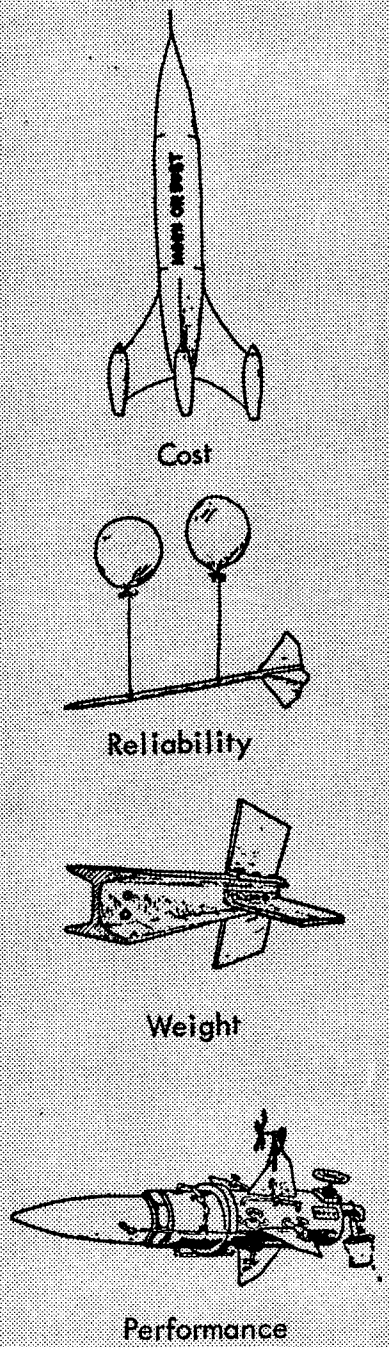

(NASA-CR-128276) DESIGN CRITERIA FOR SPACE PROPULSION SYSTEMS (Aerojet-General Corp., El Monte, Calif.) [1966] 65 p

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SG P-1069-1

DESIGN CRITERIA FOR SPACE PROPULSION SYSTEMS

AEROJET GENERAL TIRE GENERAL

SPACE-GENERAL PLANT

"DESIGN CRITERIA FOR SPACE PROPULSION SYSTEMS"

Contract NAS 7-519

- FUNDED BY NASA OART ($148,000), MONITORED BY JPL
- START DATE - 13 OCT. 1966, PROJECTED COMPLETION DATE - 13 SEPT. 1967
- OBJECTIVES
  1) PROVIDE PREDICTION TECHNIQUES FOR ESTABLISHING RELIABILITY, COSTS, WEIGHT, AND PERFORMANCE OF PROPULSION SYSTEMS
  2) EVOLVE PROCEDURES FOR ESTABLISHING MISSION-COST/EFFECTIVE DESIGN CRITERIA FOR SPACE PROPULSION SYSTEMS

INTRODUCTION

This program was funded by NASA OART to evaluate the feasibility of applying cost-effective criteria to the design of spacecraft propulsion systems. In an earlier program (Contract NAS 7-352) a methodology was evolved which allows the determination of the relative importance of reliability, cost, performance and weight in specific propulsion/mission applications. The scope of this earlier study was confined to large liquid propellant propulsion systems for manned space applications.

The Jet Propulsion Laboratory suggested that the techniques established in this earlier program should provide valuable results when applied to unmanned spacecraft applications. Objectives of the resulting program are:

1) To provide prediction techniques for establishing reliability, costs, weight, and performance of propulsion systems, and

2) To evolve procedures for establishing mission cost-effective design criteria for space propulsion systems.

The program is managed by Mr. Frank Compitello of OART and the Technical Monitor is Mr. James Kelley of the Jet Propulsion Laboratory.

PROBLEMS ASSOCIATED WITH CURRENT APPROACHES

What we would like to accomplish during this program is at least the partial elimination of some of the problems facing NASA, JPL and prime contractors when you have to select a propulsion system from among several design alternatives.

Many times conflicting data and confusing recommendations are presented for alternate system designs -- as indicated on the example shown on the chart, not only does the level of costs and reliabilities vary greatly -- the recommendation as to the cheapest or most reliable system seems to depend on who is evaluating the designs.

Subsystem tradeoffs are completed on a subsystem basis -- optimum only within a small boundary -- but certainly not, in general, providing an optimum total system.

Inconsistent requirements are used to evaluate and compare alternate designs, leading to inequitable results.

Finally, very qualitative and subjective conclusions lend to the problem facing decision makers.

The results of this program will provide a better definition of current propulsion capabilities; present a comparison of several cost and reliability prediction techniques, from which a basis for confidence in establishing these characteristics can grow; and a methodology for making design and development decisions,which can be also used as a valuable guide in program management and in analyzing program incentive considerations, will be presented.

PROBLEMS ASSOCIATED WITH CURRENT APPROACHES

- CONFLICTING DATA

CONTRACTOR	A			B			C		
DESIGN ALTERNATIVE	x	y	z	x	y	z	x	y	z
PROB. OF SUCCESS	.994	.987	.985	-	-	-	.963	.968	.924
TOTAL COSTS	-	-	-	26M	30M	30M	78	55	66

- "SUBSYSTEM" TRADEOFFS AND OPTIMIZATIONS
- INCONSISTENT REQUIREMENTS USED TO COMPARE ALTERNATIVES
- SYSTEM COMPARISONS (CONTRACTOR C)

COMPARISON	DESIGN ALTERNATIVE x	y	z
OUTSTANDING ADVANTAGES	• FLIGHT EXP. • SINGLE	• PROB.-OF-SUCCESS • LOWEST COST • FLEXIBILITY	
OUTSTANDING DISADVANTAGE	• INFLEXIBLE • COST		• SCOPE OF MODIFICATIONS • PROB.-OF-SUCCESS

PROPULSION CAPABILITIES AND DESIGN CRITERIA

This presentation is divided into two sections. The first section will review propulsion performance, weight, reliability, costs, and sterilization considerations. The comparative charts provide graphical comparisons of the solid, hybrid, RSVP, and liquid propulsion systems, and indicate quantitative differences which are discussed in the design criteria portion of the presentation.

The second section of the presentation describes cost-effective criteria, mission models, influence-coefficients, and examples which utilize the mission cost-effective design criteria together with the detailed propulsion data to indicate typical solutions to design and development trade-off decisions.

DATA PRESENTATION

DETAILED PROPULSION DATA

- SOLID, HYBRID, BIPROPELLANT, MONOPROPELLANT SYSTEMS
- REQUIRED DATA INCLUDES RELIABILITY, COSTS, WEIGHT & PERFORMANCE PREDICTION AND SCALING TECHNIQUES, LIMITATIONS, EXPECTED ACCURACY
- SUBCONTRACTORS

ROCKET RESEARCH CORP.	MONOPROPELLANT	.05 - 500 LB THRUST
TRW SYSTEMS	MONO-AND BI-PROPELLANT	.1 - 200 25 - 15,000
THIOKOL RMD	BIPROPELLANT	25 - 15,000
AEROJET-GENERAL	BIPROPELLANT (RELIABILITY)	—
LOCKHEED PROPULSION	FLUID-CONTROL	50 - 5000
UNITED TECHNOLOGY	HYBRID AND SOLID	50 - 5000
THIOKOL CHEMICAL	SOLID	50 - 15,000
AEROJET-GENERAL	SOLID	50 - 15,000
AEROJET-GENERAL	PUMPED LIQUID	5,000 - 50,000

- FINAL REPORTS OF SUBCONTRACTED STUDIES DUE IN JUNE/JULY

DATA PRESENTATION

- SUMMARY TABLES CROSS-REFERENCED TO DETAILED DISCUSSIONS
  - I - GENERAL SYSTEM DESCRIPTION
  - II - PERFORMANCE
  - III - WEIGHT
  - IV - FAILURE MODES AND EFFECTS
  - V - RELIABILITY/DEVELOPMENT FACTORS
  - VI - DEVELOPMENT COSTS
  - VII - PRODUCTION COSTS
  - VIII - EFFECTS OF STERILIZATION REQUIREMENT
- SYSTEM COMPARISON (NON-PROPRIETARY AND PROPRIETARY DATA)
- EXAMPLE PROBLEMS PREPARED BY SUBCONTRACTORS

PERFORMANCE CHARACTERISTICS

- PARAMETERS
  - STEADY STATE I_{SP}
  - PULSE MODE I_{SP}
  - THROTTLED PERFORMANCE
  - IMPULSE-BIT REPRODUCIBILITY
  - ALIGNMENT ACCURACY
- DATA REQUIREMENTS
  - PREDICTION TECHNIQUES
  - LIMITATIONS
  - EXPECTED PREDICTION ACCURACY

DELIVERED SPECIFIC IMPULSE

This chart shows achievable vacuum performance over a range of expansion ratio up to 300:1. The hydrazine motors have a noticeably smaller gain with expansion ratio since drag losses increase at low Reynolds' Numbers (25K vs 10,000K). The ARES space engine operates at about 2000 P_c and with ϵ between 250 and 300. The Solid, RSVP, Hybrid, bipropellant, and solid propulsion systems range in performance between 280 seconds to 315 seconds when earth-storable propellants are used. The fluorine compound space storables increase delivered specific impulse to the 360-380 range.

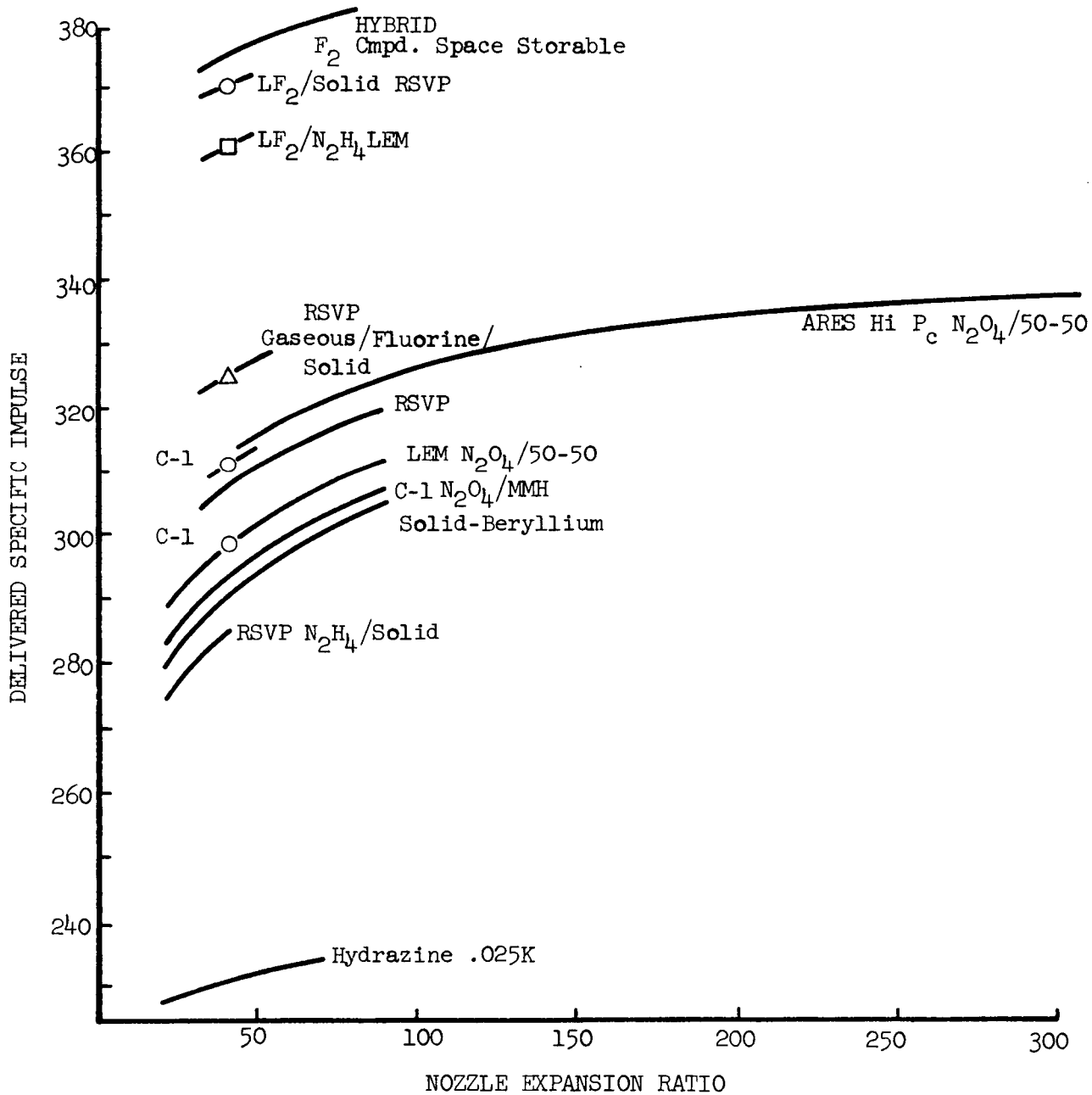
IMPULSE-BIT REPRODUCIBILITY

The typical trend is shown by the solid lines with the monopropellant system. Bi-propellant systems have competitive reproducibility with the monopropellant systems at the lower thrust levels. The RSVP system has the limitation of a minimum-bit size which is predicted by the minimum pressure to promote combustion; in addition the initial firing values of reproducibility (left-hand point) are smaller than the final values due to increased chamber volume at burnout.

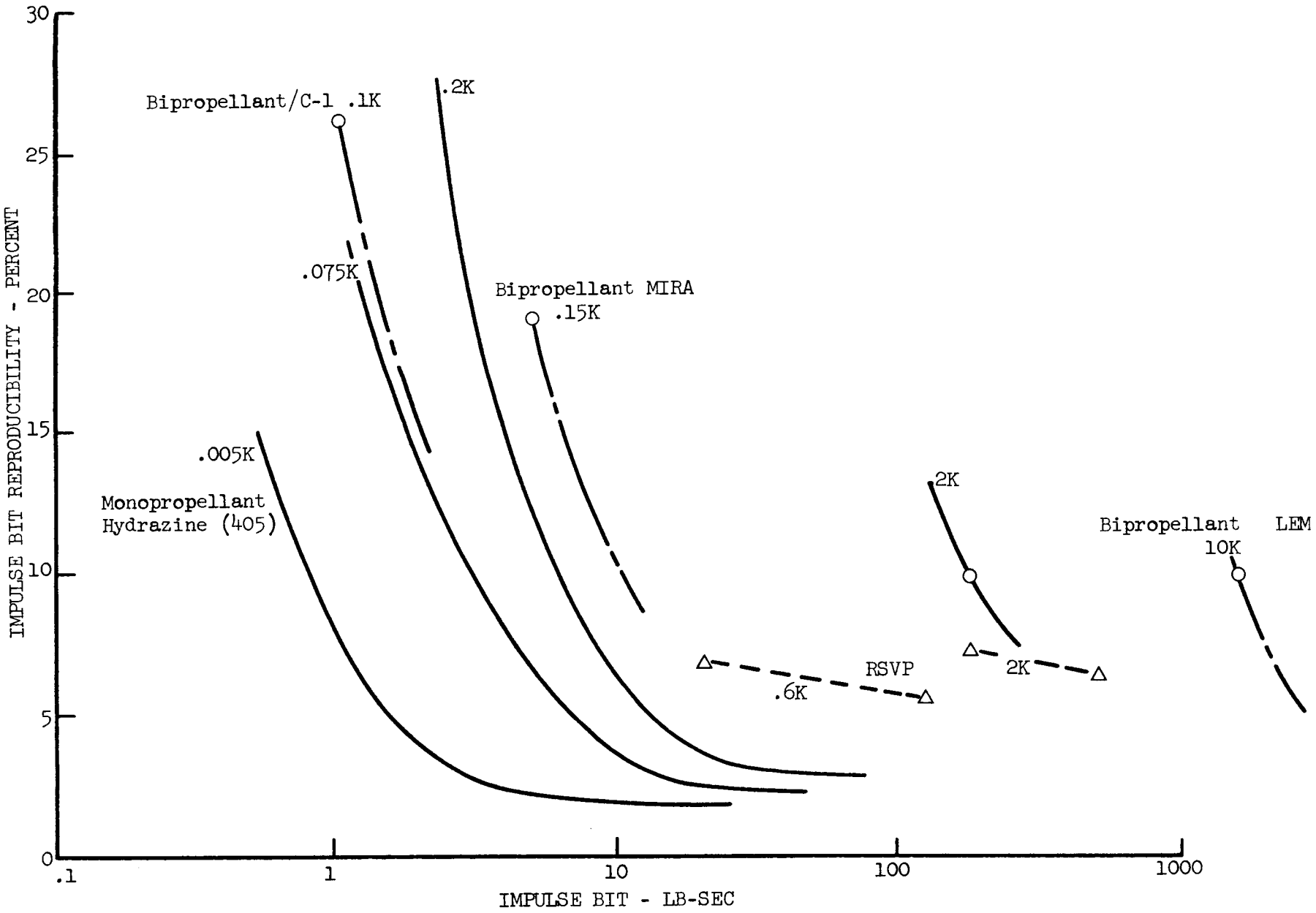
PERFORMANCE DURING THROTTLED OPERATION

All of the systems have reasonably high performance over a range in throttle ratio up to 10:1. The RSVP and Hybrid systems have additional liabilities for random throttling duty cycles due to poor propellant utilization at the throttled conditions.

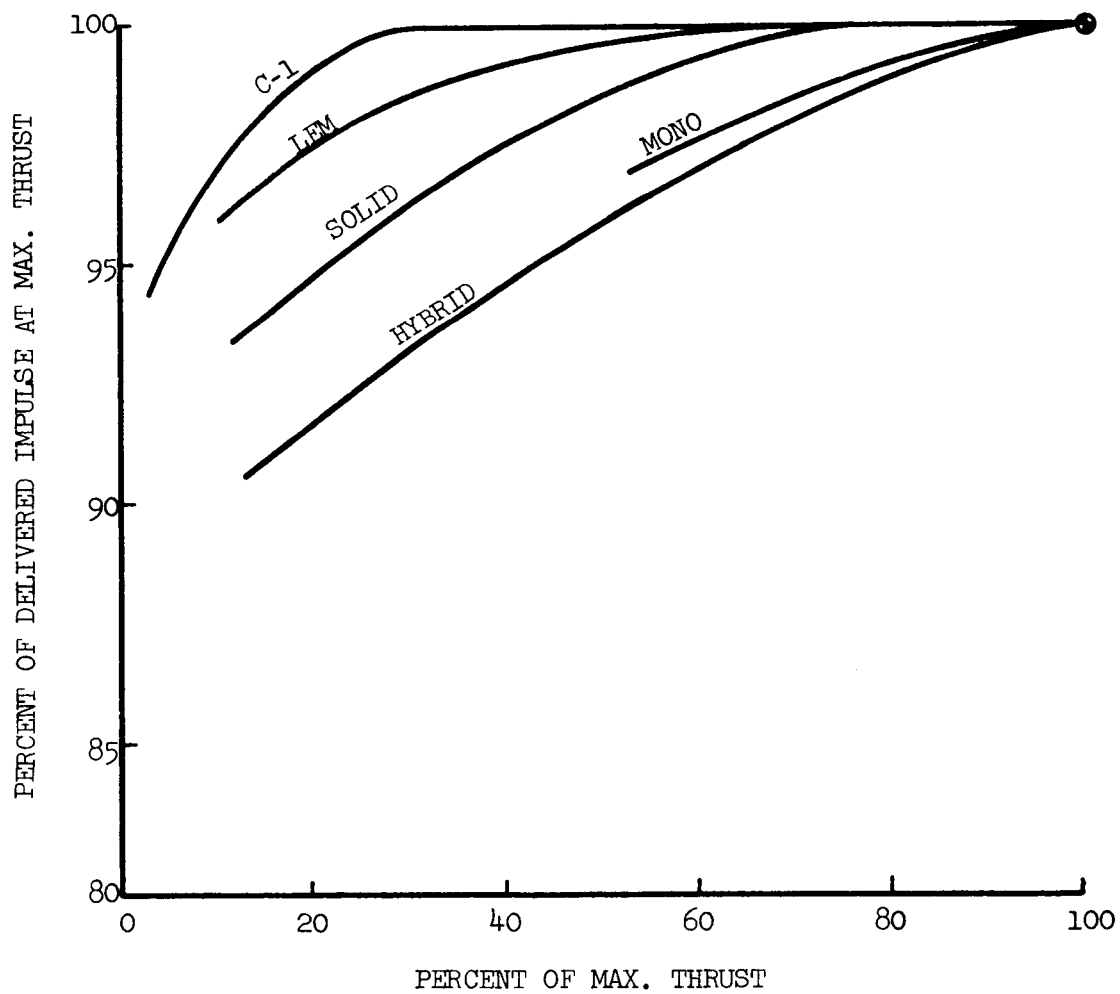
DELIVERED SPECIFIC IMPULSE



IMPULSE-BIT REPRODUCIBILITY



PERFORMANCE DURING THROTTLED OPERATION



WEIGHT CHARACTERISTICS

- PREDICTION TECHNIQUES
- LIMITATIONS
- EXPECTED PREDICTION ACCURACY

PROPULSION MASS FRACTION

Mass fraction is a good indicator of weight efficiency of propulsion systems. Propellant containers, pressurization system, thrust mount, and residuals have been added to the "engine" weight for the liquid systems shown in the chart. Storable liquid systems become more competitive as size (propellant weight) increases, and in general provide better propellant fractions at propellant weights above 20,000 pounds of propellant.

Although solid motors are more efficient at low propellant weights -- this advantage is obviously tempered by the requirements of the specific application; note that a throttlable solid motor (pintle injector) is very heavy, and that although the RSVP and hybrid motors have throttling capability, they suffer in propellant utilization efficiency (not included in weights); and that the bipropellant liquid motors must be used where pulsing is required.

The pump-fed system has weight advantages over the C-1 and LEM pressure-fed systems, however, this advantage is lost in the range of 5000 pounds of propellant; or more specifically at about the time when "minimum" gage tanks must be used and propellant tank pressurization becomes a smaller weight penalty.

RELIABILITY DATA

- COMPONENT FAILURE MODES & EFFECTS
  - FAILURE MODES & CAUSES
  - PROBABILITY OF OCCURRENCE
  - SOURCE & MAX./MIN.
  - METHODS OF ELIMINATING FAILURE
  - FAILURE RATE REDUCTION RELATIONSHIPS
- RELIABILITY GROWTH DURING DEVELOPMENT

COMPONENT FAILURE RATES

The following two charts indicate the format in which failure modes, effects, and failure probabilities have been presented for the various propulsion systems.

FAILURE RATE REDUCTION RELATIONSHIPS

These data will be used in an example presented in the final portion of the presentation.

THE ACCELERATION OF RELIABILITY GROWTH

This graph shows that a learning curve exists in the development of large liquid propulsion systems. Data points represent the Redstone (modification of the V-2); the Navahoe (a new system); the MA-1 Atlas, Jupiter, Thor, and MA-2 (modifications of the basic Navahoe engine); the H-1 and H-2 (modifications of the Atlas series); and the Titan and Centaur engines, which both represented new engine development programs (both from the standpoint of contractors and design concept). The ARES engine development program should have a reliability growth parameter, as established by this historical trend, of from 1.6 to 2.2.

COMPONENT FAILURE MODES AND EFFECTS

Component: Chamber

Component Type: Glass Filament Wound

Motor Type	Standard	Standard	Standard	Standard	Standard
Failure Mode	Inadequate glass or composite strength	Inadequate Igniter or Nozzle boss strength	Igniter Joint/Seat leakage	Nozzle Joint/Seal leakage	Inadequate skirt strength
Failure Causes	(a) Filament Under-strength (b) Irregular Roving Indexing (c) Irregular Winding Tension (d) Irregular Cure	(a) Aluminum under-strength	(a) Joint Material Failure (b) O-ring Failure (c) Attach Bolt Failure (d) Boss/chamber bond failure	(a) Joint Material Failure (b) Attach Bolt Failure (c) O-ring Failure (d) Boss/chamber bond failure	(a) Skirt Matl. Failure (b) Skirt/Chamber Bond Failure
Probability of Failure Occuring during Solid Motor Firing	Total Unsterilized .00003 .00005 .000038 Sterilized .000063	.000006 .000006	.000006 .000008	.000006 .000008	.000002 .000003
Detection	Growth: Strain Gage	None	None	None	None
Remedial Action	---	---	---	---	---
Effects on Propulsion	(1) Change motor C.G., Thrust Alignment (2) Chamber Ruptured-loss of thrust	(1) Leakage or burn thru reduced thrust (2) Igniter Nozzle ejection producing thrust spike & loss of thrust	(1) Leakage, burn thru-reduced thrust (2) Igniter ejects producing thrust spike, loss of thrust	(1) Leakage, burn thru-reduced thrust (2) Nozzle ejection-thrust spike, loss of thrust	(1) Change in Thrust Alignment (2) Chamber Rupture/Burn thru-Loss of thrust.
Methods for Elimination	(1) Increase Process Control (2) Increase number of layers	(1) Increase boss strength.	(1) Increase Joint Strength (2) Increase No. of Bolts	(1) Increase Joint Strength (2) Increase No. of Bolts	(1) Increase Skirt Mat'l Strength (2) Increase Skirt Bond Strength
Failure Rate Reduction Relationship	Failure rate is directly related to number of glass layers and design margins. A previous study indicated that a tenfold reduction of failure rate (from 10^{-5} to 10^{-6} required an increase of 0.22 lb. of total motor weight per 100 lb of propellant	Failure rate is partially a function of boss weight, partially a function of configuration	Failure rate is partially related to joint weight and number of bolts.	Failure rate is partially related to joint weight and number of bolts.	Failure is partly related to Skirt material weight.

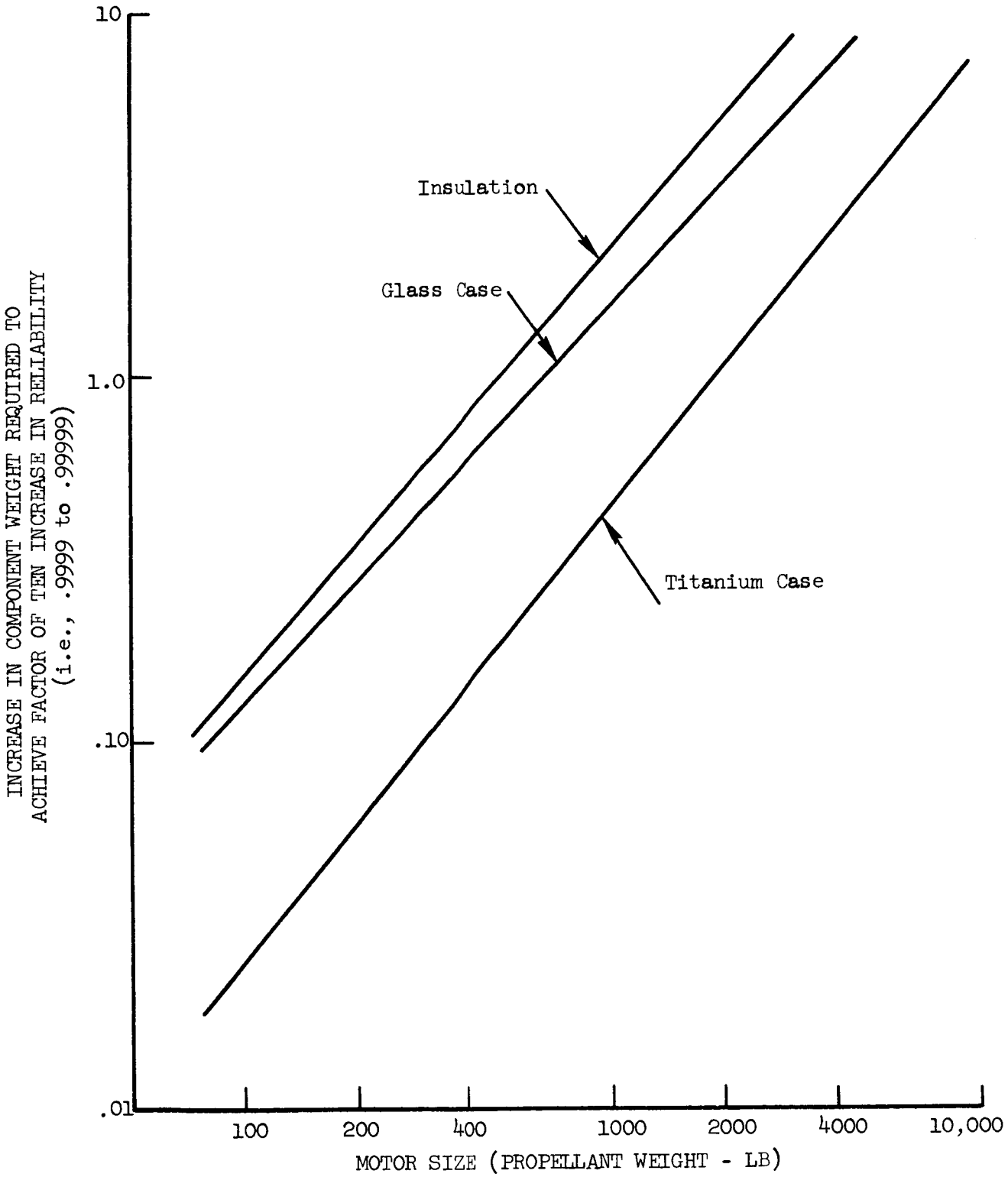
TABLE 8-D-1

II_A COMPONENT FAILURE MODES AND PROBABILITIES DURING SEVERAL MISSION PHASES

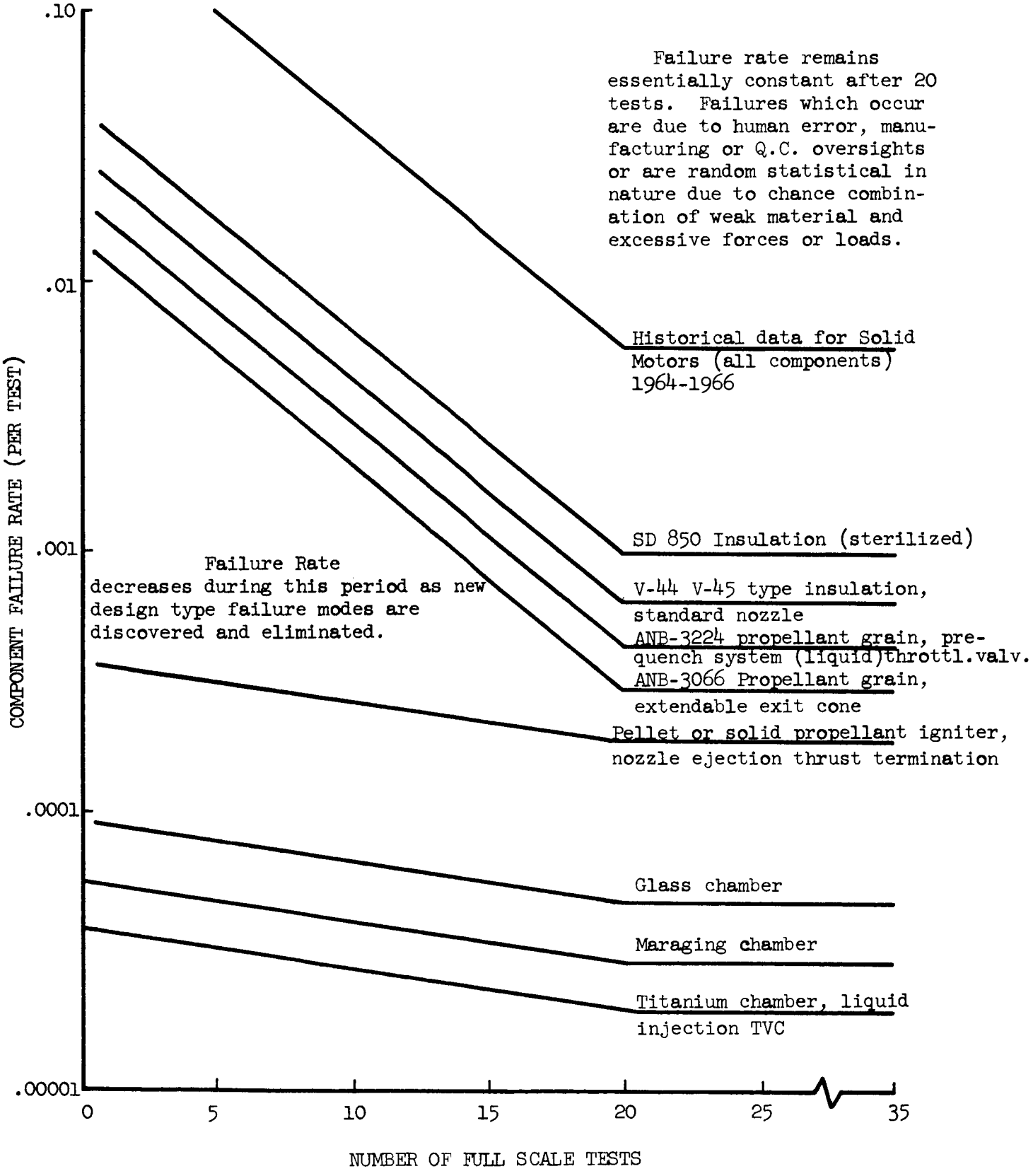
COMPONENT BiPROPELLANT VALVE

Failure Modes			Leakage, internal (through valve seats)		Leakage, external					
Failure Cause			Damaged seat - from vibration Contamination on seat Button/seat misalignment		K-seal failure (valve injector interface)					
PROBABILITY OF FAILURE OCCURRING (Per Mission)	**During Launch**	**Maximum** **Minimum** **Expected** **Confidence**	15×10^{-6} 50%	**Source** C-1 and other radiamic engine experience at RMD	0	**Source** C-1 and Surveyor Vernier Engine and RMD valve experience.		**Source**		**Source**
Surveyor Mission Duration 66 hrs Firing Time 223 sec Throttle Valve Cycles 180 Shutoff Valve Cycles 3	**During Coast**	**Maximum** **Minimum** **Expected** **Confidence**	5×10^{-6} 50%		0	"				
	At Startup	**Maximum** **Minimum** **Expected** **Confidence**	10×10^{-6} 50%		0	"				
C-1 Mission Duration-Various Firing Time 1000 sec Pulse Valve Cycles 7000	**During Operation**	**Maximum** **Minimum** **Expected** **Confidence**	50×10^{-6} 50%		15×10^{-6} 90%	"				
	At Shutdown	**Maximum** **Minimum** **Expected** **Confidence**	15×10^{-6} 50%		0	"				
1. Possibilities for detection.			Reduced propellant tank pressure		Reduced propellant					
2. Remedial action after detection.			None		Close upstream valves					
3. Effects of failure on propulsion performance and interfacing system.			Continuous propellant leak into chamber		O/F ratio change Loss of propellant					
1. Methods for eliminating or reducing probability of failure mode.			Extensive vibration and development tests		Strict in-process controls and development tests.					
2. Estimated reduction in failure probabilities and estimated cost and weight effects.										

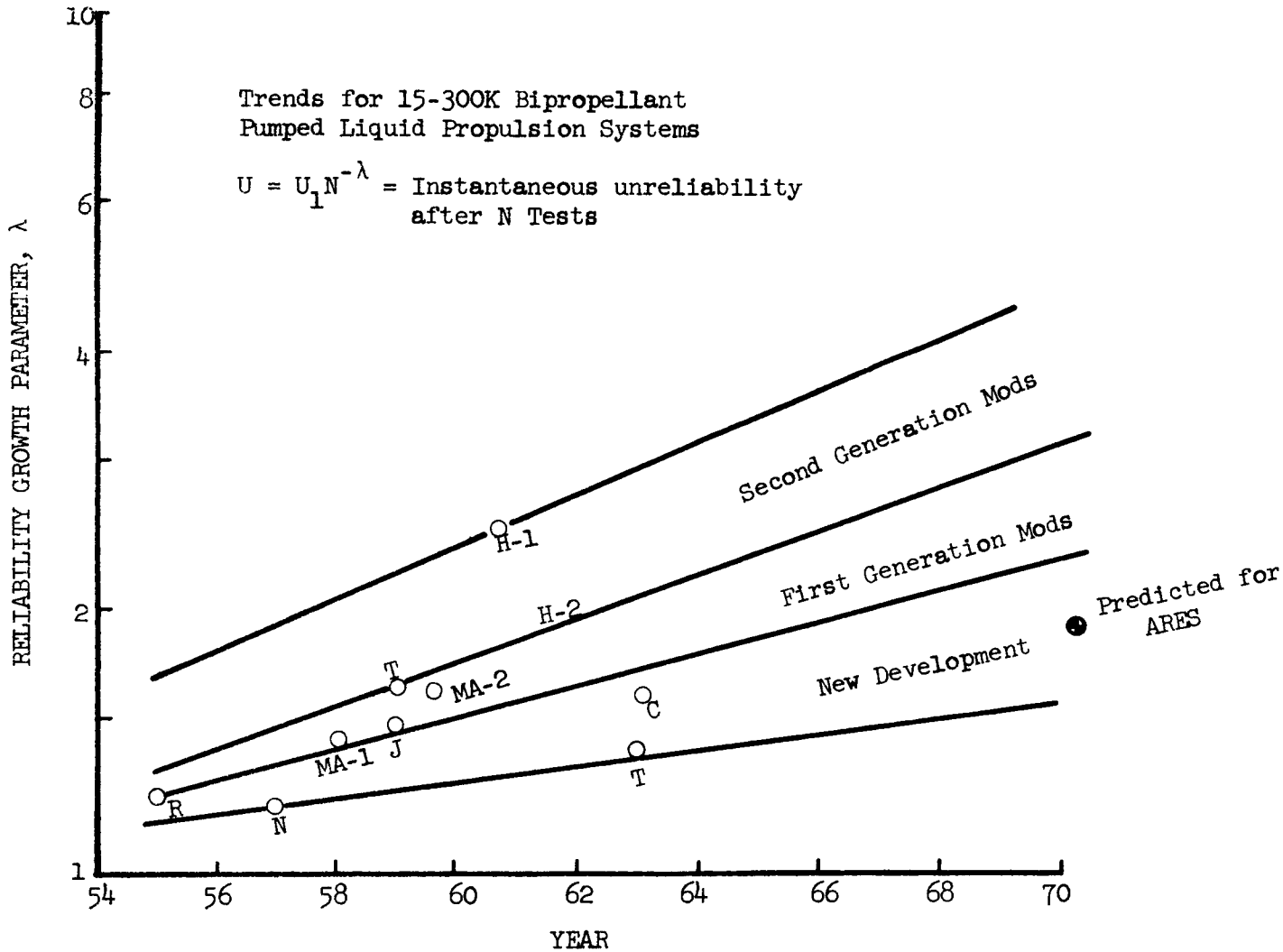
COMPONENT FAILURE/WEIGHT RELATIONSHIPS



COMPONENT FAILURE/TEST RELATIONSHIPS



THE ACCELERATION OF RELIABILITY GROWTH



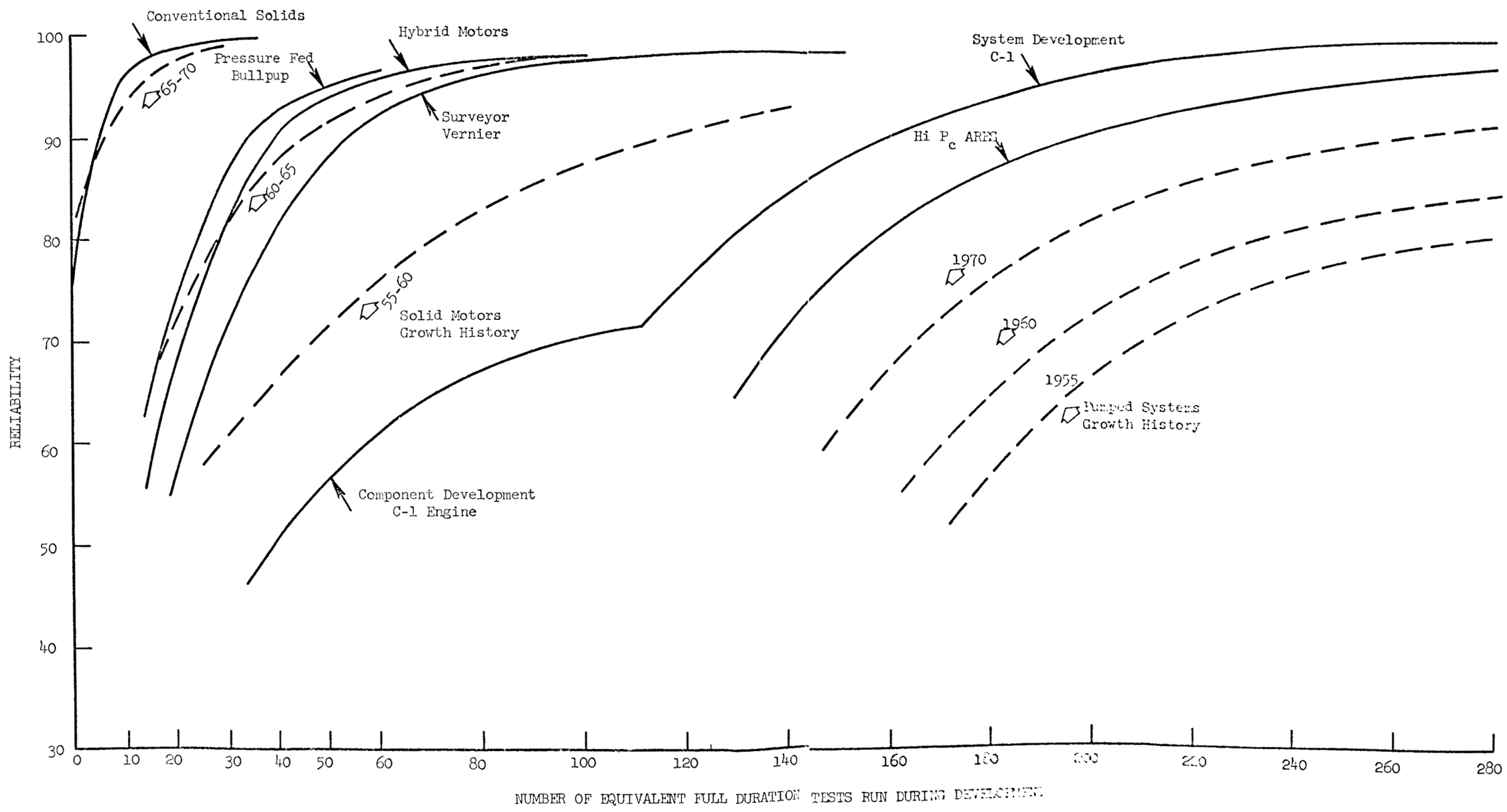
RELIABILITY GROWTH FOR PROPULSION SYSTEMS

Growth history for the liquid pump-fed systems, which has just been presented as a function of chronological time, is shown on the right-hand of this chart. As indicated by the historical trend shown on the left of the chart, the development of solid motors has also experienced a significant learning rate; however during the entire period, the data indicates that much fewer system tests have been required to achieve high reliabilities with solid systems.

The pressure-fed liquid bipropellant systems are typified by curves shown for the Bullpup, Surveyor vernier, and C-1 engines. The predicted reliability growth for hybrid motors is in-between the bipropellant liquids and the solids -- which is where one would expect the hybrid growth trend to be since this motor includes some of the more simple components of a liquid system and a solid fuel grain, case, and nozzle assembly.

Obviously, there are many other factors which can influence the rate of reliability improvement such as quality and insight of the initial design analysis, test planning, testing rate, test stress levels, data evaluation techniques, manufacturing and quality control, etc.; however since the growth characteristics presented have been provided by four separate companies, it is significant to note that the relative position for reliability growth of the various systems is consistent and justifiable. The number of full duration runs is also closely related to development costs, and as will be shown later, the trend of reliability with development costs is important when program cost-effectiveness is used as a criterion for design and development decisions.

RELIABILITY GROWTH FOR PROPULSION SYSTEMS



PRODUCTION AND DEVELOPMENT COSTS

- PRODUCTION COSTS
  - PREDICTION TECHNIQUES
  - LIMITATIONS
  - EXPECTED PREDICTION ACCURACY
- DEVELOPMENT COSTS
  - PREDICTION TECHNIQUES
  - LIMITATIONS
  - EXPECTED PREDICTION ACCURACY

COMPONENT HARDWARE UNIT COSTS FOR SOLID MOTOR DEVELOPMENT

Unit costs for components and assembly of solid motors is shown in this graph. The band indicates a range between minimum and maximum expected costs.

PROPULSION SYSTEM PRODUCTION COSTS

The dashed line has been included to show a trend for actual solid motor cost data; this curve projects through the Stanford Research predicted costs for Large (260 inch) Solid Motors. Data points around this line (Arcos, etc.) are estimated first unit costs for sounding rockets, and it is expected that solid motors for spacecraft applications will have this same trend with size but will have higher costs.

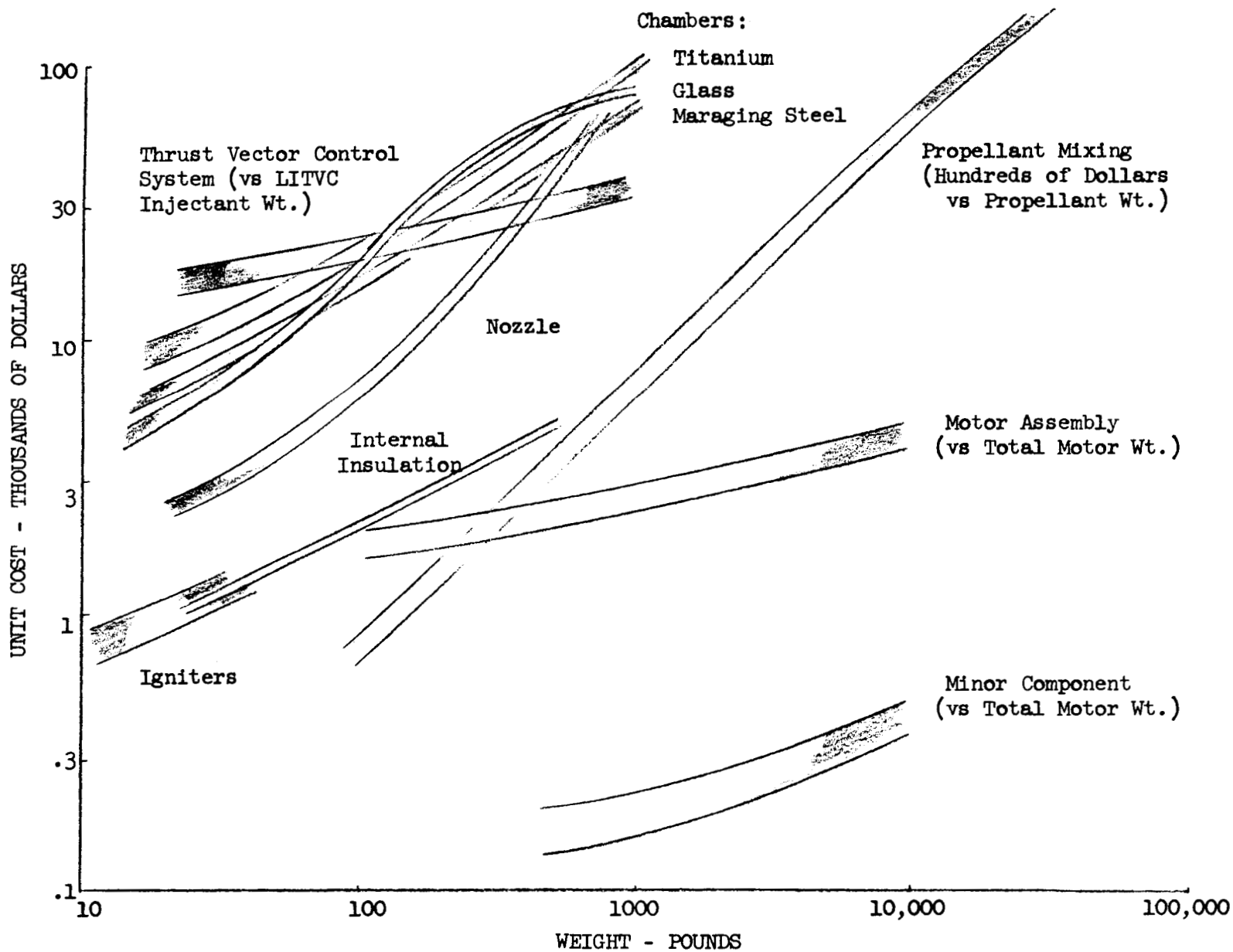
The RSVP, hybrid, bipropellant pressure-fed liquid, and pump-fed liquid systems have costs which are higher than the solid motors, in that respective order. This trend can be expected since the RSVP has a fluid (liquid) to solid ratio of .25 to .50; the hybrid motors have fluid to solid ratios in the order of 3; and liquid systems are typically more expensive than solid systems.

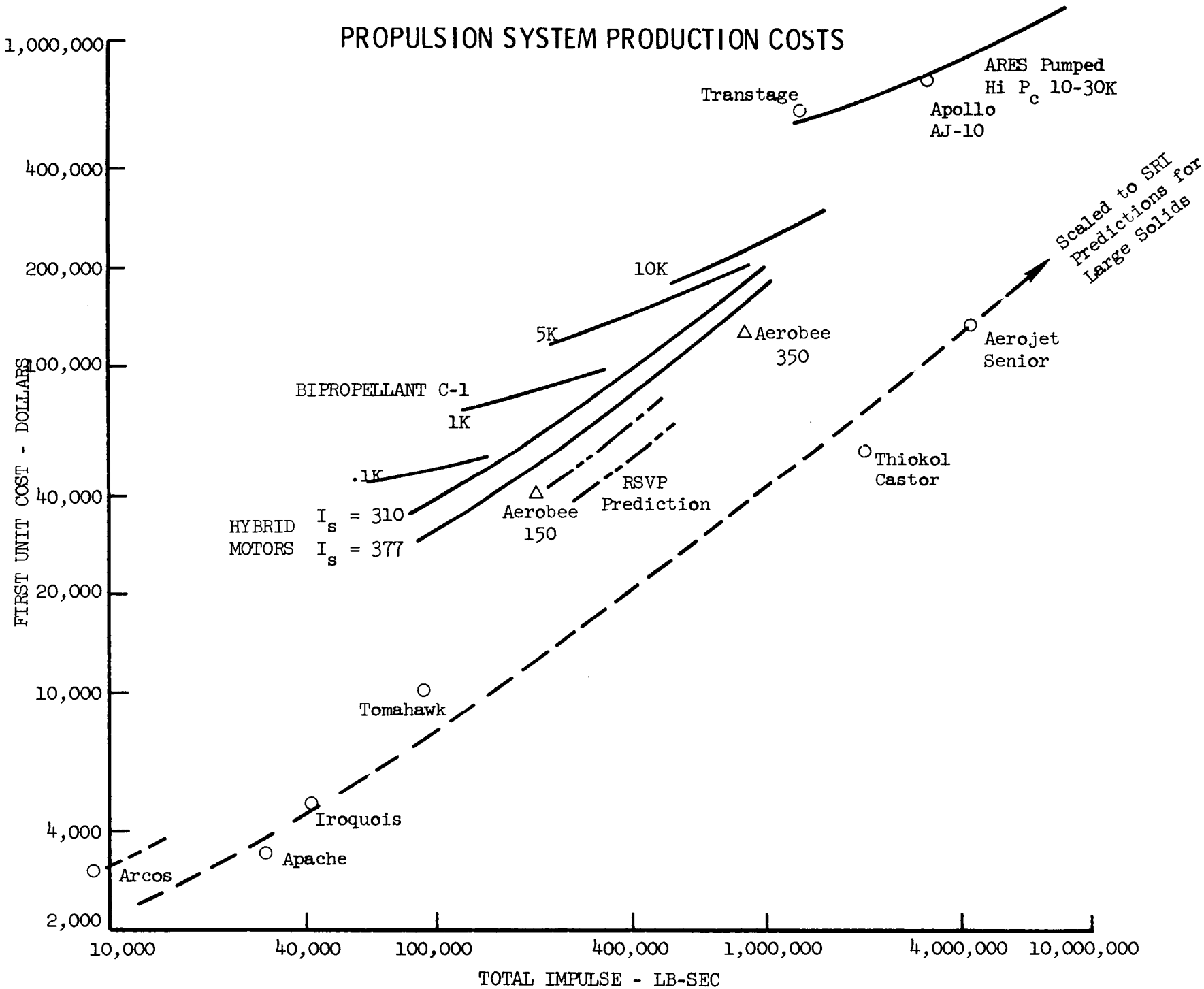
PROPULSION R&D COSTS

Costs for development of the propulsion systems is largely a function of the amount of full scale testing which must be done to attain a reasonably high reliability (refer back to the reliability vs number of tests for the various types of propulsion systems). R&D costs for the solid motors are indicated for 20, 40, and 100 tests; the band for the solid motor indicates maximum and minimum expected costs. The band for the liquid systems indicates a range in cost dependent on thrust level, i.e., .2 to 10K for the C-1 engine.

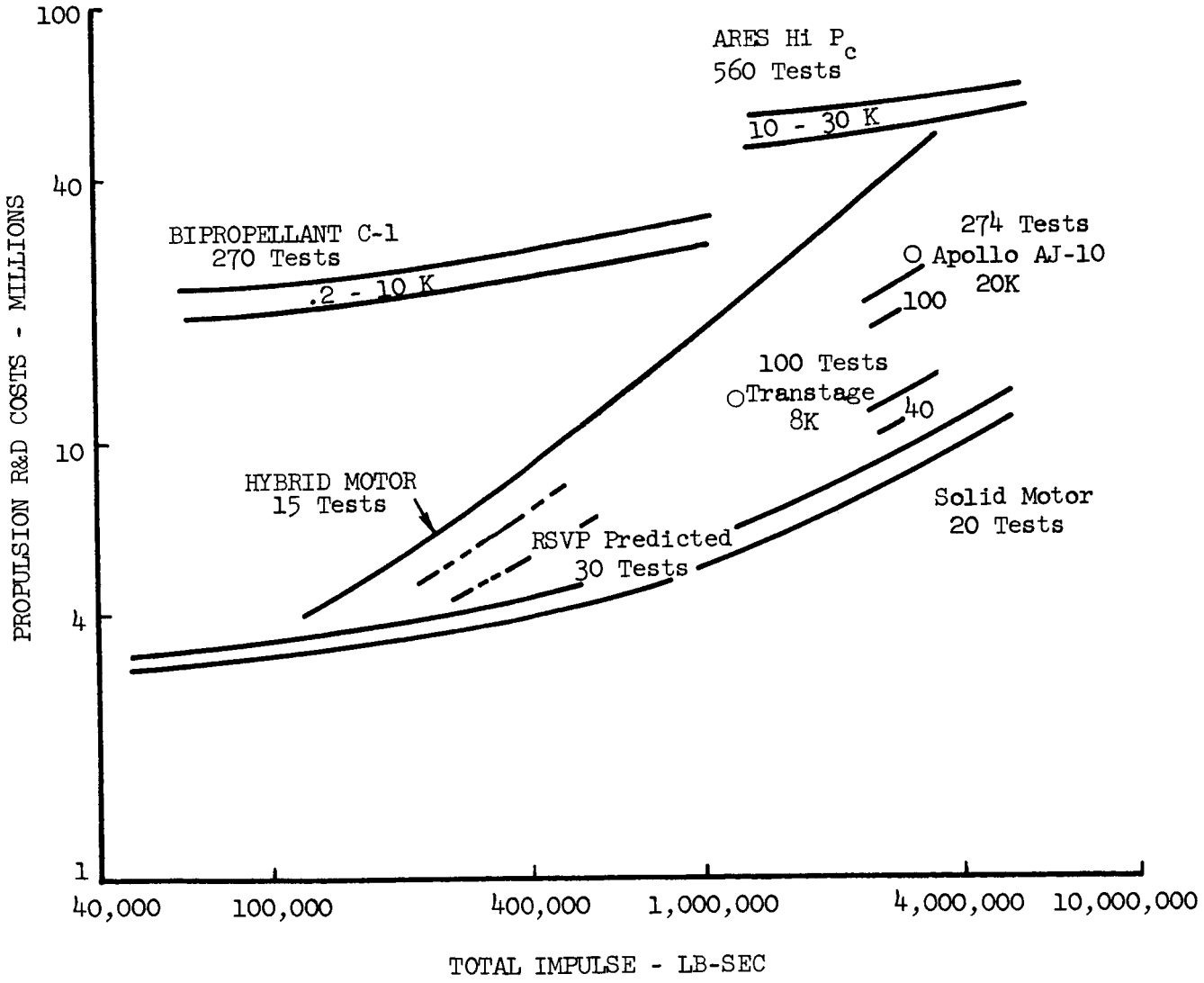
The Transtage and Apollo cost data points appear to substantiate the trends shown on the graph.

COMPONENT HARDWARE UNIT COSTS FOR SOLID MOTOR DEVELOPMENT




PROPULSION SYSTEM PRODUCTION COSTS
FIRST UNIT COST - DOLLARS
1,000,000
400,000
200,000
100,000
40,000
20,000
10,000
4,000
2,000
10,000
40,000
100,000
400,000
1,000,000
4,000,000
10,000,000
TOTAL IMPULSE - LB-SEC
Transtage
ARES Pumped
Hi P_c 10-30K
Apollo
AJ-10
Scaled to SRI
Predictions for
Large Solids
10K
5K
Aerobee
350
Aerojet
Senior
BIPROPELLANT C-1
1K
.1K
Thiokol
Castor
RSVP
Prediction
Aerobee
150
HYBRID
MOTORS
I_s = 310
I_s = 377
Tomahawk
Iroquois
Apache
Arcos

PROPULSION R&D COSTS



INFLUENCE OF STERILIZATION REQUIREMENT

- QUALITATIVE DISCUSSION OF INFLUENCES ON OPERATING CONDITIONS, PERFORMANCE, WEIGHT, DEVELOPMENT TIME, DEVELOPMENT COSTS, PRODUCTION COSTS, FAILURE MODES AND RELIABILITY
- QUANTITATIVE INFLUENCES
- REQUIREMENTS FOR TECHNOLOGY IMPROVEMENT

INFLUENCE OF STERILIZATION REQUIREMENT

The two following tables are typical of qualitative and quantitative descriptions which have been provided in regard to the influence of sterilization on the propulsion systems.

Differences in failure rates for sterilized and unsterilized solid motors is presented in tabular form for each component. One of the propulsion companies indicates a possibility of propulsion reliability improvement due to the increased likelihood of discovering (and subsequent elimination) some types of failure modes during sterilization temperature cycling.

EXAMPLE PROBLEMS

Propulsion applications have been selected by the subcontractors, where detailed design data or a developed propulsion system exists, to use as design points for predicting weight, costs, reliability, and performance by applying their prediction techniques. They will then provide an explanation of discrepancies between the predicted and "actual" propulsion characteristics. Hopefully, misinterpretation of the prediction techniques will be minimized, and confidence in use of the information will be increased through the study of these examples.

SUMMARY OF STERILIZATION DESIGN CONSIDERATIONS

Subsystem	Information Category	Influences on: Operating Conditions	Performance Characteristics	Material Selection	Weight	Development Time	Development Cost	Production Cost	Failure Modes and Reliability
Nozzle	Qualitative	None	Current plasma arc data indicate an increase in ablation or regression rate of plastic insulators after sterilization. This effect has not been verified by motor firing tests.	Special selection of some materials most capable of sterilization will be desirable.	Increase in plastic insulator weight if increased ablation or regression rate is verified.	Increase because of more stress and thermal analyses and sterilization tests of components and subassemblies.	Increase because of additional analyses and sterilization tests.	Increase if thicker plastic insulators and required or if more expensive materials are required to replace materials not suitable for sterilization.	Failure modes will be the same as those for standard nozzles. A potential reduction in nozzle reliability resulting from heat cycling effects on interface bonds, etc. This potential reduction can be compensated partly by designs that reduce bond stresses.
	Quantitative	None	Plasma arc data indicate increase in regression rate of up to 43%.	Some materials that are normally used in nozzles are not suitable for the sterilization conditions. These will be replaced or the design revised to eliminate them.	Increase in the weight of some plastic insulators of up to 20% may be necessary. (1)	Nozzle development time will increase 10 to 30%.	Nozzle development cost will increase 10 to 40%.	Production costs will increase 10 to 20% if thicker insulators are required and 5 to 30% if more expensive materials are required.	Insufficient data are available to estimate the effects of sterilization on nozzle reliability.
	Technology or Study Req'd.	Tests of nozzle assemblies to determine the effects of sterilization conditions on interface bonds and mating components are desirable.							

(1) A weight increase percentage less than the possible increase in ablation or regression rate is because a large centage of the insulator thickness is for thermal insulation only.

For a good total system design to exist, one would expect the $\partial R/\partial W$ to be approximately equal for all subsystems; otherwise some systems are over- or under-designed. This equality is tempered by the cost of making one design change relative to costs of design changes for alternate systems, as indicated by the ΔCE expression shown on the right of the chart.

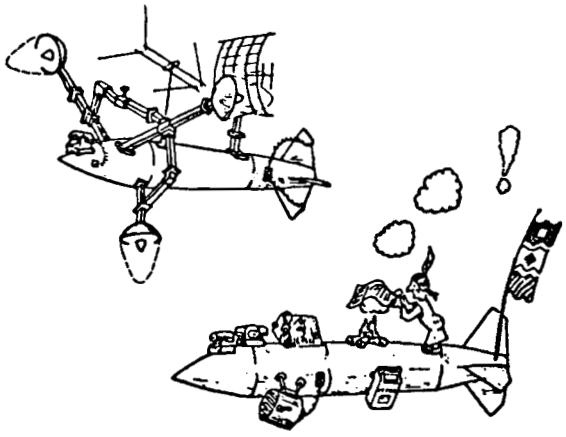
The I_{sp} and weight sensitivity range utilized in the Influence-Coefficient Table presented earlier is represented by a $\partial R/\partial W$ range of .05 to .005 which appears to be a good "design point" range for the subsystems in this chart. In other words it appears that the solid motor components are over-designed and the other three subsystems under-designed at the "nominal" design points indicated.

INFLUENCE OF STERILIZATION ON COMPONENT FAILURE RATES

Component	Type	Expected Failure Rate After 20 Full-Scale Tests	
		Unsterilized	Sterilized
Propellant	ANB 3066	.00030	----
	ANB 3289	----	.00045
	ANB 3224	.00045	.00056
Chamber	Glass	.00005	.000063
	Titanium	.00002	.00002
	Maraging Steel	.00003	.00003
Insulation	V44, V45	.00065	----
	SD850	----	.000097
Nozzle	Standard	.00065	.00081
	Extendable Exit Cone (only)	.00030	.00037
Igniter	Pellet	.00020	.00025
	Solid Propellant	.00020	.00025
TVC	Liquid Injection	.00002	.00002
Thrust Term.	Nozzle Ejection (only)	.00020	.00020
	Liquid Quench-Nozzle Ejection	.00045	.00045
Throttling Valve	Pintle Actuator	.00045	.00066

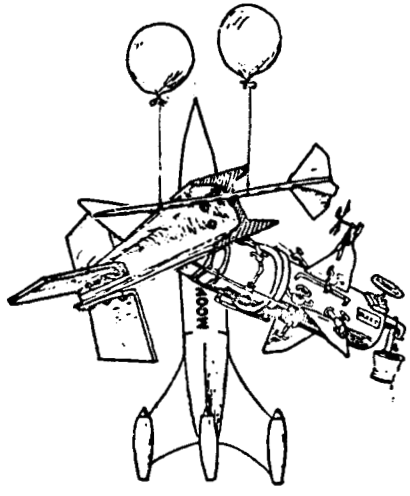
EXAMPLE PROBLEMS

- PRESENTATION OF PROPULSION APPLICATION AND REQUIREMENTS
- PROPULSION CHARACTERISTICS DETERMINED (ITEM BY ITEM IN TABLES)
- EXPLANATION OF HOW EACH PREDICTION IS MADE
- PRESENTATION OF CHARACTERISTICS OF SYSTEM RESULTING FROM DETAILED STUDIES OR DEVELOPMENT PROGRAM
- EXPLANATION OF DEVIATIONS BETWEEN PREDICTED AND "ACTUAL" DATA



MISSION

PROPULSION DESIGN CRITERIA



SYSTEM

PROPULSION DESIGN CRITERIA

- OBJECTIVES OF ESTABLISHING MISSION "FIGURE-OF-MERIT"
  1) IDENTIFY THE EFFECTS OF THE PROPULSION SYSTEM ON MISSION COST AND EXPECTED VALUE
  2) ESTABLISH A NORMALIZING PARAMETER TO DETERMINE RELATIVE IMPORTANCE OF PERFORMANCE, RELIABILITY, COST, ETC.
- PROPULSION INFLUENCES ON MISSION VALUE

PAYLOAD CAPABILITY	→	QUANTITY OF DATA PLUS ALLOCATION BENEFITS
ACCURACY	→	QUALITY AND QUANTITY OF DATA RETURNED
RELIABILITY	→	PROBABILITY OF MISSION SUCCESS
STERILITY	→	PLANETARY QUARANTINE
FLEXIBILITY	→	LAUNCH WINDOWS, PERFORMANCE DEVIATIONS, FUTURE COSTS

COST-EFFECTIVENESS MODELS

The Mars Orbiter/Lander mission has been used in this program to investigate cost-effectiveness models and to study example problems. Use of this mission provides two advantages; first it is representative of multiphase missions where "partial mission worth" is meaningful; and secondly, the detailed studies on the Voyager program can provide valuable input data for example problems.

Basic factors in evaluating the influence of propulsion systems on program cost-effectiveness include the relationships of

1) propulsion reliability to mission probability-of-success
2) propulsion performance and weight to quantity of data returned
3) propulsion impulse cut-off accuracy and alignment accuracy to quality of data returned
4) propulsion design characteristics to the probability of maintaining planetary quarantine

Mission cost-effectiveness can be defined as the ratio of mission worth to total mission cost, and for the Mars mission, worth can be accrued during four or more phases of the mission:

A - cruise science and engineering
B - orbiter spacecraft data (not related to entry or Lander data)
C - Atmospheric entry data
D - Lander data

COST-EFFECTIVENESS MODEL
MARS ORBITER/LANDER MISSION

- $\text{MISSION CE} = \dfrac{\text{MISSION WORTH}}{\text{MISSION COST}}$

$\text{MISSION WORTH} = (W_A) + (W_B) + (W_C) + (W_D) + (W_{PQ})$

Worth A, Worth B, etc.

$W_A = \left(P_{\substack{excl \\ prop}}\right)_A \left(P_{1_{prop}} \; P_{2_{prop}} \; P_{3_{prop}} \; P_{MC} \; P_{4_{prop}}\right)_{A_P}$ x (W_A as a function of weight allocated to cruise experiments and trajectory accuracy of MC prop.)

$W_B = \left(P_{\substack{excl \\ prop}}\right)_B \left(\;\right)_{A_P} \left(P_{5_{prop}} \; P_R \; P_{6_{prop}} \; P_{7_{prop}} \; P_{OA}\right)_{B_P}$ x (W_B as a function of weight allocated to orbital operations (B) and trajectory accuracy of MC, R, and OA prop.)

$W_C = \left(P_{\substack{excl \\ prop}}\right)_C \left(\;\right)_{A_P} \left(\;\right)_{B_P} \left(P_{8_{prop}} \; P_{DO} \; P_{9_{prop}}\right)_{C_P}$ x (W_C as a function of weight allocated to atmospheric data collection (C) and trajectory accuracy of MC, R, OA and DO prop.)

$W_D = \left(P_{\substack{excl \\ prop}}\right)_D \left(\;\right)_{A_P} \left(\;\right)_{B_P} \left(\;\right)_{C_P} \left(P_{10_{prop}} \; P_L\right)_{D_P}$ x (W_D as a function of weight allocated to Lander data collection (D) and trajectory accuracy of MC, R, OA, DO and L prop.)

The fifth worth term included in the chart is the "worth" of maintaining planetary quarantine; this is obviously a very subjective point. However, propulsion related influences include, (1) propulsion reliability can influence the probability of impact of non-sterile material, (2) nozzle ejecta must be sterile, and (3) confidence in the Lander propulsion sterilization procedure and subsequent measurement of the propulsion system sterility level.

"Expected Worth" terms can next be constructed of three basic factors, (1) probabilities-of-success of non-propulsion equipment, (2) probability-of-success terms for the propulsion systems (subscripts 1-10 denote mission events such as launch and injection, acquisition, cruise, midcourse correction, etc.), and (3) relative worth of the data accrued as a function of weight allocated to the experiments, and influenced also by accuracy capabilities of the various propulsion maneuvers.

GENERAL EXPERIMENT/WEIGHT ALLOCATION PROBLEM

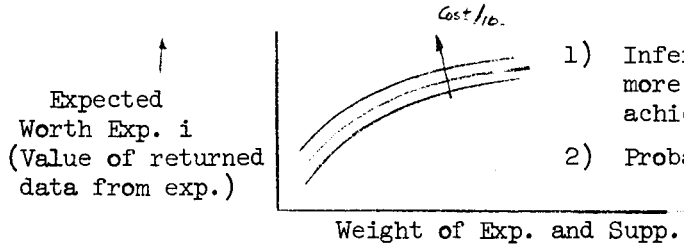
Consider the general problem of establishing how much weight to allocate to Lander versus orbital or cruise experiments -- for the moment setting aside influences of the propulsion system.

First, there are four mission phases or groups of equipment to which weight can be allocated. Secondly, this allocated weight can be used to

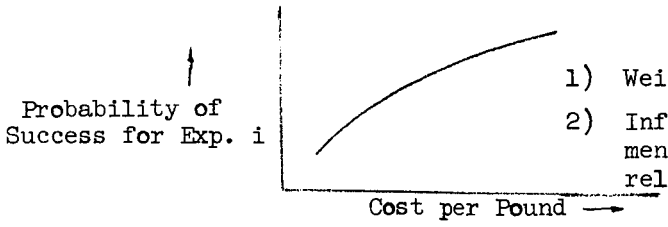
1) increase the amount of data accrued
2) increase quality of the data
3) decrease cost of equipment, or
4) increase probability of successful equipment operation.

GENERAL EXPERIMENT/WEIGHT ALLOCATION PROBLEM

- DATA FOR EXPERIMENT/SUPPORT EQUIPMENT

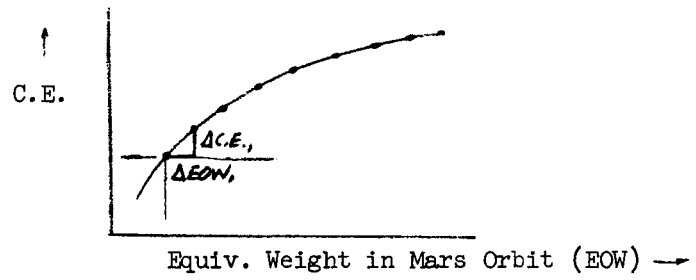


1) Infers a better quality and/or more data per pound can be achieved at increased costs
2) Probability-of-success fixed



1) Weight fixed
2) Infers higher cost (more development or quality) can increase reliability

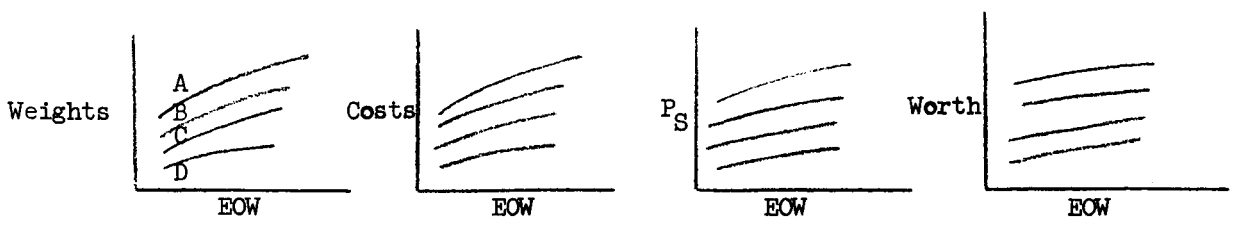
- OPTIMUM USE OF AVAILABLE WEIGHT



Each increment of weight is allocated by comparing

$$\Delta(\text{C.E.}) = \frac{\partial(\text{C.E.})}{\partial(\text{Worth})}\,\Delta(\text{Worth}) + \frac{\partial(\text{C.E.})}{\partial(\text{Cost})}\,\Delta\text{Cost} + \frac{\partial(\text{C.E.})}{\partial(P_{(S)})}\,\Delta(P_{(S)})$$

- RESULTS OF WEIGHT ALLOCATION



A step-by-step process can be followed where

a) We use an increment of weight "in the most cost-effective way" for each phase; i.e., we use it in one, or a combination of the four ways described above; the "best" way being established by use of the influence-coefficients, a concept which will be described later.

b) Compare Δ(Cost-effectiveness) of using the weight increment between the four phases, and allocate the weight where the greatest positive increment in C.E. was effected.

c) All of the equivalent orbiter weight is used up by sequentially applying this method of allocation.

A computerized solution using hypothetical inputs showed that the weight allocation is especially sensitive to the orbiter/Lander weight split.

PROPULSION INFLUENCE ON AVAILABLE WEIGHT FOR EXPERIMENTS

Now consider influences of the propulsion system on the allocation of experiments. As the equation indicates, variations in propulsion specific impulse and inert weight change the total equivalent orbital weight which is available for the four phases of experiments.

It can be seen that relative performance improvements or reliability improvements of the deorbit and Lander propulsion systems would make surface experiments more competitive with orbital or cruise experiments, on an "expected worth to weight ratio" basis; thus tending to shift more of the available weight into the Lander phases of experimentation.

For this reason, the propulsion characteristics should be taken into account in the initial planning phases of the mission.

PROPULSION INFLUENCE ON AVAILABLE WEIGHT FOR EXPERIMENTS

- EQUIVALENT ORBITAL WEIGHT

$$\text{Equiv. Mars Orbital Weight Of Worth Related Items} = \underbrace{\begin{bmatrix}\text{Cruise Science \& Related Spacecraft Weight}\end{bmatrix}}_{W_A} + \underbrace{\begin{bmatrix}\text{Orbital Ops. Not Includ. Atmospheric \& Lander Data}\end{bmatrix}}_{W_B} + \underbrace{\begin{bmatrix}\text{Orbital Ops. Atmospheric Data}\end{bmatrix}}_{W_{C\,\text{Orbital}}} + \underbrace{\begin{bmatrix}\text{Orbital Ops. Lander}\end{bmatrix}}_{W_{D\,\text{Orbital}}} + \underbrace{\begin{bmatrix}\text{Equivalent Orbital Wt. of Atm. Exp. and Lander}\end{bmatrix}}_{C,D}$$

$$= W_A + W_B + \left[W_{C\,\text{Orb Land.}} + W_C \left\{ e^{\frac{(\Delta V_{DO} + d\,\Delta V_R)}{(g\,I_{S_{DO}})}} + e^{\frac{(\Delta V_L + d\,\Delta V_{DO})}{(g\,I_{S_L})}} \right\}\right] + \left[W_{D\,\text{Orb Land.}} + W_D \left\{ e^{\frac{(\Delta V_{DO} + d\,\Delta V_R)}{(g\,I_{S_{DO}})}} + e^{\frac{(\Delta V_L + d\,\Delta V_{DO})}{(g\,I_{S_L})}} \right\}\right]$$

$$= \frac{\left[\left\{ e^{\frac{W_{gross}}{(\Delta V/GI_S)_{MC}}} - W_{\text{Ster. Can.}} \right\}\right]}{\left[\left\{ e^{\frac{(\Delta V_R + d\,\Delta V_{MC})}{(gI_{S_R})}} \right\}\right]} - \left[\left\{ e^{\frac{(\Delta V_{DO} + d\,\Delta V_R)}{(gI_{S_{DO}})}} \right\}\right]\left[W_{\text{entry shroud}} + W_{\text{inert DO}} + W_{\text{inert Lander}} \left\{ e^{\frac{(\Delta V_L + d\,\Delta V_{DO})}{(gI_{S_L})}} \right\}\right] - \left[W_{\text{inert}_{MC}} + W_{\text{inert}_{OA}} + W_{\text{inert}_R}\right]$$

$$\left[\left\{ e^{\frac{(\Delta V_{OA} + d\,\Delta V_R)}{(gI_{S_{OA}})}} \right\}\right]$$

- RELATIVE PERFORMANCE AND RELIABILITY IMPROVEMENTS IN DEORBIT/LANDER PROPULSION SYSTEMS MAKE SURFACE EXPERIMENTS MORE COMPETITIVE WITH ORBITAL EXPERIMENTS

PROPULSION "EXCESS-WEIGHT" ALLOCATION

At some time in the planning or pre-design phase, science and other system interfaces must be "fixed" -- when this stage is reached, the most beneficial allocation of weight obtained from relative improvements in the propulsion system can be provided by utilizing excess weight to improve reliability of adjacent systems. The following C.E. model and example tradeoffs were established for this situation. Obviously, for other design constraints or limitations, different models can be constructed.

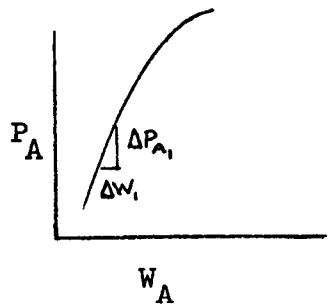
"Excess" orbiter weight can be expressed in terms of propulsion propellant and inert weights and the "nominal" weights of the experiments and adjacent subsystems. Assume that the ejected weight of the Lander capsule is fixed.

Reliability versus weight characteristics can be established for subsystems to which weight can be allocated for purposes of improving mission success. Next, a range in available orbiter weight can be used, and increments of weight allocated to the various subsystems in a way to obtain the maximum benefit in mission worth. Finally graphs of mission phase probability-of-success versus orbiter weight can be completed.

PROPULSION "EXCESS-WEIGHT" ALLOCATION

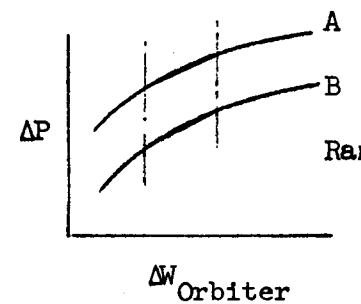
- "EXCESS" ORBITER WEIGHT AS A FUNCTION OF PROPULSION PERFORMANCE AND WEIGHT

$$\Delta W_{Orb.} = W_g - W_{P_{MC}} - W_{St.Can.} - W_{P_R} - W_{P_{OA}} - W_{inert_{MC/OA}} - W_{inert_R} - W_{\substack{Lander\\Capsule}} - W_{c_{Orb.}} - W_{o_{Orb.}} - \left[W_A + W_B\right]_{\substack{Nom.\\ @\ P_A}}$$



Typical for A & B

$$[P_A][W_A][\Delta P_A] = \Delta Worth_{\Delta W_A}$$



Range of Interest

$$C.E. = \frac{\text{Total Worth}}{\text{Total Cost}} = \frac{[P_A + \{\Delta P_A = f(W_{orb.})\}]\ [P_{A_p}][W_A] + [\ B\ ] + C + D + PQ}{\begin{bmatrix}\text{All Non-Propulsion}\\ \text{Dependent Costs}\end{bmatrix} + \begin{bmatrix}\text{MC/OA R\&D}\\ \text{Costs}\end{bmatrix}\begin{bmatrix}A_F\end{bmatrix} + \begin{bmatrix}\text{MC/OA Prod.}\\ \text{Costs}\end{bmatrix} + \ldots}$$

- PROPULSION INFLUENCE COEFFICIENTS

$$\frac{\partial(C.E.)}{\partial(I_{s_{MC}})} = \frac{\partial(C.E.)}{\partial(\Delta P)}\ \frac{\partial(\Delta P)}{\partial(\Delta W_{orb})}\ \frac{\partial(\Delta W_{orb.})}{\partial(I_{s_{MC}})}$$

$$\frac{\partial(C.E.)}{\partial(W_{Inert_{MC/OA}})} = \frac{\partial(C.E.)}{\partial(\Delta P)}\ \frac{\partial(\Delta P)}{\partial(W_{orb.})}\ \frac{\partial(W_{orb.})}{\partial(W_{Inert_{Mc/OA}})}$$

$$\frac{\partial(C.E.)}{\partial(P_{A_{MC}})}\ ,\ \frac{\partial(C.E.)}{\partial(P_{B_{MC}})}\ \ldots\ \text{Etc.}$$

Where Δ quantities are differences between two design alternatives or design conditions.

$$\Delta(C.E.) = \frac{\partial(C.E.)}{\partial(I_s)}\ \Delta I_s + \frac{\partial(C.E.)}{\partial(W_{Inert})}\ \Delta W_{Inert} + \frac{\partial(C.E.)}{\partial(P_i)}\ \Delta P \ldots\ldots + \frac{\partial(C.E.)}{\partial(Cost)}\ \Delta Cost$$

The cost-effectiveness model for this design problem will then be comprised of the product of nominal probability-of-success terms (P_A) plus delta probability-of-success terms (ΔP_A) which are a function of orbiter weight, times relative worth of the mission phase (W_A). The cost-effectiveness is the sum of worth terms divided by total program costs.

This C.E. equation can be used to evaluate the relative cost-effectiveness of alternate propulsion systems or propulsion design options. However, reliability, cost, weight and performance of each propulsion system will have been established from tradeoff analyses which, in general, would not result in an optimum total system, nor will the analyses have been based on cost-effective selection criteria.

An alternate procedure is to establish influence-coefficients relating mission cost-effectiveness to propulsion characteristics such as I_{sp}, inert weight, reliability, etc.; and then use these coefficients to conduct the tradeoff analyses within the alternate propulsion systems, such that when the systems are compared, each alternate design represents the result of cost-effective design criteria.

PROPULSION INFLUENCE-COEFFICIENTS

The cost-effectiveness model which has just been discussed was used to establish analytical (algebraic equations) influence-coefficients; and assumptions as to nominal costs, weights, probability-of-success terms, and propulsion characteristics were then used to quantify the influence-coefficients. Results of this analysis are shown on the following table.

The first column, for example, shows that a variation of .65% in midcourse propulsion reliability changes cost-effectiveness by one unit. The range in number of seconds impulse (2.5 to 25 for midcourse maneuver, and 14-140 seconds for orbit adjust maneuver) required to effect a one unit change in cost-effectiveness is brought about by the range in (ΔReliability)/(ΔWeight) characteristic of subsystems which "excess-weight" can be allocated to for purposes of reliability improvement (this range is shown on a following chart). In the second two columns the least sensitive (i.e., taking the largest I_{sp} or weight change required to effect a unit change in C.E.) number is used for purposes of comparing relative importance of the coefficients.

The second column indicates an assumed likely variation (which might exist between alternate designs) and nominal values of the propulsion characteristics, and the third column shows the change in units of C.E. due to the Δ variations in propulsion characteristics. Numbers in this column show, for example, that approximately equivalent influences on C.E. are brought about by (1) an increase of 80 (20 + 60) pounds of inert weight or (2) a decrease of .004 (.4%) in orbit-adjust propulsion reliability or (3) a decrease of ten seconds in orbit-adjust specific impulse. Similarly, the numbers indicate that approximately 24 (3x8) million dollars could be expended to increase midcourse reliability by .4 percent.

PROPULSION INFLUENCE-COEFFICIENTS
FOR MARS ORBITER/LANDER

Propulsion Characteristic	Required Variation for One Unit Change in Cost-Effectiveness	Likely Variation = Δ / Assumed Nominal	Units C.E. Variation Resulting from Δ
Midcourse Reliability	.0065 (.65%)	.004/.990	.62
Retro Reliability	.0088	.006/.985	.68
Orbit-Adjust Reliability	.0088	.004/.990	.46
R&D Cost	39M	8/ 40M	.21
Production Cost	6.6M	1/ 3M	.15
Midcourse/OA I_{sp}	2.5-25/14-140 sec	10/240 sec	.47
Retro I_{sp}	.67-6.7 sec	15/300 sec	2.2
Inert Weight	17-170 lb	$20/400_{MC/OA}$ $60/1200_{R}$	.47
Flexibility (Use in Future Missions)	39M	10/20M	.25

SUBSYSTEM WEIGHT/RELIABILITY TRADEOFFS

Sensitivity of subsystem reliability to weight change from nominal design conditions is shown in this chart. Two types of subsystems are shown.

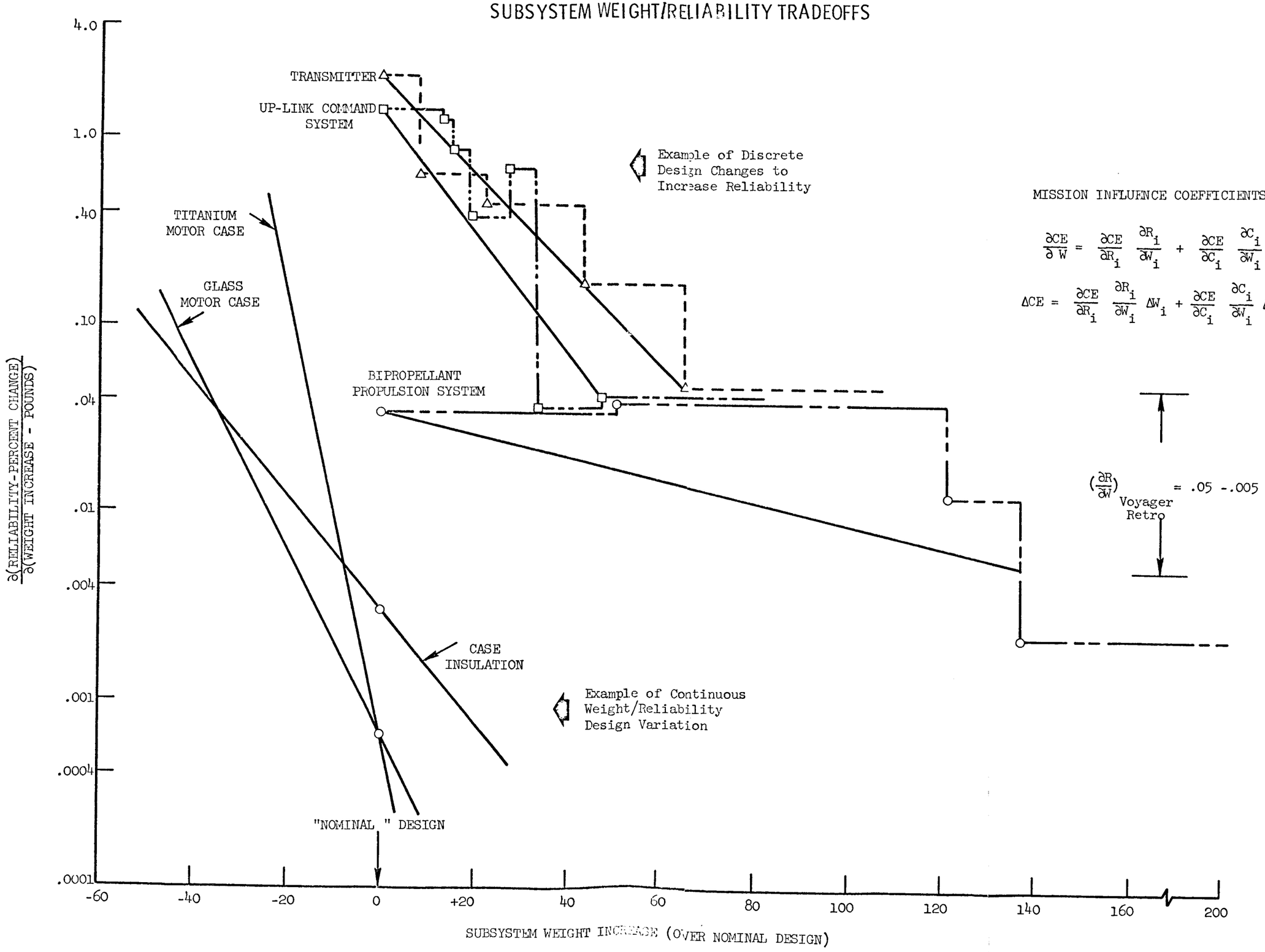
1) Transmitter, Up-Link Command, and Liquid Bipropellant propulsion system: These subsystems require discrete design changes to effect a reliability gain -- usually by adding parallel or series redundancy in components of the equipment. In several instances it is indicated that a design change has to be made which has a lower reliability increase per pound of weight expended than a subsequent change provides; this is a function of the specific system being considered. However, the general trend is that as more weight is allocated and the system becomes more reliable, a greater amount of weight is required to obtain the unit change in reliability; for example, approximately two percent reliability is gained per pound required with the first design change on the transmitter; on the last change considered for that subsystem, about .04 percent reliability is gained per pound required.

   Note also that the full increment of weight is necessary before the design change can be made on these subsystems; i.e., if only 40 pounds were available, the last change for the propulsion system could not be implemented, since it requires about 65 pounds.

2) The titanium and glass cases, and insulation components of solid motors can be designed to provide greater resistance to burst pressure or burn-through by any arbitrary increase in thickness; thus a continuous weight/reliability characteristic is shown for these components.

By adding or subtracting weight to any of the subsystems, the "nominal" design point, and attendant $\partial R/\partial Wt$ at nominal design can be changed; this would just slide the entire subsystem reliability/weight sensitivity line to the left or right. However, for the subsystems shown here the design points were as indicated on the graph.

SUBSYSTEM WEIGHT/RELIABILITY TRADEOFFS



For a good total system design to exist, one would expect the $\partial R/\partial W$ to be approximately equal for all subsystems; otherwise some systems are over- or under-designed. This equality is tempered by the cost of making one design change relative to costs of design changes for alternate systems, as indicated by the ΔCE expression shown on the right of the chart.

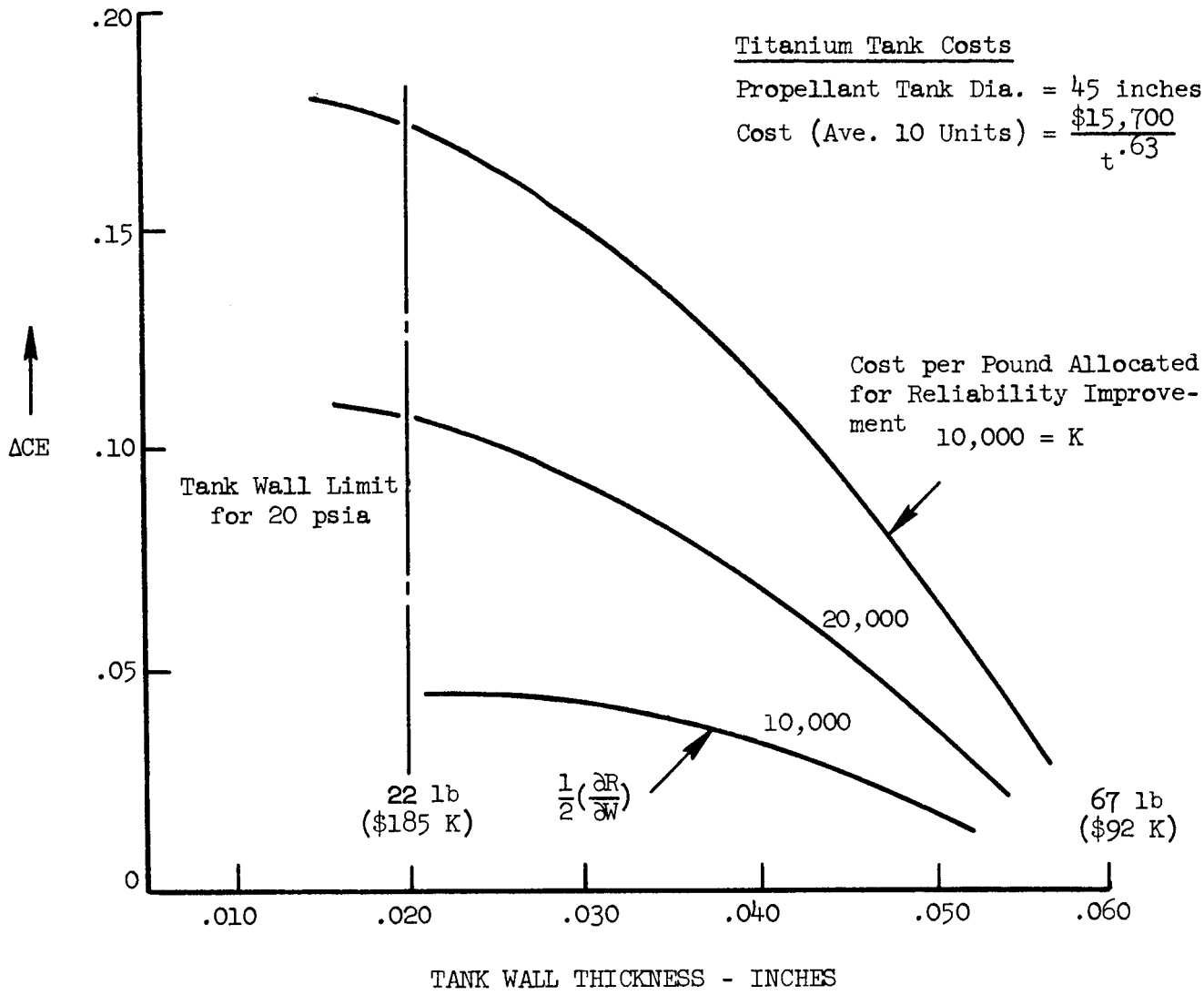
The I_{sp} and weight sensitivity range utilized in the Influence-Coefficient Table presented earlier is represented by a $\partial R/\partial W$ range of .05 to .005 which appears to be a good "design point" range for the subsystems in this chart. In other words it appears that the solid motor components are over-designed and the other three subsystems under-designed at the "nominal" design points indicated.

SUBSYSTEM WEIGHT/COST TRADEOFFS

Consider a titanium propellant tank which might generally be taken as a "minimum gage" or minimum fabrication thickness. The tank manufacturer might tell you that for the 45 inch tank, fabrication costs are "prohibitively high" at lower wall thicknesses. In reality, what is "prohibitively high" is dependent on the relative importance of cost, reliability, weight, and performance as established for the specific application, not insight of the salesman.

Using the influence-coefficients (shown earlier) for production costs and weight; and adding the influences of increased tank cost, cost per pound of improving other systems with the weight taken from the tank, and the effect of the increase in probability-of-success; the ΔCE was established for smaller tank wall thicknesses. As indicated by the graph, it proved to be beneficial to take weight out of the tank until the tank stress limit was approached at about .020 inches. This result was valid even when the $\partial R/\partial W$ coefficient was reduced by 50% and cost of reliability improvement remained at 10,000 dollars per pound.

SUBSYSTEM WEIGHT/COST TRADEOFFS



BOOSTER COST TO ACHIEVE WEIGHT:

Gross Wt/Payload Wt $\approx$ 150

Cost/lb $\approx$ 15

ΔCost = $145,000

Break even at K = $1000/lb

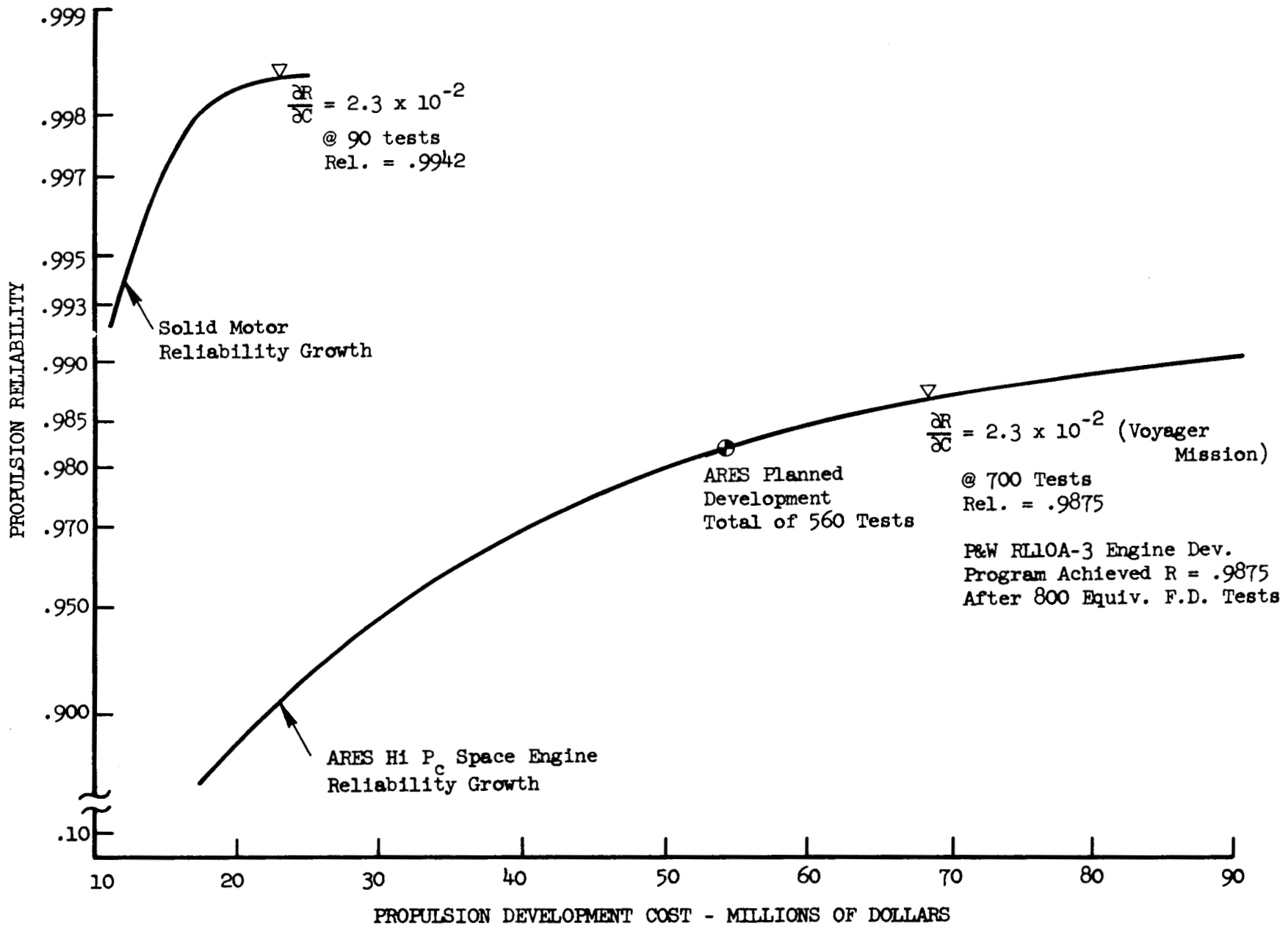
PROPULSION RELIABILITY/DEVELOPMENT-COST TRADEOFF

The cost and reliability characteristics of the solid and hi-P_c ARES engine which were presented in the detailed propulsion data section of the briefing were utilized together with the Mars Mission retro motor influence-coefficients to estimate, on a mission cost-effectiveness basis, at what point in the development program the cost per test is balanced by the predicted reliability gain.

This breakeven point is obtained at about 700 tests for the ARES engine. Data obtained by Space-General from Pratt and Whitney reports indicate that the P&W RL10A-3 engine achieved a reliability of .9875 after about 800 equivalent full duration tests.

The breakeven point for the solid motor occurs at about 90 tests, where a reliability of .9942 is predicted.

PROPULSION RELIABILITY/DEVELOPMENT-COST TRADEOFF



CONTRACT NAS 7-519

BENEFITS OF RESULTS TO SYSTEM MANAGEMENT CAPABILITIES

AND TO PROPULSION TECHNOLOGY

- PROGRAM AND SYSTEM MANAGEMENT

  1) The general cost effective approach is applicable to system management problems of all types, including civil as well as space and military applications.

  2) The techniques provide criteria for defining optimum system interface characteristics based on total program constraints.

  3) The approaches should also be applicable to the problem of establishing quantitative relationships between contract incentives and the actual system cost, reliability and performance characteristics resulting from system development programs.

- PROPULSION SYSTEM DESIGN AND DEVELOPMENT

  Generation, accummulation and distribution of meaningful propulsion cost, reliability, performance and weight data provides the following benefits:

  1) Increase in the knowledge of the capabilities of existing systems and their scaling limitations which must be available when investigating future mission/ propulsion applications.

  2) Intersystem tradeoff data is made available to NASA, JPL and "prime contractors"; thus reducing possibilities of establishing specifications which unduly penalize one system or the total system, and hopefully decreasing the feedback cycles between "primes" and "subs" -- thereby reducing predevelopment time lags.

  3) Better cost data enables more accurate predictions of total program costs.

- DETAILED COMPONENT AND SUBSYSTEM DESIGN

  1) The influence-coefficients can be effectively utilized to make selections between design alternatives having different cost, weight, and reliability characteristics.

  2) The influence-coefficients allow consistent, definable, traceable decisions which can be reviewed by NASA -- with a greatly reduced amount of built-in subjectivity.

CURRENT CONTRACT STATUS

- SUBCONTRACTED EFFORT
  - ALL FINAL REPORTS DUE ON OR BEFORE 1 SEPTEMBER
- SPACE GENERAL EFFORT
  - EVALUATION OF SUBCONTRACTED STUDIES
  - COMPARISON OF VARIOUS PROPULSION SYSTEMS
  - DOCUMENTATION OF PROGRAM RESULTS (DESIGN GUIDE)
- NAS 7-519 CONTRACT FINAL REPORT
  - ROUGH DRAFT DUE 13 SEPTEMBER

FOLLOW-ON AND RELATED PROGRAMS

- FOLLOW-ON PROGRAM TO CONTINUE THE ANALYSIS AND DOCUMENTATION OF PROPULSION DESIGN CHARACTERISTICS TO MAINTAIN AN UP-TO-DATE PROPULSION DESIGN GUIDE
- INITIATE PROGRAM TO REVIEW AND DOCUMENT CURRENT PROPULSION STATE-OF-THE-ART MANUAL - TO FACILITATE CONTINUED FLOW OF TECHNOLOGY TO THE USERS
- CONDUCT LIQUID PROPULSION RELIABILITY ANALYSIS PROGRAM UTILIZING TECHNIQUES SIMILAR TO MATERIAL/ENVIRONMENT VARIABILITY METHODS CURRENTLY BEING STUDIED FOR SOLID MOTORS
- ANALYZE COST-EFFECTIVE SYSTEM DESIGN CRITERIA FOR SPECIFIC MISSION APPLICATIONS - PROPULSION SYSTEM AND OTHER SPACECRAFT SYSTEMS