Flight system</td>
<td>44.0 inches</td>
<td>50.9 inches</td>
</tr>
<tr>
<td>0.75 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>32.68</td>
<td>34.91</td>
</tr>
<tr>
<td>min accept</td>
<td>31.62</td>
<td>33.41</td>
</tr>
<tr>
<td>0.50 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>31.15</td>
<td>32.74</td>
</tr>
<tr>
<td>min accept</td>
<td>30.49</td>
<td>31.81</td>
</tr>
<tr>
<td>0.25 deg/sec rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>29.90</td>
<td>30.97</td>
</tr>
<tr>
<td>min accept</td>
<td>29.48</td>
<td>30.39</td>
</tr>
<tr>
<td>&quot;no response&quot;</td>
<td>&lt;29.48</td>
<td>&lt;30.39</td>
</tr>
<tr>
<td>Null position</td>
<td>27.31</td>
<td>27.31</td>
</tr>
</tbody>
</table>

NOTES: (1) See para IV.D.1 for discussion on "target" and "minimum acceptable" case terms.
(2) Based on nozzle ID of 54.706 inches and Table 9 data.
(3) Based on cone angle at nozzle exit plane of 20° 55'.
(4) Per NASS duct criteria, inlet radius is 32 inches. According to assumed safety criteria (para IV.B) conditions left of line are considered safe.
TABLE 11

ESTIMATED ALLOWABLE THRUST VECTOR MISALIGNMENT
RELATIVE TO A 64-IN. DIAMETER DUCT
AS A FUNCTION OF GOAL OPTION MAXIMUM GIMBAL AMPLITUDE

<table>
<thead>
<tr>
<th>Goal Option(2)</th>
<th>Assumed Cylinder Projection(3)</th>
<th>Assumed Cone Projection(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Circular Pattern(4)</td>
<td>Square Pattern(4)</td>
</tr>
<tr>
<td>Flight system</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>0.75 deg/sec rate</td>
<td>target: none</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td>min accept: 0.38 inches</td>
<td>none</td>
</tr>
<tr>
<td>0.50 deg/sec rate</td>
<td>target: 0.85</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td>min accept: 1.51</td>
<td>0.19 inches</td>
</tr>
<tr>
<td>0.25 deg/sec rate</td>
<td>target: 2.10</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>min accept: 2.52</td>
<td>1.61</td>
</tr>
</tbody>
</table>

NOTES: (1) Thrust vector misalignment relative to the duct centerline as attributed to non-gimbaling causes (i.e., static compliance, mechanical assembly stackup, thermal bending).

(2) See para IV.D.1 for discussion on "target and "minimum acceptable" case terms.

(3) Based on data in Table 10 and assumed safety criteria in para IV.B.

(4) See para IV.D.3.d for discussion on "circular" and "square" gimbaling vector sum terms.
**TABLE 12**

NUCLEAR STAGE TVC REQUIREMENTS

<table>
<thead>
<tr>
<th>TVC Characteristic</th>
<th>LMSC(1)</th>
<th>IBM(2)</th>
<th>MDAC(3)</th>
<th>NPRD Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude, deg</td>
<td>3.0</td>
<td>2.5</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Rate, deg/sec</td>
<td>0.75</td>
<td>0.25</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>Acceleration, deg/sec²</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

NOTES: (1) Reference 19  
(2) Reference 20  
(3) Reference 21
### TABLE 13

**ESTIMATED TEST FACILITY DELTA COSTS**
FOR INCREASING NASS DUCT INLET DIAMETER

A. ETS-1 Inlet ID = 64 inches, E/STS-2 Inlet ID varies

<table>
<thead>
<tr>
<th>Inlet Diameter, Inches</th>
<th>Gimbal Angle, degrees</th>
<th>$\dot{W}_s$, lb/sec</th>
<th>Delta Cost ($$, Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETS-1</td>
<td>E/STS-2</td>
<td>ETS-1</td>
<td>E/STS-2</td>
</tr>
<tr>
<td>64</td>
<td>64</td>
<td>+ .5</td>
<td>+ .5</td>
</tr>
<tr>
<td>64</td>
<td>68</td>
<td>+ .5</td>
<td>+ 1.0</td>
</tr>
<tr>
<td>64</td>
<td>73</td>
<td>+ .5</td>
<td>+ 1.5</td>
</tr>
<tr>
<td>64</td>
<td>77</td>
<td>+ .5</td>
<td>+ 2.0</td>
</tr>
<tr>
<td>64</td>
<td>95</td>
<td>+ .5</td>
<td>+ 4.0</td>
</tr>
</tbody>
</table>

B. ETS-1 and E/STS-2 Inlet ID are equal and vary with gimbal capability.

<table>
<thead>
<tr>
<th>Inlet Diameter, Inches</th>
<th>Gimbal Angle, degrees</th>
<th>$\dot{W}_s$, lb/sec</th>
<th>Delta Cost ($$, Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETS-1</td>
<td>68</td>
<td>+ 1.0</td>
<td>1250</td>
</tr>
<tr>
<td>ETS-1</td>
<td>73</td>
<td>+ 1.5</td>
<td>1650</td>
</tr>
<tr>
<td>ETS-1</td>
<td>77</td>
<td>+ 2.0</td>
<td>2000</td>
</tr>
<tr>
<td>ETS-1</td>
<td>95</td>
<td>+ 4.0</td>
<td>4500</td>
</tr>
</tbody>
</table>

**NOTES:**

1. Diameters were determined from gimbal angles using nozzle area ratio $\varepsilon = 24:1$ configuration.
2. Includes redesign, scale model tests, fabrication, facility changes, and operation delta costs.
3. Reference 22.
FIGURE 13

PLOT OF ESTIMATED DELTA FACILITY COSTS AS RELATED TO NASS DUCT INLET DIAMETER INCREASE FROM 64 INCHES

REFERENCE: DATA IN TABLE 13
### TABLE 14

**ESTIMATED TEST FACILITY DELTA COSTS AS RELATED TO GROUND FIRING TVC GOAL OPTIONS**

<table>
<thead>
<tr>
<th>Goal Option</th>
<th>Delta Cost, $ Millions&lt;sup&gt;(4)&lt;/sup&gt;</th>
<th>Cylindrical Plume Assumption&lt;sup&gt;(2),(3)&lt;/sup&gt;</th>
<th>Conic Plume Assumption&lt;sup&gt;(2),(3)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delta Cost&lt;sup&gt;(5)&lt;/sup&gt;</td>
<td>Unrestricted&lt;sup&gt;(6)&lt;/sup&gt;</td>
<td>Delta Cost&lt;sup&gt;(5)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Flight system</td>
<td>28</td>
<td>&gt; 44</td>
<td>37</td>
</tr>
<tr>
<td><strong>0.75 deg/sec rate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>1-4</td>
<td>5-6</td>
<td>4-5</td>
</tr>
<tr>
<td>min accept</td>
<td>0</td>
<td>3-4</td>
<td>3-4</td>
</tr>
<tr>
<td><strong>0.50 deg/sec rate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>0</td>
<td>1-4</td>
<td>3-4</td>
</tr>
<tr>
<td>min accept</td>
<td>0</td>
<td>0</td>
<td>1-4</td>
</tr>
<tr>
<td><strong>0.25 deg/sec rate</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>min accept</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>&quot;no response&quot;</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**NOTES:**
1. See para IV.D.1 for discussion on "target" and "minimum acceptable" case items.
2. Based on plume radial projection data in Table 11.
3. See para III.C for assumption discussion.
4. Based on cost data in Table 13.
5. Based on the gimbal actuator pattern being restricted to a circle related to the maximum stroke of a single actuator.
6. Based on an unrestricted gimbal square pattern.
APPENDIX A

USE OF TEST CELL "C" AS AN ALTERNATE FACILITY FOR TVC RESPONSE VERIFICATION DURING ENGINE GROUND TESTING
A1.0 SCOPE

This support study pertains to the use of Test Cell C as an alternate facility to ETS-1 and E/STS-2 for TVC response verification during engine ground testing. The basis for this consideration is that Test Cell C does not have the engine facilities requirement for limited altitude simulation (vacuum). An advantage is apparently gained by the removal of the gimbal amplitude constraint as provided by the NASS exhaust duct inlet diameter imposed within ETS-1 and potentially within E/STS-2. The purpose of this investigation is to determine whether this advantage can be realized within the other constraints associated with Test Cell C.

A2.0 FUNCTIONAL AND TECHNICAL REQUIREMENTS

2.1 Verification Program

As presented in the NERVA Verification Plan (Reference 10), five NERVA reactor assemblies are programmed for testing at Test Cell C. The test sequence is shown in Figure A-1.

The test setup is represented by a pressure vessel-reactor (PVARA) - nozzle assembly with attaching propellant and coolant lines-valve assembly modules. Area ratio for the nozzle exit plane is planned to be 24:1.

It is currently planned to test this assembly with a nozzle up attitude and exhaust into a duct system at the nozzle exit plane. The function of this duct is to collect and direct the flow of exhaust gas into a scrubber for the removal of radioactive contaminants. Since altitude simulation is not required, greater flexibility in the duct inlet diameter is available. Horizontal and vertical (nozzle down) attitudes are also being considered.
2.2 Restrictions

As shown on NRTO Milestone Network dated 27 October 1970, the reactor power start dates are as follows:

- DR-1: October 1973
- DR-2: September 1974
- PQR-1: September 1975
- QR-1: March 1976
- QR-2: November 1976

These dates shall be considered as a constraint on the incorporation of TVC response verification into the reactor assembly testing at Test Cell C.

It shall be assumed that there are no constraints external to the engine inhibiting the maximum gimbal amplitudes of the flight system actuators\(^{(1)}\). These considerations include the exhaust collector duct diameter sizing and any necessary separations with the facility shielding to prevent contact due to lateral motion of the gimbaled engine.

It is assumed that the engine/stage interface requirements for ETS-1 and E/STS-2 equally apply for a Test Cell C alternate. In addition to the stiffness requirement\(^{(2)}\) the NPRD requires that the ground test engine be designed and constructed such that it can be remotely installed and removed from the engine test facility.

\(^{(1)}\) See discussion on gimbal amplitude requirements in para. III.B.1.

\(^{(2)}\) See discussion on interface stiffness in para. III.B.3.a.
A3.0  TECHNICAL DISCUSSION

3.1 Available Facility Options

Two general options are available. One is the assembly attitude in the test facility, and the second is a programmatic allocation.

Attitude options were considered to be the following cases:

(1) Vertical-nozzle down
(2) Vertical-nozzle up
(3) Horizontal (cantilever support)

The first case provides the same attitude as ETS-1 and E/STS-2.

The options available from program adjustment would be the allocation of gimbaled test assemblies as follows:

(1) Shift ground firing of at least two of the seven engines planned for ETS-1 and E/STS-2.

(2) Include at least two more engines into the test program specifically to verify TVC requirements in Test Cell C.

(3) Upgrade at least two reactor assemblies with engine components with respect to TVC simulation requirements (para. IV.B).

The first schedular option was discarded due to an apparent compromise in the engine verification program with the requirement for limited altitude simulation (vacuum). The second schedular option was discarded since the engine and test operations costs would exceed modification costs for ETS-1 and E/STS-2 facilities.

The purpose of this latter option was to provide an alternate which would not compromise either the intent of the reactor tests or the engine altitude simulation tests. The only remaining schedular option considered feasible was upgrading the reactor test assemblies.
3.2 Criteria

As presented within para. IV.B (Criteria), TVC response verification during ground firing requires that a ground test configured, functioning engine be used. Any makeshift PVARA-nozzle assembly (less than an engine) is considered as invalid due to inadequate simulation of the stated characteristics. Although a true engine assembly could be used, the primary areas of testing verification would be the reactor program as originally intended and the addition of the TVC function.

All components of the ground test engines which contribute to the assembly misalignment and/or motion under load, should be the same as the flight design in regard to assembly, thermal and stiffness characteristics. Similarly, components used for engine testing in two different facilities should be of common design.

3.3 Method of Evaluation

The evaluation was primarily conducted for the three facility assembly attitude options using those parameters presented in para. III.D found sensitive to the scope of this support study. In some cases, however, the trade discussion pertains more to comparisons between Test Cell C and the engine test facilities, rather than between the Test Cell C options. A quantitative approach was limited due to technical status; therefore, a subjective approach was generally used.

Discussion for each parameter is presented within the following scope:

1. General

Effect of removing amplitude constraint on verification, reliability and potential growth/flexibility as compared to ETS-1 and E/STS-2.
3.3 2. **Performance**
   a. Effect of test facility constraints on verification quality.
   b. Effect of test facility constraints on engine design.

3. **Safety**
   Effect of gravity moment due to engine attitude.

4. **Schedule**
   Compatibility with the reactor test program.

5. **Cost**
   a. Effect on engine development program.
   b. Facility modifications
   c. Test Operations
   d. Support equipment

3.4 **Evaluation Results**

3.4.1 **General**
   With the removal of restrictions on the gimbal amplitude, the Test Cell C alternate provides an obvious advantage compared to ETS-1 and E/STS-2 with respect to functional requirements and reliability verification capabilities. It also provides a needed capability for potential growth in requirements and flexibility contingency for uncertainties in the TVC response verification goal option amplitude estimates (para. IV.D.1.a).

3.4.2 **Performance**
   The stage/engine interface, loads and environmental simulation, as a function of Test Cell C option, is presented in Table A-1(1). Major differences of concern between the attitude options pertain to loads conditions.

---

(1) A similar presentation for ETS-1 and E/STS-2 is shown in Table 3
Thermal conditions between the Test Cell C facility site and the Engine Test Compartment (ETC) of the engine test facilities are different; however, the relative significance is unknown.

For a nozzle-up firing, the gravity overturning moment simulates the backdriving effect on the actuator which occurs during vehicle TVC maneuvers (para. III.B.1). A comparison of their magnitudes as a function of gimbal amplitude is shown:

- Flight (max condition, ALM) \((-3.65 \times 10^6)\theta\) in-lbs
- Test Cell C - nozzle-up \((-3.04 \times 10^6)\theta\) in-lbs

where \(\theta\) is in radians. For the nozzle-down firings in ETS-1, E/STS-2 and Test Cell C, the sign is positive since gravity acts as a restoring moment. For small amplitudes, as restricted within the two engine facilities, the variance in sign does not have a major affect on the TVC verification. The torque to overcome the system inertia is the dominant loading when commanding from the null position.

For the horizontal attitude (cantilever support) option in Test Cell C, the gravity moment about the gimbal center is a constant value of about \(3 \times 10^6\) in-lbs. In terms of actuator output load, this moment requires an additional 120,000 lbs capability to the 30,000 lb stall load capability presently planned for the flight actuators. A special gimbal system design including an upgrade of the structural members and the actuator drive motor power level would be required.

A comparison of non-gimbaling condition direct loads at the gimbal center due to full thrust and static acceleration is shown in Table A-2 for the flight, engine test facility and the two Test Cell C vertical attitude
cases. Due to the additive effect of thrust and gravity for nozzle-up firing, this Test Cell C case loading exceeds the flight engine case loading by 35 to 45 percent.

Of the three attitude options, the nozzle down case is considered as best since flight hardware can be used without incurring a weight penalty. To comply with both the NERVA structural design criteria\(^{(1)}\) and use flight hardware in a nozzle-up test, additional weight would be necessary to satisfy the strength and elastic stability criteria. The amount of extra weight is unknown; but in any case, it is considered as an undesirable option. The horizontal attitude (cantilever support) option is unacceptable due to excessive loads to certain engine components, in particular those of the space operation designed gimbal system. The loads, due to the lateral g's, are comparable to launch loads. Weight increase estimates for components sensitive to the 1g lateral acceleration have been previously presented to SNPO-C.\(^{(2)}\) In accordance with subsequent SNPO-C direction the gimbal system components are presently designed for space operations loads only.\(^{(3)}\)

### 3.4.3 Safety

Of the four problem areas discussed in the study for ETS-1 and E/STS-2, a discussion of the potential hazard associated with actuator failure for the nozzle-up firing case appears pertinent. Snubbing in the actuator remains unchanged. Intermediate facility shield contact loads and the nozzle exhaust plume exceeding the duct inlet diameter were eliminated by assuming that these conditions would not occur.

---

\(^{(1)}\) SNPO-C-1, NERVA Program Structural Design Requirements, 19 December 1968
As shown in para. A.3.4.2, for a nozzle up firing, gravity provides an overturning moment when the gimbaled engine center of gravity shifts from the null position. Resistance to motion for this "unstable" condition is provided by the gimbal actuator. The other components crossing the gimbal plane provide insufficient resistance for this purpose. If an actuator failure were to occur, as discussed in para. IV.D.3.a, the engine would rotate to one side until mechanical stops either within the actuator or externally on the engine were reached.

3.4.4 Schedule

As shown in the program sequence test chart of Figure A-1, the reactor testing is to be completed well ahead of the engine qualification. For example, QR-2 is sequenced at about the same time as the initial gimbaling test, DE-2. To meet the TVC verification requirement of engine characteristics simulation within the existing reactor test schedule, the engine hardware development would have to move considerably ahead of present plans.

3.4.5 Cost

Cost data for the Test Cell C alternate is unavailable at this time. However, two significant cost factors can be stated:

(1) Engine component development costs would be incurred earlier in the program to support a schedule which is based on the present reactor testing program, and

(2) It is reasonable to assume that the costs will exceed those previously stated for the rate response goals using the ETS-1 and E/STS-2 facility options (Table 14).

Sources of delta costs for these facility options are identified as:

(1) Two additional sets of engine hardware (less reactor test assembly components) to provide proper stiffness and mass properties representation of the engine,
(2) Possible engine redesign due to the increased load requirements in the nozzle-up case (para. A.3.4.2),
(3) Facility modification for engine support, shielding and collector duct, which are adaptable for both reactor test assembly and engine installation,
(4) Engine ground handling equipment for either engine nozzle up or down installation, and
(5) Expanded reactor test operations costs.

A4.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached:

1. With the removal of any restrictions on gimbal amplitude, the Test Cell C vertical orientation for both nozzle-up and nozzle-down firing provides an obvious advantage compared to ETS-1 and E/STS-2 with respect to functional requirement and reliability verification capabilities. It also provides adequate allowance for gimbal rate growth and amplitude estimate uncertainties.

2. Of the three Test Cell C attitude options considered, the nozzle-down option was found to be best since flight design hardware could be used without incurring a weight penalty. Ground test axial load requirements for the nozzle-up option would exceed the flight operation load requirements. The associated weight increase for use of a flight system in this latter option has not been assessed.

3. The horizontal test firing option in Test Cell C was found to be unacceptable due to excessive ground test load requirements. If a flight system actuator were to be used, the flight weight penalty would be severe. If a special design were used for the ground test, the verification would be invalid.
4. The assembly schedular option to shift ground firing of at least two of the seven engines from ETS-1 and E/STS-2 to Test Cell C was discarded due to an apparent compromise in the engine verification program with the requirement for limited altitude simulation (vacuum). The assembly schedular option to add additional engines to the test program to specifically verify TVC requirements in Test Cell C was also discarded since engine and test operations cost would exceed ETS-1 and E/STS-2 facility modification or upgrading costs.

5. The final assembly option considered was to upgrade the PVARA-nozzle assembly to a representative engine to satisfy TVC verification simulation requirements. Due to earlier phasing of the reactor test program, this incorporation of the TVC verification would require a substantial shift forward of the engine component hardware development program. To implement this plan, a significant cost increase can be expected and more funds will be needed earlier for the component development.

It is recommended that TVC response verification during engine ground firing be conducted in ETS-1 and E/STS-2 as presently programmed.
### TABLE A-1

**INTERFACE, LOADS AND ENVIRONMENTAL SIMULATION**

**AS RELATED TO TEST CELL C ATTITUDE OPTIONS**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Facility Attitude Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stage/engine interface</td>
<td>Vertical</td>
</tr>
<tr>
<td>2. Mechanical loads</td>
<td></td>
</tr>
<tr>
<td>a. Thrust</td>
<td>improbable</td>
</tr>
<tr>
<td>b. Thrust load misalignment</td>
<td>&lt; 66K</td>
</tr>
<tr>
<td>c. Vehicle pitching motion moment</td>
<td>reduced</td>
</tr>
<tr>
<td>d. Spring rates of gimbaled components</td>
<td>partial</td>
</tr>
<tr>
<td>e. Single turbopump</td>
<td>Yes</td>
</tr>
<tr>
<td>3. Thermal loads</td>
<td></td>
</tr>
<tr>
<td>a. Cryogenic filling PIL's</td>
<td>Yes</td>
</tr>
<tr>
<td>b. Fluids in other lines</td>
<td>Yes</td>
</tr>
<tr>
<td>4. Induced vibration from engine operations</td>
<td></td>
</tr>
<tr>
<td>(turbopumps, nozzle exhaust)</td>
<td>Yes</td>
</tr>
<tr>
<td>5. Induced nuclear radiation</td>
<td>Yes</td>
</tr>
<tr>
<td>6. Thermal conditions</td>
<td></td>
</tr>
<tr>
<td>a. Nuclear induced</td>
<td>Yes</td>
</tr>
<tr>
<td>b. Solar soak</td>
<td>No</td>
</tr>
<tr>
<td>c. Cold soak</td>
<td>No</td>
</tr>
<tr>
<td>d. Heat sink conditions</td>
<td>No</td>
</tr>
<tr>
<td>NOTES:</td>
<td></td>
</tr>
<tr>
<td>(1) For a comparison with ETS-1 and E/STS-2, see Table 3.</td>
<td></td>
</tr>
<tr>
<td>(2) Assumed thrust of 66,000 lbs for 24:1 area ratio nozzle. Will be less for exhausting to atmospheric pressure in Test Cell C.</td>
<td></td>
</tr>
<tr>
<td>(3) The amount of reduction relative to the flight case is dependent on the noted decrease in ground firing thrust and the amount of correcting adjustment for assembly tolerance stackup.</td>
<td></td>
</tr>
<tr>
<td>(4) For a nozzle-up attitude the gravity moment acts as a backdriving condition, but magnitude of moment vs gimbal angle is less. For a nozzle-down attitude, it acts as a restoring moment.</td>
<td></td>
</tr>
<tr>
<td>(5) Moment is based on a minimum of 1g since the engine is in the horizontal position. Severe loading about one axis compared to about .06 g in flight case.</td>
<td></td>
</tr>
<tr>
<td>(6) Spring rate on ground will be higher as a result of emergency cooldown line and more electrical wiring (harness).</td>
<td></td>
</tr>
<tr>
<td>(7) Assumes that single pump operation is performed.</td>
<td></td>
</tr>
<tr>
<td>(8) Nozzle exhaust induced vibration may be higher due to firing into atmosphere.</td>
<td></td>
</tr>
<tr>
<td>(9) Will have ambient temperature with convection from possible ambient and induced winds.</td>
<td></td>
</tr>
<tr>
<td>ENGINE SYSTEM</td>
<td>NRDS (ETS-1/ESTS-2)</td>
</tr>
<tr>
<td>----------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>NUCLEAR SUBSYSTEM</td>
<td>NRDS (TEST CELL C)</td>
</tr>
<tr>
<td>PROPELLANT FEED SUBSYS</td>
<td></td>
</tr>
<tr>
<td>NOZZLE ASSY SUBSYSTEM</td>
<td></td>
</tr>
<tr>
<td>PRESSURE VESSEL SUBSYS</td>
<td></td>
</tr>
<tr>
<td>THUST STRUCTURE SUBSYS</td>
<td></td>
</tr>
<tr>
<td>EXTERNAL SHIELD SUBSYS</td>
<td></td>
</tr>
<tr>
<td>GIMBAL ASSY SUBSYSTEM</td>
<td></td>
</tr>
<tr>
<td>INSTRUMENTATION &amp; CONTROL SUBSYSTEM</td>
<td></td>
</tr>
<tr>
<td>DESTRUCT SUBSYSTEM (TBD)</td>
<td></td>
</tr>
</tbody>
</table>

* CATEGORY II TESTING ON A HIGHER LEVEL ASSEMBLY

** OPERATING PLAN RESCHEDULING REQUIRED

REFERENCE 10
<table>
<thead>
<tr>
<th>Condition</th>
<th>Direct Loading, lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight</td>
<td>70,000(^{(2)})(^{(3)})(^{(4)})</td>
</tr>
<tr>
<td>Test Cell C (nozzle-up attitude)</td>
<td>100,000(^{(4)})(^{(5)})</td>
</tr>
<tr>
<td>ETS-1, E/STS-2 and Test Cell C (nozzle-down attitude)</td>
<td>31,000(^{(4)})(^{(5)})</td>
</tr>
</tbody>
</table>

**NOTES:**

1. Effects of axial vibratory loading and lateral loading are not included.
2. Thrust of 75,000 lbs.
3. Acceleration based on assumed 428,000 lbs weight for fully loaded ALM vehicle (Reference 7).
4. Inertial force based on 34,800 lbs weight for gimbaled engine (Table 1).
5. Assumed thrust of 66,000 lbs for 24:1 area ratio nozzle. Will be less for exhausting to atmospheric pressure in Test Cell C.
APPENDIX B

SUPPLEMENTARY MEANS OF VERIFICATION FOR THOSE TVC REQUIREMENTS WHICH EXCEED THE TEST FACILITY CAPABILITY DURING GROUND FIRING
B.1.0  **SCOPE**

This support study pertains to the investigation of supplementary means of verification for those TVC requirements which exceed the capabilities of ETS-1 and/or E/STS-2 during engine ground firing. In Section V of this report it was concluded that provision for flight system gimbal amplitudes was not feasible in these facilities. It may be seen in Table 2 which requirements remain to be verified as related to a verification capability that has been fixed by the gimbal amplitude allocations. It is the purpose of this study to identify and evaluate various assembly configurations for testing which will satisfy these remaining response requirements and recommend the best approach.

B.2.0  **FUNCTIONAL AND TECHNICAL REQUIREMENTS**

2.1  Actuator and Gimbal System Verification Test Program

The gimbal actuator verification tests consist of structural, electrical and command-response type tests. The first includes static proof and vibration testing. The second includes tests for verifying motor electrical constants and electromagnetic interference requirements. The third includes response to step and ramp commands, life cycling and maintaining fixed position control for long durations of time. The engine gimbaled mass moment of inertia is to be simulated and critical loads, both independent of and dependent on stroke amplitude, will be applied. Shown in Figure B-1, this closed loop response testing setup is similar to the one that was used for qualification and acceptance testing of the Apollo Service Propulsion System (SPS) engine gimbal actuator.\(^1\)

Testing at non-ambient temperature conditions may be accomplished by providing an enclosure around the actuator and flowing a suitable fluid to either add heat

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to, or remove heat from, the component, or by radiant heating with the use of quartz lamps. Due to the expected complexity, a steady-state control temperature at an analytically established critical sub-component (i.e., motor, clutch) is the objective.

TVC demonstration at the gimbal system level consists of ambient temperature response, life cycling, and duration-hold tests similar to those mentioned for the actuator. Planned use of actual thrust structure components and gimbal pivot assembly hardware provides the gimbal loop stiffness simulation and a major portion of the basic engine stiffness simulation. Due to the massive-ness of the gimbaled moment of inertia simulation required for the GA tests, stiffness simulation has been considered as more easily accomplished at the engine assembly level as compared to single actuator component testing. Additional test sub-assemblies are planned to simulate mass distribution, center of gravity, and inertia for the turbopumps and PVARA nozzle assembly.\(^1\) The test setup, as shown in Figure B-2, can be adapted to include lines and the electrical harness that cross the gimbal plane. This modification would provide both spring rate simulation for the actuator verification and load-cycle data for these components. Both flight and ground test load conditions are verified in this setup.

2.2 Inert Engine Testing Program

As shown in Figure B-3, three inert NERVA engine assemblies are provided in the program to evaluate and confirm operational procedures and system responses prior to the introduction of the radioactive environment. These assemblies have been designated as WEMU-1 and -2 (Weight and Envelope Mockup), and E-C. Their applicability to this study pertains to the relative simulation of engine assembly characteristics discussed in para. IV.B and possible use as an alternate means of test assembly.

\(^1\) As presented in 8-year NERVA Program Plan prepared during contract year 1970
The WEMU-1 and WEMU-2 assemblies will be utilized to develop and demonstrate facility interfaces, engine transport and handling, and maintainability procedures. In addition, these mockups will be used to develop and demonstrate the operational capability of Aerospace Ground Equipment (AGE), Maintenance Ground Equipment (MGE), and Test Support Equipment (TSE), and demonstrate engine maintainability and maintenance concepts. Checkout activities utilizing a WEMU will be initiated approximately 24 months prior to the scheduled installation of Engine DE-1.

The WEMU-1 assembly will simulate external dimensions, approximate weight, moment of inertia, some structural characteristics, and interface functions of the NERVA engine, and will be utilized mainly during the pre-development preparation period.

The WEMU-2 assembly shall include dry actual engine hardware with a simulated non-radioactive core, and shall be used in a planned program to accomplish development testing program objectives qualifying MGE and AGE, training personnel, and evaluating techniques of engine maintenance.

The E-C assembly shall be an inert prototype engine used to evaluate cold flow compatibility of the engine and test stands ETS-1 and E/STS-2 in association with an engine simulation. This engine will also be used on transportability maintainability and some environmental (induced and natural), space, and ground storage test programs.

2.3 Restrictions

The WEMU-2 and E-C inert engine assemblies shall be considered to be available from other program commitments about mid-1976. Initially consisting of development phase hardware, the assemblies shall be considered upgraded as necessary for any use associated with the engine qualification test series.
It is assumed that TVC response verification coincident with cryogenically applied thermal loadings of the gimbaled engine lines, and engine induced operating environment (vibration, nuclear radiation, thermal) shall be accomplished during the engine ground test firings.

B.3.0 TECHNICAL DISCUSSION

3.1 Available Assembly Options

The following assembly options are considered as possible means of providing TVC verification during a non-firing ground test.

(1) Mockup inert engine WEMU-1.
(2) Prototype inert engines WEMU-2 and E-C.
(3) Ground test engine in facility test stand prior to power run.
(4) Gimbal system simulation method presented in para. B.2.1.

In the third option, a fueled engine is used in the facility test stand prior to the power runs. The intent is to install flight-type gimbal actuators, perform the required TVC verification tests and then replace these actuators with the special short stroke ground test actuators for the power tests. In this approach the side shields would not initially be in the mating-locked position.

The E-X engine assembly was discarded as a possible option since the assembly will include a fueled reactor.

3.2 Criteria

A major criterion for this support study pertains to the simulation quality of the following items:

1) The same approach could be used with "non-gimbaled" engines (nozzle exit rate $c = 29.1$); however, locked actuators or actuator simulated links would be installed for the power runs

2) Same as Items 1, 2, and 3 presented under "Criteria" in para. IV.B.

---

(1) The same approach could be used with "non-gimbaled" engines (nozzle exit rate $c = 29.1$); however, locked actuators or actuator simulated links would be installed for the power runs.

(2) Same as Items 1, 2, and 3 presented under "Criteria" in para. IV.B.
(1) Proper stiffness, mass properties and structural connection characteristics representation of the engine and of components crossing the gimbal plane.

(2) Proper stiffness representation of the stage/engine interface,

(3) Applied mechanical design loads consistent with gimbaled amplitude.

As previously assumed, verification under the effect of cryogenic thermal loadings and engine induced environment is to be conducted during engine ground firings (para. B.2.3). It is intended that the verification testing discussed herein will be performed at ambient temperature and under closely controlled test conditions.

Verification tests performed with non-firing engine assemblies (or simulated assemblies) shall precede the associated engine firing, leaving sufficient time for data evaluation and additional testing if the results indicate that it is necessary. Results will be used to supplement analytical data as a means of predicting TVC performance prior to and during the checkouts and power runs and for EP data analysis correlations subsequent to the power runs. As a minimum, one series shall precede the assembly of the initial DE and QE "gimbaled" engines.

3.3 Method of Evaluation

The evaluation was conducted in a subjective manner for the four assembly options using those parameters presented in para. III.D found sensitive to the scope of this support study. Discussion for each parameter is presented within the following scope.

1. **Performance**
   
   Quality of loads, stiffness and mass properties simulation.
2. **Reliability**
   a. Effect of test simulation
   b. Capability for margin testing

3. **Safety**
   Effect of possible hardware degradation due to endurance and margin (peripheral) testing.

4. **Schedule**
   a. Effect on ground firing engine hardware requirements
   b. Effect on test stand availability

5. **Cost**
   Effect of combining gimbal system and engine TVC verification testing.

3.4 **Evaluation Results**

3.4.1 **Performance**

   Overall test requirements simulation, as a function of assembly method option, is presented in Table B-1. In all cases, the verification testing is based on the use of flight configuration gimbal actuators.

   Regarding engine characteristics representation, the option considering the WEMU-2 or E-C assemblies has the highest rating since prototype engine hardware is used for these configurations. Use of prototype hardware eliminates additional variables in the analytical process to extrapolate the verification test results to the flight condition. Use of the ground test engine in the pre-power test option was rated good. Installation of special ground power test fluid lines and a more extensive electrical wiring harness tends to slightly downgrade the otherwise prototype simulation. As previously planned (para. A.2.1), the gimbal system level testing approach has a marginal rating since simulation of the PVARA-nozzle
assembly and turbopumps with steel and concrete is going to be limited. However, use of spent hardware (turbopumps, pressure vessels, nozzles, external shield, etc.) from component development programs in this test assembly option could improve this simulation with an equivalence to the WEMU-2/E-C option. As presently planned, the WEMU-1 option does not meet the TVC minimum quality of simulation for stiffness and mass properties and is therefore considered unacceptable. Very little of this assembly is considered to be of value to refurbish this option to an acceptable representation.

For each of these options, load jacks of 5-10 Hz response are considered necessary to adjust all loads to flight conditions without affecting the servo system flight conditions. It is assumed that suitable load simulators can be designed, installed and controlled within these requirements. For the options where the nozzle is pointed upward, the dead weight partially simulates the thrust. As earlier discussed (para. A.3.4.2), the gravity overturning moment also tends to simulate the backdriving flight load. In both cases, some additional correction will be needed; however, it should be considerably less complex doing this task in a nozzle-up setup than in the test facility pre-ground test option with nozzle pointed downward. As presently planned for the gimbal system test option, the spring rates for the lines and electrical wiring harness that cross the gimbal plane would be simulated by load jacks. However, a better approach would be to use prototype hardware. This method provides both proper spring rate simulation and testing feedback for these components. This form of piggyback testing is considered very important during the life and margin cycle gimbal system tests.

3.4.2 Reliability

System level TVC verification testing discussed within this support study is expected to be a major contributing means to the following reliability objectives for flight:
(1) Gathering of data in support of reliability design analyses of those failure modes determined by the failure mode analyses (FMA), and

(2) Developing the malfunction detection and trend data analysis procedures.

Each of the tests verifying the requirements of Table 2, contributes to the above objectives to some degree; however, the duration tests and programmed malfunction-switching exercises are considered very important to the TVC reliability and flight safety demonstration. Margin tests will also be performed at the culmination of the basic requirements verification testing for a given setup. This latter plan has the function of identifying potential gimbaling system weaknesses, indicating the mechanism of failure and determining the magnitude of capability margin.

Additional design confidence gain is provided by better test control at ambient temperature, increased instrumentation, and emphasis on TVC objectives including:

(1) Life cycle margin testing,

(2) Extra long duration holds,

(3) Planned electrical channel malfunctions - switch to backup channel, and

(4) Verify deceleration criteria at various locations in the engine with accelerometer measurements.

During Item (1) tests, other components affected by gimbaling can be concurrently evaluated by this piggyback method. Also, during these cycle tests, periodic checkouts will be conducted to provide data for the development of the flight trend data analysis system. Item (4) should be of particular interest to the Nuclear Sub-system, nozzle and nozzle extension design activities.

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(1) See para. IV.D.2.b for more discussion on the gimbal system trend data analysis approach.
The option which considers use of the WEMU-2 or E-C assemblies provides the best conditions to furnish the above reliability data at a system level. The gimbal system test option, supplemented with additional hardware as previously discussed, would provide a backup means. The pre-ground-firing test option has a less significant value since endurance testing would likely be limited and margin testing would be prohibited (see Safety, para. B.3.4.3).

3.4.3 Safety

Although the gimbal actuators will be replaced prior to the power test series, the pre-ground-firing test option is restricted in part or entirely, relative to certain planned verification response tests. The possibility of contributing to a premature failure of other engine components either prior to or during ground firing could occur if extensive response cycling and margin testing were conducted using the assembly. A separate assembly would be required to perform these tests.

3.4.4 Schedule

For the initial series (prior to DE-2) of assembly level gimbaling verification tests, the best approach was found to be the gimbal system test option upgraded with refurbished or usable development hardware. Simulators which meet the previously specified requirements (para. B.3.2) could be considered to represent PVARA-nozzle assembly components. Based on the previously specified program commitments and schedular restrictions for the WEMU-2 and E-C assemblies, these prototype assemblies are not available for this series. Secondly, it is desirable that hardware with no subsequent program commitment be used so that margin tests can be performed, and sufficient activity time can be planned for data evaluation between the different tests of the series. The pre-ground-firing test option
requires that the engine assembly be made available about three months earlier than planned. This additional time is considered necessary for adequate test and evaluation cycling between each test condition of the series. No interference in the assembly phase or test stand utilization is shown for DE-2.

For the qualification (prior to the first gimbaling QE engine) assembly level verification tests, the WEMU-2 and E-C assemblies are expected to be available. Upgrading assembly components to qualification design level (as affects stiffness, mass properties, fastening, etc.) is required for the tests to be representative. As indicated on the NRTO Milestone Network (10-27-70), test stand interference is shown for consideration of the pre-ground-firing test option.

As discussed under "Safety", additional hardware would have to be scheduled to perform, as a minimum, the extensive cycling and margin tests if the pre-ground-firing test option is selected.

3.4.5 Cost

A major cost consideration for the alternate means of gimbaling verification is whether these tests are merged with the gimbal system testing. Schedule permitting, the cost increase due to handling a more complex assembly may be kept small and eliminate the duplication.

Hardware cost savings would be accomplished by using the WEMU-2 and E-C inert engine assemblies due to the prototype representation. From a cost consideration, this is the recommended option for verifying those TVC requirements which cannot be demonstrated during the engine ground firings. Upgrading the gimbal system tests would require an increase in additional prototype hardware to meet the verification requirements. However, use of reusable hardware or acceptable simulators (pressure vessel, inert reactor, nozzle, external shield, lines, turbopumps, wiring harness) could represent means of minimizing the cost increase. Verification
testing in the test stand prior to the firing would incur costs primarily in the load fixturing due to more complex conditions than expected in an engineering laboratory oriented test.

In each of these instances, it has been assumed that at least minimum rate response would be demonstrated during the engine firing. Further, it has been assumed that these alternate means of verification include none of the environmental conditions, thus permitting a more controllable test. If such is not the case, the complexity involved to simulate these environmental conditions consistent with the performance and reliability requirements will become exceedingly expensive with questionable effectiveness.

B.4.0 CONCLUSIONS AND RECOMMENDATIONS

The evaluation results are summarized in the parameter matrix shown in Table B-2.

The WEMU-2 and E-C engine assemblies provide the best engine characteristics simulation of the options considered. However, these assemblies are limited as to availability and possible use for extensive cycle and margin testing. A cost savings can be achieved by combining this testing and the planned gimbal system testing.

The gimbal system test assembly meets all parameter requirements provided that refurbished or simulated hardware, which meet the specified characteristics, are available for the assembly buildup. This option is advantageous for extensive cycling and margin testing.

The WEMU-1 assembly was found unacceptable due to an inadequate engine stiffness and mass properties characteristics simulation.

The major weakness of the use of a ground firing engine for TVC verification in the engine test facilities prior to power testing was the apparent safety risk
of hardware damage to non-gimbal actuator components due to extensive cycling and margin testing. Inclusion of additional assemblies for these tests would be required. Some test stand schedule interference is likely during the qualification test phase.

It is recommended that an upgraded gimbal system development test assembly be used for the development level TVC verification prior to the DE-2 "gimbaled" engine power test.

It is recommended that either the WEMU-2 or the E-C engine assembly be used for the engine qualification level TVC verification prior to the initial QE "gimbaled" engine power test.
FIGURE B-1

GIMBAL ACTUATOR SETUP FOR RESPONSE TESTING
FIGURE B-2
SETUP SCHEMATIC FOR GIMBAL SYSTEM
RESPONSE TESTING

75K THRUST LESS INERTIA
ADJUSTMENTS

OFFSET LOADING FOR
THRUST MISALIGNMENT

SIDE LOAD
ACTUATOR

SIMULATED MASS AND
INERTIA OF ENGINE
BELOW LTS

EXTERNAL RADIATION
SHIELD

LOWER THRUST STRUCTURE

GIMBAL PIVOT ASSEMBLY

GIMBAL ACTUATOR

UPPER THRUST STRUCTURE

STAGE INTERFACE SIMULATOR

COMPUTER
### FIGURE B-3
INERT ENGINE TEST SEQUENCE

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
<td>FUELED ENGINE PROGRAM (SEE FIGURE 1)</td>
</tr>
<tr>
<td>73</td>
<td>WEMU-1 E-MAD ASSEMBLY</td>
</tr>
<tr>
<td>74</td>
<td>E-MAD TRANSPORTATION</td>
</tr>
<tr>
<td>75</td>
<td>ETS-1 TEST STAND BUILDUP TRANSPORTATION &amp; HANDLING</td>
</tr>
<tr>
<td>76</td>
<td>E-MAD TRAINING, MAINTAINABILITY, ETC TESTING</td>
</tr>
<tr>
<td>77</td>
<td>WEMU-2 E-MAD ASSEMBLY AGE, MGE TVC, MAINTAINABILITY, SEQUENCING, CHECKOUT TESTING, ETC</td>
</tr>
<tr>
<td>78</td>
<td>E-C E-MAD ASSEMBLY TRANSP., &amp; MAINTAINABILITY</td>
</tr>
<tr>
<td>79</td>
<td>ETS-1 COLD FLOW TESTING TRANSP. &amp; HANDLING</td>
</tr>
<tr>
<td>80</td>
<td>ENVIRONMENTAL TESTING (LOCATIONS TBD)</td>
</tr>
</tbody>
</table>

* OPERATING PLAN RESCHEDULING REQUIRED

REFERENCE 10
## Table B-1

**Flight Condition Simulation as Related to Alternate Means of Verification**

<table>
<thead>
<tr>
<th>Simulated Characteristic</th>
<th>WEMU-1</th>
<th>WEMU-2/E-C</th>
<th>Pre-Ground Firing</th>
<th>Gimbal System Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stage/engine interface stiffness</td>
<td>Yes(2)</td>
<td>Yes(2)</td>
<td>No (ETS-1)</td>
<td>Yes (E/STS-2)</td>
</tr>
<tr>
<td>2. Engine stiffness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Gimbal loop</td>
<td>No</td>
<td>Yes(3)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>b. Basic engine</td>
<td>No</td>
<td>Yes(3)</td>
<td>Yes</td>
<td>Partial(4)</td>
</tr>
<tr>
<td>c. Structural</td>
<td>Some</td>
<td>Yes</td>
<td>Yes</td>
<td>Partial(4)</td>
</tr>
<tr>
<td>3. Gimbaled engine mass properties</td>
<td>Approximate</td>
<td>Yes</td>
<td>Yes(6)</td>
<td>Yes(5)</td>
</tr>
<tr>
<td>a. Weight</td>
<td>Not Defined</td>
<td>Yes</td>
<td>Yes(6)</td>
<td>No</td>
</tr>
<tr>
<td>b. Mass distribution</td>
<td>Not Defined</td>
<td>Yes</td>
<td>Yes(6)</td>
<td>Yes(5)</td>
</tr>
<tr>
<td>c. Center of gravity</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes(6)</td>
<td>Yes(5)</td>
</tr>
<tr>
<td>d. Pitching moment of inertia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Mechanical loads</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Thrust</td>
<td>Yes(8)</td>
<td>Yes(8)</td>
<td>Note(7)</td>
<td>Yes(8)</td>
</tr>
<tr>
<td>b. Thrust load misalignment</td>
<td>Yes(8)</td>
<td>Yes(8)</td>
<td>Note(7)</td>
<td>Yes(8)</td>
</tr>
<tr>
<td>c. Vehicle pitching motion moment</td>
<td>Yes(8)</td>
<td>Yes(8)</td>
<td>Note(9)</td>
<td>Yes(8)</td>
</tr>
<tr>
<td>d. Spring rates of gimbaled components</td>
<td>No</td>
<td>Yes(11)</td>
<td>Yes(11)</td>
<td>Yes(12)</td>
</tr>
<tr>
<td>e. Single turbopump</td>
<td>No</td>
<td>Yes(11)</td>
<td>Yes(11)</td>
<td>Yes(12)</td>
</tr>
<tr>
<td>5. Thermal loads</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Cryogenic filling PIL's</td>
<td>No</td>
<td>No</td>
<td>Yes(13)</td>
<td>No</td>
</tr>
<tr>
<td>b. Fluids in other lines</td>
<td>No</td>
<td>No</td>
<td>Yes(13)</td>
<td>No</td>
</tr>
<tr>
<td>6. Induced vibration from engine operation (turbo pumps, nozzle exhaust) Note (13)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Induced nuclear radiation</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>8. Thermal conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Nuclear induced</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>b. Solar soak</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>c. Cold soak</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>d. Heat sink conditions</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

**Notes:**

1. See para B.3.1 for discussion on the options.
2. Assumes use of special interface simulator from thrust structure test program.
4. Lack simulation aft of PV-thrust structure interface.
5. Minimum requirements of the mass properties simulators.
6. Based on ground test engine using nozzle extension inertia simulator.
7. Since engine is hanging nozzle down, weight is applied in direction opposite to the thrust. Test would require load jacks providing reaction of thrust + weight to simulate proper loading.
8. Hydraulic and/or pneumatic load jacks to be used and programmed according to independent or dependent on actuator stroke.
9. Assumes attaching pneumatic load jack to ETC wall.
10. Spring rate will be higher due to inclusion of emergency cooldown line and additional electrical cabling for ground firing.
11. Assumes pressurizing engine system to 30 psi with use of nozzle plug.
12. Assumes simulated PIL's can contain 30 psi.
13. Assumes cold flow of hydrogen is allowed.
TABLE B-2

COMPARISON OF PARAMETER EVALUATION AS RELATED TO ALTERNATE MEANS OF VERIFICATION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WEMU-1</th>
<th>WEMU-2/E-C</th>
<th>Pre-Ground Firing</th>
<th>Upgraded Gimbal System Test Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance Simulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Loads (1)</td>
<td>Satisfactory</td>
<td>Satisfactory</td>
<td>More complex. Dependent on load fixture capability in the test facility</td>
<td>Satisfactory</td>
</tr>
<tr>
<td>b. Engine characteristics</td>
<td>Not acceptable</td>
<td>Excellent</td>
<td>Satisfactory</td>
<td>Good</td>
</tr>
<tr>
<td>Reliability</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. General</td>
<td>Not acceptable</td>
<td>Good</td>
<td>Satisfactory</td>
<td>Good</td>
</tr>
<tr>
<td>b. Extensive cycling and</td>
<td>Not acceptable</td>
<td>May be restricted depending on later use</td>
<td>Not permitted due to safety risk</td>
<td>Capable</td>
</tr>
<tr>
<td>margin testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schedule</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Pre- (DE-2) firing</td>
<td>Available</td>
<td>Not available</td>
<td>Stand available (2)</td>
<td>Available provided upgraded hardware is received</td>
</tr>
<tr>
<td>b. Pre- QE firing</td>
<td>Available</td>
<td>Available</td>
<td>Anticipated stand (2) interference</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Requires complete rebuilding</td>
<td>Can combine with gimbal system tests</td>
<td>Requires extra assemblies to perform deleted &quot;safety risk&quot; cycling and margin tests.</td>
<td>Obtain reusable hardware, simulators, etc.</td>
</tr>
</tbody>
</table>

NOTES: (1) Assumes use of load fixturing.
(2) Require engine assembly completed about 3 months earlier for testing than presently programmed if option is selected.
APPENDIX C

GIMBAL ACTUATOR RESPONSE RESULTS AND ANALYSIS SUPPORTING RATE OPTION GIMBAL AMPLITUDE ESTIMATES
Servo analyses for ground testing conditions have been conducted using data parameters representing two GA concepts, 1138420 and 1138345. These characteristics are presented in Reference 18. The former is a bidirectional high speed, gear reduced d.c. motor-driven linear actuator (see Figure 10). The latter is a bidirectional direct drive torque motor-driven linear actuator (see Figure C-7). Both concepts are shown since the variable rate analysis was conducted with the 1138345 concept. The 1138420 concept is presently shown on the engine layout 1137400C.

Engine mass properties were referenced from the April issue of S-047 (Reference 12). Cases are presented in which ALM flight engine properties (Group A) were used to represent conditions where the inertia simulator is attached to the 24:1 ground test nozzle. A couple of cases were conducted for comparison where no simulator is included (Group B). A summary of these properties are given in Table C-1.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Group A</th>
<th>Group B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight, K lbs</td>
<td>33.9</td>
<td>33.3</td>
</tr>
<tr>
<td>Mass moment of inertia, slug-ft²</td>
<td>120,000</td>
<td>103,200</td>
</tr>
<tr>
<td>Center of gravity, Eng. Sta, inches</td>
<td>130.0</td>
<td>126.4</td>
</tr>
</tbody>
</table>
A comparison of ALM and ground test system characteristics for the servo
loop are provided in Table C-2 for the two concepts.

TABLE C-2

COMPARISON OF ALM AND GROUND TEST(1)
GENERAL SYSTEM CHARACTERISTICS(2)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Concept 1138420 ALM</th>
<th>Concept 1138420 Ground</th>
<th>Concept 1138345 ALM</th>
<th>Concept 1138345 Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undamped frequency, rad/sec</td>
<td>7.0</td>
<td>7.6</td>
<td>6.85</td>
<td>7.4</td>
</tr>
<tr>
<td>Damped frequency, rad/sec</td>
<td>5.0</td>
<td>5.35</td>
<td>5.18</td>
<td>5.57</td>
</tr>
<tr>
<td>Damping ratio</td>
<td>0.70</td>
<td>0.70</td>
<td>0.66</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Response to various rate commands initiated from the null position are
presented in Figures C-1 through C-6. Position feedback was used in each case. A
listing noting actuator concept, mass properties group and command rate are as
follows:

<table>
<thead>
<tr>
<th>Figure</th>
<th>Concept</th>
<th>Mass Properties Group</th>
<th>Command Rate, deg/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1</td>
<td>1138420</td>
<td>B</td>
<td>0.75</td>
</tr>
<tr>
<td>C-2</td>
<td>1138420</td>
<td>A</td>
<td>0.75</td>
</tr>
<tr>
<td>C-3</td>
<td>1138345</td>
<td>B</td>
<td>0.75</td>
</tr>
<tr>
<td>C-4</td>
<td>1138345</td>
<td>A</td>
<td>0.75</td>
</tr>
<tr>
<td>C-5</td>
<td>1138345</td>
<td>A</td>
<td>0.25</td>
</tr>
<tr>
<td>C-6</td>
<td>1138345</td>
<td>A</td>
<td>0.50</td>
</tr>
</tbody>
</table>

(1) Based on mass properties without nozzle extension (Group B).
(2) Based on a simplified model where the engine structure was assumed to be
infinitely stiff.
A summary of response characteristics to these commands are presented in Table C-3. In comparison of the 0.75 deg/sec responses, the 1138345 concepts indicate greater overshoot. This characteristic is influenced by the lower damping ratio (0.66 compared to 0.7 for 1138420). Adjustment with a rate feedback would reduce the difference.

**TABLE C-3**

**GROUND TEST RAMP COMMAND RESPONSE CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>GA Concept 1138420</th>
<th>GA Concept 1138345</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration, deg/sec²</td>
<td>Case C-1</td>
<td>Case C-2</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Rate overshoot, %</td>
<td>Case C-3</td>
<td>Case C-4</td>
</tr>
<tr>
<td></td>
<td>2.9</td>
<td>4.1</td>
</tr>
<tr>
<td>Steady-state rate</td>
<td>Case C-5</td>
<td>Case C-6</td>
</tr>
<tr>
<td>Error, %</td>
<td>3.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Deg/sec</td>
<td>.024</td>
<td>.026</td>
</tr>
<tr>
<td>Rate stabilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to reach + 5% of command</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>Rate, sec (3)</td>
<td>0.40</td>
<td>0.40</td>
</tr>
</tbody>
</table>

NOTES: (1) Cases C-1 through C-4, rate is 0.75 deg/sec. C-5 is 0.25 deg/sec and C-6 is 0.50 deg/sec.

(2) Cases C-1 and C-3 represent no inertia simulator.

(3) Since rate overshoot < 5%, time represents the lower limit.
Gimbal amplitudes needed to reach the "steady-state" response can be approximated from the response curves in Figures C-1 through C-6. As shown, this condition is reached in about 1.0 to 1.2 seconds, resulting in the following positions. Recommended amplitudes are shown in Table C-4.

TABLE C-4

GIMBAL AMPLITUDE FOR RATE "MINIMUM ACCEPTABLE" CASE

time, sec

<table>
<thead>
<tr>
<th>Rate</th>
<th>1.0</th>
<th>1.2</th>
<th>Recommended Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>0.59 degree</td>
<td>0.73 degree</td>
<td>± 0.70 degree</td>
</tr>
<tr>
<td>0.50</td>
<td>0.38</td>
<td>0.47</td>
<td>± 0.45</td>
</tr>
<tr>
<td>0.25</td>
<td>0.19</td>
<td>0.25</td>
<td>± 0.25</td>
</tr>
</tbody>
</table>

If about 300 milliseconds is allowed for demonstrating that a "steady-state" response can be maintained, additional amplitudes of 0.075, 0.15 and 0.225 degrees are needed for the 0.25, 0.50 and 0.75 deg/sec rates, respectively. The "target" case amplitude estimates are obtained by adding these values to the amplitude estimates for the "minimum acceptable" case (Table C-5).

TABLE C-5

GIMBAL AMPLITUDE FOR RATE "TARGET" CASE

<table>
<thead>
<tr>
<th>Rate</th>
<th>Recommended Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75 deg/sec</td>
<td>0.93 degree</td>
</tr>
<tr>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>0.25</td>
<td>0.33</td>
</tr>
</tbody>
</table>

C-5
FIGURE C-1
RESPONSE TO A 0.75 DEG/SEC RAMP COMMAND FROM THE NULL POSITION DURING ENGINE GROUND TESTING
GA CONCEPT 1138420

GIMBAL POSITION, DEG

GIMBAL RATE, DEG/SEC

TIME, SEC

COMMAND RATE POSITION

-.17 DEG POSITION ERROR

RESPONSE POSITION

\[ \dot{\theta} = 2.3 \text{ DEG/SEC}^2 \]

PO = 0.9%

\[ \sim 0.024 \text{ DEG/SEC RATE ERROR} \]

Response Rate
FIGURE C-2
RESPONSE TO A 0.75 DEG/SEC RAMP COMMAND FROM THE NULL POSITION DURING ENGINE GROUND TESTING WITH INERTIA SIMULATOR - GA CONCEPT 1138420

1.5

GIMBAL POSITION, DEG

0.5

1.0

0.0

1.5 1.0 0.5 0.0

TIME, SEC

0.5 1.0 1.5 2.0

COMMAND RATE POSITION

-.17 DEG POSITION ERROR

RESPONSE POSITION

GIMBAL RATE, DEG/SEC

0.75

0.50

0.25

0.0

1.00

0.75

0.50

0.25

0.0

TH = 2.3 DEG/SEC²

P0 = 2.1%

-.026 DEG/SEC RATE ERROR (-3.5%)

RESPONSE RATE

TIME, SEC

0.5 1.0 1.5 2.0

C-7
FIGURE C-3
RESPONSE TO A 0.75 DEG/SEC RAMP COMMAND FROM
THE NULL POSITION DURING ENGINE GROUND TESTING -
GA CONCEPT 1138345

GIMBAL POSITION, DEG

TIME, SEC

GIMBAL RATE, DEG/SEC

TIME, SEC

COMMAND RATE POSITION

- .17 DEG POSITION ERROR

RESPONSE POSITION

\( \dot{\theta} = 2.3 \text{ DEG/SEC}^2 \)

\( \theta_0 = 2.9\% \)

RESPONSE RATE

- .023 DEG/SEC RATE ERROR

C-8
FIGURE C-4

RESPONSE TO A 0.75 DEG/SEC RAMP COMMAND FROM THE NULL POSITION DURING ENGINE GROUND TESTING WITH INERTIA SIMULATOR - GA CONCEPT 1138345

GIMBAL POSITION, DEG

TIME, SEC

GIMBAL RATE, DEG/SEC

TIME, SEC

θ" = 2.3 DEG/SEC²

PO = 4.1%

-.024 DEG/SEC RATE ERROR (3.3%)
FIGURE C-5
RESPONSE TO A 0.25 DEG/SEC RAMP COMMAND FROM THE NULL POSITION DURING ENGINE GROUND TESTING WITH INERTIA SIMULATOR - GA CONCEPT 1138345

GIMBAL POSITION, DEG

1.5
1.0
0.5
0

TIME, SEC

0
0.5
1.0
1.5
2.0

GIMBAL RATE, DEG/SEC

1.00
0.75
0.50
0.25

TIME, SEC

0
0.5
1.0
1.5
2.0

0 = 0.8 DEG/SEC^2

PO = 4.0%

-0.008 DEG/SEC RATE ERROR (-3.2%)
FIGURE C-6
RESPONSE TO A 0.50 DEG/SEC RAMP COMMAND FROM THE NULL POSITION DURING ENGINE GROUND TESTING WITH INERTIA SIMULATOR - GA CONCEPT 1138345

GIMBAL POSITION, DEG

COMMAND RATE POSITION

RESPONSE POSITION

-.107 DEG POSITION ERROR

TIME, SEC

GIMBAL RATE, DEG/SEC

\[ \ddot{\theta} = 1.5 \text{ DEG/SEC}^2 \]

COMMAND RATE

PO = 4.0%

-.017 DEG/SEC RATE ERROR (3.4%)

RESPONSE RATE

TIME, SEC
APPENDIX D

SUPPORTING ANALYSIS FOR RATE OPTION SNUBBER DISPLACEMENT ESTIMATES

D-1
A preliminary estimate for the flight gimbal cooling snubber amplitude is 0.50 degrees (Reference 9). Based on the present 25-inch actuator lever arm, this amplitude represents about 0.22-inch of actuator linear motion.

Kinetic energy parameters at snubber contact were assumed as follows:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Rotational About</th>
<th>Linear Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass/inertia</td>
<td>1.80 x 10^6 lb-in.-sec^2</td>
<td>2880 lb-sec^2/in.</td>
</tr>
<tr>
<td>Velocity</td>
<td>2.5 deg/sec</td>
<td>1.10 in./sec</td>
</tr>
</tbody>
</table>

The angular velocity was estimated as a reasonable upper limit using servo analysis results for the 1138420 and 1138345 GA concepts as a guide. The condition used for maximum possible velocity was a 3 degree saturated command in which the operational electrical channel fails at the time of achieving linear amplifier control. As a conservative approach, the decelerating effect of switching in the standby channel was neglected. For the ground case, consider a similar approach as a rough approximation.

Representing the GA concept 1138420 servo system, a typical rate versus position curve is presented in Figure D-1 corresponding to a 3 degree saturated command initiated from the null position. In this case maximum rate was found to be 1.82 deg/sec. For a preliminary snubber displacement estimate, consider the following expression to determine requirements for reduced maximum velocity capability.

\[
(\theta_s)_{\text{ground}} = \left(\frac{\dot{\theta}_2}{\theta_1}\right)^2 \cdot (\theta_s)_{\text{flight}}
\]

(1) 80 percent represents gimbaled engine inertia. Remainder is for actuator inertia.
where

\[ \dot{\theta}_s = \text{gimbal amplitude for snubbing} \]

\[ \dot{\theta}_1 = 1.82 \text{ deg/sec representing analytical model results for} \]

flight GA concept 1138420

\[ \dot{\theta}_2 = \text{maximum rate for a ground test saturated command with a} \]

displacement at the snubber contact amplitude.

Displacement results are shown in Table D-1 for each of the TVC amplitudes required as related to the verification option goal and case condition (see para IV.D.1).
FIGURE D-1

GIMBAL RATE VERSUS GIMBAL POSITION DURING
A 3 DEGREE SATURATED COMMAND INITIATED
FROM THE NULL POSITION

NOTE: DATA IS BASED ON ALM FLIGHT CONDITION LOADS.
SOURCE DATA IS PRESENTED IN REFERENCE 6
TABLE D-1

GIMBAL AMPLITUDES
AND
ACTUATOR LINEAR DISPLACEMENTS FOR SNUBBING

<table>
<thead>
<tr>
<th>Goal Option (1)</th>
<th>TVC Amplitude (1)</th>
<th>Velocity, $\dot{\theta}_2$ (2)</th>
<th>Gimbal Amplitude</th>
<th>Actuator Linear Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight system</td>
<td>+ 3.5 deg</td>
<td>1.82 deg/sec</td>
<td>+ 0.50 deg</td>
<td>+ 0.218 inches</td>
</tr>
<tr>
<td>0.75 deg/sec rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>+ 0.93</td>
<td>1.52</td>
<td>+ 0.35</td>
<td>+ 0.153</td>
</tr>
<tr>
<td>min accept</td>
<td>+ 0.70</td>
<td>1.48</td>
<td>+ 0.33</td>
<td>+ 0.144</td>
</tr>
<tr>
<td>0.50 deg/sec rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>+ 0.60</td>
<td>1.46</td>
<td>+ 0.32</td>
<td>+ 0.140</td>
</tr>
<tr>
<td>min accept</td>
<td>+ 0.45</td>
<td>1.43</td>
<td>+ 0.307</td>
<td>+ 0.134</td>
</tr>
<tr>
<td>0.25 deg/sec rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>target</td>
<td>+ 0.33</td>
<td>1.38</td>
<td>+ 0.286</td>
<td>+ 0.125</td>
</tr>
<tr>
<td>min accept</td>
<td>+ 0.25</td>
<td>1.33</td>
<td>+ 0.267</td>
<td>+ 0.116</td>
</tr>
</tbody>
</table>

NOTES: (1) Goal options and respective amplitudes are discussed in para. IV.D.1.
(2) Data obtained from Figure D-1 based on amplitude position.