TAGUCHI SIZING EXPERIMENTS IN A CAPSTONE AIRCRAFT DESIGN COURSE

Kenneth R. Sivier [#]
University of Illinois
Urbana, IL

Steven J. D'Urso [*]
McDonnell Douglas Corporation
St. Louis, MO

Abstract

The senior capstone design course, in the Department of Aeronautical and Astronautical Engineering at the University of Illinois, is typically organized in two parts: (1) an individual student sizing exercise (based on the semester's design project specification) and (2) a small design team response to the project specification. In the spring semesters of 1991 and 1992, Taguchi sizing experiments were conducted as part of the individual student sizing exercises. The experiments were designed and evaluated by McDonnell Douglas Corporation (MDC) engineers who were acting as the "customers" for the aircraft design classes For both years, the experiment involved an L_{27} (3^{13}) array; five factors (design variables) at three levels each.

The design projects were a U.S. Navy Advanced Tactical Surveillance System (ATS) in 1991 and a Multiple Mission Tactical Aircraft (MMTA) in 1992. In 1991, a "smaller-is-better" Taguchi experiment was performed with the take-off gross weight (TOGW) as the quality parameter. The five design variables were mission profile, propulsion system type, payload, climb rate, and maneuvering performance. In 1992, a "larger-is-better" experiment was performed with mission effectiveness as the quality parameter and payload, penetration radius, loiter time, maneuvering performance, and intercept acceleration as the design variables.

This paper discusses the details of these two experiments and how the results were used to establish the final RFP's for the design projects. It also discusses the usefulness of such an experiment in the conceptual design process. Finally, the success of this approach as an educational tool is considered.

1. Intoduction

The Department of Aeronautical and Astronautical Engineering's capstone design course is Aerospace Flight Systems Design, AAE 241. It is a required, three semester-hour, senior level, design course offered only in the spring semester. Students in this course have had no previous experience in design. The work in AAE 241 is organized as follows.

a. An initial sizing of the project aircraft by individual students to introduce them to the design process.

b. An initial sizing by small design teams, drawing on their experience from the individual sizing exercise.

c. The conceptual design of the aircraft by the design teams, with each team member responsible for one or two subsystems (e.g., aerodynamics, propulsion, weights, etc.).

In the fall of 1990, the author other engineers at the McDonnell Douglas Corporation (MDC) in St. Louis offered to act as the "customer" for the aircraft design class(2). In that capacity, they proposed to generate the project Request For Proposal (RFP), to act as technical consultants for the design class,

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[#] Associate Professor Emeritus, Aeronautical and Astronautical Engineering; Associate Fellow AIAA

[*] Principle Technical Specialist, Configuration Synthesis ; Member AIAA

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and to evaluate the resulting design reports. During preparation of the RFP for the spring 1991 semester, the MDC engineers suggested that the individual student sizing exercise be organized as a Taguchi experiment to evaluate the significance of several design parameters. The results of this experiment would then be used, by MDC, to revise and finalize the RFP for the design teams. In addition, this approach was consistant with an overall plan to add elements of systems engineering to the course and afford the students a "hands-on" experience in the use of fractional factorial experiments in the design process.

In the spring 1991 semester, the design project was a U.S. Navy Advanced Tactical Surveillance System (ATS) to replace one or more of the aging S-3, EA-6, E-2 and C-2 aircraft. Because of the wide diversity of the missions of these aircraft, the sizing exercise specifications involved elements from the several aircraft. A "smaller-is-better" Taguchi experiment was designed with take-off gross weight (TOGW) as the quality parameter. Five factors (design variables), at three levels each, were used in an L_{27} (3^{13}) array. The factors were mission profile, propulsion system type, payload, climb rate, and maneuvering performance. 27 different sets of specifications were involved; 30 students participated.

In the spring 1992 semester, a Taguchi experiment was again included in the individual sizing exercise. This time, the project was a Multiple Mission Tactical Aircraft (MMTA) combining requirements for close air support (CAS), airfield attack or offensive counter air (OCA), battlefield air interdiction (BAI), and defensive counter air (DCA). The mission used for the sizing experiment included the significant elements from all four of these missions. A measure of mission effectiveness was used as the quality parameter in a "larger-is-better" experiment. The design variables were payload, penetration radius, loiter time, maneuvering performance, and intercept acceleration. Again an L_{27} (3^{13}) experiment, with 27 different specifications, was involved. This time 35 students participated.

The mission descriptions and general specifications for the 1991 and 1992 classes are given in Appendices A and B, respectively.

For the team design work, the results of the Taguchi experiments were used to generate a different set of detailed specificatons for each design team. This approach provided a way of evaluating the effect of the detailed specifications on the resulting aircraft designs. The design team organization was five teams of six students each in 1991 and six teams, three with five students each and three with six students each, in 1992.

2. Taguchi Experiment Design

2.1 Background

The Taguchi method is beneficial in determining optimum values for design parameters, as well as investigating the independent system control factors and how they relate to the factors of variability. This is accomplished through a series of experiments that test the effect of selected factors on the design outcome. The factors are selected by designers who, through experience, have a sense of the potential interrelationships. Optimization of the control factors is obtained by the observation of the signal-to-noise ratios. This determines the sensivity of the solution results to the control factors. The designer gains insight about which factors are important and require control (i.e., become part of the product specification) and which factors do not affect the solution quality and can be allowed to "fall out" of the design process or be determined by secondary considerations.

The design of a Taguchi experiment is highly dependent on the intent of the investigation. It is normal to construct a study so that it will yield information about the design and the independent parameters that drive the design solution. The experiments used in 1991 and 1992 were developed to investigate the suitability of using Taguchi methodologies in the aircraft conceptual design process. In these experiments, Taguchi parameter design techniques were applied to the fusion of the several design parameters that make-up the aircraft specifications. The objective was to determine whether Taguchi techniques would be useful in the initial sizing decisions and in specification prioritizing for multi-mission aircraft.

2.2 Description of Experiments

An $L_{27}(3^{13})$ orthogonal array configuration, shown in Table 1, was used for both years' experiments. This array provides for three levels (1,2,and 3) for each of five parameters (A through E). It also provides for interactions between parameter A and the remaining four parameters (i.e., A x B, A x C, A x D and A x E). This array was translated into the student configuration sizing ssignments for both 1991 and 1992. The 27-trial experiment was selected because it was the largest array to fit within the number of students involved; each student analyzed one of the 27 configurations. A few cases were repeated by a second student. In addition, each configuration result was checked by a graduate assistant.

Case	Parameters								
	A	B	AxB	C	AxC	D	AxD	E	AxE
1	1	1	1 1	1	1 1	1	1 1	1	1 1
2	1	1	1 1	2	2 2	2	2 2	2	2 2
3	1	1	1 1	3	3 3	3	3 3	3	3 3
4	1	2	2 2	1	1 1	2	2 2	3	3 3
5	1	2	2 2	2	2 2	3	3 3	1	1 1
6	1	2	2 2	3	3 3	1	1 1	2	2 2
7	1	3	3 3	1	1 1	3	3 3	2	2 2
8	1	3	3 3	2	2 2	1	1 1	3	3 3
9	1	3	3 3	3	3 3	2	2 2	1	1 1
10	2	1	2 3	1	2 3	1	2 3	1	2 3
11	2	1	2 3	2	3 1	2	3 1	2	3 1
12	2	1	2 3	3	1 2	3	1 2	3	1 2
2	2	2	3 1	1	2 3	2	3 1	3	1 2
14	2	2	3 1	2	3 1	3	1 2	1	2 3
15	2	2	3 1	3	1 2	1	2 3	2	3 1
16	2	3	1 2	1	2 3	3	1 2	2	3 1
17	2	3	1 2	2	3 1	1	2 3	3	1 2
18	2	3	1 2	3	1 2	2	3 1	1	2 3
19	3	1	3 2	1	3 2	1	3 2	1	3 2
20	3	1	3 2	2	1 3	2	1 3	2	1 3
21	3	1	3 2	3	2 1	3	2 1	3	2 1
22	3	2	1 3	1	3 2	2	1 3	3	2 1
23	3	2	1 3	2	1 3	3	2 1	1	3 2
24	3	2	1 3	3	2 1	1	3 2	2	1 3
25	3	3	2 1	1	3 2	2	2 1	2	1 3
26	3	3	2 1	2	1 3	1	3 2	3	2 1
27	3	3	2 1	3	2 1	2	1 3	1	3 2

Table 1. L_{27} (3^{13}) Orthogonal Array

In 1991, the focus was on system level parameters of the aircraft. These parameters were part of the aircraft's specifications. Two of the parameters were mission profile (for the E-2, S-3, and EA-6B aircraft) and propulsion system type (advanced turboprop, high bypass-ratio turbofan, and unducted fan). (The mission profiles and specifications for these aircraft are presented in Appendix A.) The remaining three parameters were performance related. They were payload, climb rate, and maneuvering load factor. The parameter levels used in this experiment are given in Table 2. The corresponding configuration assignments are included in Table 4. The "quality" parameter was the take-off gross weight (TOGW), which is a traditional measure of "goodness" in aircraft design. A "smaller-is-better" experiment, using this parameter, allowed optimization of the design to get the smallest aircraft that satisfied the requirements.

In the 1991 experiment, the mission itself was found to be the most important design factor. On the basis of that result, in 1992 the focus was on the components of the design sizing mission and their influence on the resulting configuration. The goal was to design an aircraft that acheived the highest balanced aircraft effectiveness for all four missions. To do this, a single composite mission profile (see Figure B-1) was used for the study. This composite mission included the critical elements (in terms of performance and fuel usage) of all four of the target aircraft missions. Elements of this composite mission were selected as the variable parameters for the study. Conceptually, an aircraft designed to this mission, with the appropriate segment values, would be insensitive to the various missions it is required to perform.

	Description	Level		
		1	2	3
A	Propulsion System(1)	ATP	UDP	HBP-TF
B	Mission Profile	E-2	S-3	EA-6B
C	Payload, lbs.	2000	5000	6000
D	Climb Rate(2), fpm	5000	6000	8,600
E	Man. Load Factor, g's: Maximum Instantaneous(3) Maximum Sustained(3)	 +4.0 +3.0	 +5.0 +4.0	 +6.5 +5.0

(1) ATP = Advanced Turboprop
UDF = Unducted Fan
HBP-TF = High Bypass Ratio Turbofan
(2) Maximum at sea level
(3) See specifications for Mach number/altitude requirements

Table 2. Taguchi Parameter Design; Spring 1991

The 1992 experiment was designed as a "bigger-is-better" experiment, with an aircraft effectiveness factor as the "quality" parameter. This parameter was notional in nature and was formulated specifically for this exercise. It's value represented how well the design satisfied the given specifications; higher values represented more efficient designs. The effectiveness parameter E was defined as

$$E=\frac{aP+bR+cL+dM+eA}{W}$$

where a, b, c, d, and e are weighting constants and

P = payload in number of TMD's
R = dash radius in nautical miles divided by 25
L = loiter time in ten's of minutes
M = maneuverability in the number of 0.5g increments above 3

A = the acceleration time in seconds less than 90 divided by 5
W = TOGW in thousands of pounds

To remove the propulsion system type sensitivity from the study, a generic advanced, low bypass-ratio, turbofan engine with afterburner, was assumed for all cases.

The mission parameters, that were used in this study, were:

1. Payload. The payload is a true variable in any multiple mission tactical aircraft.
2. Loiter Time. Often the aircraft will be required to remain on station for some length of time with the design payload.
3. Penetration Radius. On many interdiction missions the vehicle is required to penetrate, at high subsonic speeds and relatively low altitude, to make a behind-the-line strike. An airfield is often the target of such a mission.
4. Maneuverability. The amount of maneuvering capability is of concern with any aircraft that is designated as a "fighter".
5. Acceleration. Acceleration is important in the battlefield area after weapons have been dropped or after several high-g maneuvers.

The study values of these parameters are given in Table 3. The corresponding configuration assignments are included in Table 5.

Factor	Description	Level 1	 2	 3
A	Payload(1), No. of TMD's	2	4	8
B	Loiter Time (2), min.	30	60	90
C	Penetration Radius(3), nm.	50	100	200
D	Man. Load Factor (4), Max. Sustained g's	+3.0	+5.0	+7.0
E	Intercept Acceleration(5), M = 0.8 to 1.6, sec.	50	70	90

(1) Weight of TMD's, with rack and pylon, estimated as 1110 lbs each. Payload also included 460 lbs of missiles for all levels.
(2) At 40,000 ft and best loiter M.
(3) At sea level.
(4) At M = 0.75 and 20,000 ft.
(5) At 20,000 ft

Table 3.Taguchi Parameter Design; Spring 1992

3. Sizing Method

The individual student sizing analyses for both years used the method presented in Chapter 3 of Raymer(1). This was supplimented by a constraint analysis based on the method described by Mattingly, Heiser and Daley(6). In 1991, the work was done manually. The results were checked by a spreadsheet program developed by A. Palusamy(4). In 1992, the students used a modified version of Palusamy's analysis program(5). This program differed from the method in Raymer(1), in that the climb weight fraction was given as a function of Mach number rather than a constant. Also, the acceleration was treated as a climb for fuel-use calculations.

3.1 1991 Analysis

3.1.1 Propulsion System Data

For the 1991 analysis of the ATS, the following propulsion system performance data and relationships were used.

Advanced Turboprop (ATP)

a. The altitude/Mach number model for the power specific fuel consumption, c_p, for altitudes less than 20,000 ft., was

$$c_p = c_{p_0}(1.0 - 0.15M)$$

where M = Mach number
and c_{p_0} = sea level static specific fuel consumption
= 0.276 lb/h_p - hr

For altitudes above 20,000ft.,

$$c_p = c_{p_0}(1.0 + 0.15M)\left[1.0 + 1.1\mathrm{x}10^{-5}(h - 20{,}000)\right]$$

where h = altitude in ft.

b. The power model was

$$P = P_0(1.0+0.72M^2)\sigma$$

where P = engine shaft power
P_0 = sea level static engine power
and σ = atmospheric density ratio

c. The engine thrust was calculated from

$$T = \eta_p P/V$$

where T = system thrust in pounds
η_p = propeller propulsive efficiency
= 0.80 for $M \leq 0.60$, falling to 0.48 at M = 0.90.
V = airspeed in ft./sec
and P is in units of ft-lb/sec.

High Bypass Turbofan (HBP-TF) and Unducted Fan (UDF)

a. The altitude/Mach number model for the thrust specific fuel consumption, c_t, was

$$c_t = c_{t_o}(1.0 + 0.35M)\theta^{1/2}$$

where c_{t_o} = sea level static specific fuel consumption
= 0.360 lb/lb-hr for the HBP-TF
= 0.250 lb/lb-hr for the UDF
and θ = atmospheric temperature ratio

b. The thrust model was

$$T = T_o[0.568 + 0.25(1.20 - M)^3]\sigma^{0.6}$$

where T = engine net thrust
and T_o = sea level static engine thrust.
and σ = atmospheric density ratio

3.1.2 Additional Data

Additional data provided to the students included:

a. A fuel reserve of 750 lbs per engine

b. Instead of the empty weight fraction data given in Ref. 1, the following were specified.

EA-6B and S-3::

$$\frac{W_e}{W_o} = 1.08W_o^{-0.07}$$

where W_e = empty weight
and W_O = gross take-off weight

E-2:

$$\frac{W_e}{W_o} = 1.29W_o^{-0.07} + \frac{6524}{W_o}$$

The second term provides an allowance for a fixed weight avionics suite.

c The "clean" aircraft zero-lift drag coefficient was specified as .

$$C_{D_o} = 0.015$$

d. Wing span $\leq$ 80 ft.

e. Landing weight, W_L, was given by

$$W_L = W_O - 0.5W_P - 0.2W_F$$

where W_P = payload weight
and W_F = fuel weight

3.2 1992 Analysis

1. The thrust specific fuel consumption and thrust were calculated from the following relationships for a low bypass-ratio turbofan engine model(6).

$$c_t = c_{t_o}(1.0 + 0.35M)\theta^{1/2}$$

For military power

$$\frac{T}{T_o} = 0.72\left[0.88 + 0.245(|M - 0.6|)^{1.4}\right]\sigma^{0.7}$$

and for power with afterburner

$$\frac{T}{T_o} = \left[0.94 + 0.38(M - 0.4)^2\right]\sigma^{0.7}$$

where θ = atmospheric temperature ratio
and σ = atmospheric density ratio.

2. Afterburner (maximum power) was used only for segments 10 and 11 (see Fig. 1); military power was used for all other segments.

3. Take-off and landing ground rolls were required to be 2500 ft. or less.

4. No mission fuel reserve was required.

5. The payload allowances (weapons plus pylons, racks and launches) were given as
TMD: 1110 lbs. each
ASRAAM: 415 lbs. each

6. One crew member

7. Maximum normal load factor of 9.0.

8. No rate of climb or excess specific power requirement were specified.

9. The avionics suite weighed 1800 lbs.

10. "Clean" aircraft C_{D_o}'s were given as

$$\begin{aligned} C_{D_o} &= 0.015 \quad \text{for } M \leq 0.80 \\ &= 0.017 \quad M = 0.90 \\ &= 0.040 \quad M = 1.50 \end{aligned}$$

11. For this project, the design effectiveness parameter E was calculated from the relationship

$$E = \frac{8P+10R+7L+6M+5A}{W}$$

4. SIZING RESULTS

Tables 4 and 5 present the initial sizing results for 1991 and 1992, respectively. The configuration assignments, as determined for the Taguchi experiment, are also included in these tables.

1991: ATS Assignments						
Case	A	B	C (lbs)	D (fpm)	E (g's)	Design TOGW (lbs)
I	ATP	E-2	2000	5000	4.0;3	59617
2	ATP	E-2	5000	6000	5.0;4	67412
3	ATP	E-2	6000	8600	6.5;5	84943
4	ATP	S-3	2000	6000	6.5;5	19036
5	ATP	S-3	5000	8600	4.0;3	30296
6	ATP	S-3	6000	5000	5.0;4	30587
7	ATP	EA-6B	2000	8600	5.0;4	10873
8	ATP	EA-6B	5000	5000	6.5;5	24170
9	ATP	EA-6B	6000	6000	4.0;3	23984
10	UDF	E-2	2000	5000	4.0;3	42574
11	UDF	E-2	5000	6000	5.0;4	55106
12	UDF	E-2	6000	8600	6.5;5	59513
13	UDF	S-3	2000	6000	6.5;5	19165
14	UDF	S-3	5000	8600	4.0;3	28288
15	UDF	S-3	6000	5000	5.0;4	27415
16	UDF	EA-6B	2000	8600	5.0;4	10804
17	UDF	EA-6B	5000	5000	6.5;5	19827
18	UDF	EA-6B	6000	6000	4.0;3	20337
19	HBP-TF	E-2	2000	5000	4.0;3	53697
20	HBP-TF	E-2	5000	6000	5.0;4	73056
21	HBP-TF	E-2	6000	8600	6.5;5	64962
22	HBP-TF	S-3	2000	6000	6.5;5	15777
23	HBP-TF	S-3	5000	8600	4.0;3	26490
24	HBP-TF	S-3	6000	5000	5.0;4	29716
25	HBP-TF	EA-6B	2000	8600	5.0;4	12765
26	HBP-TF	EA-6B	5000	5000	6.5;5	20527
27	HBP-TF	EA-6B	6000	6000	4.0;3	21764

A. Propulsion System
B. Mission
C. Payload(lbs)
D. Climb Rate(ft/min)
E. Maneuvering Load Factor: Instantaneous;Sustained(g's)

Table 4. 1991: ATSConfiguration Assignments and Results

5. Taguchi Analysis And Results

5.1. 1991 Results

As mentioned earlier, the Taguchi experiment used five parameters with three levels each. The parameters were: propulsion system type, mission profile, payload, climb rate, and maneuvering load factor. The quality parameter was TOGW in a smaller-is-better analysis. The resulting sizing data were analyzed by the MDC staff.

The signal-to-noise ratio data for the 1991 experiment, are presented in Figs. 1 and 2. It represents the relative influence to the quality parameter with relation to the other parameters. All parameters that have signal-to-noise ratios greater than 50% of the largest are considered to significant to a particular quality parameter. This is known as the 50% rule(3) Using the 50% rule, the data indicated that only the mission profile parameter (Factor B) was critical, with a delta of 43,650 pounds; the E-2 mission had the greatest TOGW, the EA-6B mission the smallest. Since the other four parameters had deltas much less than 50% of this amount, they were not considered important and, therefore, could be varied as other conditions dictated. Payload (Factor C), with a delta of 30% of that for the mission profile, was considered marginal in this analysis. It could be allowed to vary with little chance of adverse effect on the outcome. It would be desirable to choose a payload of at least 5000 pound and thereby increase

1992: MMTA Assignments						Results	
Case	A	B.	C	D	E	Design TOGW (lbs)	E
1	2	30	50	3	90	39,200	1.47
2	2	30	100	5	70	43,300	2.46
3	2	30	200	7	50	75,200	2.60
4	2	60	50	5	50	52,400	2.20
5	2	60	100	7	90	75,900	1.51
6	2	60	200	3	70	65,800	2.27
7	2	90	50	7	70	108,500	1.53
8	2	90	100	3	50	72,500	2.15
9	2	90	200	5	90	79,900	2.72
10	4	30	50	3	90	54,600	1.42
11	4	30	100	5	70	51,000	2.17
12	4	30	200	7	50	93,400	2.23
13	4	60	50	5	50	50,500	3.17
14	4	60	100	7	90	88,400	1.38
15	4	60	200	3	70	81,500	2.14
16	4	90	50	7	70	105,800	1.29
17	4	90	100	3	50	91,300	2.01
18	4	90	200	5	90	129,900	1.32
19	8	30	50	3	90	71,500	1.58
20	8	30	100	5	70	103,300	1.66
21	8	30	200	7	50	115,000	1.94
22	8	60	50	5	50	131,200	1.53
23	8	60	100	7	90	148,000	1.32
24	8	60	200	3	70	174,000	1.80
25	8	90	50	7	70	152,600	1.31
26	8	90	100	3	50	135,600	1.54
27	8	90	200	5	90	249,600	1.11

A: Payload (no. of TMDs)
B: Loiter (min)
C: Radius (nm)
D: Sustained Maneuvering Load Factor (g's)
E: Acceleration Time (sec)

Table 5. 1992 MMTA Configuration Assignments and Results

the design versatility. If the mission (which is the strongest factor) is ignored and the 50% rule is applied, Fig. 2 shows that the propulsion system becomes a significant factor.

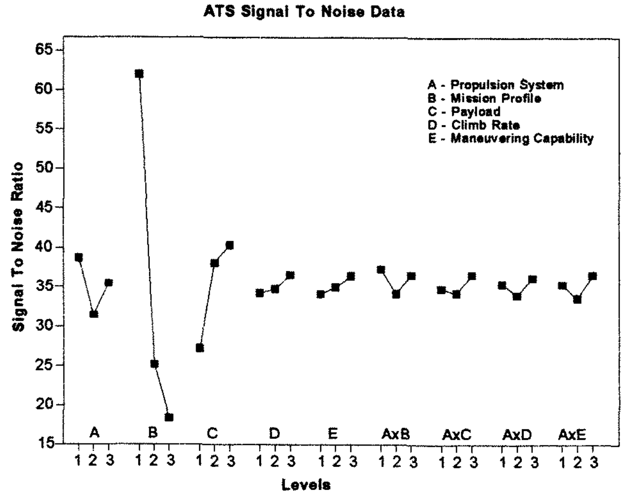

Figure 1. ATS Signal-To-Noise Ratio Results

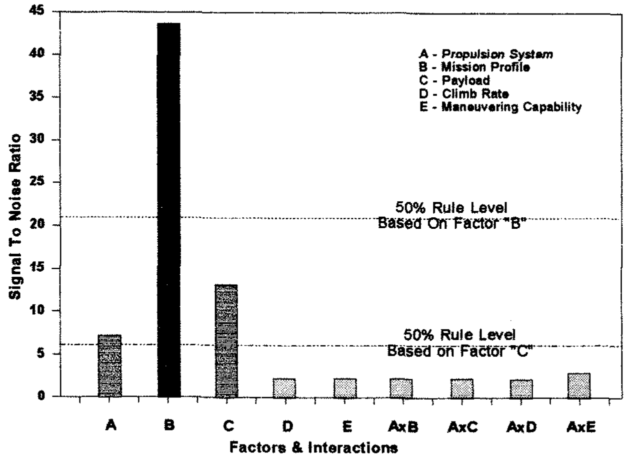

Figure 2. ATS Signal-To-Noise Range Comparison

The results indicate that the propulsion system (Factor A) is insensitive to the process. It must be noted, however, that the methods of analysis for this parameter are of low fidelity in this study. This is particularly true in the case of the turboprop system in which some of the higher propeller tip speed effects are not accounted for. Higher fidelity analysis methods could effect the magnitude of the effects, but they are thought to still be secondary. The results should hold for the other two propulsion systems, however.

Analysis of the interactions indicated that none of them is important; the largest delta was 7.2% of the mission profile delta (Fig. 2). Based on these results, there appears to be no significant interaction between propulsion system and the other four parameters; i.e., the mission profile, the payload, the climb rate, or the maneuvering requirements. For the purpose of the this study, any parameter combination with the mission profile of the EA-6B should result in a minimum weight design. It should be noted, however, that this does not imply that this is the most effective solution or combination, but only that it is the lightest weight solution.

5.2. 1992 Results

The signal-to-noise ratio data for the MMTA are presented in Figs. 3 and 4. They show that three control factors (i.e., payload, loiter time and acceleration) are significant to this experiment. Acceleration has the largest deviation with a range of 3.08. Using the 50% rule (Fig. 4), the threshold value is 1.54. In addition to acceleration, two other parameters exceed this value. Payload has a value of 2.18, or 70.0% of the maximum deviation, and loiter has a value of 1.95 or 62% of the maximum deviation. None of the other factors or interactions have large enough deviations to be considered significant.

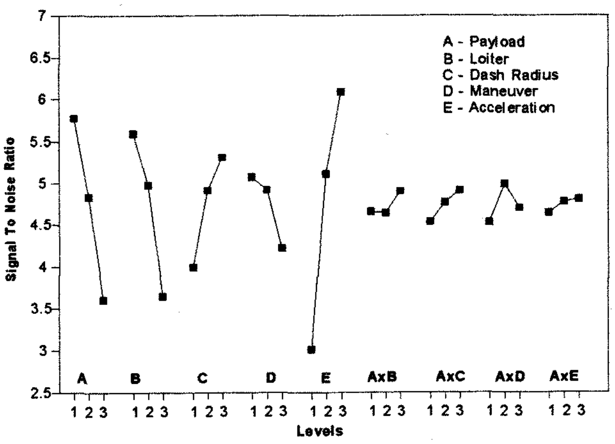

Figure 3. MMTA Signal-to-Noise Results

The analysis of the interactions in comparison to the primary factors (Fig. 4), indicate that they are not of major concern at this level of aircraft sizing. However, the interactions do show some interesting trends. The results of an interaction analysis are shown in Fig. 5. These results show the interaction of the payload (Factor A) with the other parameters. They all show comparable levels of significance. In particular, note the reversal shown in the interaction with the maneuvering load factor (Factor D).

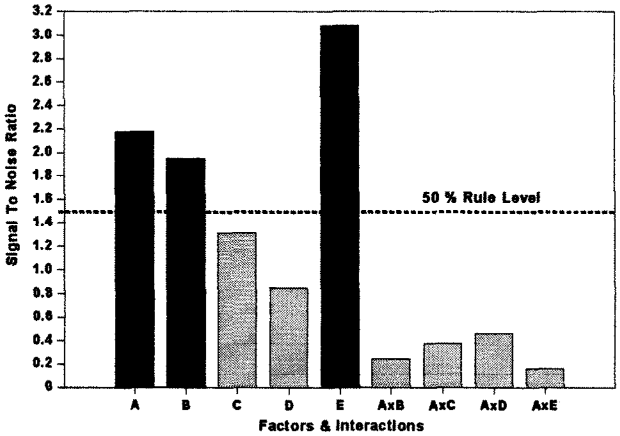

Figure 4. MMTA Signal-to-Noise Range Comparison

Interactions with reversals can be interpreted in several ways. In Fig. 5, the payload versus loiter interaction (AxB) suggests a detimental influence on both drag and weight from the additional weapons. The effectiveness parameter, E, involved a weighting constants of "8" on the payload and "7" on loiter time. The sum of the factors for maneuvering load factor and acceleration is "11", outweighing either of the other parameters. It is also known that the extra weapons are added at the expense of acceleration and maneuvering capability for a given aircraft weight. The additional fuel for loiter also drives the aircraft to be larger and, therefore, not as efficient (per pound of aircraft) for producing the accelerations and maneuvering limits.

These results may indicate that there are influences that were not measured in the experiment. Other factor assignments in the experimental array could possibly show the interaction. It is also possible that the effects are coupled in three or more ways and, therefore, a different array other than an L27 would be required to fully explore these effects. Even with this uncertainty in the interactions, the strength of the main effects, compared to the interactions, indicate that the main trends are valid.

These effects are certainly demonstrated in real life design. From WWII aircraft to those of today, the most efficient way to get a highly maneuverable and quick aircraft is to make it small (i.e., light weight). The Supermarine Spitfire and the F-16 are among the many good examples of this. Both are very maneuverable in comparison to their contemporary aircraft and also are light weight. However, if either of these designs require a loiter, even with a modest weapons load, the aircraft effectiveness is reduced sharply. The needed fuel weight and associate growth in structural weight is a large percentage of TOGW when compared to larger aircraft. Figure 5 also shows that as extra fuel is added to an aircraft required to carry heavier loads, the impact is not nearly as dramatic. The case of four bombs (A2) produces very little loss in effectiveness when the loiter is doubled. It is only when the loiter time is tripled that effectiveness is significantly reduced. The largest of the vehicles with the 8-bomb requirement (A3) shows an almost linear decrease in effectiveness as loiter time increases.

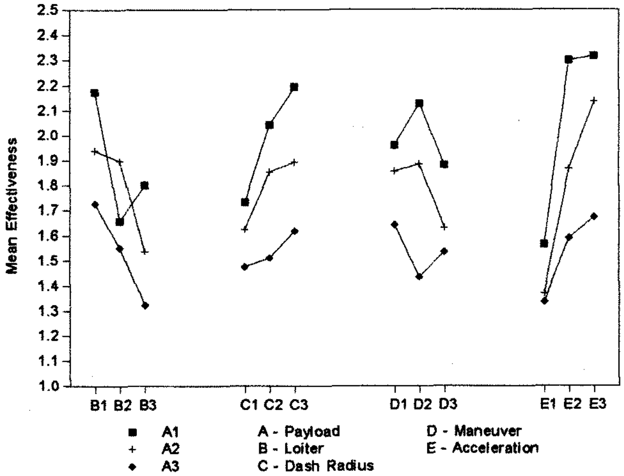

Figure 5. MMTA Interactions Analysis

These results alone cannot be used to determine which combination of parameters will actually best optimize the hypothetical effectiveness parameter for this study. This is because this experiment has not fully mapped out all of the possible interactions. But it is clear that the results do agree with known real-life effects.

The above results were used to establish the design team assignments. The 1991 assignments are presented in Table 6. Each design team had the following overall design assignment.

1. Meet the specifications of the "primary" mission (see Table 6); the minimum requirement.
2. Meet the specifications of the "secondary" mission without compromising the "primary" requirements or by a justifiable compromise.

3. Evaluate the design to see how many of the "fallout" specifications were met.

Team	Primary	Secondary	Fallout
1	E-2	S-3	EA-6B
2	S-3	EA-6B	E-2
3	E-2	C-2	S-3
4	S-3	C-2	E-2
5	EA-6B	E-2	S-3

Table 6. 1991 ATS Design Team Assignments

The following major changes in the ATS mission specifications were also assigned.

a. An internal load of 10,600 lbs of electronic gear was added to the E-2 mission.

b. An internal load of 3900 lbs of weapons was added ot the S-3 mission. It was also to be designed for a 5100 lb overload.

c. Team 5 was required to use a low bypass-ratio turbofan engine to optimize high-speed penetration.

The 1992 design team assignments are presented in Table 7. The overall design objectives were the same as in 1991.

Team	Primary	Secondary	Fallout
1	BAI	DCA	CAS & OCA
2	BAI	OCA	CAS & DCA
3	OCA	DCA	CAS & BAI
4	OCA	BAI	CAS & DCA
5	DCA	BAI	CAS & OCA
6	DCA	OCA	CAS & BAI

Table 7. 1992 MMTA Design Team Assignments

6. Design Course Impact

The opportunity to use Taguchi experiments in a typical capstone design course was fundamentally related to the way in which the course was organized. With all students doing, individually, a sizing exercise, it was possible for each student to work from a different set of specifications. This made the many different specification sets, required for a Taguchi experiment, a practical possibility.

Using the results of these experiments as part of the process of determining the final specifications for the team design work and interacting with the MAC engineers added both a dynamic component and a real-world flavor to the design course. In addition, the introduction of these experiments provided the opportunity to introduce, explicity, some Systems Engineering content to the design course. Finally, the possibility that the experiment results would have a practical value to MDC added to the positive environment of the course.

These experiments were not introduced into the desgn course without cost. With only 15 weeks to complete the design work, including the Taguchi ex-periments required very careful and thorough planning. In addition, using the results of the experiments to set the final specifications required some intense work by MDC to meet the schedule requirements of the course.

7. Conclusions

In retrospect, each time one of these experiments is completed something is learned about the use of the methodology in the design process. It may be imprecise at first, but the usage improves with practice.

The first year's experiment showed that, although the method generally worked, only a modest insight into it's potential usefulness in the sizing process. In this first application, take-off gross weight was used as the quality parameter. One result of optimizing this parameter in a smaller-is-better experiment is the observation that the least capable aircraft weighs the least. This may be obvious to any experienced designer.

In the second year, an aircraft effectiveness measure was used as the quality parameter. Optimizing this parameter worked much better from the application viewpoint, and the results were better suited to further investigation. The true applicability is, of course, tied directly to the formulation of an effectiveness factor that correlates well with real aircraft performance and operation tactics.

There are still many areas that merit study using Taguchi methods in this type of design. One would be the introduction of "noise" into the experiment Thus far, it has been assumed that all of the analytical methods used for aircraft sizing are without variation. This is of course not the case.

Integration of noise into the experiments in an appropriate way will be an essential improvement to the process and subject of possible future studies.

From the educational point-of-view, the Taguchi experiments were a positive, and demanding, addition to a typical senior capstone design course. The close interaction with the MAC engineers produced a valuable "real-world" component to the course. The critical element for such an undertaking is very thorough planning and organization.

8. References

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Appendix A

	Missions			
Leg	C-2	E-2	EA-6b	S-3
1. Warm-up and taxi	20 Min	20 Min	20 Min	20 Min
2. Take Off				
3. Climb	(1)	(1)	(1)	(1)
4. Cruise	2,000 nm @ BCMA (5)	525 NM @ BRA (6) and Mach Number	400 NM @ 30,000 ft and Mach 0.75	500 Nm @ BCMA
5.	NA	Loiter; 3.75 Hr @ 35,000 ft and BEM(4)	a. Dash: 65 Nm @ 1,000 ft and Mach 0.8 b. Dash: 35 NM @ 1,000 ft and Mach 0.85-0.90	Loiter: 1.50 hr @ IP(2) and 1,000 ft
6. Loiter	NA	NA	NA	20 min @ IP and sea level
7.	NA	NA	a. Dash: 35 Nm @ 1,000 ft and Mach 0.85-0.9 b. Dash: 65 NM @ 1,000 ft and Mach 0.80	1.5 hr @ 1,000 ft and BEM
8. Cruise	NA	525 Nm @ BRA and Mach 0.7	400 Nm @ 30,000 ft and Mach 0.75	550 Nm @ BCMA
9. Loiter	(3)	(3)	(3)	(3)
10. Land				

(1) Climb at normal power to cruise altitude and Mach; include range credit. (2) IP = Intermediate Power; 0.85-0.90 Maximum thrust / power (3) 20 Min @ Sea Level and BEM (4) BEM = Best Endurance Mach Number (5) BCMA = Best Cruise Mach Number and altitude (6) BRA = Best range Altitude

Table A-1
ATS - Team Design Mission Sprecifications

APPENDIX A

	Aircraft			
Leg	C-2	E-2	EA-6b	S-3
Engine	Open(1)	Open(1)	Low Bypass Turbofan	Open(1)
Payload (lbs)	10,000	13,630	5,000	5,000
Sea Level Climb rate (fpm)	NA	6,000	8,600	6,000
Range NM: Cruise	2,000	525	500	2,300
Ferry (internal Fuel No Payload)	3,000	2,500	2,000	3,000
Endurance (hr)	NA	5.75	3.50	5.5
Maneuver Requirement (g's)				
Instantaneous	NA	5.0	6.0	5.0
Sustained	NA	4.0	4.0	4.0
Max. Airspeed (Kts/M) Altitude	305/@ Best	345/0.75 @ SL and 325/0.85 best Altitude	0.85-0.90 @ SL and 0.90 @ 30,000 ft	480/0.8 @ SL
Cruise Mach Number / Altitude	0.75 @ Best	0.80 @ Best	0.75 @ 30,000 ft	0.75 @ Best
Ceiling (ft)				
Absolute	NA	45,000	47,000	NA
Service (500 fpm)	30,000 to 40,000	40,000	40,000	40,000

Common Specifications	
Maximum Wing Span	80 Ft
Max. TOGW:	
Carrier Limit	80,000 lbs
Target	65,000 lbs
Number Of Crew	3
Take off	
Conventional	4,000 ft
Carrier	Use c-13, Mk1 catapult with zero wind over the deck
Landing	
Conventional	4,000 ft
Carrier	Use Mark 7, Mod 3 Arresting Gear
Approach Speed	120 Kts
Loiter Mach Number	0.4
Fuel reserves:	
For High Bypass Rate Turbofan, the Unducted Fan and the turboprop	750lb / engine
For the low bypass Ratio Turbofan	1,000 lb. / engine
Trapped Fuel	5% of mission fuel

(1) Teams select advanced turboprop, unducted fan, low bypass turbofan or high bypass turbofan

Table A-2
ATS Team Design Performance Specifications

APPENDIX A

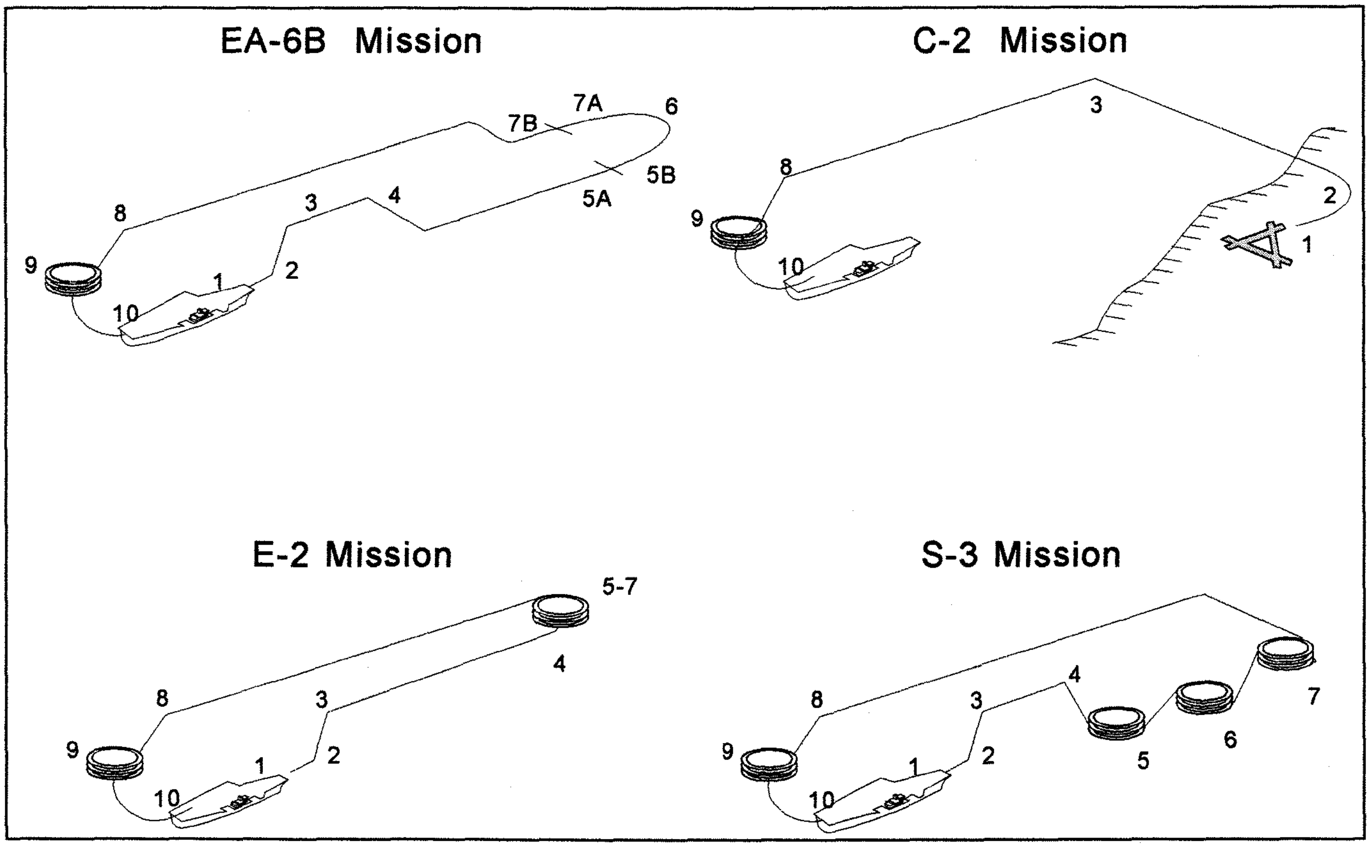
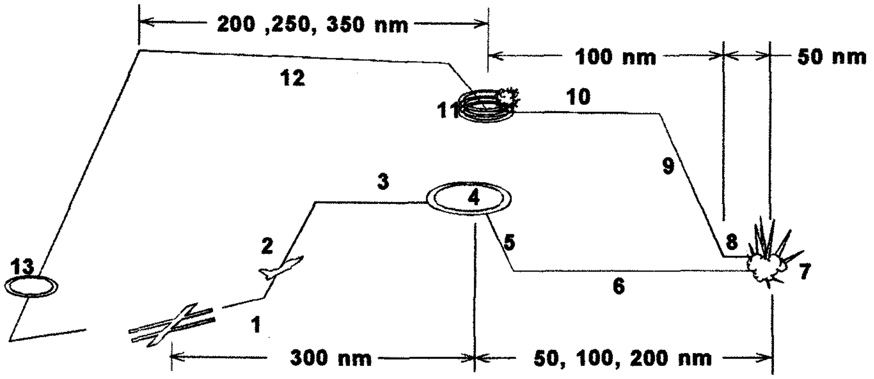


Figure A-1 ATS - Team Design Misions

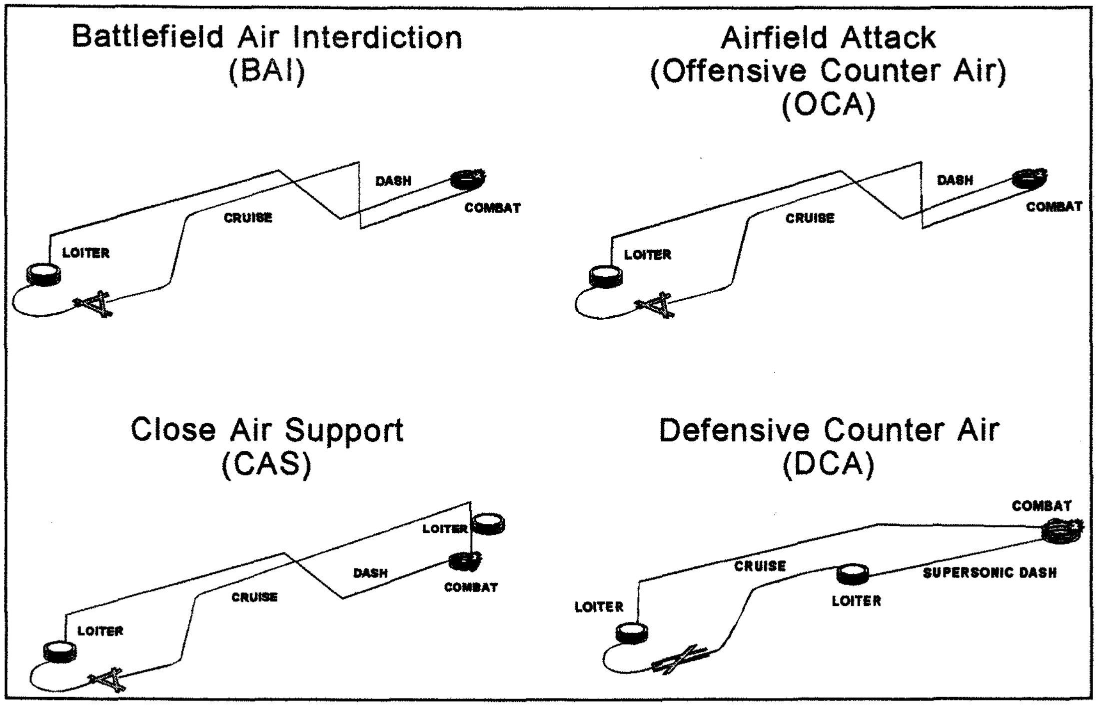
APPENDIX B



Preliminary Sizing Exercise Mission Segment Breakdown

1 Warm-up 20 Min, Taxi, Take-off (MIL-PWR)
2 Climb To Cruise Altitude
3 Cruise (40000 Ft, Best M to 300 nm)
4 Loiter (30 or 60 or 90 Min)
5 Descent to 500 ft (SL data OK) M=0.9
6 Penetration at 50 or 100 or 200 NM, M=.90, Alt = 500 ft (SL)
7 Drop Air-To-Ground Weapons
Allow 2 min at Mil power for 2 Passes at target
and assume 1/2 weapons drop on first pass
8 Egress at 50 nm , M =.9, @ Alt= 500 ft (SL) SL
9 Climb to 20,000 ft Altitude (min time to climb profile)
10 Accel to .8 to 1.4 Mach in 50 or 60 or 70 sec
Dash dash to (intercept) at 1.4 M to 100 nm
11 Air-to-Air Combat
2 Max Sustained G Turns (3,5,7) at M=0.75 @ 20,000 ft
and fire 1 ASRAAM
12 Cruise at 40000 ft, M=best, 200 or 250 , or 350 nm
13 Descent and Land (Allow a loiter of 20 min at 10,000 ft
at the best endurance MACH number)

Figure B-1 MMTA Preliminary Sizing Exercise



Battlefield Air Interdiction
(BAI)

Airfield Attack
(Offensive Counter Air)
(OCA)

Close Air Support
(CAS)

Defensive Counter Air
(DCA)

Figure B-2. MMTA - Design Missions

APPENDIX B

			OCA	BAI	DCA	CAS
1	WUTO	TO @ Mil Pwr	20 min	20 min	20 min	20 min
2	Min Fuel Climb	@ Mil Pwr	to 35k	to 25k	to 25k	to25k
3	Cruise	Best M	350nm @35k	300nm @25k	200nm @25k	300nm @ 25k ft
4	Descent		to 15kft	to 200 ft		to 5k ft
	Loiter	M=0.7	---	---	45min @25kft	---
5	Dash	nm/ft/M	50/15k/.835	50/200/.835	---	---
	Accel to =M	max pwr	-----	-----	1.5 @20kft	-----
	Loiter	Best M				30min @5kft
6	Dash	M=1.5	-----	-----	25nm20kft	-----
	Descent to		----	-----	-----	500 ft
7	Combat		90 sec @ 15kft & 500kts; Mil Pwr; Drop A/G Weapons	90 sec @ 500ft &M=0.76; Mil Pwr; Drop A/G Weapons	Fire (2) AIM-120's	(4)-360 deg turns @ 500ft & 450kts; Mil Pwr; Drop (8) CBU87 bombs
8	Combat		(2) 360 deg, 9g turns@ 15kft & M=0.76; Fire(1)AIM -9	(2) 360 deg ,9g turns @ 500ft &M=0.76; Fire (1)AIM -9	(2) 360 deg turns @ 20kft & M=0.9; Max Pwr; Fire (1) AIM-120	(2) 360 deg , 9g turns @ 500 ft & 450 kts; Pwr As Req
9	Combat		-----	-----	(1)-360 deg turn @ 20kft & M=0.9; Max Pwr; Fire (1) AIM-9	-----
10	Dash		50 nm @ 15kft & 450kts (M=0.835)	50 nm @ 200ft & 550kts (M=0.835)	-----	-----
11	Min Fuel Climb	Mil -Pwr	to 35 kft	to 25kft	to 35 kft	to 25kft
12	Cruise		350 nm @ 35kft Best M	300 nm @ 25kft Best M	225 nm @ 35kft Best M	200 nm @ 25kft Best M
13	Descent		to 10 kft	to 10 kft	to 10 kft	to 10 kft
14	Loiter		20 min @ 10 kft Best M	20 min @ 10 kft Best M	20 min @ 10 kft Best M	20 min @ 10 kft Best M
15	Descent		to Sea Level	to Sea Level	to Sea Level	to Sea Level
16	Land		Land	Land	Land	Land
Payload:		A/G	(2) Adv Conf. Bombs	(2) Adv Conf. Bombs	------	(8) CBU 87 TMDs
		Gun	(1) M61 with 500 Rnds	(1) M61 with 500 Rnds	(1) M61 with 500 Rnds	(1) M61 with 500 Rnds
		A/A	(2) AIM-9 (IR)	(2) AIM-9 (IR)	(2) AIM-9 (IR)	(2) AIM-9 (IR)
			-----	-----	(4) AIM120 (Radar)	(1) 300 Gal CL
		Fuel	-----	-----	-----	Fuel Tank

Table B-1. MMTA Group Design Mission Definitions