USE OF TAGUCHI DESIGN OF EXPERIMENTS TO DETERMINE ALPLS ASCENT DELTA-V SENSITIVITIES AND TOTAL MASS SENSITIVITIES TO RELEASE CONDITIONS AND VEHICLE PARAMETERS

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ABSTRACT

NASA is currently assessing the engineering feasibility, safety and reliability, and the infrastructure and operational requirements of an of an air launched personnel launch system (ALPLS) for transportation of personnel to low earth orbit. One of the Study Requirements calls for the determination of ALPLS ascent delta-V sensitivities to release conditions (Altitude, Mach, Flight Path Angle, Delay Time) and vehicle parameters (Isp, Ignition Tvac/W, L/D).

Previous parametric studies of this type have been accomplished by varying and optimizing one parameter at a time. Parameter interactions are considered by re-evaluating sensitive parameters while holding other variables at or near previously determined optimal values. A traditional, scientific, approach results in the experimenter methodically evaluating every possible combination of the parameters. Note that if an experiment involved seven parameters, each with only two possible levels, a total of 2^7 or 128 experiments would have to be conducted. Statisticians, as advocated by Taguchi, have developed more efficient test plans, which are referred to as fractional factorial experiments (FFEs). Certain treatment conditions are chosen to maintain orthogonality among the various factors and interactions. Taguchi design of experiments methods can be used to more efficiently analyze the optimal values of the parameters indicated above. By using Fractional Experiment Designs (Orthogonal Arrays) the number of runs can be significantly reduced with a better evaluation of the parameter interactions. Orthogonal experiment design is a time-saving testing strategy that draws on orthogonal arrays to pinpoint areas where variation may be successfully reduced.

The objective of this study is to evaluate the use of Taguchi's Design of Experiment Methods to improve the effectiveness of this and future parametric studies. Taguchi Methods will be applied in addition to the typical approach to provide a mechanism for comparing the results and the cost or effort necessary to complete the studies. It is anticipated that results of this study should include an improved systematic analysis process, an increase in information obtained at a lower cost, and a more robust, cost effective vehicle design.

INTRODUCTION

The objective of this study is the demonstration of an improved methodology for the Parametric Design Phase of the space vehicle design process utilizing Taguchi Design of Experiment Methods. Although the design of experiment methods such as fractional orthogonal arrays are in common use in experimental settings, they are not being utilized in areas where computer models are available. Computer analysis of complex models can be more efficiently accomplished if computer runs are viewed and planned as experiments. Standardizing the evaluation process using design of experiment methods eliminates many of the common solution approaches such as random trial and error, the varying of one variable at a time, or the methodical and time consuming evaluation of every possible combination of variable levels. The use of experimental design should result in better designs using fewer computer runs while obtaining an interpretable evaluation of the designs sensitivity to their environment or more robust designs.

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 common test plan is to evaluate and optimize 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. Although design of experiments has been around for some time, it is seldom used for product development.

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.

The goal of the experiment is to determine the combination of parameters that gives the most stable and reliable performance at the lowest cost.

PROBLEM STATEMENT

The Systems Definition Branch, Systems Engineering Division, is currently assessing the engineering feasibility, safety and reliability, and the infrastructure and operational requirements of an Air Launched Personnel Launch System (Air Launched PLS) for transportation of personnel to low earth orbit. One of the study requirements calls for the determination of the ascent delta-V sensitivities to release conditions (Altitude, Mach, Flight Path Angle, Delay time) and vehicle parameters (Isp, Ignition Tvac/W, L/D).

Previous parametric studies of this type have been accomplished by varying and optimizing one parameter at a time. Parameter interactions are considered by re-evaluating sensitive parameters while holding other variables at or near previously determined optimal values. This approach, while time consuming, is preferred by analysts as it provides considerable insight regarding the sensitivities and costs associated with deviations from optimal conditions. This study will evaluate the use of Taguchi Design of Experiment Methods for space vehicle design parametric studies by performing an analysis of the Air Launched PLS in conjunction with the traditional approach to provide a mechanism for comparing the results and the effort necessary to complete the studies.

EXPERIMENTAL DESIGN AND ANALYSIS

Referring to the Air Launched Personnel Launch System study statement of work, section IIIB called for the following:

> "Determine ALPLS ascent delta-V sensitivities to release conditions (Altitude, Mach, Flight Path Angle, Delay Time) and vehicle parameters (Isp, Ignition Tvac/W, L/D). Sensitivities are to be evaluated over the following parameter ranges using a two-stage vehicle analysis:
>
> - Altitude: 25K to 45K ft.
> - Mach: 0.7 (or based upon aircraft performance)
> - Gamma: 0 to 30 deg.
> - Delay Time: 0 to 6 sec.
>
> - Isp: Based upon selected propulsion systems
> - Ignition Tvac/W: 1.3 to 1.9 (Ballistic
>   0.9 to 1.9 (Aero Assisted)
> - L/D: Ballistic, low, medium, high aero assist"

The process of designing, conducting, and analyzing the parametric study directly followed the steps given earlier.

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.
Gamma:	0 degrees	10 degrees	20 degrees
Delay Time:	2 seconds	4 seconds	6 seconds
Isp:	LO_X/LH_2	$A50/N_2O_4$	HTBP
Ign Tvac/W	1.5	1.7	1.9
L/D	Ballistic	Winged	

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 Lift to Drag ratio (L/D) was reduced to two levels with project teams decision to model only one aero-assist version having wings sized to maintain a horizontal flight path and facilitate separation from the aircraft at the time of release.

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; however, it was believed that the engine type (Isp) and L/D parameters were the dominant factors. The L18 orthogonal array, shown in Table I, was selected for the study as it can accommodate two and three level parameters and the interactions between the three level columns are distributed more or less uniformly to all of the other three-level columns (2).

Assignment of Factors to Columns

Table II contains the parameter column assignments. The Lift to Drag ratio was assigned to column one as it was the only two level parameter while the Isp was assigned to column two to enable the modeling of the interactions between the two probable dominant variables. It was believed that the prevalent interaction would occur between these two parameters due to the significant differences in the magnitude of the Isps. These column assignments also facilitated the setup for the various trials as different computer models were needed when switching from a ballistic vehicle to a winged vehicle and different rocket sizing models were needed for each different engine type. Columns seven and eight remained unassigned providing a measure of error. It should be pointed out at this time that the selection of the L18 orthogonal array was not appropriate for this study as the main effects of the first two columns and their interaction dominated the experiment. This can be readily seen in the raw data, also shown in Table II. The very large masses (m glow) of the Winged-HTBP vehicles significantly affected the results of the study to the extent that

Table I. L18 Orthogonal Array

$L_{18}(2^1 \times 3^7)$

Trial no.	1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	3	1	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

Note: This is a specially designed array. An interaction is built between the first two columns. This interaction information can be obtained without sacrificing any other column. Interactions between three-level columns are distributed more or less uniformly to all the other three-level columns, which permits investigation of main effects. Thus, it is a highly recommended array for experiments.

Table II. Air Launched PLS Parameter Column Assignments

	L/D	Isp	Alt	Gamma	Delay	T/W	Error		Results	
	Column no.								Total ΔV	m glow
Trial no.	1	2	3	4	5	6	7	8	(ft/sec)	(lbm)
1	Ballistic	LOx/LH2	25	0	2	1.5	1	1	29,661	730,965
2	Ballistic	LOx/LH2	35	10	4	1.7	2	2	28,572	661,753
3	Ballistic	LOx/LH2	45	20	6	1.9	3	3	27,875	624,690
4	Ballistic	A50/N2O4	25	0	4	1.7	3	3	29,690	1,949,102
5	Ballistic	A50/N2O4	35	10	6	1.9	1	1	28,393	1,654,014
6	Ballistic	A50/N2O4	45	20	2	1.5	2	2	28,042	1,485,159
7	Ballistic	HTBP	25	10	2	1.9	2	3	28,417	2,349,550
8	Ballistic	HTBP	35	20	4	1.5	3	1	28,384	2,332,576
9	Ballistic	HTBP	45	0	6	1.7	1	2	28,369	2,324,922
10	Winged	LOx/LH2	25	20	6	1.7	2	1	27,929	722,221
11	Winged	LOx/LH2	35	0	2	1.9	3	2	27,808	773,352
12	Winged	LOx/LH2	45	10	4	1.5	1	3	28,309	904,770
13	Winged	A50/N2O4	25	10	6	1.5	3	2	28,157	1,914,820
14	Winged	A50/N2O4	35	20	2	1.7	1	3	27,777	2,028,850
15	Winged	A50/N2O4	45	0	4	1.9	2	1	27,781	2,467,980
16	Winged	HTBP	25	20	4	1.9	1	2	27,601	2,789,500
17	Winged	HTBP	35	0	6	1.5	2	3	27,839	3,502,700
18	Winged	HTBP	45	10	2	1.7	3	1	27,542	4,488,800

all of the parameter levels used in the 18th trial were found to be the worse possible settings in the data analysis phase although an altitude of 45,000 ft. and a delay time of two seconds were expected to be optimal.

Performance of the Experiment

The computer analysis necessary for the completion of the 18 trial runs was performed by the System Definition Branch of the Systems Engineering Division and their Engineering Support Contractor, Lockheed Engineering and Science Company. The parametric study using the traditional approach required approximately 90 computer program setups, each requiring approximately 30 computer runs for a total number of computer runs in the order of 2500 to 3000. The Taguchi Method required only 18 program setups with only a few computer runs to determine optimal delta-V splits and flight profile to minimize total vehicle mass at the specified initial parameter conditions. At this point the effort required to perform the Taguchi study is significantly less than the traditional approach; however, more analysis will be necessary before the Taguchi Method provides the information required for the Air Launched PLS study.

Analysis of Results

Analysis of variance is typically used to determine the extent to which factors contribute to variation and to test significance of factorial effects. The factors that strongly effect variation can, however, be determined by recognizing the differences in the average effects of factors. These differences in effect are clearly seen in response graphs (3).

The Response Graphs, shown in Figure 1, show the response of the gross lift off mass with respect to each of the six parameters studied. The graphs show a slight, possibly significant preference to the ballistic configuration and a strong preference for the LO_X/OH_2 fueled engine. The remaining parameters appear to have little effect on the vehicle mass, with the optimal release conditions at 25,000 ft altitude, a flight path angle of 20 degrees, a drop time of six seconds prior to firing of the engines and an optimal thrust to weight ratio of 1.9. The preference for a low release altitude can be explained by the realization that the winged space craft requires a significantly larger wing to support the craft in the thinner atmosphere of the higher altitude. The preference for large drop times is caused by the insensitivity of the winged vehicles to drop time as the available lift minimized the loss in altitude over time and the dominance of the winged vehicles due to their larger masses.

The Interaction Graphs, given in Figure 2, demonstrate the interactions between the Lift to Drag parameter and the other five parameters. Although the L18 orthogonal array is only designed to model the interaction between the first two columns, L/D versus Isp, considerable insight can be obtained from the study of all of the graphs. The L/D versus Isp graph shows that an interaction is present as the lines are not parallel. It should also be noted that both ballistic and winged vehicles preferred the LO_X/OH_2 engines. The L/D versus Altitude graph shows the preference for a high altitude release for the ballistic vehicle and a low altitude release for the winged space vehicle. The remaining graphs are more severely hampered by the interactions not modeled with unexplained switches in the preferences of the ballistic and winged vehicles. The Interaction Graphs, given in Figure 3, show a much more erratic behavior. The Altitude versus L/D graph again clearly shows the preference of a low altitude release for the winged vehicle and a high altitude release for the ballistic one. However, the Altitude versus Flight Path Angle, Altitude versus

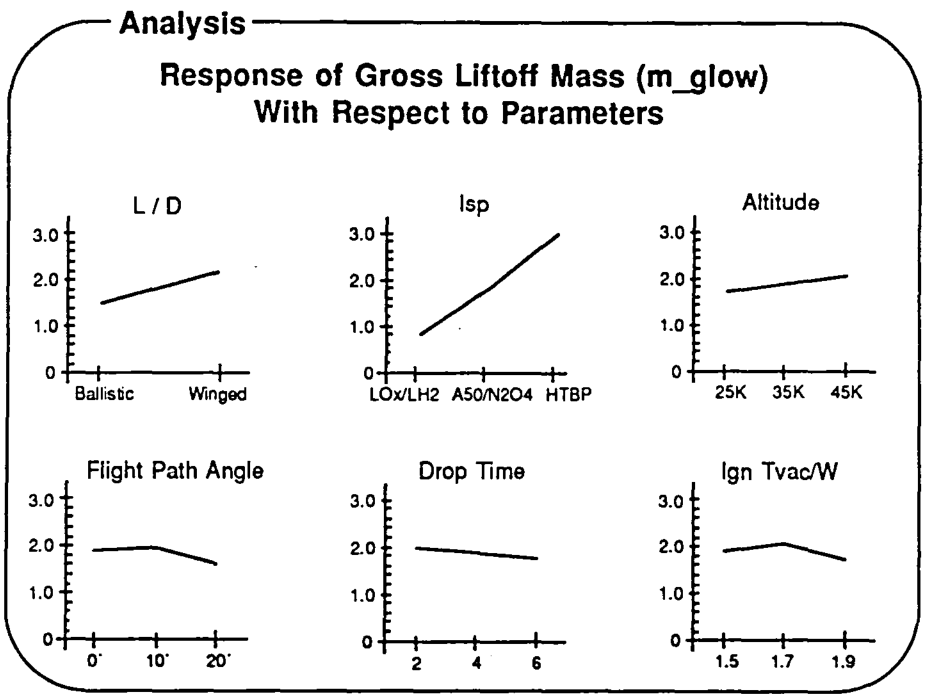

Figure 1. Air Launched PLS Response Graphs

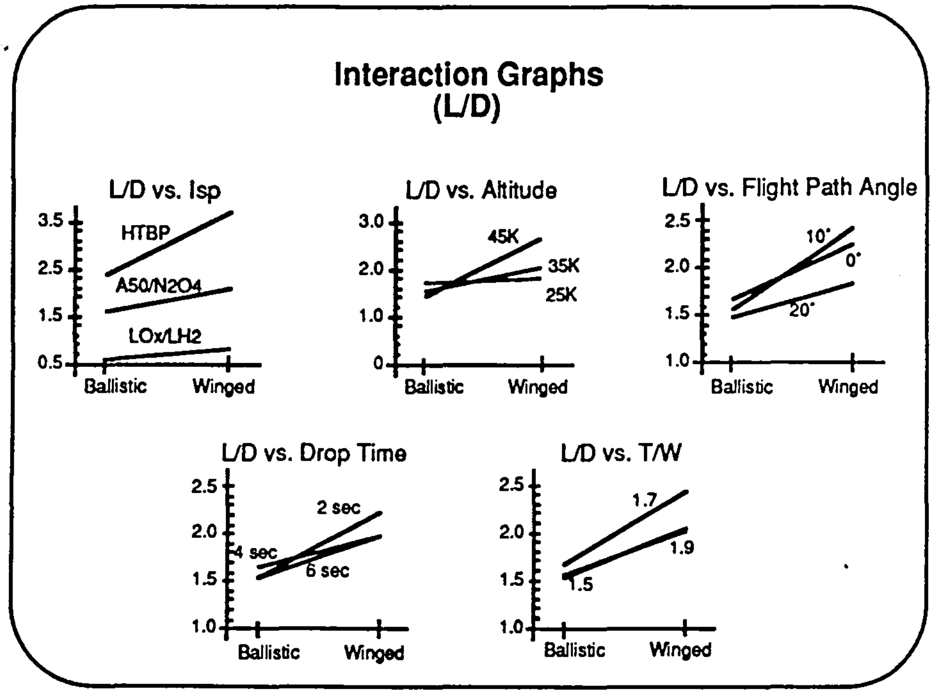

Figure 2. Lift to Drag Interaction Graphs

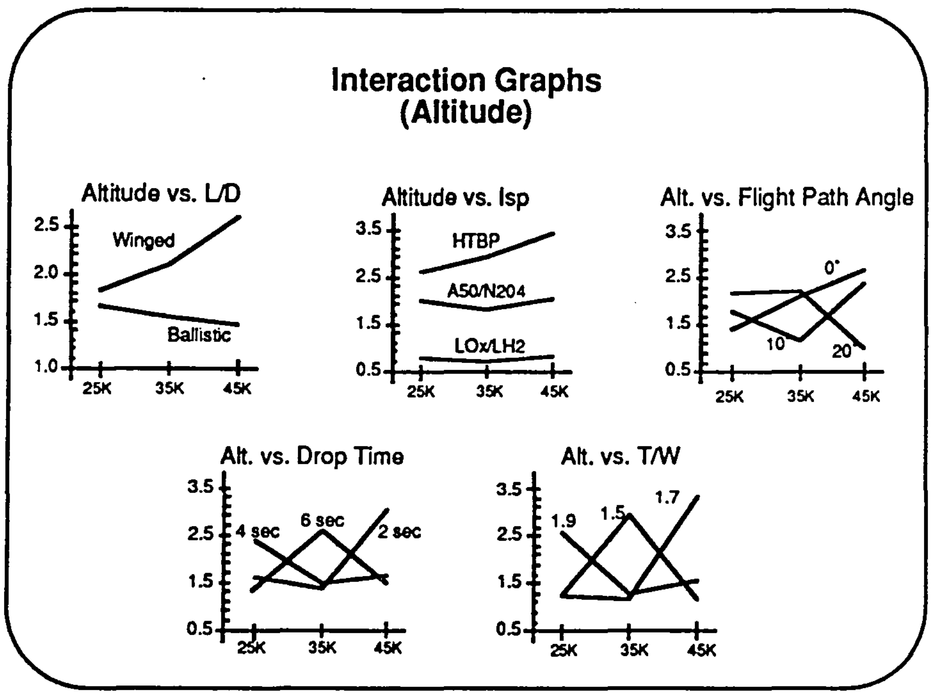

Figure 3. Altitude Interaction Graphs

Drop Time, and Altitude versus Thrust to Weight Ratio graphs only demonstrate the significance of the interactions. The primary conclusion that can be drawn from these graphs is that the L18 orthogonal array was not suitable for this study as the interactions were not as "uniformly distributed" as originally anticipated.

Another indication regarding the significance of the interactions can be seen in the analysis of variance, refer to Table III. The sum of squares for the factors in columns one and two are clearly more significant than the remaining factors. It is estimated that L/D, Isp, and their interaction account for as much as 90% of the total observed variation. It should be noted, however, that an analysis of variance is not valid, as an estimate of experiment error cannot be determined unless the experiment is replicated (4). As this experiment consist of computer runs, a repetition of the entire set of conditions would result in exactly the same values containing the same errors due to the simplifying assumptions and convergence tolerances.

RECOMMENDATIONS

The L/D - Isp interaction problem can be circumvented by studying the ballistic and winged vehicles separately. An L27 orthogonal array has been selected for further study as the anticipated interactions between Isp and the remaining parameters can be evaluated as shown in Table IV. The same 27 trials will be repeated for both L/D configurations. This will require an additional 54 computer setups and enough computer runs to minimize vehicle mass at the specified parameter conditions.

Table III. ANOVA for Air Launch PLS

	L/D	Isp	Alt	Gamma	Delay	T/W	Error		Results	
	Column no.									
Trial no.	1	2	3	4	5	6	7	8	Total ΔV	m glow
1	Ballistic	LOx/LH2	25	0	2	1.5	1	1	29,661	730,965
2	Ballistic	LOx/LH2	3	10	4	1.7 2		2	28,572	661,753
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
17	Winged	HTBP	35 0		6	1.5 2		3	27,839	3,502,700
18	Winged	HTBP	45	10	2	1.7 3		1	27,542	4,488,800
Level 1	14.113	4.418	10.456	11.749	11.857	10.870			L/D vs. Ips interactions	
Level 2	19.592	11.499	10.953	11.973	11.106	12.176			Ball-LOx/LH2	2.017
Level 3		17.788	12.296	9.983	10.742	10.659			Ball-A50/N2O4	5.088
Totals	33.705	33.705	33.705	33.705	33.705	33.705			Ball-HTBP	7.007
									Wing-LOx/LH2	2.400
SS	1.668	14.915	.302	.396	.108	.225			Wing-A50/N2/O4	6.411
v	1	2	2	2	2	2			Wing-HTBP	10.781
V	1.668	7.458	.151	.198	.054	.112			SS	17.604
									v	2
F	4.57	20.42	.41	.54	.15	.31			V	8.802
									F	24.10

Table IV. L27 Orthogonal Array

ORTHOGONAL ARRAY RECOMMENDED FOR FURTHER STUDY

	Isp	T/W			Alt			Gamma			Delay			L/D	
	Column no.														
Trial no.	1	2	3	4	5	6	7	8	9	10	11	12	13	Ballistic	Winged
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	HTBP	1.9	2	1	35K	1	3	0°	3	2	6	2	1		
27	HTBP	1.9	2	1	45K	2	1	20°	1	3	2	3	2		

An L27 (3^{13}) array is recommended for further study with the Ballistic and Winged studies to be done separately. The L27 array was selected as it allows for the modeling of the interactions between Isp and each of the other parameters. The interactions between Isp and T/W will be modeled by columns 3 & 4, interactions between Isp and Altitude in columns 6 & 7, etc. This design should accurately evaluate the main effects (T/W, Altitude, Flight Path Angle, and Drop Time) as well as their interactions with Isp at a cost of requiring a total of 54 trials.

If this new experiment design successfully obtains the information required by the study's original statement of work, a total of 72 computer setup will have been required. Although the Taguchi Method is approaching the number of setups used in the traditional approach (90), a smaller number computer runs will be required using significantly less computer time than the traditional parametric study.

CONCLUSIONS

The application of Taguchi's Design of Experiment Methods to improve the effectiveness of complex computer models is a new learning process subject to a learning curve. A common initial strategy requires the evaluation of a large number of parameters using a saturated array. This assists the analyst in determining which factors are relevant for further experiments. Knowledge of the system being modeled greatly reduces the initial effort required by improving the process of determining the proper parameters. The initial selection of the L18 matrix was made with the knowledge that interactions existed, but without anticipating their significance. The project is currently in the second phase with an experimental design better suited to the interactions found.

As the study is not complete the anticipated results have not been achieved. The interim conclusions are as follows:

Anticipated results:

* Improved systematic analysis process -- While Taguchi's design of experiment methods are clearly more systematic, this project has not demonstrated the methods effectiveness.

* More information obtained at lower costs -- At this point in the project Taguchi Methods have not obtained the information required for the Air Launched PLS study.

* More robust, cost effective designs -- Sensitivity to noise and small variations in control parameters have not been addressed at this time.

Actual results:

* Considerable experience has been gained in the application of Taguchi Techniques in non-manufacturing environments.

* The first point in the learning curve has been obtained.

REFERENCES

1. Ross, P.J.: Taguchi Techniques for Quality Engineering. McGraw-Hill, 1988.

2. Taguchi, G.; Konishi, S.: Orthogonal Arrays and Linear Graphs: Tools for Quality Engineering. American Supplier Institute, Inc. (Dearborne), 1987.

3. Center for Taguchi Methods and Quality Function Deployment: Taguchi Methods Introduction to Quality Engineering, Workshop Course Manual. American Supplier Institute, Inc. (Dearborne), 1989.

4. Miller, I.; Freund, J.E.: Probability and Statistics for Engineers. Prentice-Hall, 1985.