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PROBABILITY OF EOSS MISSION SURVIVAL EVALUATION OF THE IMPACT OF ARTIFICIAL-GRAVITY OPERATIONS ON THE OVERALL MISSION RELIABILITY

Preliminary Report

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SUMMARY

This report documents the work accomplished in determining the impact that artificial-gravity operations would have on the overall probability of Early Orbital Space Station mission success. It fulfills the requirements of Technical Directive 2-4-15, Subtask 5, dated 26 January 1968.

This analysis evaluated both qualitatively and quantitatively the effects on overall EOSS mission reliability of having artificial-gravity operations performed as part of the mission. The additional hardware and operations required for the artificial-gravity mode results in a reduction in overall EOSS reliability of approximately 1.0 percent.

Artificial-g operations will result in additions and changes to the following systems which will degrade the overall reliability of the space station and/or degrade their operation:

1. Electrical Power System
2. Reaction Control System
3. Stabilization and Control System
4. Communication and Data Management System
5. Structural and Mechanical System
6. Environmental Control/Life Support System
7. Crew Systems

It is recommended that analyses be performed as soon as possible to determine the impact of artificial-g operations on (1) Safety, Escape and Failure Detection, and (2) EVA operations.

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1.0 INTRODUCTION

The purpose of this study is to provide additional information on the impact that artificial-gravity operations will have on the probability of success of an Early Orbital Space Station mission. This information is presented to further assist in determining the most effective configuration to accomplish the various mission goals under consideration.

The baseline Early Orbital Space Station (EOSS) operates in a zero-g mode. It may provide an onboard centrifuge as a therapeutic tool and/or an experiment for periodic conditioning of the space station personnel. Of necessity, the capacity of the centrifuge would be limited. If experiment requirements or if space experience (e.g., Apollo, MOL, Saturn I Workshop, etc.) proves the need for continuous g-forces for long-term crew effectiveness/health, a modification of the baseline EOSS configuration will have to be made to provide this artificial-gravity condition.

The modification of the baseline EOSS configuration would take the form of providing for rotation of the entire space station. This report treats the qualitative and quantitative effects of the modifications (i.e., hardware and operations) on the baseline configuration with respect to the probability of mission success.

Artificial-g operations will result in additions and changes to the following systems which will degrade the overall reliability of the space station and/or degrade their operation:

1. Electrical Power System
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3. Stabilization and Control System
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5. Structural and Mechanical System
6. Environmental Control/Life Support System
7. Crew Systems

2.0 QUALITATIVE ANALYSIS

2.1 General

The EOSS will be capable of both zero- and artificial-gravity operation. It will be required to have a rotational capability to provide a contingency artificial-gravity mode of operation that would be put into effect as an experiment. The artificial-gravity environment will be produced by rotating the entire space station. It is assumed that this alternate configuration will retain all baseline EOSS capabilities.

The configuration considered for this analysis has the spent S-II stage attached to the EOSS. The S-II Stage is the counterweight for the artificial-gravity operation. This configuration solution provides for (1) a maximum-length extension (approximately 90 feet) between the space station and the counterweight (S-II Stage) to attain the required 0.2-0.3 g-level environment at the experiment area, (2) a means of spin-up and de-spin for rotation, and (3) a system to provide stabilization and control.

Rotation of the space station will have a significant impact on station operations, subsystems, interior layout and experiment performance. Table 2.1 summarizes some of the impacts of artificial-gravity operation. The artificial-gravity mode will require more functions and equipment than the baseline EOSS. This will result in a degradation of reliability and safety (e.g., the reliability problem will increase with added complexity and crew hazards will increase due to the spin/de-spin dynamics of the space station, probably causing abort or delay constraints). It is assumed that the S-II Stage cannot provide additional services (e.g., electrical power, crew quarters, reaction control, etc.) to the EOSS.

2.2 Electrical Power System

The solar panels provided on the EOSS may not be designed for spin operations. Modifications of the present solar panel design concept to withstand the station rotation dynamics is likely. In order to provide sufficient power, the space station will have to be operated in a solar orientation during rotation. This would entail some propellant penalty. It may be possible to relocate the solar panels and/or provide them with a gimballing capability so that the array always will be solar oriented no matter what orientation the space station has. Another alternate approach to consider is to provide an added power capability (e.g., fuel cells, additional batteries, etc.) to meet the needs of the space station while in the artificial-gravity mode of operation. It should be noted that, with this alternate approach, the baseline EOSS orientation is not precluded by the artificial-gravity (rotation) mode operations.

2.3 Reaction Control System (RCS)

The artificial-gravity operational mode for the EOSS will have an impact on the RCS. The addition of reaction motors, fuel, oxidizer, and pressurization systems to the baseline EOSS will be required to provide the required spin-up and de-spin

TABLE 2.1: IMPACT OF ARTIFICIAL-GRAVITY OPERATIONS ON EOSS BASELINE

AREA	IMPACT
Mission	Limits the number of experiments that can be performed.
Space Station	Interiors will require rearrangement.
Systems:	
Electrical Power	Provide added power capability (e.g., batteries, fuel cells, etc.) OR maintain solar orientation. Redesign of solar array to withstand rotation dynamic forces may be required.
Reaction Control	Provide RCS in addition to that present on the baseline. Additional thrusters and propellant are necessary.
Stabilization and Control	Provide additional control logic and mode switching. Gyroscopes may precess abnormally during artificial-gravity mode.
Structural and Mechanical	Provide sufficient support to CSM's while they are docked to the EOSS to withstand forces generated during artificial-gravity operations.
Experiments	Some experiments will be curtailed during artificial-gravity operations.
Counter-Weight Deployment	This system must be designed and added to the baseline EOSS configuration.
Communication	It may be necessary to provide new antenna and data links.

capability. The special RCS and propellant requirements (i.e., precession control, orientation and orbit keeping as well as spin-up and de-spin functions) will be provided by the EOSS. An increase in the unreliability of the baseline EOSS configuration will occur due to the additional hardware and operational requirements.

Use of the S-II Stage as a counter-weight restricts the location of the RCS to the forward end of the EOSS. The use of the thrusters provided for zero-g operation appears impractical because of their high propellant consumption. The added RCS will provide a slow, steady and continuous thrust to provide the necessary spin to the space station. A counterweight will be used to accomplish the de-spin operations. The RCS will be used also as a backup to the stabilization and control system to accomplish wobble damping.

2.4 Stabilization and Control System (SCS)

The demands upon the SCS will be increased by the artificial-gravity (rotating) mode requirement. With respect to the baseline EOSS configuration, the added SCS elements and operations will decrease the overall probability of success.

A major aspect of the artificial-gravity mode of operation will be the influence of the space station's spin orientation on the complexity of the control logic as well as on propellant consumption. Table 2.2 presents a summary of the four possible spin orientations. Any orientation, other than the spin-in-orbit plane, will complicate orbit keeping. Relatively complex control logic and additional sensors will be required to control the RCS (i.e., thrusting functions) during the spin and orbit cycles.

TABLE 2.2: SUMMARY OF POSSIBLE EOSS SPIN ORIENTATIONS

ORIENTATION	DESCRIPTION
1. Spin-In-Orbit Plane	The spin axis is normal to the orbit plane. It must be precessed to compensate for orbit-plane regression.
2. Solar	The spin axis is pointed at the sun. This is the orientation assumed for this analysis. It is used primarily for the application/function of the solar panels to provide the necessary electrical power. A sun tracker will be required to precess the spin axis to compensate for the Earth's rotation about the sun.
3. Inertial	The spin axis is positioned with respect to an arbitrary inertial reference. Operations for this orientation are the same as those for the spin-in-orbit plane.
4. Random	The direction of the spin axis is uncontrolled except during spin-up. After spin-up, the spin axis is allowed to precess as disturbance torques dictate. Of the four orientations, this one will have the least propellant consumption.

Artificial-gravity operations will require additional SCS equipment. Table 2.3 summarizes the SCS equipment necessary for this mode of operation. Primary control actuation during zero-g operation (i.e., baseline EOSS configuration/mission) is to be provided by three double-gimbal control moment gyros (DG CMG) arranged in the NASA Langley SIXPAC configuration as used for the

Apollo Telescope Mount (ATM). Two of these DG CMG's would be used to provide primary control actuation for wobble damping during artificial-gravity operation (NOTE: RCS thrusters would provide a backup for the damping mode).

During artificial-gravity operation, the SCS in conjunction with the RCS will be required to perform six operations. These operations are as follows:

1. Orbit Keeping
2. Precession Control
3. Sun Tracking
4. Gravity Gradient
5. Spin-up
6. De-spin

The SCS defined for the zero-g mode of operation has the necessary sensors to mechanize the artificial-gravity mode. The rate gyros would be utilized to provide the necessary error signals to the DG CMG's for wobble damping. However, additional mode switching electronics and control logic will be required for the SCS to provide the mechanization of the artificial-gravity (rotation) mode.

2.5 Structural and Mechanical System

Station rotation (i.e., artificial-gravity operation) will automatically provide an up-down orientation reference for the crew. Therefore, the space stations' interior equipment arrangement must be adaptable to the artificial-gravity mode where the

TABLE 2.3: SUMMARY OF SCS EQUIPMENT FOR ARTIFICIAL-G OPERATION

EQUIPMENT	FUNCTION
1. Rate Gyro and Electronics	Spin rate control
2. Horizon Detectors and Electronics (e.g., Thermistor Bolometer Types)	Orbit keeping
3. Masked Sun Sensor	Attitude sensing
4. Star Tracker	Attitude sensing
5. Manual Controllers and Displays	Manual control
6. Control Logic and Associated Electronics	Orbit keeping and precession control
7. Double Gimbal Control Moment Gyro	Wobble damping

"upper" deck will act as a floor. It may be necessary to modify the baseline EOSS configuration systems so that they can withstand g-levels imposed in one direction during launch and the opposite direction during the artificial-gravity mode of operations

Possible degradations within this system (i.e., airlock seals, hatch deformation and seals, etc.) are possible. In addition, the multiple docking adapter (MDA) must be reinforced and provisions made for additional support for the control and service modules (CSM's) while docked to the space station in order to preclude damage to the docking rings and their associated structural and mechanical components when artificial-gravity operations are in progress.

2.6 Experiments

The defined experiment (i.e., baseline program) may have to be curtailed, redesigned or redefined for operation during artificial-gravity (rotation) operations. Most EOSS experiment installations are designed for use during zero-g operations and will be restricted while the space station is in the rotating mode. In order to increase the availability of the experiments during this period, it may be necessary to provide the capability of operations involving independent modules for the astronomy-astrophysics technology and/or bioscience technology experiments. This contingency will entail a further reliability degradation (Ref. 7).

2.7 Counterweight Deployment System

The deployment system is responsible for the detachment and progressive separation of the counterweight (i.e., spent, purged and passive S-II Stage) from the space station. The design under consideration is a rigid extension system providing an extended length of approximately 90 feet. The design concept is a folded, octagonal cross-section truss divided into four sections terminating into 30-inch segments of the S-II/S-IVB interstage. The structure is deployed one section at a time through the action of torsion bars. The added complexity and function of the deployment system will decrease the overall probability of baseline EOSS mission success. (NOTE: Two basic assumptions associated with the use of the S-II as a counterweight for the artificial-gravity operation are (1) the S-II Stage can be purged and passivated, and (2) no moments will be generated during this process.)

2.8 Communications System

In order to maintain communication with the Earth, new, additional antennas may have to be provided. In addition, new and additional up- and down-links may have to be established. This will hold true for the telemetry data links also. This added complexity will increase the unreliability of the baseline EOSS configuration. It should be noted that all antennas (i.e., both baseline and added) will have to be designed and structured to withstand the rotational, dynamic forces present during artificial-gravity operation.

3.0 QUANTITATIVE RELIABILITY ANALYSIS

3.1 General

The artificial-gravity mode of operations imposes significant additional equipment and functional complexities on the baseline EOSS configuration. Examples of some of the equipment and changes specifically required for the artificial-gravity mode that will increase the reliability problem are:

1. Additional functional requirements for double-gimbal control moment gyros (DG CMG) and rate gyros.
2. Logic changes and additions within the stabilization and control system (SCS).
3. Modifications of the related displays and controls.
4. Added thrusters and associated control logic to the reaction control system (RCS).
5. Modifications of the electrical system (i.e., solar array structures and/or additional power sources such as fuel cells).
6. Added system to extend/deploy the counterweight (S-II Stage) required for the artificial-gravity mode.
7. Modifications and additions to the communication system (i.e., added antenna and up- and down-links as well as strengthening the antenna structures).
8. Modification of the space station structural and mechanical system.

3.2 Approach and Results

The results of previous detailed analyses of artificial-gravity modes of operation for space stations (i.e., EOSS, References 1, 2, 3 and 4; and MORL, Reference 6) were analyzed to determine the percent increase in unreliability of the affected systems due to this mode. Table 3.1 summarizes the results of this analysis. The applicable percentage was then applied to the reliability goals (Reference 5) of the EOSS systems to determine the impact of artificial-gravity operations on the overall baseline EOSS probability of mission success. Table 3.2 summarizes the results of this determination.

The results of this evaluation indicate that there will be a decrease in the overall reliability of the baseline EOSS mission of approximately 1.1 percent if the solar orientation is maintained. However, if this is not possible due to other constraints (e.g., excessive propellant requirements, etc.) and fuel cells are utilized to provide the required power, a decrease in the overall reliability of approximately 7.1 percent will result.

The following example is provided to clarify the procedure used in establishing the reliability of the EOSS with artificial-g operations:

A. The following information about system A is obtained from the applicable references:

   1. Baseline system reliability (R_B): 0.835

   2. Baseline system unreliability (Q_B): 0.180

   3. Increased unreliability due to artificial-g operations (ΔQ): 0.002

B. The fractional increase in unreliability (Δ) is calculated:

$$\Delta = \frac{\Delta Q}{Q_B} = \frac{0.002}{0.180} = 0.011$$

C. The new reliability (R_G) of the comparable EOSS system (A') due to artificial-g operations is calculated:

$R_G = R_B' (1-\Delta) = 0.989\ R_B'$, where R_B' is the EOSS baseline system reliability.

TABLE 3.1: DETERMINATION OF PERCENT INCREASE IN UNRELIABILITY DUE TO ARTIFICIAL-GRAVITY OPERATIONS

System	Increased Unreliability (1)	Percent Increase in Unreliability
Electrical Power	None	-
	(0.06294)*	(6.101)
Reaction Control	0.00003	0.010
Stabilization and Control	0.00169	1.053
Structural and Mechanical	**	-
Counterweight Deployment	0.00015	0.015
Communication and Data Management	0.00010	0.010
Environmental Control/ Life Support	0	-
Crew Systems	0	-
TOTAL	0.00197 (0.06491)*	1.088 (7.189)*

NOTE: * Unreliability due to use of fuel cells in a redundant configuration to provide all required power. This may be reduced if batteries or a combination of fuel cells, batteries and solar array are used instead of fuel cells alone.

** Some degradation may occur.

(1) Derived from previous EOSS and MORL detailed analyses (References 1, 3 and 6).

TABLE 3.2: PROBABILITY OF EOSS MISSION SUCCESS

System	Reliability[1] of EOSS Baseline Mission Configuration (R_B)	Reliability[2] of Alternate (Artificial-g) Mission Configuration (R_G)	% Difference [$\%D = (1 - \frac{R_G}{R_B})\ 100$]
Electrical Power	0.9975	0.9975 (0.9366)*	- (6.101)*
Reaction Control	0.9950	0.9949	0.010
Stabilization and Control	0.9974	0.9869	1.053
Structural and Mechanical	0.9978	0.9978**	**
Counterweight Deployment	-	0.9999	0.015
Communication and Data Management	0.9952	0.9951	0.010
Environmental Control/Life Support	0.9975	0.9975	-
Crew Systems	0.9976	0.9976	-
TOTAL	0.9783	0.9678 (0.9085)*	1.073 (7.135)*

NOTE: (1) Reliability values from reference 5 (Rpt. No. AS-S-223-67).

(2) Estimated reliability values based on results of analyses reported in references 1, 3 and 6.

* If fuel cells in a redundant configuration are used to provide all required electrical power (i.e., if an orientation other than solar is used). Reliability may increase if fuel cells are supplemented by additional batteries and partial power available from solar array.

** Some degradation internal to the space station may occur.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The artificial-gravity mode of operations poses significant increases in the complexity of the EOSS configuration. Additions and changes to the following systems will degrade the overall reliability of the space station:

A. Electrical Power System

B. Reaction Control System

C. Stabilization and Control System

D. Communication and Data Management System

The remaining systems (i.e., Structural and Mechanical, Environmental Control/Life Support, and Crew Systems) should not be reduced in their reliability, but degradations may occur. In addition, a new system must be added to the baseline EOSS in order to accomplish the deployment of the S-II Stage counterweight This added system will degrade the overall reliability of the EOSS also.

The total reliability degradation due to the artificial-gravity mode of operations will be on the order of 1.1 percent if a solar orientation of the space station is maintained during the rotation mode. If this orientation is precluded due to other considerations, the degradation in overall reliability will be on the order of 7.1 percent. This is due to the necessity of utilizing fuel cells as a power source, rather than the solar array to supply the required power while the EOSS is in the artificial-gravity mode.

4.2 Recommendations

. As soon as possible, consideration must be given to the impact that artificial-gravity operations will have on Safety and the probability of crew survival. The question of whether the CSM's can be undocked prior to the complete cessation of space station rotation will have to be answered.

. The effect of the artificial-gravity mode on the operation and reliability of present designs and proposed hardware is unknown; for example, (1) hatches and/or airlock seals may have to be redesigned, (2) operation of gyroscopes will have to be analyzed to determine if unwarranted precessions will occur due to changes in the gravity environment, and (3) functioning of the Guidance and Navigation Computer to react to moments generated during spin-up, spin and de-spin will have to be studied. Detailed analyses should be conducted to determine the effects of artificial-gravity operations of present zero-g designs and operations.

. A determination and analysis of rotational dynamic effects on docked CSM's is needed. There is a likelihood that the docking rings/multiple docking adapter (MDA) and/or the docked CSM/LCSM may be damaged during artificial-gravity operations (i.e., forces generated by and exerted during spin-up, spin and de-spin operations could cause failure and/or degradation). Supporting structures may be required to insure against failure.

. Whether or not the space station is maintained in a solar orientation, the solar arrays, designed for a zero-gravity environment, probably will have to be modified of redesigned structurally (added support) and/or operationally (folded and retracted during space station rotation) to survive the artificial-gravity mode of operations. Therefore, this aspect of the impact of artificial-gravity operations should be analyzed in more detail.

- A determination should be made as to the amount of reduction in experiment activity that will be acceptable during the periods of space station rotation. Consideration may have to be given to utilizing independent modules (i.e., for astronomy-astrophysics and/or bioscience technology experiments) to accomplish the required program of experiments.

- Other means of attaining space station rotation should be considered. An alternate to utilizing thrusters of one kind or another may be the use of electrical energy driving a reaction flywheel to rotate the space station (see Journal of Spacecraft and Rockets, Vol. 4, No. 1, January 1967, "A New Concept in Artificial Gravity Systems" by C. A. Lindley, Aerospace Corporation).

- Consideration must be given to the problem of verification/qualification testing when artificial-gravity operations must be accounted for.

- The impact of artificial-gravity operations on the failure detection system must be evaluated. In addition, the safety and escape contingency modes during periods of space station rotation must be determined.

- Artificial-gravity operations must be considered when planning logistics and resupply operations.

- The effect of artificial-gravity operations on EVA and independent module operations should be determined.

5.0 REFERENCES

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