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Use of Taguchi Design of Experiments to Optimize and Increase Robustness of Preliminary Designs

Final Report

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ABSTRACT

The research performed this summer includes the completion of work begun last summer in support of the Air Launched Personnel Launch System parametric study, providing support on the development of the test matrices for the plume experiments in the Plume Model Investigation Team Project, and aiding in the conceptual design of a lunar habitat.

After the conclusion of last years Summer Program, the Systems Definition Branch continued with the Air Launched Personnel Launch System (ALPLS) study by running three experiments defined by L27 Orthogonal Arrays. Although the data was evaluated during the academic year, the analysis of variance and the final project review were completed this summer.

The Plume Model Investigation Team (PLUMMIT) was formed by the Engineering Directorate to develop a consensus position on plume impingement loads and to validate plume flowfield models. In order to obtain a large number of individual correlated data sets for model validation, a series of plume experiments was planned. A preliminary "full factorial" test matrix indicated that 73,024 jet firings would be necessary to obtain all of the information requested. As this was approximately 100 times more firings than the scheduled use of Vacuum Chamber A would permit, considerable effort was needed to reduce the test matrix and optimize it with respect to the specific objectives of the program.

Part of the First Lunar Outpost Project deals with Lunar Habitat. Requirements for the habitat include radiation protection, a safe haven for occasional solar flare storms, an airlock module as well as consumables to support 34 extra vehicular activities during a 45 day mission. The objective for the proposed work was to collaborate with the Habitat Team on the development and reusability of the Logistics Modules.

OVERVIEW OF PARAMETER DESIGN AND TAGUCHI METHODS

During product development, engineers and scientists are typically faced with two opposing requirements; improve or optimize performance and reduce or minimize cost. The process of searching for factors or parameters affecting performance and/or cost is usually experimental in nature. After a set of relevant parameters are assembled, the experimenter is faced with the task of determining which combination of parameter values achieve the desired results. It is the quality of this decision that can be improved when proper tests strategies are used. The most commonly used test plan is the evaluation and optimization of one parameter at a time. If there happens to be an interaction of the factor being studied with any other factor, the interaction will not be observed as all other factors are being held constant. This loss of interaction information is accepted as unavoidable as the only other perceived alternative is to perform a full factorial experiment, testing every possible combination of factors. This is usually not feasible as most real problems involve many parameters with three or more possible levels requiring thousands of experiment runs. Taguchi is an advocate of more efficient test plans, which are referred to as fractional factorial experiments (FFEs). FFEs use only a portion of the total possible combinations to estimate the main factor effects and some, not all, of the interactions [1] . FFEs are balanced experiments developed using orthogonal arrays. They can be used to evaluate many parameters with a minimum number of tests.

As suggested above, the goal of parameter design is to determine the parameter values of a product or process so that the product is functional, exhibits a high level of performance and is minimally sensitive to noise. The strategy is to design a high quality product which can be produced from low grade, low cost components with broad tolerances. This improved quality and reduced variability is achieved by selecting the optimum parameter values so that the product is least sensitive to input and noise variations. Conventional quality improvement techniques reduce product variation by removing the cause which is usually expensive, while Taguchi methods reduce variation by becoming less sensitive to input variations without removing the cause of variation. Improved quality is, therefore, achieved without or with minimal increase in cost. Taguchi Methods take advantage of non-linear effects and the interaction between control factors and noise factors in order to obtain designs that are more "robust". Taguchi's approach to design of experiments utilizes techniques that are cost effective and directly applicable to the problems and requirements of modern industry.

A parameter design experiment typically involves two types of factors:

Control Factors whose levels can be set and maintained.

Noise Factors whose level either cannot or will not be set or maintained, yet which could affect the performance of the functional characteristics.

Parameter design examines interactions between control factors and noise factors in order to achieve robustness. It is a search for parameter levels at which a characteristic is stable, despite the use of inexpensive components and materials or external conditions.

The major steps in designing, conducting, and analyzing an experiment are as follows:

1. Selection of factors and/or interactions to be evaluated
2. Selection of number of levels for the factors
3. Selection of appropriate Orthogonal Array
4. Assignment of factors and/or interactions to columns
5. Performance of experiments
6. Analysis of results
7. Performance of confirmation experiment.

In the design of products or processes, Taguchi's design of experiments can be used to determine the optimal parameter settings to obtain the best and most robust design with the least number of experiments. Even for optimization using analytical approaches, Taguchi's methods can significantly reduce computer time. When testing or experimenting to gain new knowledge or better understand how something works, the need to obtain usable results with the least number of tests is important as time, equipment, and funding are always limited.

AIR LAUNCHED PERSONNEL LAUNCH SYSTEM (ALPLS) PROJECT

The Systems Definition Branch, Systems Engineering Division, recently assessed the engineering feasibility, safety and reliability, and the infrastructure and operational requirements of an Air Launched Personnel Launch System for transportation of personnel to low earth orbit. One of the study requirements called for the determination of ascent delta-V sensitivities to release conditions (Altitude, Mach, Flight Path Angle, Delay Time) and vehicle parameters (Specific Impulse, Ignition Thrust to Weight Ratio, Lift to Weight Ratio).

This parametric study was accomplished by both the traditional one parameter at a time approach and with Taguchi's design of experiment methods. The goal was to evaluate the use of Taguchi methods for space vehicle design parametric studies by performing an analysis of the ALPLS using both approaches to provide a mechanism for comparing the results and the effort necessary to complete the studies.

Selection of Parameters and Levels to be Evaluated

The number of parameters given above was reduced to six with the conclusion that the aircraft would be flown at maximum velocity for the release of the PLS. The parameters and the levels selected for the Taguchi Study were as follows:

Variable	Levels		
Altitude:	25,000 ft.	35,000 ft.	45,000 ft.
Flight Path Angle:	0 degrees	10 degrees	20 degrees
Delay Time:	2 seconds	4 seconds	6 seconds
Specific Impulse (Isp):	LO_X/LH_2	$A50/N_2O_4$	HTBP
Ign Thrust to Weight (T/W):	1.5	1.7	1.9
Lift to Weight (L/W):	0.0	1.0	

The Flight Path Angle (gamma) was varied in 10 degree increments to conform with the increment size being used in the traditional approach. This limited the range to a total of 20 degrees in order to limit the number of levels in the Taguchi study to three. The remainder of the parameters conformed well with the parameter ranges used in the traditional approach.

Selection of Appropriate Orthogonal Array

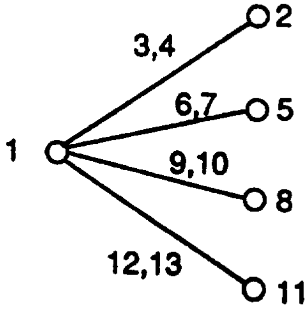
The selection of an orthogonal array depends on the number of factors and interactions to be modeled and the number of levels for the factors. Initially, little was known about the relevant interactions. It was assumed that the engine specific impulse and L/W parameters were the dominant factors; therefore, only the interaction between Isp and L/W was modeled. This resulted in a total of 13 degrees of freedom suggesting the use of an L_{18} Orthogonal Array. The L_{18} Array was also deemed appropriate as it can model one 2-level and seven 3-level parameters [2]. It is a specially designed array that models the interaction between the first two columns without sacrificing any other column and distributes interactions between the 3-level columns more or less uniformly among all of the 3-level columns [3]. After analyzing the data obtained from this initial set of computer runs, it became apparent that the selection of the L18 orthogonal array was not appropriate. The gross lift-off mass (m_glow) was very responsive to changes in L/W and Isp and there were significant interactions between altitude and the other parameters.

In order to eliminate the L/W - Isp and the L/W - Altitude interactions the ballistic and winged vehicles were studied separately. An L27 orthogonal array was selected with Isp occupying the first column. As Isp was the dominant parameter, two way interactions with the other parameters were modeled. Refer to Table I. The same 27 trials were repeated for three different levels of L/W (0.0, 0.5, & 1.0). This required a total of 81 computer setups and enough computer runs to minimize the vehicle mass at the specified parameter conditions.

Performance of the Experiment

The computer analysis was performed by the Systems Definition Branch of the systems Engineering Division and their engineering support contractor, Lockheed Engineering and Science Company. The analysis required for the traditional parametric study consisted of approximately 90 computer program setups, each requiring approximately 30 computer runs for a total of approximately 2700 computer runs. The Taguchi approach required a total of 99 computer setups, including the initial L18 experiment, each requiring only a few computer runs to determine optimal delta-V splits and flight profile to minimize total vehicle mass at the specified parameter conditions. Although only about one-quarter as many computer runs were necessary, Lockheed personnel indicated that the Taguchi method required approximately one-half the effort of the traditional approach.

Table I. Assignment of Factors to Columns



	Isp	T/W			Alt			Gamma			Delay		
	Column no.												
Trial no.	1	2	3	4	5	6	7	8	9	10	11	12	13
1	LOx/LH2	1.5	1	1	25K	1	1	0°	1	1	2	1	1
2	LOx/LH2	1.5	1	1	35K	2	2	10°	2	2	4	1	1
:	:	:			:			:			:		
:	:	:			:			:			:		
26	HTPB	1.9	2	1	35K	1	3	0°	3	2	6	2	1
27	HTPB	1.9	2	1	45K	2	1	20°	1	3	2	3	2

Analysis of Results

The Response Graphs, shown in Figure 1, show the sensitivity of the Delta-V with respect the five parameters modeled for a winged vehicle having a L/W ratio of 1.0. By observing the slope of the curves, it can be seen that the Delta-V is sensitive to Isp and Ignition T/W and relatively insensitive to variations in Release Altitude, Flight Path Angle, and Drop Time. This compares favorably with the data obtained by the traditional parametric study as demonstrated in Figure 2.

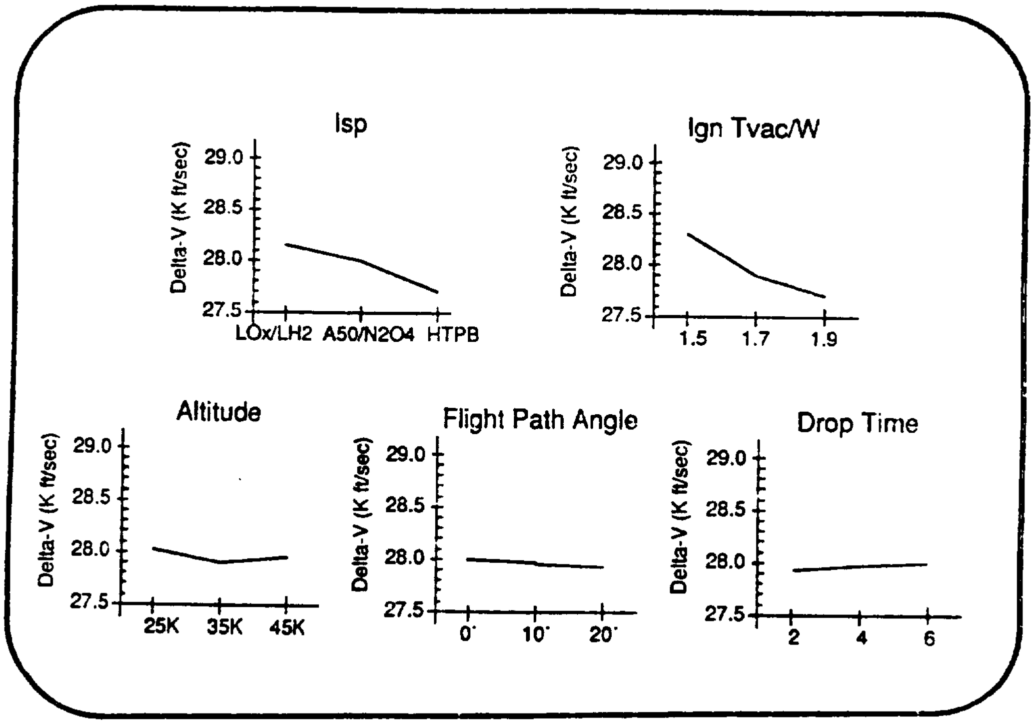


Figure 1. Delta-V Response with Winged Vehicle

This agreement with the traditional parametric results was obtained with less engineering time and significantly less computer time.

Engineering Man/Hours Needed for Study

Traditional Parametric Study
(90 computer setups) x (0.5 hours/setup) = 45 hours

Taguchi Approach
(72 computer setups) x (0.5 hours/setup) = 36 hours

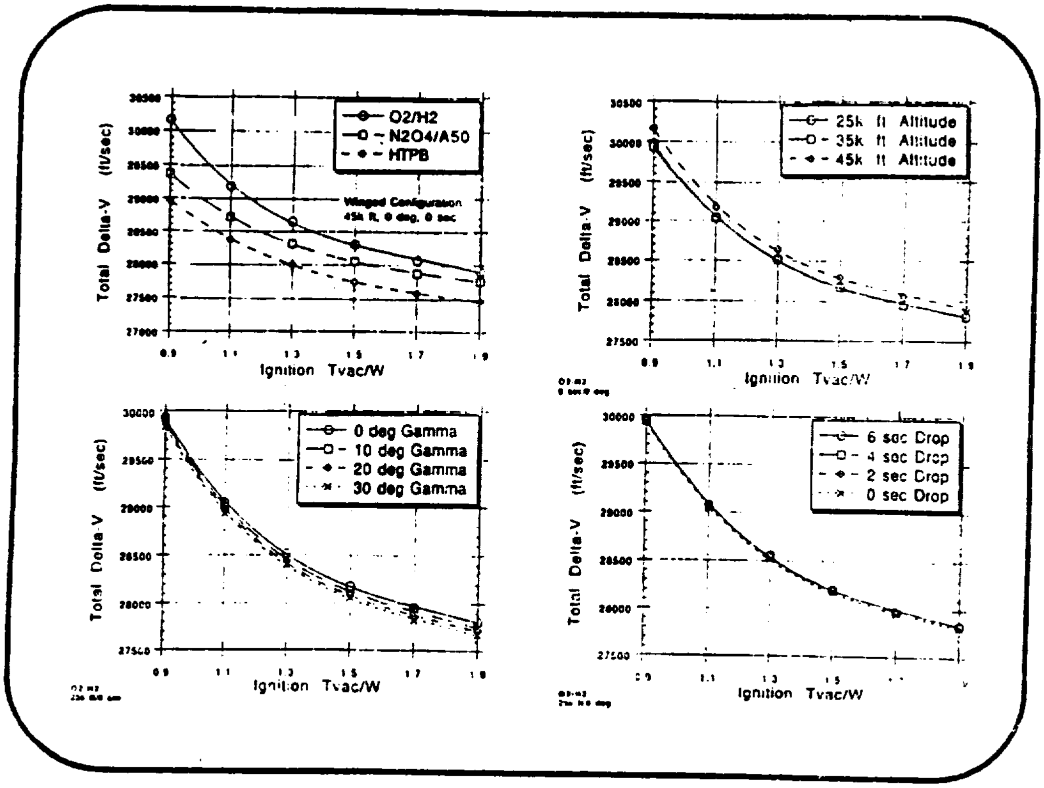


Figure 2. Results from Traditional Parametric Study

Computer Run Time

Traditional Parametric Study

(90 setups) x (21 runs/setup) x (0.1 hrs/run) = 189.0 hours

Taguchi Approach

(72 setups) x (1 run/setup) x (0.1 hours/run) = 7.2 hours

It should be noted that the savings resulting from the application of Taguchi's design of experiment methods were achieved at the cost of reduced detail in the sensitivity analysis. In addition the validity of the Taguchi results would have been questionable without the availability of the traditional data as the L27 Orthogonal Array did not model all of the parameter interactions that were observed.

Conclusions

Knowledge of the system being modeled is important to reduce the total number of experiments necessary to model the significant interactions. Significant experience has been gained through this project. The application of Design of Experiments must be evaluated with regard to the objectives of the study and the available resources. If determining the optimal level for the parameters is the primary concern or if the analysis results are needed very quickly, DOE would be the preferred approach; however, if little is known of the system being studied or if a detailed sensitivity analysis is needed a traditional parametric study is recommended.

PLUME MODEL INVESTIGATION TEAM (PLUMMIT)

The PLUMMIT goal is to "validate Space Station plume impingement load predictions in a timely and cost effective manner." The team recently completed a series of vacuum chamber tests to validate instrumentation utilizing Johnson Space Center's (JSC) Vacuum Chamber E. The next phase of the investigation includes instrumentation checkout and chamber effects characterization in JSC's Vacuum Chamber A, followed by the plume flowfield mapping.

The PLUMMIT test program is designed to validate plume impingement calculation methodologies for application to space station load predictions. This series of experiments will provide baseline data for the validation of source flow plume models, gas surface interaction data for validation of impingement models, and data for the validation of high fidelity plume models. In addition, sufficient data will be obtained to characterize the uncertainty of current baseline plume impingement tools and construct models for nozzle scarfing, multiple jet interactions, and temporal plume variations which are neglected at this time.

Experiment Plan

The current test plan in progress is comprised of:

1. Instrument Validation Testing
    - Utilizes JSC Vacuum Chamber E
    - 1.25# cold gas jet with conical nozzle
    - Characterize instrument response, sensitivity, and accuracy
    - Test dates of June 6-10, July 27-31, and August 24-28
2. Plume Characterization Testing
    - Utilizes JSC Vacuum Chamber A
    - 2.5# and 10# cold gas jets, 25# O_2H_2 thruster
    - Characterize plume flowfield parameters
    - Test dates of November 16-20 and December 7-11
3. Numerical Code Development
4. Material Accommodation Testing (proposed for FY'93)
5. SPIFEX flight experiment (currently in design, with flight in FY'94)

The experimental layout, shown in Figure 3, requires the mounting of the cold gas jets and the O_2H_2 thruster near the chamber floor with the main instrument cluster mounted on a boom with the capability of sweeping ±45° and having a vertical movement from 0 to 40 feet above the engine platform.

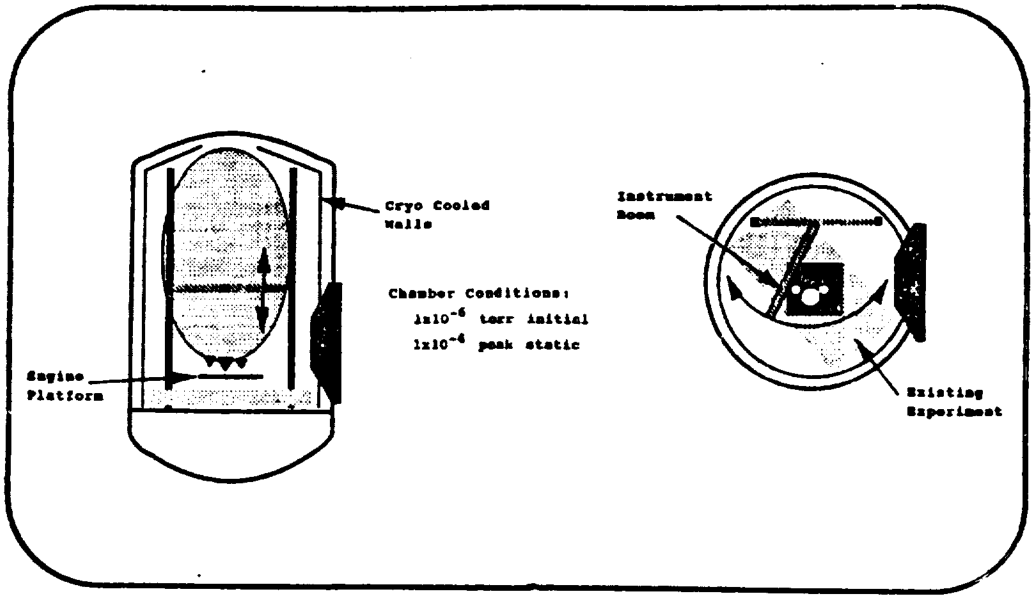


Figure 3. Vacuum Chamber A Test Schematic

Experiment Optimization

As the testing must meet the project objectives at minimum cost, a significant effort has been made to optimize the plume characterization testing utilizing Vacuum Chamber A. The initial test matrix, given on Table II, was modeled using an inner array having six parameters, two with two levels, two with three levels, and the remaining two parameters with four levels. The sweeping of the sensing instrumentation was modeled as an outer or noise array with sweep angles of -45° to +45° (stepped every 15°) and a total of 28 vertical positions. This resulted in an initial full factorial experiment that would require 73,024 rocket firings. Careful review of the relevant parameters and their levels has resulted in a reduction of the number of rocket firings to 679. The most recent inner and outer test matrices are given in Tables III and IV. As a better understanding of the instrumentation and the plume flowfield is obtained after each chamber test, the Vacuum Chamber A test matrices will continue to be revised to permit the optimization of each subsequent experiment.

Table II. Initial Test Matrix

Engine Parameters

	-Hot-	-Cold-
Types of Propellants	O2/H2	N2,Ar,CO2
°'s of Scarfing	0°	0°,15°,30°
°'s of Gimbal	0°	0.0°,2.5°,5.0°
# of Engines	1	1,2
Firing Duration	80,160, 240,480 m.s.	
Thrust Levels	1	1,2

Boom Position Parameters

Sweep Angles	-45° to +45° by 15 steps (Scarfed) 0° to +45° by 15° steps (Unscarfed)
Vertical Position	1 point at less than 100R 1 point at 100R 1 point at slightly more than 100R 25 points at 120R to 40 feet.

Total Number of Test Runs

$$4*112 + 3 * (48*112 + 96*196) = 73{,}024$$

Continuing Effort

Prior to the November test week, the final inner and outer matrices will be combined forming a single matrix with each of the 679 experiments defined by a row of the matrix. This matrix will then be sorted in such a manner that the time necessary to set-up for each following run will be minimized. It is hoped that the selection of an optimal test sequence will permit the completion of all 679 runs during the first week. This would permit the use of the second week of testing to repeat questionable data points and perform multiple runs under the most important configurations to reduce the uncertainty of the results.

Table III. Final Inner Experimental Array

Experimental Array *(Rows 8-11 & 12-15 utilize a Full Factorial L4 OAs)*
(Rows 16-24 utilize a Full Factorial L9 OA)

	Propellents	*Scarfing*	*Gimbal*	*No. Engines*	*Thrust*	*Duration*	*Outer Array*		*Comments*
1	O_2/H_2	0°	0.0°	1	1	80 ms	A	25	*Reacting Chem/High Enthalpy Flows*
2	O_2/H_2	0°	0.0°	1	1	240 ms	A	25	Outer Array has four sweeps with
3	O_2/H_2	0°	0.0°	1	1	480 ms	A	25	a fuller sweep at the third level.
4	N_2	0°	0.0°	1	1	80 ms	B	18	*Instrument & Flow Characterization*
5	N_2	0°	0.0°	1	1	240 ms	B	18	Outer array has three sweeps with
6	N_2	0°	0.0°	1	1	480 ms	B	18	a fuller sweep at second level.
7	N_2	0°	0.0°	1	1	720 ms	C	6	Last row has reduced Outer Array.
8	N_2	0°	0.0°	1	1	240 ms	D	28	*Multi-jet Effects*
9	N_2	0°	0.0°	1	2	240 ms	D	28	Outer array has three sweeps with
10	N_2	0°	0.0°	2	1	240 ms	D	28	fuller sweeps at the lower levels.
11	N_2	0°	0.0°	2	2	240 ms	D	28	Need better defined levels & angles.
12	N_2	0°	0.0°	1	1	240 ms	D	28	*Multi-jet Effects with Electron Gun*
13	N_2	0°	0.0°	1	2	240 ms	D	28	
14	N_2	0°	0.0°	2	1	240 ms	D	28	Same outer arrays as above.
15	N_2	0°	0.0°	2	2	240 ms	D	28	
► 16	N_2	0°	-15°	1	1	240 ms	E	38	*Scarfing Characterization*
17	N_2	0°	0°	1	1	240 ms	E	38	*Gimbal used to increase*
► 18	N_2	0°	15°	1	1	240 ms	E	38	*plume area being mapped*
► 19	N_2	15°	-15°	1	1	240 ms	F	28	The E outer array has five sweeps
20	N_2	15°	0°	1	1	240 ms	F	28	each from -45 to 45 as the plume
► 21	N_2	15°	15°	1	1	240 ms	F	28	is not symmetric. The F outer array has been reduced
► 22	N_2	40°	-15°	1	1	240 ms	F	28	to only three sweeps.
23	N_2	40°	0°	1	1	240 ms	F	28	Marked rows may be omitted for a
► 24	N_2	40°	15°	1	1	240 ms	F	28	reduced minimal matrix.
25	Ar	0°	0.0°	1	1	240 ms	G	19	*Gamma Effect* Three sweeps, first fuller
26	CO_2	0°	0.0°	1	1	240 ms	G	19	*Gamma Effect* Three sweeps, first fuller

► These experiments can be omitted for the reduced set of experiments.

Number of Reduced Experiments	491
Number of Primary (Baseline) Experiments	679
Number of Secondary Experiments	

Table IV. Final Outer Arrays

Outer Array A (O_2/H_2 Engine)
(Symmetric Plumes)

	Vert. Position	*Sweep Angle*
1	6'	0°
2	8'	0°
3	10'	0°
4	10'	15°
5	10'	30°
6	10'	45°
7	15'	0°
8	20'	0°
9	25'	0°
10	25'	7°
11	25'	15°
12	25'	22°
13	25'	30°
14	25'	37°
15	25'	45°
16	30'	0°
17	33'	0°
18	33'	15°
19	33'	30°
20	33'	45°
21	35'	0°
22	40'	0°
23	40'	15°
24	40'	30°
25	40'	45°

Outer Array D (Symmetric Plumes)
(Multi-Jet Interactions)

	Vert. Position	*Sweep Angle*
1	3'	0°
2	7'	0°
3	10'	0°
4	10'	3°
5	10'	6°
6	10'	9°
7	10'	12°
8	10'	15°
9	10'	20°
10	10'	25°
11	10'	30°
12	10'	45°
13	13.5'	0°
14	17.5'	0°
15	25'	0°
16	25'	5°
17	25'	10°
18	25'	15°
19	25'	20°
20	25'	30°
21	25'	45°
22	30'	0°
23	35'	0°
24	40'	0°
25	40'	15°
26	40'	30°
27	40'	45°
28	45'	0°

Outer Array B (N_2 Engine)
(Instrument Characterization)

	Vert. Position	*Sweep Angle*
1	3'	0°
2	5'	0°
3	5'	5°
4	5'	10°
5	5'	20°
6	17.5'	0°
7	25'	0°
8	25'	7°
9	25'	15°
10	25'	22°
11	25'	30°
12	25'	37°
13	25'	45°
14	30'	0°
15	40'	0°
16	40'	15°
17	40'	30°
18	40'	45°

Outer Array C (N_2 Engine)
(Instrument Characterization)

	Vert. Position	*Sweep Angle*
1	25'	0°
2	25'	22°
3	25'	45°
4	40'	0°
5	40'	22°
6	40'	45°

Outer Array F (Non-Sym. Plumes)
(Gimbal with scarfing)

	Vert. Position	*Sweep Angle*
1	5'	-45°
2	5'	-30°
3	5'	-15°
4	5'	0°
5	5'	15°
6	5'	30°
7	5'	45°
8	10'	-45°
9	10'	-30°
10	10'	-15°
11	10'	0°
12	10'	15°
13	10'	30°
14	10'	45°
15	20'	-45°
16	20'	-30°
17	20'	-15°
18	20'	0°
19	20'	15°
20	20'	30°
21	20'	45°
22	30'	-45°
23	30'	-30°
24	30'	-15°
25	30'	0°
26	30'	15°
27	30'	30°
28	30'	45°

Outer Array E (Non-Sym. Plumes)
(Gimbal without scarfing)

	Vert. Position	*Sweep Angle*
1	3'	0°
2	7'	0°
3	7'	7°
4	7'	15°
5	7'	22°
6	7'	30°
7	7'	37°
8	10'	0°
9	10'	7°
10	10'	15°
11	10'	22°
12	10'	30°
13	10'	37°
14	10'	45°
15	15'	0°
16	20'	0°
17	20'	7°
18	20'	15°
19	20'	22°
20	20'	30°
21	20'	37°
22	20'	45°
23	25'	0°
24	30'	0°
25	30'	7°
26	30'	15°
27	30'	22°
28	30'	30°
29	30'	37°
30	30'	45°
31	35'	0°
32	40'	0°
33	40'	7°
34	40'	15°
35	40'	22°
36	40'	30°
37	40'	37°
38	40'	45°

Outer Array G (Ar & CO_2 Engines)
(Symmetric Plumes)

	Vert. Position	*Sweep Angle*
1	5'	0°
2	10'	0°
3	10'	5°
4	10'	10°
5	10'	15°
6	10'	20°
7	10'	30°
8	10'	45°
9	15'	0°
10	20'	0°
11	20'	15°
12	20'	30°
13	20'	45°
14	25'	0°
15	30'	0°
16	30'	15°
17	30'	30°
18	30'	45°
19	40'	0°

FIRST LUNAR OUTPOST PROJECT

The development and evaluation of the reusability of Logistics Modules to increase the lunar habitat usable volume was performed independently by Carolina Vargas, a student participant in the Faculty Fellowship Program. The results of her study have been reported separately in Section 25 of the Annual Summer Faculty Fellowship Program Report.

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