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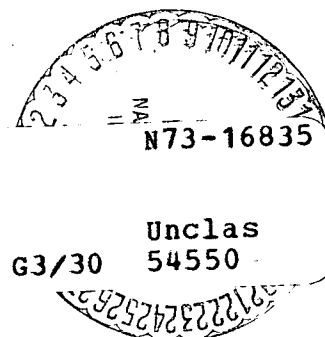
SPACE PROGRAM PAYLOAD COSTS AND THEIR POSSIBLE REDUCTION

Edgar M. Van Vleck, Jerry M. Deerwester, Susan M. Norman, and Larry R. Alton

Office of Aeronautics & Space Technology
Advanced Concepts & Missions Division
Moffett Field, California 94035

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SUMMARY AND CONCLUSIONS

This report contains results of a study dealing with possible ways in which NASA payload costs might be reduced in the future. The objectives of the study were twofold: (1) to examine the cost makeup of historical space mission payloads (i.e., spacecraft) and, (2) to consider ways in which payload costs might be reduced in the future, with explicit attention being given to the advent of the shuttle. The organization of the report reflects these two objectives.

The general study approach was to, first, accumulate as much historical payload cost data as feasible to gain some insight into the reasons why costs are, and have been, as they are. Next, techniques that might yield lower payload costs in the future were considered and reports obtained that addressed these areas. Where references were not available, private conversations were held with knowledgeable individuals within government and industry.

It is concluded that the two major contributors to the high cost of unmanned NASA spacecraft have been the continual development of scientific payload and subsystem technologies per se (thus eliminating any possibilities to realize economies of scale) and the fact that, in turn, wholly new spacecraft were often developed to employ the technologies. The degree of NASA/contractor interface has apparently been greater than that exhibited by other agencies with space programs of their own; yet this does not by itself appear to have been a major factor in high cost.

If NASA could take advantage of certain design techniques and philosophies that are being exhibited by the more operationally-oriented agencies (NOAA, DoD and COMSAT) cost savings of perhaps an order of magnitude could be realized. Yet, to have adopted in the past, features of these other agencies would have meant far less devotion to advances in space flight technologies--a primary reason for NASA's existence.

Therefore, given that the way the Agency has carried out its mission may have been the only way, we simply state that the largest portion of spacecraft cost has been devoted to the design and test phases--about

35 percent and 30 percent respectively. The individual subsystems taken collectively represent about half of the total cost; experiments themselves represent about 25 percent of project costs

Since it has often been suggested that the shuttle might reduce future payload costs by permitting operations akin to those of aircraft, features of the Ames Research Center airborne science program were investigated. And it is indeed true that payload costs for airborne experiments are low--about three orders of magnitude cheaper than spaceborne experiments. Speculations concerning the impact of wedding the shuttle to such aircraft-type operations suggests that sortie mode payloads may cost on the order of $1000/kg. This contrasts with current costs for unmanned spacecraft of over $100,000/kg and with costs for airborne sciences of about $60/kg.

In analyzing the various sources of high cost in the past and the various solutions proposed for the future, the criteria that must be applied are not only how important is each source of high cost, but what can theoretically be done about it, how feasible is the proposed solution and, finally, how much can costs thereby be reduced. Because of the continuous pursuit of new technology, the primary source of high cost can be traced to attempts at minimizing program risk.

The shuttle represents a significant step toward reducing risk, particularly by making it possible for a spacecraft to fail without jeopardizing an entire program. The proposed solution is as feasible as implementation of the shuttle and the corresponding aircraft-type operations which it should permit. At this time, of course, it is impossible to estimate in detail the savings which can be realized by dramatically removing risk as a management consideration, but if the opportunities which this presents are effectively exploited (as the analysis of the airborne science program suggests), the savings in cost could be tremendous.

The second most important area identified for future cost reductions is the relaxation of constraints. Again, in the absence of clear situations in which a project was carried out in two ways (with and without weight and volume constraints), and a comparison made, it is difficult to

offer quantitative estimates of cost savings. But preliminary study results indicate that the relaxation of weight and volume constraints afforded by the shuttle will permit reductions in cost that, although not dramatic, will certainly not be negligible. The benefits of this kind of cost reduction are mainly limited by the difficulty in achieving savings for synchronous orbit satellites to the same extent possible for low Earth orbit satellites. Nevertheless, a total program cost savings on the order of 16 percent can be obtained through these relaxed constraint techniques.

The development of standard modular subsystems appears as a technically promising means for reducing costs, but because such standarization will cut across multiple programs it represents a fairly radical change from the current manner of business. The development of standard spacecraft and cluster spacecraft (i.e., the deployment of several spacecraft from a single shuttle) represent a still further step toward standardization that represents fairly promising incremental cost improvements over the standard modular subsystems approach. The effect of applying all three approaches in optimal combination is an incremental cost savings of 12 percent, or about $5.5 billion in savings within a 91-program mission model having a total baseline cost of $46 billion.

Examination of other potential cost reducing proposals leads to the following conclusions: Reliability optimization (i.e. design for optimal repair schedules) would only be useful for spacecraft that cost at least $10 million each; relaxation of documentation requirements will be of somewhat doubtful value; probably little can be done to avoid "handcraft-ing" within the NASA context (so long as advancing space flight capability remains a primary goal), but the standard subsystem approach would help achieve reasonable production runs and, thereby reduce costs to some extent. Forcing the technology will probably not be as great a source of program risk in the shuttle era and, in fact, it may be that the availability of well checked-out modules will encourage attempts to advance technology in selected areas.

To the extent that the traditional program approaches and orienta-tions have become embedded in institutions and industries they constitute

a social infra-structure. Therefore, to institute effective changes leading to low cost programs may require much more than a mere technical understanding of how to achieve low cost systems. A thorough understanding of space programs as a total social process will be needed to implement fundamental improvement. Only relatively dramatic changes in program approach can be expected to help much; yet immediate dramatic changes are improbable. Even if a strong stand is taken to emphasize low cost approaches, it may be that significant change will be difficult and that only modest and evolutionary progress can be expected.

Perhaps it is premature to issue any words of caution concerning low cost approaches until the concept has at least been tried. But it should be remembered that just as an extreme emphasis on performance in the past has led to nearly total neglect of low cost as a criterion, so it is possible, in the attempt to extract every last degree of low cost potential from a program, to go too far and sacrifice program objectives. Thus, for example, in such areas of low cost design as "commonality", it is essential that the search for commonality not overlook significant differences in detailed objectives among programs lest they be eliminated.

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LIST OF ILLUSTRATIONS

1. INTRODUCTION

This report deals with possible ways by which NASA payload costs might be reduced in the future. That a serious study of methods to reduce spacecraft and payload costs is in order is demonstrated in Table 1-1. This table indicates costs in dollars/kg per flight unit for selected development projects from Reference 1. It has been found that unit costs for unmanned spacecraft correlate fairly well with the following three categories: (1) spin stabilized spacecraft with design lifetimes of one year or less; (2) spin stabilization with three year design lifetimes; and (3) three-axis stabilized spacecraft. The table is organized in this manner.

Figure 1-1 depicts these tabular results and also shows the correlation of unit cost with spacecraft weight.

The objective of our effort was to examine the major historical reasons for payload costs being as they were and to determine if there are technologies (hard and soft), or criteria for technology advances, that could significantly reduce total costs of payloads.

Fundamental to our analysis has been a very liberal interpretation of "technology". Thus, we have considered factors that might contribute to reduced payload costs such as economies of scale, relaxed documentation requirements, modular subsystems, standard spacecraft and the like. But, at the same time, we have also explicitly considered the impact of a "hard" technology--the advent of the shuttle. Permeating the entire analysis are such potential effects of an operational shuttle as relaxed weight and volume constraints, payload refurbishment, on-orbit testing, aircraft type (as opposed to spacecraft) project management, and so forth.

It was not possible in this study to generate any new data. Rather, the approach was to, first, accumulate as much historical payload cost data as we could assimilate to gain some insight into the reasons why costs are, and have been, as they are. Next, we considered the areas that might yield lower payload costs in the future. Finally, we obtained reports and papers that addressed these areas, and where none

TABLE 1-1   SPACECRAFT COSTS

Project	Stab.	Lifetime (yr)	Number of Fl't Units	Avg. S/C Gross Wt. (kg)	Total Cost (million $)	Avg. S/C Cost (thousand $/kg)
SSS	Spin	1	1	50	6.6	132
IMP	Spin	1	10	155	71	46
GEOS	Spin	1	4	170	34	50
SAS	Spin	1	3	185	40	73
RAE	Spin	1	2	290	21	36
AE	Spin	1	5	350	46	26
OSO	Spin	1	11	405	196	44
SMS	Spin	3	2	245	41	83
Pioneer F,G	Spin	3	2	255	99	195
ATS 1-5	Spin	3	5	730/380*	148	40/78
MVM '73	3-axis	1	1	450	100	222
Nimbus	3-axis	1	7	550	342	89
ERTS	3-axis	1	2	815	160	98
ATS F,G	3-axis	2	2	930	196	105
MM '71	3-axis	1	2	1,030	129	63
OAO	3-axis	1	4	2,020	363	45
Viking	3-axis	1	2	3,440	830	121
ALSEP	Apollo	1	6	160	190	198
EREP	Skylab	1	1	975	55	56
ATM	Skylab	1	1	10,075	199	20

* Dry Weight

UNIT COSTS FOR MANNED & UNMANNED SPACECRAFT
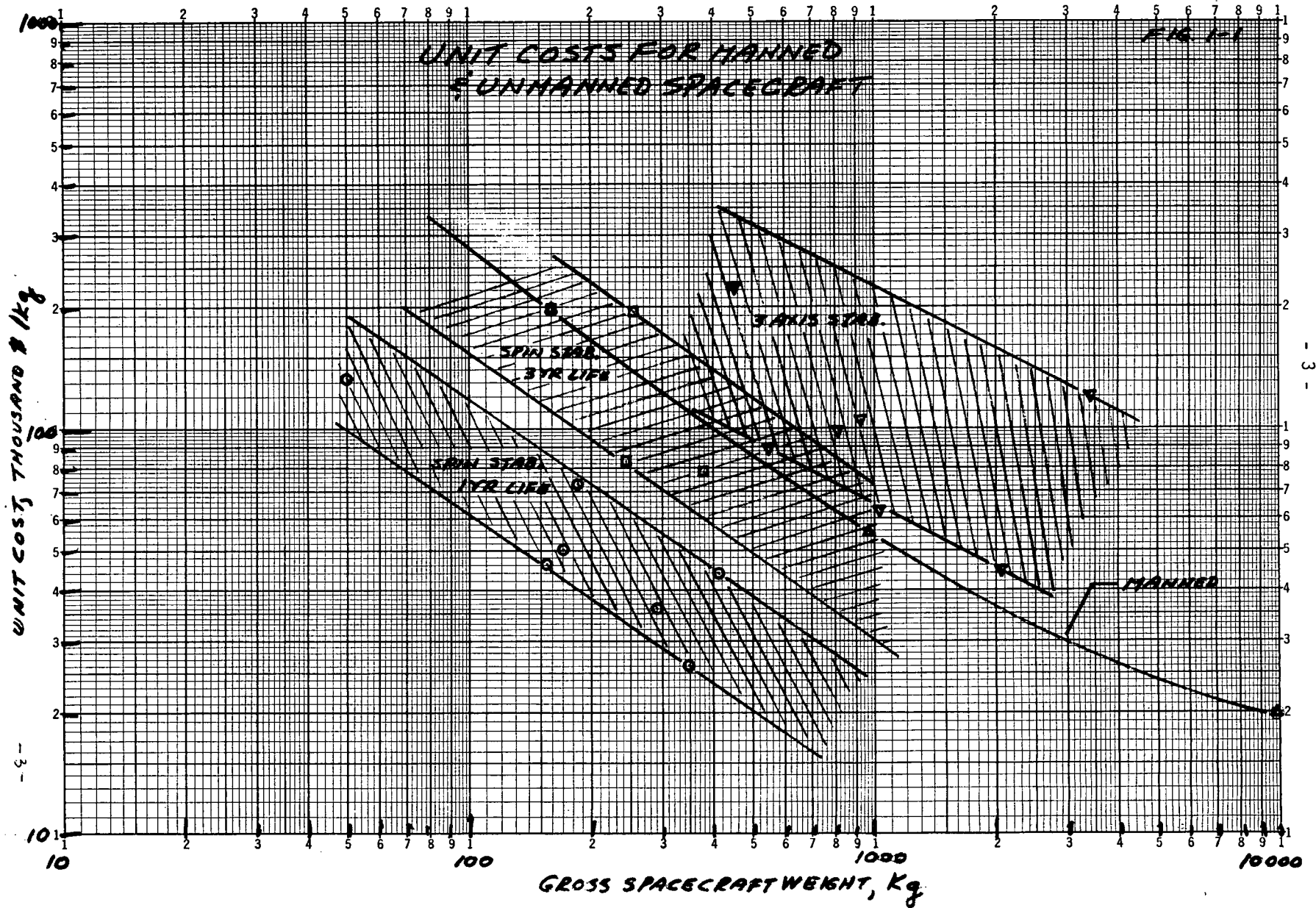
were readily available, held private conversations with individuals felt to be knowledgeable in specific areas.

As a final word of introduction, the distinction we make between "payload" and "spacecraft" must be made clear. For unmanned missions (or autonomous satellites deployed from the shuttle), the spacecraft represents everything above the launch vehicle, or for planetary missions, above the earth departure stage. The payload represents that portion of the spacecraft devoted to sensors and experiments. In this study we consider, for unmanned missions, only the spacecraft costs. For manned spacecraft we are only concerned with payload or the payload support module (e.g., EREP, ATM)--not the entire spacecraft.

The remainder of the report is organized into two main sections. In the next section, payload costs are placed in historical context. Some historical cost breakdowns for unmanned NASA payloads are presented to suggest where future cost reductions could be most significant. Space programs of NOAA, DoD and COMSAT are then examined to ascertain if payload reductions have been brought about by the operational (as opposed to developmental) nature of such programs, economies of scale, the ability to rely on previously developed technology, or by differing management structures and attitudes. The final discussion investigates the potential impact of NASA aircraft-type management on spacecraft program costs and concludes with some examples relating previous costs associated with aircraft costs on the one hand and manned and unmanned costs on the other.

The last section of the report deals with the future. It begins with a narrative which sets forth the reasons why previous spacecraft have been so expensive and is based largely, but not entirely, on the prior examples. The section concludes with a discussion of potential solutions to the problem of high cost. This discussion is aided by examples taken from recently completed studies.

2. HISTORICAL COSTS

To better our understanding of how payload costs might be reduced in the future, it is necessary to understand why costs are as they are. Such is the purpose of this section. In order, we examine NASA space missions, non-NASA space missions, and the NASA airborne science program.

Cost Summaries

Historically, the interest in unmanned spacecraft cost estimating has largely centered around obtaining cost estimates for future projects. This task involves isolating pertinent information about the spacecraft and mission and relating this information to the program cost. Obtaining cost estimates for completed missions in a form amenable to systematic analysis, however, is no easy task. Each project is generally unique in method of operation, design, and capability. The problem is then one of comparing different missions, isolating relevant cost information and generalizing the data. Our purpose here is to examine such data for representative flight projects to suggest where the impact of future cost reductions may be most significant.

Table 2-1 illustrates, for representative projects, the type of information (Ref. 2) which is generally available.

Table 2-1
Representative Project Costs (million $)

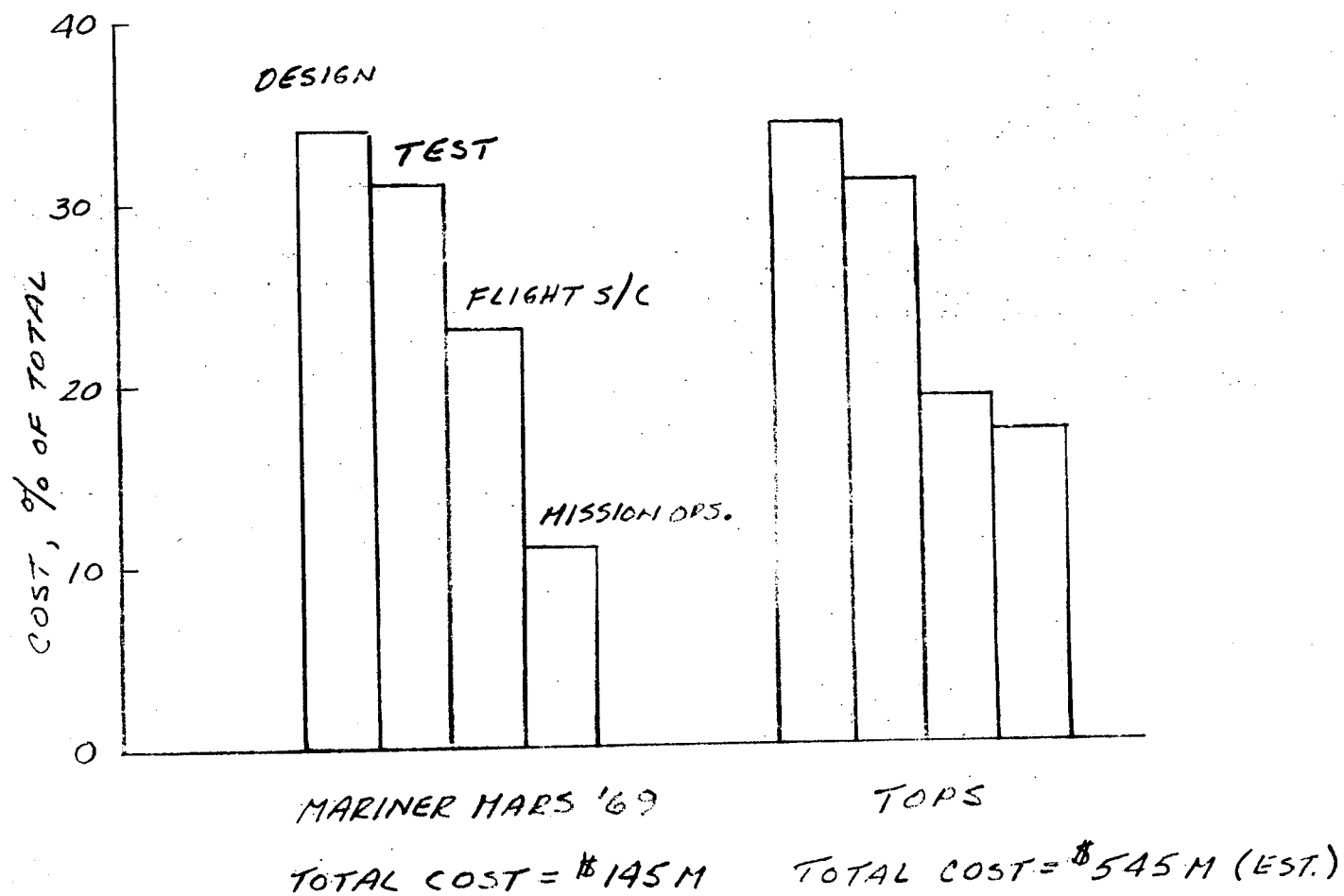|	S/C	P/L	Ground Ops & Mgmt.	Data Users
Mariner Mars '69	86	15	17	22
TOPS (2 flights)	375	110	55	11
Pioneer F&G	50	17	14	8
OAO A, B, C	263	64	23	--
ATS F&G	97	46	12	--

The projects include both completed and continuing projects as well as earth orbital and planetary missions. The data for TOPS (although no longer a project) is included since very detailed cost estimates were available. The cost categories in the table are quite broad and generally reflect the work breakdown structure unique to each project, NASA center, and contractor.

They are neither sufficient for cost projection nor for understanding the underlying cost determinants. Cost breakdowns indicating major program elements are more likely to indicate critical cost elements. Since this data is not easily obtained, the remainder of this discussion will not present data for the flight projects of Table 2-1 to equal levels of detail.
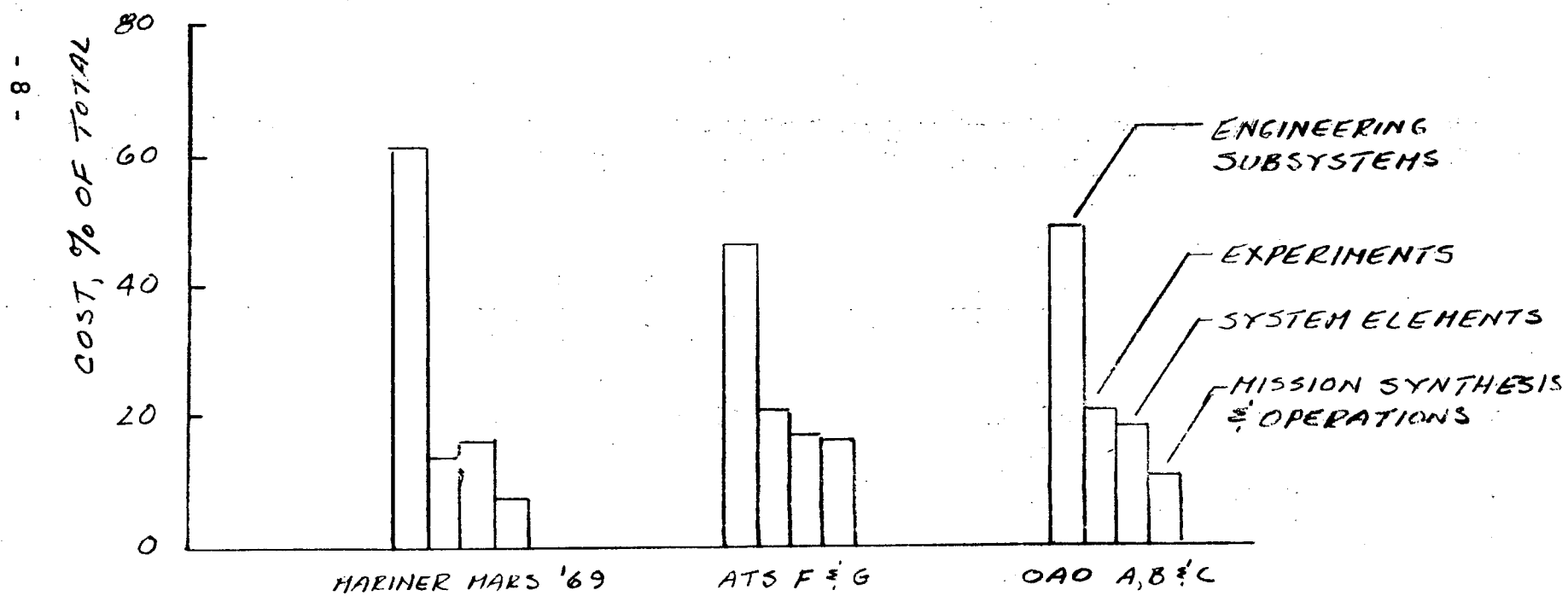
Figure 2-1, a cost breakdown by program area, indicates that major cost areas are design and test (Ref. 3). "Design" refers to the hard design and includes bench testing. "Test" includes all ground testing of hardware, including the purchase of test hardware. These two categories represent about 65 percent of the total cost. Spacecraft complexity and mission reliability are the major considerations in these categories. JPL sources (Ref. 4) indicate that about 70 percent of the cost of testing is attributable to reliability and quality assurance while 30 percent depends on design complexity.

Figure 2-2 indicates a cost breakdown by system group (Ref. 5). "Engineering subsystems," the largest contributor to cost, includes design, development, testing, and acquisition of the subsystem elements. As seen, this represents about 50 percent of the project cost for the three projects shown. "Experiments" is similar to the preceding category but applies only to the scientific instruments (i.e., the payload). "System elements" include integration and testing of the total spacecraft (with experiments) as well as acquisition of the ground support equipment. "Mission synthesis" includes mission/system design compatability and actual flight operations.

FIG 2-1

COST BREAKDOWN BY PROGRAM AREA

2. FLIGHT SPACECRAFT

MARINER MARS '69
TOTAL COST = $145 M

TOPS
TOTAL COST = $545 M (EST.)

FIG 2-2

COST BREAKDOWN BY SYSTEM GROUP

Since the engineering subsystems comprise about 50 percent of the costs, a further breakdown of this area is instructive. Table 2-2 lists the major subsystem elements. For the earth orbital mission (ATS), no particular element seems to dominate. This is in contrast, for example, with the communications system for Mariner Mars '69. This would tend to emphasize the critical requirements placed on communication systems for planetary missions. Power, of course, becomes more critical for long distance missions as indicated by the Pioneer data.

Table 2-2

Cost Breakdown of Engineering Subsystems (millions)

	Mariner* Mars '69	ATS* F&G	Pioneer** F&G
Structures	18	19	4
Propulsion	5	2	3
Guidance	15	15	3
Communications	26	16	10
Power	7	17	9

* Source: Ref. 3
** Source: Ref. 4

In summary, the design and test phases of NASA unmanned space projects represent the largest portion of total cost--about 35 percent and 30 percent, respectively. The individual subsystems taken collectively represent about 50 percent of the total cost but their integration into a spacecraft only requires about 20 percent of the total. The cost of the experiments themselves (including their testing) represents about 25 percent of the project cost.

Operational Projects

In this discussion, the costs of ESSA/NOAA and certain DoD and COMSAT spacecraft are examined. The intent is to ascertain the differences in costs between projects that are basically developmental (NASA) and those that are basically operational (non-NASA). Where differences are found we attempt to explain their origins--at least to the extent that the available data and, in some cases, limited statistics permit.

Aggregate Comparison

Table 2-3 summarizes the space programs of the various agencies through 1971 based on data from Refs. 6-10. To guard against any misinterpretations the various entries are briefly explained in the following paragraphs.

Number of Launches. For NASA, all sub-orbital flights and OAST missions are excluded. All orbital missions of the remaining agencies are included, including the ARPA missions of the late 1950's and early 1960's.

Total Spacecraft Weight. This represents the total weight above the launch vehicle, as defined in Section 1. For the manned NASA missions it includes, among other things, the gross weight of the Apollo CSM, i.e., the propellant weight has not been subtracted.

Average Spacecraft Weight. - This item is self-explanatory.

Costs. Since space flight operations costs (tracking, data acquisition and analysis) are not insignificant, it seems desirable to ultimately express spacecraft unit costs in two versions--with and without the operations costs. With the exception of such costs for the DoD program, the references allow these costs to be either identified explicitly or to be estimated rather closely. But, as we have come to expect, the accounting procedures vary; and thus, to preserve the raw reference data the entries have been arranged as shown with explanatory footnotes.

Table 2-3   U.S. Space Program Through 1971

	NASA (unmanned)	NASA (manned)	ESSA	DOD	INTELSAT
No. of Launches	149	41	12	384	15
Total S/C Wt. (kg)	38,900	596,000	2,180	482,000 (est.)	2,514
Avg. S/C Wt. (kg)	260	14,500	180	1,250	168
Costs (million $)					
Basic	7,150[1]	24,100[2]	279[3]	20,800[4]	103
Operations	1,280[5]	1,280[5]	- -	- - -	65[6]
Cost Exclusions (million $)					
L.V. Dev. & Ops	2,070	9,220	60	3,600 (est.)	- -
MOL	- - -	- - -	- -	1,500	- -
Net S/C Cost (million $)					
With Operations	6,360	16,160	219	15,700	168
W/O Operations	5,080	14,880	127	- - -	103
Unit S/C Cost (thousand $/kg)					
W/W.O. Ops	164/130	27/25	100/58	33/-	67/41

(1) OSSA R&D.
(2) OMSF R&D.
(3) Includes operations cost of $92 M.

(4) Total (Ref 10) + $1B ARPA R&D pre FY 59 (est.).
(5) One-half OTDA R&D.
(6) Investment in ground stations.

Cost Exclusions. Since spacecraft costs are of interest, the launch
vehicle development and operation costs must be excluded from the total
costs. Moreover, since we can only compare unmanned programs, the
development costs for MOL must be excluded from the DoD costs.

Summary. This indicates the spacecraft unit costs with and without
the operations costs. Figure 2-3 depicts these results in the same
format as Figure 1-1. Also shown is the general unit cost-weight trend
from the earlier figure.

It is seen that, indeed, the costs for NASA spacecraft are substan-
tially greater than those for the other agencies. Some gross reasons
for these cost differences are hypothesized in Table 2-4. The following
paragraphs consider the hypotheses in more detail by examining the
projects of the non-NASA agencies.

ESSA/NOAA

NOAA (formerly ESSA) has the responsibility for establishing,
operating, and improving the nation's system of operational environmental
satellites. To satisfy the operating requirement NOAA commands and
controls satellites in orbit, acquires and processes data from satellites,
arranges for dissemination of both processed and unprocessed data, and
works to maintain an archival system for making data available for
research and application to specific environmental problems. NOAA
maintains and improves current data handling systems, plans for future
spacecraft systems, and coordinates with NASA in the development of new
and improved sensors and spacecraft systems. Major research and develop-
ment efforts are devoted to the analysis and application of satellite
data, and the development of new sensor systems for use on or with space-
craft.

To date twelve spacecraft of two basic classes have been purchased;
9 original ESSA satellites weighing 140 kg each and 3 newer 3-axis
stabilized ITOS satellites weighing 310 each. These spacecraft designs
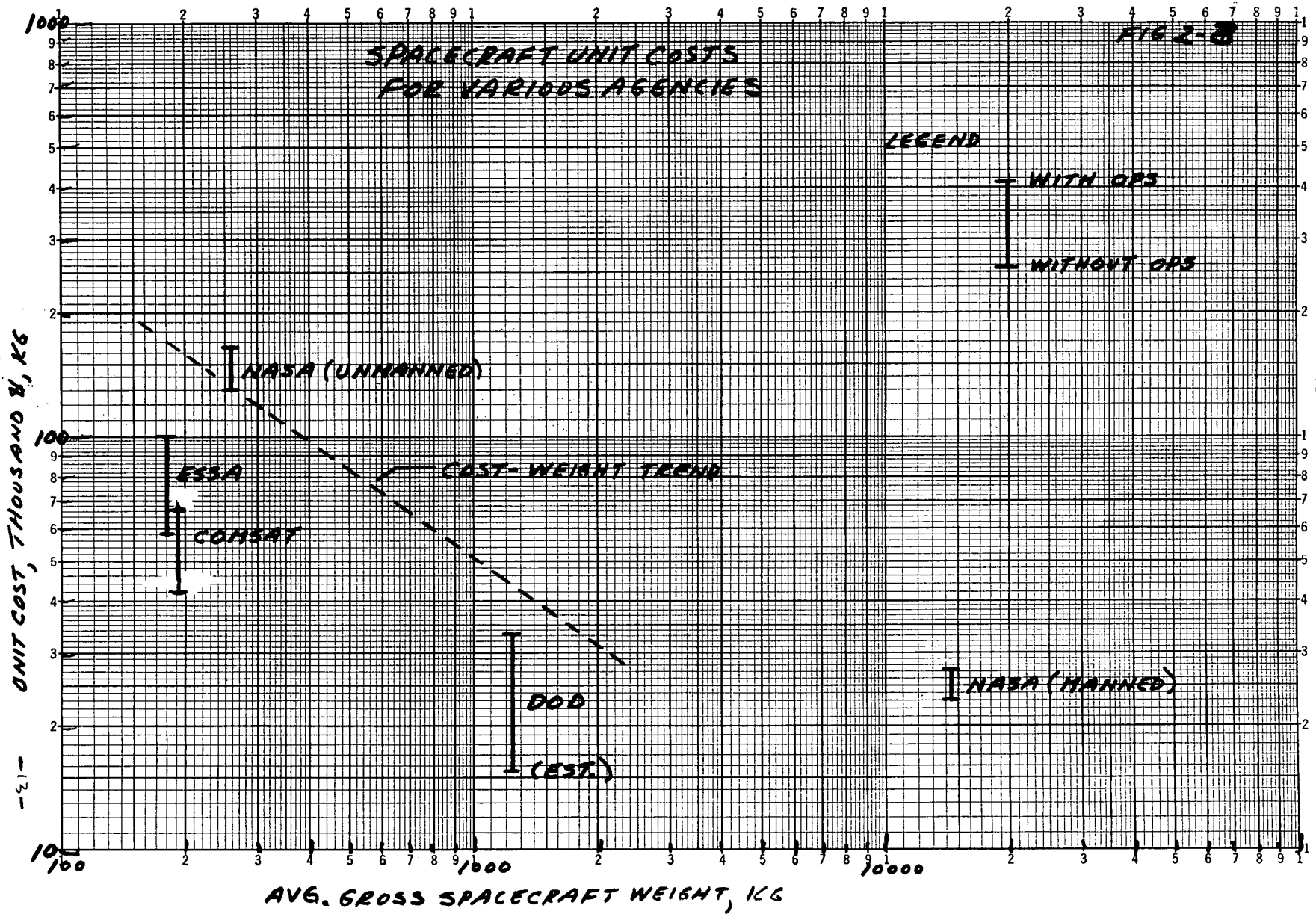drew heavily on the previous TIROS satellites developed by NASA.

SPACECRAFT UNIT COSTS FOR VARIOUS AGENCIES

FIG 2-8

Table 2-4
Differences Between NASA and Non-NASA Projects

Category	NASA	Non-NASA
Technology Advance	Major objective is technology development.	Often use current technology; some developed by NASA.
Economies of Scale	Small number of spacecraft within each project.	May involve dozens of essentially identical payloads.
Standardization	Virtually all spacecraft are unique.	May involve single spacecraft design for on-orbit payload support of various projects.
Management Philosophy	Public scrutiny & high cost demand rigorous Q/A; much documentation; much NASA/contractor coordination.	Less public outcry from failure may permit greater risk (DoD); small isolated project teams; fewer engineering changes; greater reliance on contractors.

We would classify the ESSA program as one which takes advantage of modest economies of scale; which is responsible in the long run for only modest technology advances; and which has a management approach, by definition, similar to that of NASA.

DoD

Over the years, DoD has conducted almost 400 space missions. These have satisfied a wide variety of objectives including communications, geodesy, navigation, technology development, etc. Many of the projects are classified and, for most, it is not possible to obtain cost and weight data. (The summary data of Table 2-3, for example, is based only

on the cited references together with a general knowledge of launch vehicle costs and performance capabilities.)

Nevertheless it has been possible to obtain unclassified data on four separate projects as shown in Table 2-5. The first three are geosynchronous military communications satellite projects related superficially, at least, to the ATS and Intelsat projects. However, unlike ATS 1-5 and the INTELSAT spacecraft (discussed later) these DoD spacecraft do not employ apogee motors but rather are injected into synchronous orbit directly by the Titan III Transtage.

The IDCSP (Ref. 11) and DCS II projects can be categorized as having substantial technology advances but also having substantial economies of scale, within the IDCSP project particularly.

The Tacsat* spacecraft, exclusive of the payload, is the predecessor of INTELSAT IV. The payload, however, differs in that in other antenna designs, more advanced repeater technology and multiple frequencies are employed. Tacsat, therefore, must be categorized as a project with moderate technology advance but with no economies of scale.

Insofar as the management philosophy of these projects is concerned, it is likely somewhat different from that of NASA (and NOAA). First, since technology advance per se is not an objective, fewer project scientists and engineers are involved. Consequently, fewer managers are needed and documentation requirements are reduced. Second, although these projects are not classified, launches are not normally announced in advance so that there is no public expectation. Moreover, even though the "military-industrial complex" is under widespread criticism and even though NASA is considered by its critics to be a part of this complex the military space program seems to be immune. Thus, it would appear that risk avoidance is not a major consideration within DoD. This risk acceptance factor must logically contribute to reduced project costs.

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* We are indebted to TRW and Hughes Aircraft Corp. for their cooperation in providing data for DCS II and Tacsat respectively.

Table 2-5

DoD Spacecraft Costs

Project	Stab.	Lifetime (yr)	Number of Fl't. Units	Avg. S/C Gross Wt. (kg)	Total Cost (million $)	Avg. S/C Cost (thousand $/kg)
IDCSP	spin	2	34	45	53	35
DCS II	spin	5	6	500	65	21.6
Tacsat	spin	2	1	725	15	20.6
Project A	3-axis	<1	40[1]	685[1]	400	14.5[2]

(1) Values shown are approximate.

(2) Includes basic spacecraft costs of $7000/kg plus estimates for payload costs.
   Total project cost is an imputed value and probably includes little, if any, operations cost.

The final project listed in Table 2-5 (identified as Project A) is classified. The data shown is not classified, however, and was provided on an informal basis by Lockheed Missiles and Space Company. This project differs from those described previously in that a large number of identical, and reasonably heavy, spacecraft were launched to low altitude orbits. This project differs further in that the spacecraft were actively, rather than spin, stabilized and that the mission duration was considerably shorter.

The project cost includes all costs associated with the basic spacecraft and those of the payload--assumed equal to those of the spacecraft. Even though the actual contribution of payload development costs to the total is not known, the fact that these costs were amortized over about 40 flights makes this uncertainty of secondary importance.

In addition to this unique example of economies of scale of large spacecraft, other differences also exist. The first concerns spacecraft standardization--undoubtedly a major factor in cost reductions. All missions in this project employed the Agena spacecraft. The Agena was developed as a combination upper stage propulsion system and spacecraft. To date, approximately 330 Agena vehicles have been launched; about 280 of these have been in the spacecraft configuration. As a three-axis stabilized spacecraft, the Agena provides structural and functional support to various integrated payloads. Among these functions are on-orbit maneuvering from either the main engine or a secondary propulsion system, initiation of payload recovery from orbit, launch of subsatellites, wide band data transmission to ground station, and various sequencing operations based on both preprogrammed and transmitted commands.

The Agena spacecraft was used in Project A to provide the attitude stabilization and electrical power for the payload. (Although since the mission duration was rather short, the power supply system may have been of only modest sophistication.) With the incorporation of such items as large solar arrays, control moment gyros, and with the normal evolution of the various subsystems, the lifetime capability of the Agena spacecraft has increased considerably. Several vehicles have remained in operation for about one year in orbit.

The management philosophy for this class of DoD projects is vastly different from that of NASA. The projects are highly classified with stringent need-to-know requirements. Consequently the number of personnel associated with a project is limited. The project team functions virtually as a mini-corporation behind a "green door". By traditional standards correspondence and documentation is meager and there is far less interface between DoD project management and the contractor.

Since we are more interested in this study in spacecraft costs rather than in spacecraft plus operations costs, it is desirable at this point to estimate the contribution that operations have made to the total DoD program costs. A gross estimate can be made by plotting the cost versus weight of the four programs listed in Table 2-5 and noting the cost at the average DoD spacecraft weight of 1,250 kg. This point was shown earlier as the estimated cost without operations in Figure 2-3. That the operations cost thus obtained are so large may seem questionable. One firm data point, however, does exist. The tracking and data acquisition costs for the IDCSP project were $75 million (Ref. 11). This is considerably in excess of the basic project costs (see Table 2-5). When one considers the various tracking and command stations that exist, operation of the Satellite Test Center, and the data analysis it is plausible that DoD operations costs are indeed high.

COMSAT/INTELSAT

As a result of the Communications Satellite Act of 1962, the Communications Satellite Corporation (COMSAT) was created to establish, in conjunction and in cooperation with other countries, a commercial communications satellite system. U.S. common carriers can own no more than 50 percent of COMSAT stock (about 29 percent is now owned by AT&T) and the public holds the remaining amount. The Corporation has public directors, those representing the carriers and three appointed by the President of the United States. In 1964 the International Telecommunications Satellite Consortium (INTELSAT) was established to develop, own and operate the international commercial communications satellite system. COMSAT is the manager of the 83 member INTELSAT organization, and approximately 53

percent of the financial investment in INTELSAT is owned by COMSAT.

Table 2-6 summarizes the INTELSAT program to date. INTELSATS I and II were direct descendents of the NASA developed SYNCOM satellites. INTELSAT II differed from INTELSAT I primarily in that it had three times the effective radiated power and employed narrower beam-higher gain antennas.

INTELSAT III represented a new generation of spacecraft having ten times the radiated power of INTELSAT II. As seen from the table, this permitted more than a fivefold increase in the number of voice channels.

INTELSAT IV, in turn, represented a significant advance in capability. Radiated power was increased by another factor of ten; redundant global horns were available; for the first time, spot beams were employed; and a better repeater design was available. These improvements resulted in another fivefold increase in the number of channels.

It is apparent that considerable technological advances have been employed within the INTELSAT series of spacecraft. A sizeable (but unknown) portion of this technology was developed by NASA. Consequently we would judge the INTELSAT costs to reflect, on the average, only minor technology developments.

Unlike the NASA, ESSA and DoD programs, however, for which it is virtually impossible to measure the real value of technology, the INTELSAT satellites do permit such measurements; namely the cost per channel, and of more importance, the cost per channel-year. The cost per channel has been reduced by a factor of seven between INTELSAT I and INTELSAT IV. And measured on a channel-year basis an improvement by almost another factor of five has resulted.

This last factor has given rise to a management philosophy centered around the principle that spacecraft lifetime is a primary goal. All INTELSAT contracts are of the fixed price-incentive type. The fixed price reflects the fact that the basic technology is at hand; the incentive payments are based on spacecraft operating lifetime. COMSAT feels that requiring the contractor to have an investment in the system is a means to long lifetimes and low costs.

TABLE 2-6   INTELSAT COSTS

Project	Stab.	Lifetime (yr)	No. of Flight Units	Avg. S/C Gross Wt. (kg)	Total[2] Cost ($M)	Avg. S/C Cost $K/kg	No. 2-way Voice Channels	Cost per Channel Year ($K)
Intelsat I	spin	1½	2	67/32[1]	10	75/156	240	13.9
Intelsat II	spin	3	5	160/76	18	22/47	240	5.0
Intelsat III	spin	5	8	290/126	56	24/55	1,200	1.17
Intelsat IV	spin	7	8	1395/585	112	10/24	5,500	0.40

(1) Dry weight.

(2) All "COMSAT" costs, here and in Table 2-4, represent total Intelsat consortium costs.

Conclusions

Based on the previous discussion, the following reasons for the relatively high cost of unmanned NASA spacecraft are offered by contrasting the NASA program with those of the other agencies. These reasons are summarized in Table 2-7.

Table 2-7

Contributions to NASA Costs

Agency	Normalized S/C Cost	Primary Reasons for Lower Costs
NASA	1	- -
ESSA	1/2	Less reliance on new technology
COMSAT	1/3	Borrows much technology; somewhat less contractor interface.
DoD	1/9	Economies of scale dilute effects of new technology costs; less contractor interface; large standardized S/C adaptable to new P/L and subsystem technologies.

It is seen that the two major contributors to the high cost* of NASA spacecraft have been the continual development of payload and subsystem technologies per se (thus eliminating possibilities to realize economies of scale) and the fact that, in turn, wholly new spacecraft were often developed to employ the technologies. The degree of NASA/contractor interface has been greater than that exhibited by other agencies; yet this does not by itself appear to have been a major factor in high cost.

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* It should be mentioned here that on one occasion NASA has launched a low cost spacecraft--Nimbus 3. The average cost of six of the seven Nimbus spacecraft was about $50 million per copy (with little variation in these costs). Nimbus 3 was simply assembled from spare hardware (including spare sensors) and cost $10 million.

Some Lessons Learned from Aircraft

Since 1965 the Airborne Science Office of Ames Research Center has managed a program of scientific observations from aircraft--primarily a Convair 990 and a Lear Jet and, more recently, Lockheed U-2 aircraft in support of the ERTS project. It has often been suggested that in the era of the shuttle the costs of space projects could be markedly reduced if such projects were to be managed in a manner akin to "aircraft-type operations". It is the purpose of this discussion to describe these operations and, in so doing, to suggest which aspects may be most conducive to future space program cost reductions.

Aircraft Operations

The following discussion is taken essentially verbatim from Ref. 12. Since that reference offers a rather concise description of the airborne science program, and since the adaptation of such a program to space flight potentially offers dramatic reductions in payload costs, it is felt best to explain the program rather completely here. Some of the numerical examples, however, have been modified to conform more closely to the contents of this report.

The program is managed at ARC by a staff of about 15 people, including scientific, payload, and logistics management, but excluding aircraft maintenance and flight crews. One man (mission manager) is responsible for each scientific discipline, and is supported by a few engineers and technicians. Mission approval and experiment selection are NASA Headquarters functions involving a five-man committee (Airborne Research Steering Committee) and requiring up to three months. All subsequent decisions are made by the ARC mission manager responsible for the scientific discipline which has first priority on the mission. No documentation or reporting is required other than the manager's formal entry in his log book. Typically, a dozen experiments are mounted aboard the CV-990 for a major mission. They are selected for complementary objectives and compatible flight requirements (location, duration, etc.).

Equipment construction and operation is the responsibility of the participating scientist. No documentation is required of him other than a calculated stress analysis of the mounting bracketry to meet safety requirements. A visual inspection by a trained ARC aircraft inspector is made after the equipment is aboard the aircraft to verify that the construction was according to submitted blueprints and stress analyses and meets special regulations on chemicals and cryogenics. Each participating scientist is self-motivated to ensure the proper performance of his instrument (as contrasted to safety), though the ARC staff is personally interested and offers suggestions based on experience. Nearly all instruments are laboratory-type with only minor modification to adapt to aircraft requirements. The construction and installation of the scientific equipment take from a few days up to nine months, during which time mission logistics are planned and preflight problems are resolved.

The time span from proposal to first data flight is thus a year or less, which compares favorably with ground laboratory experiments. The investigator is totally occupied with the science and technology of his experiment--no committees, complex chains of approval for changes, documentation, or delays. The safety record has been perfect. The experiment failure rate has been about 3 percent on CV-990 missions, which have accumulated nearly 3,000 flight-hours to date.

Typical costs for an airborne scientific expedition are summarized in Table 2-8. These represent average costs for two auroral expeditions conducted in 1968 and 1969 (Ref. 13). The average aircraft payload per flight was 7,430 kg consisting of 3,840 kg of scientific equipment with its ancillary equipment and 35 persons (at 102 kg per person) totalling 3,590 kg.

Table 2-8   CV-990 Airborne Auroral Expedition

	Cost	Unit Cost	Unit Cost (w/o people)
Experimenters' Funding	$234,000	$32/kg	$ 61/kg
Operations	$315,000	$42/kg	$ 82/kg
Total Cost	$549,000	$74/kg	$143/kg

The philosophical point underlying the economy of the aircraft scientific payloads is the total reliance on the investigators' close personal involvement to assure proper functioning of his equipment. The economies are possible in large measure because scientists attend their own experiments in flight, an advantage heretofore unavailable to managers of space missions--but an advantage that can be realized in the shuttle era. This advantage manifests itself in several areas related to lower costs:

Experiment Selection. In contrast to a three month experiment selection process for the aircraft, one or two years elapse before final selections for space flights which, in turn, will not be launched until three to five years hence. Upon final selections, costs are negotiated and constraints on the payloads agreed to. Improvements in the space experiment over the years from proposal to launch must be cycled through the approval structures. The complex series of briefings, communications, proposals, and reviews stretch the schedules and escalate initial costs.

Cargo Management. Aircraft cargo management for a typical mission including a dozen experiments is performed by the mission manager assisted by one engineer. Safety is reviewed by one engineer and one aircraft inspector (a pilot and an aerodynamicist are also consulted when needed).

Typical spacecraft missions have an overall project manager with a staff of deputy managers responsible for major aspects of the program. Each deputy has a supporting staff of technical and administrative specialists. Generally, one or more large aerospace contractors are involved in interfacing the spacecraft with the experiments. Each contractor has a project manager and a staff of deputy managers, each with supporting staff. Severe quality control and reliability constraints are imposed on experimenters and contractors, and elaborate documentation is required to ensure conformance. Staffs of writers, illustrators, typists, and expediters are assembled (with managers) to handle this paper stream. Communication is difficult, and conferences

at all management levels are required. Documents detailing every discussion and decision flow in all directions.

Experiment Management. Experiment management in the airborne research program is the sole responsibility of the scientist. Hardware constraints are broad and general. Weight, space, and power allocations are generous and can be made realistically since leadtimes are short and the hardware is mostly "off-the-shelf."

On satellite missions, the scientists' preparations are managed by the project manager's experiments office which dictates in minute detail the size, shape, weight, power, location, reliability, quality, data rate, and most other spacecraft-related limitations on the experiment. With long leadtimes and much development needed, the requirements cannot be set realistically. Economy is not attainable because equipment must be built to standards developed by the project manager's experiments office. To cope with the demands of the project office-contractor complex, the scientist develops his own staff of managers (with staff).

Scientist Participation. Scientist participation during aircraft flight is required. Each scientist is responsible for the success or failure of his own experiment, and thus is motivated to devote his time to laboratory research ensuring the best possible experiment. In satellite programs, the scientist becomes a virtual bystander and larger and larger staffs accumulate to protect against increasing chances for human error.

Payload Simplification. Payload simplification is a natural outcome of the airborne science approach. The scientist assembles only one payload unit, usually from his own laboratory equipment. He tests, redesigns, modifies, improves, and retests until he is satisfied the device is ready for flight. He carries it aboard, is aided in its installation by ARC, checks the payload as he did in the laboratory with simple instruments, and then operates the equipment in flight. Any malfunctions are corrected there by the scientist. Since aircraft flights are frequent, the scientist is constantly able to upgrade the payload in his laboratory, maintaining it at the current state of the art.

By contrast, satellite programs require many duplicate payload models: breadboards, prototypes, mockups, engineering test models, training models, spares, and flight models. In addition, complex ground support equipment and checkout consoles often are required, all subject to rigid quality control and reliability programs that raise exponentially the experiment costs.

Data Processing. Data processing and reporting are the responsibility of the scientist. Except for aircraft-related data (altitude, speed, direction, air temperature, mission time, geographic location), the scientist records his own data with his own equipment. A central recording console is available on the CV-990 for experimenters who wish to use it. There are no requirements by ARC for data copies. Experimenters take their recordings with them when they vacate the aircraft.

Satellites, of course, must rely on complex data storage and transmission systems. Transmitted data are recorded at telemetry ground stations where special staffs separate each experiment's data from the rest. Master recordings and many duplicates are made. Often the experimenter's data are initially processed by the project manager's staff so the manager is assured the equipment is working. Data transmission systems are a critical item to the success of the mission, and costly reliability programs are imposed to guarantee successful operation.

Documentation. Documentation is limited to the original proposal and a calculated stress analysis of the experiment mounts. Both scientists and ARC staff maintain laboratory-type notebooks (hand entries) for keeping essential notes. No formal reports, progress reports, meeting report, or memoranda are required of the participating scientists.

Documentation demands for space missions are infamous; monthly progress reports often exceed hundreds of pages; daily correspondence and test reports fill cabinets, as do drawings, change orders, study reports, and documents ensuring quality control and tracing the history of high reliability parts.

Application to the Shuttle

In this discussion (also based on Ref. 12), we consider what increases in hardware costs might be expected in going from aircraft to the shuttle sortie, but retaining the aircraft management philosophy.

Safety. If one accepts the principle that it is human responsibility, rather than documentation per se, that creates safety, there should be little differences in payload costs between aircraft and the shuttle. Mechanical restraints can be calculated (stress analyses) and construction can be visually inspected: Aircraft standards require 9-g restraints, which is more than enough for the shuttle. In both cases, chemicals are restricted, pressure vessels have relief valves, and cryogenics are specially contained. The vibration and sudden unanticipated brusque motion environment of the aircraft is far more severe than that of the shuttle. The only obvious difference from the safety standpoint is that aircraft cabin air is replaced, while shuttle cabin air is recycled. This leads to a few additional restrictions on volatile construction materials for the shuttle experiments. A 20 percent increase in cost for this factor would seem to be a generous allowance, assuming again that the experimenter is motivated by his desire to survive the mission rather than by extensive documentation requirements. Preflight inspection is, of course, required.

Reliability. The somewhat less than 3 percent failure rate of CV-990 experiments does not imply such a low figure for repairable malfunctions. Equipment is realined and minor repairs and adjustments are made, both in flight and on the ground between flights. The situation most similar to that of a shuttle sortie is the basing of the CV-990 for several weeks at a remotely located airport, with only basic aircraft turnaround support available, but no access to parts nor technical support for experimental equipment. The weight of payload repair tools and spare parts carried aboard the CV-990 can be about 25 percent of that of the equipment. In the shuttle case, one might want a higher degree of redundancy, that is, more replacement and less repair. A factor of two is allowed here for this possible cost increase.

Environmental considerations affecting experiment hardware reliability are felt to be no more complex in the shuttle than in the aircraft. Experiments aboard the CV-990 have operated continuously under 2-g loadings (60° banks), at -50°C, and in 500-knot winds (externally mounted equipment, which involves special safety and aerodynamic considerations); hard landings and rough runways have also made severe demands on experimental equipment.

Operations. The principal differences in payload operation aboard the shuttle as contrasted to the aircraft are the 0-g environment and the smaller number of attendants (by a factor of five or more). While alinements, adjustments, acquisitions, and scientific decisions are still performed by man in situ, a somewhat higher degree of equipment automation is desirable in the shuttle to reduce the crew's workload and training time.

Experience aboard the CV-990 has shown, however, that the scientists' and technicians' time onboard is spent primarily in real-time redirection of their experiment, and relatively little in routine operation and maintenance. Typically, when the scientific conditions encountered are approximately as expected, most of the passengers are idle while a few scientists keep an eye on data readouts and displays. Only in highly dynamic situations, such as auroral or meteorological studies, is the crew continuously busy. The key function of the scientist onboard is to make real-time decisions with full knowledge of circumstances, and not so much to operate equipment.

The reduced number of attendants per experiment thus does not require great increases in automation though some increase is unquestionably desirable. We assume a factor of two in the cost of the hardware for this slight increase in degree of automation.

Summary. The foregoing has identified a possible increase of about 4.8 in scientific experiment hardware cost for a shuttle sortie mode as compared to a CV-990 expedition, or about $300/kg (w/o people). This value is felt to be the lower bound of payload costs for the shuttle, in the sortie mode, and considerably less than minimum spacecraft costs for unmanned spacecraft of the future even if such vehicles are deployed from the shuttle.
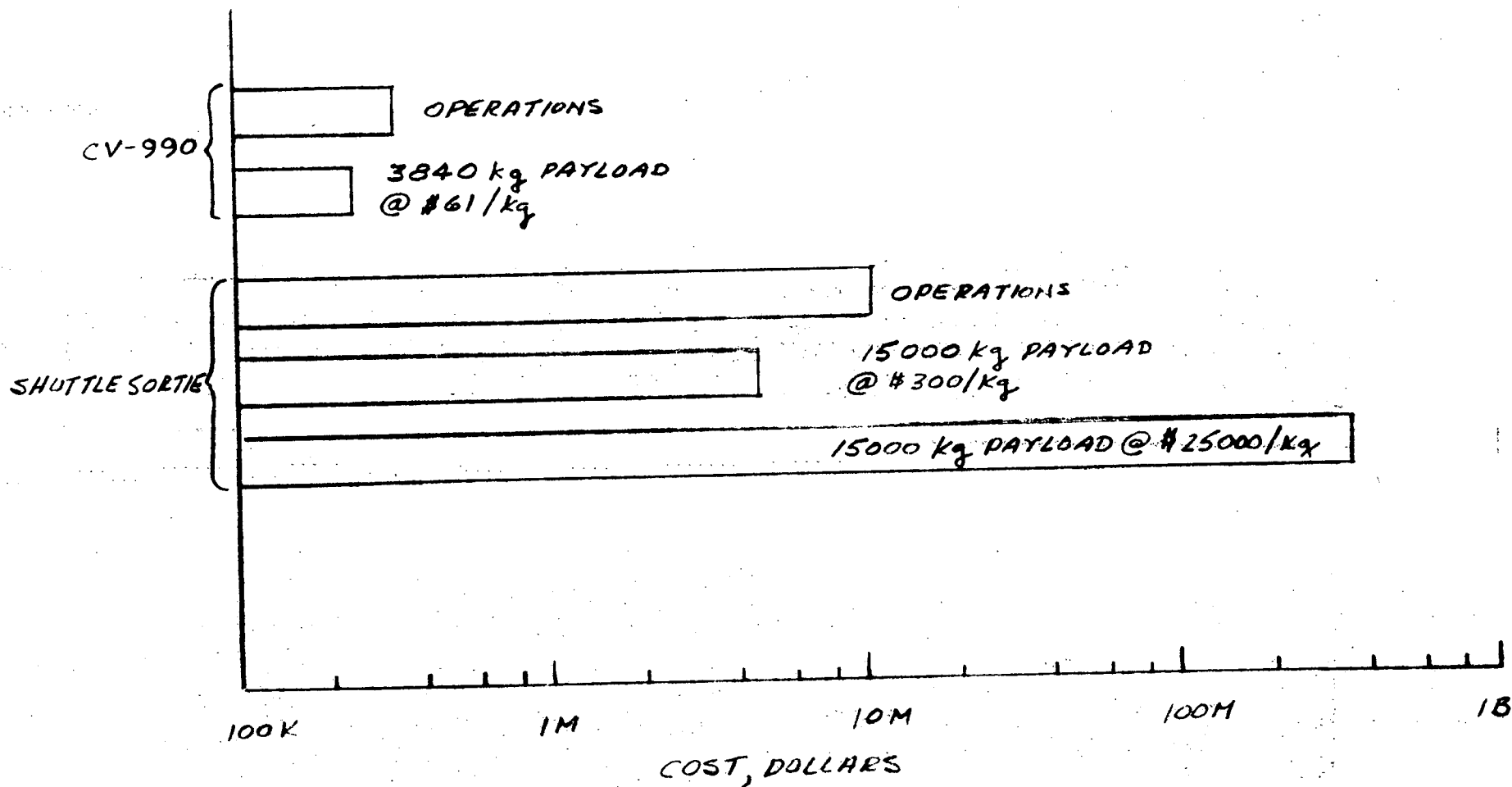
Based on a $10 million operations cost per shuttle mission and assuming a payload weight of about 15,000 kg (degraded by a factor of two from the nominal payload to account for sortie mode passenger support and higher energy orbits), the aircraft/shuttle cost comparisons can be shown as in Figure 2-4. Note that the ratio of operations-to-payload costs for the shuttle approximate those of the CV-990. Also shown for comparison is the payload cost if these costs cannot be reduced below current values of, typically, $25,000/kg for manned mission (see Figure 2-3).

Aircraft/Spacecraft Payload Cost Comparison

In this discussion, a historical example is given that illustrates the differences in cost between payloads carried aboard aircraft, manned spacecraft, and unmanned spacecraft. The comparison concerns spectrometers flown aboard the CV-990 aircraft, the Mariner spacecraft and Apollo 17. Dr. William Fastie of the Applied Physics Laboratory of Johns Hopkins University has been a Principal Investigator in each of these projects and provided, on an informal basis, the material that follows. His rather extensive background makes it possible to assess some of the cost implications of various management techniques, quality assurance criteria, relaxed weight and volume constraints, etc., and by inference to shed further light on payload cost reductions that the shuttle may afford.

CV-990

First, concerning the cost of the spectrometer flown during one of the CV-990 missions: The hardware itself cost $10,000; calibration of the final instrument and evaluation of the optics cost $20,000; an additional $15,000 was required to mount the instrument in the aircraft; $12,000 was required for a tape recorder; a total of $8,000 was spent to purchase two pen-and-ink recorders; and an additional $10,000 was needed to install the instrument control panel. Finally, $25,000 was required for aircraft operations-related costs, resulting in a total cost for this spectrometer experiment aboard the CV-990 aircraft of $100,000.

FIG 2-4

AIRCRAFT & SHUTTLE SORTIE PAYLOAD COSTS

CV-990 {

OPERATIONS

3840 kg PAYLOAD @ $61/kg

SHUTTLE SORTIE {

OPERATIONS

15000 kg PAYLOAD @ $300/kg

15000 kg PAYLOAD @ $25000/kg

100K   1M   10M   100M   1B

COST, DOLLARS

Apollo 17

Turning now to manned spacecraft operations, essentially the same instrument, weighing 16 kg, was flown aboard Apollo 17. The cost breakdown for this experiment is as follows:

Building of hardware	$ .5 M
Calibration of the final instrument and evaluation of the optics	.5 M
Services of Principal Investigator. (This included meetings, making plans, travel, and also included the expenses of six co-experimenters.)	.25 M
Payload check-out & installation at KSC	.25 M
Paperwork at Applied Physics Lab	.5 M
Test program. (This included shake tables, shock testing, thermal testing, etc., and included the inspection required during the test programs, and assembly of the test vehicle.)	1.5 M
Total	$ 3.5 M

It should also be pointed out that, whereas in the CV-990 program one instrument was required, four instruments were required for Apollo 17, including one prototype unit, one qualification unit (which was tested to a degree that exceeded the anticipated flight environment) and, finally, two flight units.

The total cost of $3.5 million, however, was not viewed by Dr. Fastie as being totally unreasonable because, as he pointed out, with the great deal of testing, inspection, and overall attention to details by the project management, he, as well as other principal investigators, are as certain as humanly possible that when their experiment flies aboard Apollo it:

a. Will produce the scientific data that they wish to obtain,
b. Will cause no danger to the mission as a whole and in particular, to the astronauts.

Mariner

With regard to the Mariner program, the cost for a similar experiment was about one-half of that associated with Apollo 17, or about $1.75 million. Much of the cost reduction was brought about because it was not necessary to man-rate the system. (Sharp edges were allowed, high voltages were allowed, etc.).

Conclusions

It must be emphasized that the experiment costs just discussed have not been formally documented by the Principal Investigator and are only his personal recollections. Nevertheless, they are not without merit and indicate that aircraft-type operations can result in cost reductions by a factor of 15-30 compared to spacecraft operations. Applying the factor of 30 for manned mission payloads to a payload that weighs, for example, 5,000 kg (currently costing about $25,000/kg, from Figure 1-1), we may speculate here that the shuttle sortie mode payloads might cost in the neighborhood of $1,000/kg. This is in contrast with the earlier estimate of $300/kg.

3. LOW COST SPACE PROGRAM POTENTIALS

The relatively high cost of accomplishing space missions has been
blamed on many separate factors, and many novel solutions have been
proposed. Yet, space missions are so complex that only twenty years
ago it was not certainly known whether space missions could be accom-
plished at _any_ price. Therefore, it may not be surprising that pro-
posals for lowering costs by dramatically changing our way of implementing
space missions have only been cautiously adopted if at all. But the
completion of the Apollo program and particularly the inauguration of
the space transportation system or "shuttle" represents a new phase in
the exploration and exploitation of space and therefore an ideal oppor-
tunity to re-examine all the old concepts for reducing costs by modify-
ing management philosophy, design approaches, operational procedures,
etc.

The matrix of Table 3-1 displays frequently mentioned cost improve-
ment areas and potential solutions. Each potential solution impacts
one or more areas of potential improvement, and not all of the impacts
are positive. A solution to one specific cost problem may trigger a
cost rise in other areas, perhaps even eliminating the anticipated
savings. For example, excessive management data requirements have been
frequently cited as a major factor in high space program costs. Pro-
posed reductions in the amount of detailed review by the contracting
agency could conceivably reduce this cost. But, among other things,
this detailed review is a key source of information for planning and
estimating new programs, and eliminating it might greatly reduce the
capacity to make accurate program estimates and to perform reliable
planning. Since inaccurate early estimating is a major cause of pro-
grams getting into budget and other difficulties, and ultimately being
terminated at great cost to the Nation, it is possible that the second
order effect of reducing the detailed overview of programs would be
to increase costs rather than to decrease them.

Table 3-1

Areas for Potential Improvement and Potential Solutions

		Potential Solutions							
		Risk		Management		Performance			Con-straints
Areas for Potential Improvement		Refurbishment & Upgrading	Reliability Optimization	Relaxing Documentation Rqmts.	Aircraft Type Contracting Reporting & Ops	Standard Modular Subsystems	Standard Spacecraft	Cluster Spacecraft	Big Dumb Design Approach
Risk	Obsolescence or Failure Requiring Total Replacement	X		X	X	X	X	X	
	Estimating			X	X				
Management	Interface Management	X			X	X	X	X	X
	Program Changes	X			X				
	Data Requirements	X	X	X	X				
	Specifications & Contracting	X		X	X	X			
Performance	Emphasis on Performance, Not Cost	X				X			X
	Technology Forcing	X	X			X	X	X	X
	Handcrafting					X	X	X	X
	Concept Selection	X	X		X	X	X	X	X
Con-straints	Weight & Volume	X			X	X	X	X	X
	Launch Environment				X	X	X	X	X

Whether the total costs become higher or lower due to a specific change can ultimately only be settled by actually making the procedural change and observing the result, and even the results will be open to debate. The space program has been highly successful using approaches that have evolved to do a very complex job. The praiseworthy efforts to obtain the same successes at lower cost by changing these procedures will probably also have to follow an evolutionary or incremental approach so that the prime benefits of the traditional approach are not lost and the secondary harmful effects of major changes in approach are avoided.

Areas for Potential Improvement

Most areas for potential cost improvement involve new management approaches in one way or another. Management itself may only amount to a few percent of the man-hours in a program, but the management philosophy, the program approach taken by management, the management attitude toward risk-taking, etc., undoubtedly strongly affect the ultimate cost of a program. Management is the art of steering a complex technological organization through the intricate steps of designing, building, flying, and evaluating a system using available subsystem technologies to provide a high level of performance, within weight and volume constraints, on an optimal schedule, within a limited budget, with the minimum possible risk. Nearly all the specific reasons that have been given in the literature for the high cost of space programs can be traced at least indirectly to the complex task of balancing these factors.

To categorize the various areas of potential cost improvement, we recall that the basic aim of space system management is to achieve an acceptable level of performance within a given set of constraints with an acceptable degree of risk. Thus, the subsections are divided into categories of risk, management, performance and design, and constraints. In summary, the risk may now be reduced using, in particular, the new options available as the result of the shuttle; space management

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techniques are now sufficiently mature that certain simplifications may now be possible; extreme emphasis on performance per se should probably be reduced; and advantage should be taken of relaxed program constraints, particularly possible through the shuttle. By focusing on the potential areas for improvement, it is hoped to elucidate and to justify the potential solutions to be presented in the next section.

Risk

The desire to reduce program risk results in a heavy reliance on the development of highly reliable components, highly redundant designs, repetitive testing and qualification procedures, intricate and restrictive specifications, massive requirements for data submission and reporting, and large scale duplication or parallelism of development tasks. The need to continually advance performance requirements leads to the forcing of technology state-of-the-art and to a heavy emphasis on performance that frequently leads to low cost techniques being relegated to second place or worse. The professional rewards are highly weighted toward program success rather than low cost so it is not surprising to have a program manager try to decrease the risk of program failure even at the expense of incurring an overrun situation.

The need to keep the flight item within weight and volume constraints leads to complex interfacing procedures that may require much coordination and many iterations in the course of the program which, in turn, makes it difficult to keep to schedule without resorting to premium time and leads to the temptation to compromise performance objectives or to make program changes which are inevitably extremely expensive from a cost effectiveness standpoint.

Nearly every element of high cost is directly or indirectly related to the concept of risk. No program manager is willing to accept the risk of total program failure if there is any kind of component redundancy, duplication of development tasks, additional testing, redesign, or additional data requirement that can help reduce the risk or at least increase understanding of it. Any proposed concept for cost reduction must adapt to this fact.

Two areas of potential cost improvement that are particularly related to risk are opportunities for reducing total program risk through refurbishment and repair and improvement of risk decisions through better estimating.

Obsolescence or Failure Requiring Total Replacement. Currently the only remedy for an obsolete spacecraft system is to design and launch a totally new replacement system. In many cases, relatively minor changes would permit reinstatement or updating of the system, particularly if the system was initially designed to facilitate refurbishment. The advent of the shuttle should permit gradually phasing into a concept of incremental upgrading of spacecraft. Thus, the risk associated with spacecraft failure should no longer be so closely associated with the risk of program failure. This relaxation should permit economies at each step in a program where extreme measures are now taken to prevent all failures.

Hopefully, the future ability to retrieve, repair, and refurbish spacecraft from orbit and to flight test modular subsystems individually before final assembly will help reduce the risk of total program failure, so that many of the extreme, costly measures currently taken to reduce program risk may be relaxed and the costs may be reduced correspondingly.

Estimating. In all the above discussion, it is plain that there is probably an optimal amount of risk to accept, an optimal schedule to work to, an optimal level of performance to attempt, and so forth. The making of the corresponding decisions is highly complex and depends upon the most accurate estimating of resource levels, development requirements, completion times for tasks, reliabilities, etc., that is possible. One source of high cost is, therefore, inaccurate estimating. If inaccurate estimating leads to a serious revision of the program schedule, for example, it may lead to the high cost of crash program activities or of program stretchout with its associated de-learning, skyrocketing overhead costs, inflation, and interest charges.

Management

Within the risk environment described above, management must design and assemble a complex program organization to attack an equally complex set of program tasks. To do this in a low cost manner is a goal that is not always achieved. Some of the sources of cost are interface management, program changes, data requirements, and specifications and contracting.

Interface Management. To manage a space program at all, it is necessary to structure an organization divided into sections roughly corresponding to the subsystem breakdown of the spacecraft system itself, to permit progress in each area to be carried out semi-autonomously, to assign responsibility, and to achieve accountability for failures, slippages, overruns, etc. The larger and more complex the program, the more semi-autonomous organizational elements there will be. Since spacecraft must work as a system, all of the separate functions assigned to the semi-autonomous organizations must interface harmoniously, so there is a need for regular communications between the organizations. Unfortunately, the number of such interface contacts increases as the square of the number of organizational elements.* Therefore, an increasingly large fraction of the effort in a large program organization tends to be related to the large number of interface meetings and communications that must be accommodated. Because larger programs may additionally involve considerable geographical dispersion of the organizational elements, this frequent interfacing can become rather formal, time consuming, and expensive. The solutions are easier to state than to achieve and involve trying for simplicity of design whenever possible, making the subsystems as separable or modular as possible, and doing everything possible to facilitate informal types of interfacing arrangements, to locate interfacing organizational elements in near proximity, etc.

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* The number of contacts between n organizations is given by contacts = $n(n-1)/2$, which for large n is nearly proportional to n^2.

Program Changes. Program changes are a major source of high cost. A typical example would be the program that is planned for a cost of $50 million RDT&E and ten flights at $5 million each. The total cost per flight is then $10 million. For any of a variety of causes, the RDT&E cost may escalate and the only way to stay within budget is to eliminate, say, five flights. Even though the total cost may have been kept to $100 million, the cost per flight is now $20 million, or double the original price per unit of effectiveness. Program changes that result in stretching out a program may be particularly costly since many charges such as sustaining engineering must be paid throughout the life of a program regardless of the launch rate and increase directly in proportion to the program duration. The initial buy usually puts the supplier in a highly advantageous position regarding later additional procurements so that a program change leading to unexpected additional procurements will frequently result in a higher cost for the additional items because the negotiating position is shifted unfavorably.

Data Requirements. The amount of information required to perform all the management, coordination, design, testing, etc., in a space program is staggering. A recent issue, Ref. 14, of the MSF Document Index, for example, listed 1,241 pages of documents with about fifteen documents per page, or about 18,500 documents. Yet, it is proposed as a challenge to the reader to try to identify any substantial number of specific reports that could be eliminated without adversely affecting the program in some way. The high cost of data is not so much in the visible cost of producing the report as it is in the indirect cost in man-hours required to read the reports, particularly those that must be acted upon.* Simplifications probably can be obtained in the future by the more extensive use of semiautomated management information systems, and in spite of their problems such approaches are worth attention. But as long as programs involve myriad complex interactions which

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* McDonnell Douglas, in Ref. 15, page 7-17, states, for example, ". . . the cost of a formal approval type of document would approach 30 percent over that of an identical information-only type document."

affect the overall program risk, and as long as risk is something to be avoided "at all cost," data requirements are likely to remain a contributor to the high cost of space programs.

Specifications and Contracting. Overly tight or unrealistic specifications and multiple overlays of contractual requirements are often mentioned as a reason for high cost space programs. Because a single organization cannot accomplish a large scale, complex space program, thousands of contracts and subcontracts must be written for the many organizations who must be involved. The parties to the contracts may wish to simplify contractual obligations or to accommodate each other in making changes that become desirable as the program progresses, but webs of legalities make changes or accommodations time-consuming, expensive, and troublesome. The systems criterion is "functional," that is, whether the component works in the system; but the legal criterion is "descriptive," that is, whether it outwardly conforms to specifications. Frequently, legal liability is shifted by making specifications overly detailed. This common practice decreases the flexibility of the supplier to strive for low cost design within a less restrictive set of functional specifications. Instead of describing the function the item must perform and allowing the supplier some latitude in the specific manner of accomplishing it, too often specifications describe in the most minute detail the physical characteristics the item must have. One common claim is that if the specifications were not so overly detailed, an off-the-shelf item might be supplied at very low cost, but because of slight variances in the detail of the specification an entirely new "gold-plated" item must be developed from scratch at great expense.

Performance and Design

Performance has been generally treated as an unmitigated good in space systems. In the past, this was certainly a useful point of view, and the attitude has certainly contributed toward the continual advance of space technology and the excellence of the resulting individual programs. The same attitude toward low cost space program techniques can

undoubtedly result in equally successful but much lower cost programs in the future if all of the new opportunities for cost reduction, in particular the shuttle, are fully exploited.

The topics of this section related to performance are the areas of cost improvement resulting from excessive emphasis on performance instead of low cost design, the "forcing" of technological advance, the "handcrafting" approach to spacecraft design and construction, and the opportunities for low cost design available particularly during the concept selection process.

Emphasis on Performance, Not Cost. The aerospace industry evolved in an atmosphere in which the primary emphasis was on accomplishing the mission at all rather than at specific price; the entire training and career development of the aerospace engineer emphasize technological advancement rather than economy. Therefore, the endless search for improved performance is a theme that has permeated space programs and works strongly against attempts to emphasize low cost design. For these reasons, it is probably unrealistic to expect to immediately achieve program structures and design techniques that emphasize low cost rather than performance. Even a concerted effort may lead only to an evolutionary change in this attitude since the high-performance approach is a way of life in the industry.

This emphasis on low cost, rather than high performance exclusively, should be made particularly in the early phases of the system, such as during concept selection. Each decision made in a program decreases the scope for further cost reduction of later decisions, and if the initially-selected concept is not inherently suited to low cost implementation, only marginal cost improvements may be made in subsequent program phases in spite of the best intentions.

Technology Forcing. Technology forcing is another well-known factor in high cost. The cost overrun factor of a series of programs studied by the Rand Corporation was shown to be, among other things, a function of the degree of technology advancement exhibited by the program. Although programs that involve little technology advancement are

the cheapest, it does not directly follow that a low cost space program
would include only such projects. Each program produces a legacy of
technology that permits the cost of succeeding programs to be reduced
(for fixed performance) or that otherwise improves their cost effective-
ness. A balance must be struck in which a program induces technological
advancement but does not attempt so much advancement that the program
is jeopardized either by exceeding budget limits or increasing the risk
of not achieving program objectives.

Handcrafting. Related to the problem of causing gold-plating by
tight specifications is the fact that spacecraft are now essentially
handcrafted on an item-by-item basis. Spacecraft, like any other manu-
factured items, could benefit from mass production techniques, but with
the exception of certain programs such as Agena-based defense systems,
little advantage has been taken of cost savings from larger production
runs. In the well-known learning curve effect, the second spacecraft
may cost only 90 percent of the first, the fourth only 81 percent of
the first, the eighth only 73 percent of the first, and so forth. A
much more significant factor is the opportunity to amortize the initial
fixed costs over a larger number of flights. Generally, of course, this
would not apply to planetary programs* in which only a few vehicles
with a given sophistication of instrumentation are required, but it
might become an important consideration in earth orbital programs,
particularly if obsolescence could be avoided by later returning the
spacecraft to earth for updating with more advanced instruments or
support subsystems and then returning it to orbit, as would be possible
by using the shuttle.

Concept Selection. Very little can be done to reduce the cost of
a program in its latter stages if an inherently costly concept has been
chosen during the concept selection stages. Although it is here that

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* The exception would occur if it turned out to be possible to extend
the concept of the standard spacecraft, to be discussed later, to
planetary spacecraft. This concept, unfortunately, has not yet been
examined.

the greatest cost reductions may be obtained, it is unfortunately also at this stage that the least certain knowledge exists about the characteristics of the low cost systems under consideration. Frequently, the critical piece of knowledge that could be used to select the lowest cost system is some "soft" or nontechnological variable such as user requirements, or demand, or some uncertain factor such as a valid traffic model. For example, one of the ways a low cost program could be realized is to spend money during the RDT&E phase to find ways to reduce the unit cost of an item or to increase its refurbishment factor. But this decision as to how much to invest in unit cost reduction can only be made correctly if the traffic model or utilization rate is known. The subsequent actual utilization may be lower than expected so that the effect of lower unit cost is diminished and the additional effort at cost reduction is wasted. And yet, the prediction of future traffic is beset with an extreme degree of uncertainty, so that the decision to attempt this form of cost reduction must be made under extreme uncertainty. A thorough exploration and analysis of alternative systems and technologies in which the system is considered as a whole is probably the only approach in this area, even though it is at best a partial answer.

Constraints

It is a standard theorem in optimization theory that an unconstrained optimal solution is usually better than, but always at least as good as, a constrained optimal solution, and this corresponds precisely to the common-sense point of view. There are already so many constraints that can't be controlled acting upon a space program that the addition of constraints on payload weight and volume, and those posed by the launch environment usually leaves cost as the only constraint that is considered relaxable. The result is that cost tends to increase whenever a program gets into difficulty with these constraints. The main constraints to be considered in this section as potential sources of cost escalation are weight and volume and the launch environment.

Weight and Volume. The U. S. space program has evolved along the lines of smaller payload, in general, rather than the more "brute force" approach of the USSR. This has led to severe weight and volume constraints on payloads so that they can be lifted by available launch vehicles and can be fitted into existing shrouds. A mission's performance objectives may be difficult enough to achieve within a budget to begin with, and the addition of severe weight and volume constraints, on top of high performance goals, may make the mission impossible to perform at low cost (or even at any cost as in the case of the Advent Program).* Certainly, the optimal spacecraft for low cost may be many times larger and heavier than a spacecraft of the same performance designed to fit tight weight and volume constraints. Later, we show evidence that a reduction in RDT&E cost of 35-50 percent can be obtained by a design that results in a spacecraft several times heavier than the traditional design. This area offers particularly great potential in the shuttle era in which weight and volume are no longer so important.

Launch Environment. A different constraint, but of a similar type to weight and volume constraints, is that payloads must be designed to withstand a severe launch environment, including extreme vibration (as much as 158 db) and acceleration loads that may exceed 9g at burnout. A "softer" launch environment might permit a relaxation of this constraint so that certain costs such as structural testing might be somewhat reduced and payloads may be designed more cheaply. Elaborate design and rigorous testing are required to ensure that the payload will survive the launch. Since nearly one out of four spacecraft failures now occur at or immediately after launch, and nearly one out of two within the first 100 hours, one can appreciate the severity of the present launch environment. The economies that may be possible by reducing the severity of the launch environment are not so clear. Pinpointing such savings is difficult and they would be unlikely to represent more than about 4 or 5 percent of R&D. In the future, if an environment much better than the 145 db acoustic and 3g acceleration of the shuttle can be achieved, then it may be possible to exploit this particular cost savings potential.

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* There is general agreement that the main reason for cancelling the Advent Program was that its ambitious program objectives made it impossible to get the spacecraft weight and volume within the constraints of the Centaur vehicle.

Potential Solutions

Just as the various areas of potential cost improvement are interrelated, the potential solutions are also to a large extent interrelated. The implementation of one proposed solution would certainly affect the desirability of additionally implementing a second solution. No single solution appears to solve, or even impact upon, all the areas of improvement we have mentioned. Each potential solution may have an effect (positive or negative) on one or more improvement areas, as we have already pointed out. As we have also previously mentioned, any change in the present manner of performing space missions carries with it a distinct possibility of upsetting the entire apple cart, and yet only relatively radical changes in the present manner of doing things will have much chance of dramatically reducing the present cost of doing space business. This section does not recommend any of the specific solutions proposed. It merely tries to bring together a variety of proposals that have been made over the years so that we may discuss their impact on the problems we have mentioned, their relation to each other, their apparent advantages and disadvantages, and their probable overall effect on the cost of future systems.

This subsection is divided into risk, management, performance and design, and constraints, just as was the corresponding subsection on potential areas of improvement. Methods of risk reduction discussed include refurbishment, upgrading, and reliability optimization. The specific changes in techniques of management include relaxing documentation and shifting from the rigorous contracting and documentation procedures of space to the less detailed aircraft type procedures. A series of performance and design approaches is described, including standard subsystems, standard spacecraft, and cluster spacecraft. Regarding constraints, the combined techniques for designing in a relaxed constraint environment, called collectively the "big dumb" design approach, are finally discussed.

Risk

In the subsection devoted to causes of high cost, risk was seen
to be an important factor. The capability of the shuttle should per-
mit the reduction of risk in general with all the varieties of cost
reduction throughout the program that this implies, and in addition,
may permit reductions in cost through refurbishment and upgrading and
through the selection of optimal mean mission durations that will re-
sult in less expenditures on reliability attainment.

Refurbishment and Upgrading. Figure 3-1 shows the percentage of
failures occurring at various times during space missions (Ref. 16).
It has been proposed that the Space Shuttle could provide pre-placement
checkout of payloads. Thus, the 26 percent failures occurring immedi-
ately at launch could be detected, the payload returned and repaired,
and the satellite re-orbited. In some cases, conceivably the fault
could be immediately corrected without returning the payload. If, in
addition, the capability for immediate post-placement recovery and
repair is considered, an additional 20 percent of payloads might be
salvaged. The remaining failures can be similarly handled by an
optimally scheduled maintenance flight or a nonscheduled flight occur-
ring when failure is detected. On the scheduled revisit approach, even
though failure may not have occurred at the time of revisit, it will
probably be desirable to replace modules that theory and/or testing
indicate should be approaching their wear-out or failure time.

As spacecraft subsystem technology continues to advance, a space-
craft, particularly if it has been designed for very long life to
achieve economies, becomes out of date before it wears out. Therefore,
even though it is not as closely related to low cost as the other
factors discussed here, it should be mentioned that the same philosophy
that applies to refurbishment applies to the upgrading of obsolete
components or subsystems of spacecraft. When the subsystem becomes
obsolete, it is returned and replaced with another upgraded module
having the same interface characteristics. In the case of extensive
modifications, it may be desirable to return the entire spacecraft for
upgrading.

CUMULATIVE
PERCENTAGE
FAILURES
VS
MISSION
DURATION

FIG. 3-1

MISSION DURATION ~ HOURS

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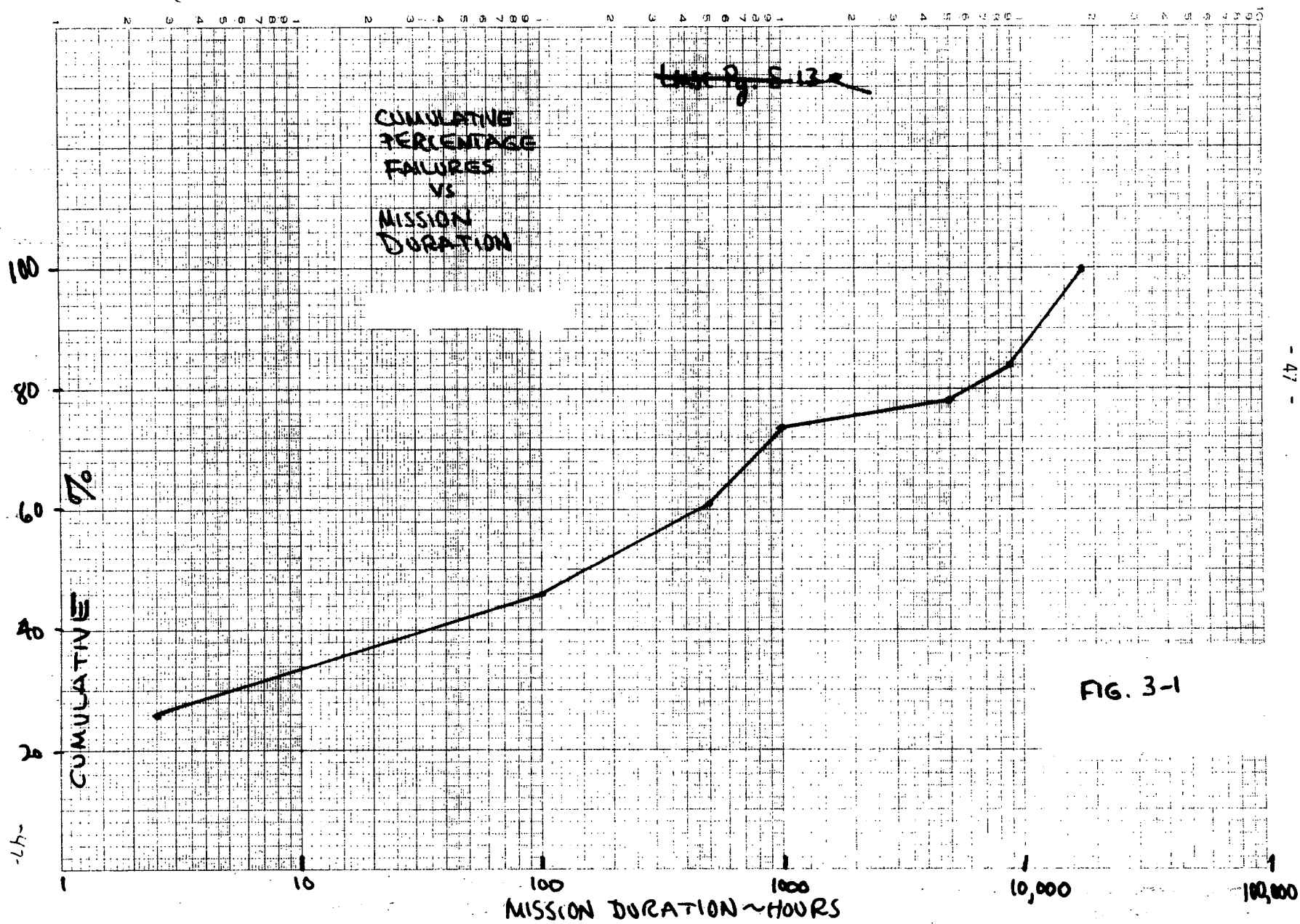
Reliability Optimization. Some of the problems of reliability have already been discussed when we were discussing the relationship between high cost and risk reduction. When it becomes possible to visit and revisit spacecraft, to return them for repair, to relax the constraints on high density packaging, etc., as will be possible by the use of the shuttle, many of the previous risk avoidance patterns will change. Rather, the problem will be one of fully exploiting the new reliability environment in spite of a long history of doing things the traditional way. The tight packaging that was previously required was a source of failure because of the workmanship required with such packaging, interaction between part failures, heating, etc. This can be relaxed with the shuttle. A spacecraft failure will rarely jeopardize an entire program since it can be retrieved and repaired unless the failure was catastrophic. Because it will be possible to revisit a spacecraft, the economical design life may be made shorter.

Figure 3-2 (Ref. 16) illustrates how cost escalates with increasing reliability in an exponential manner. Because the shuttle can retrieve payloads, it should not be necessary to design for 0.95 reliability, for example, but for something on the order of, say, 0.7 and the large savings can be applied to planned revisits and repairs of the spacecraft with considerable to spare.

Management

In discussing management sources of high space program cost, we mentioned problems ranging from the management philosophy itself to specific difficulties such as data requirements, specifications, etc. Two of the corresponding solutions discussed in this paper have to do with implementing the philosophy of management used in commercial airline operations and the relaxing of documentation requirements.

Relaxing Documentation Requirements. One source of the high cost of programs that has been mentioned is data and documentation requirements. Solutions that have been proposed include relaxing the documentation requirements, actually decreasing the total detailed overview
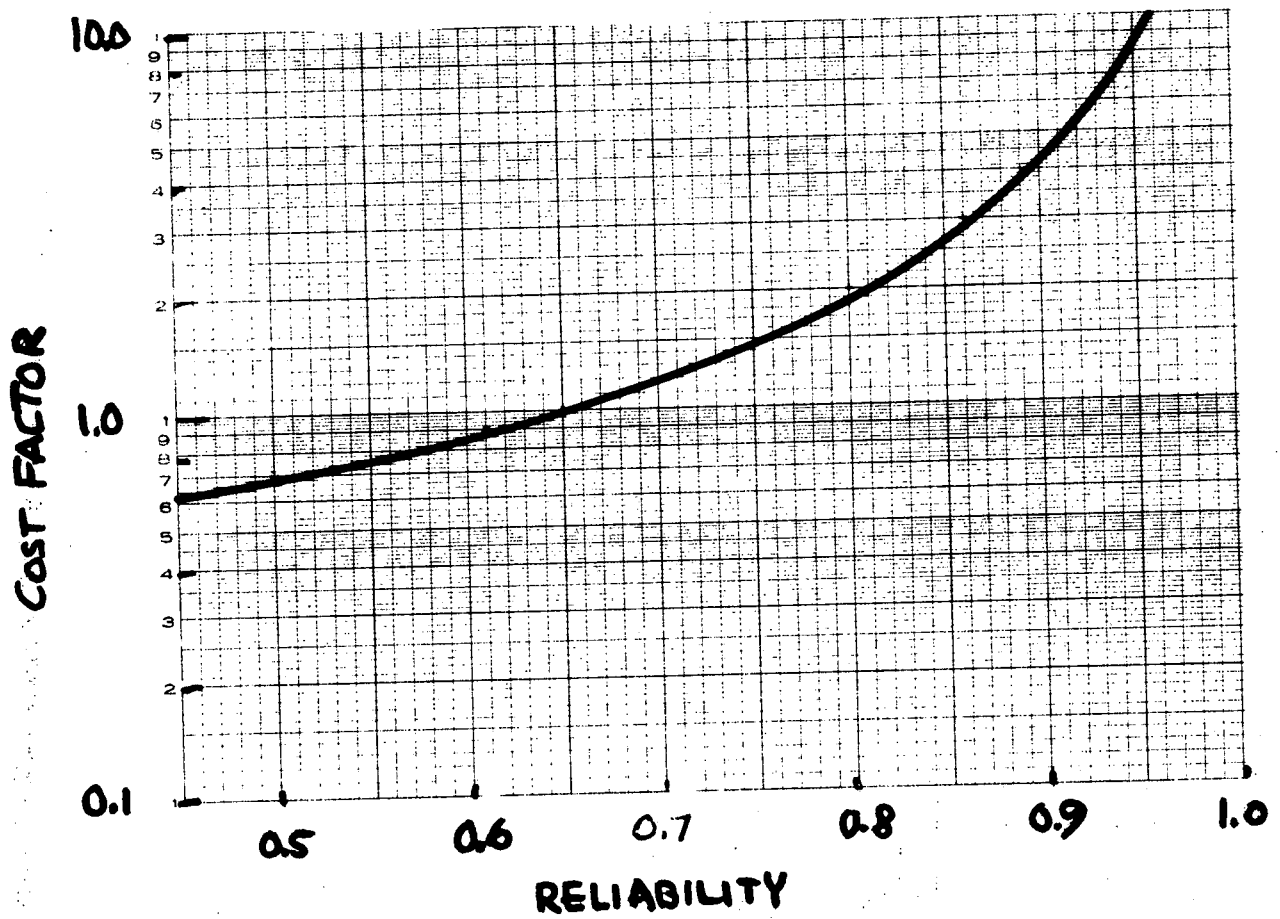
FIGURE 3-2

COST VS RELIABILITY

that the customer has of the development process, or even going completely to a concept such as is used in contracting between the airlines and the airframe industry.

In these concepts, program deletions and additions, for example, are handled informally between the supplier and purchaser (Ref. 15). Many of the reports are of an information-only nature, and nearly half of the pages reported are in satisfaction of FAA requirements, such as certification.

The number of contacts between the developer and the purchaser is reduced, thus reducing one of the major sources of data generation and transfer.

The data requirements of some of the early boosters have been in the tens of thousands of pages per year (see Figure 3-3) while the Saturn class boosters require on the order of several million pages per year for each stage. There have been proposals from industry (Ref. 15) which claim to reduce cost by reducing these documentation requirements by as much as two orders of magnitude. These proposals are based on preparing only data essential to the contractor to do the various program tasks, delivering the minimum amount of data needed by the customer to monitor the fiscal and technical aspects of the program, and keeping to an absolute minimum the data requiring customer approval. This latter category has been shown to be much more costly in terms of staff required to read and act upon the reports.

Aircraft Type Contracting, Reporting, and Operations. It should be mentioned that aircraft type operations may become possible with the advent of the shuttle and represent a promising solution to the problem of high cost. This approach has been described earlier in Section 2.

Performance and Design

The main tool available to management to achieve performance at low risk within the given system constraints is clearly the design itself. Since management is involved in the major design decisions but
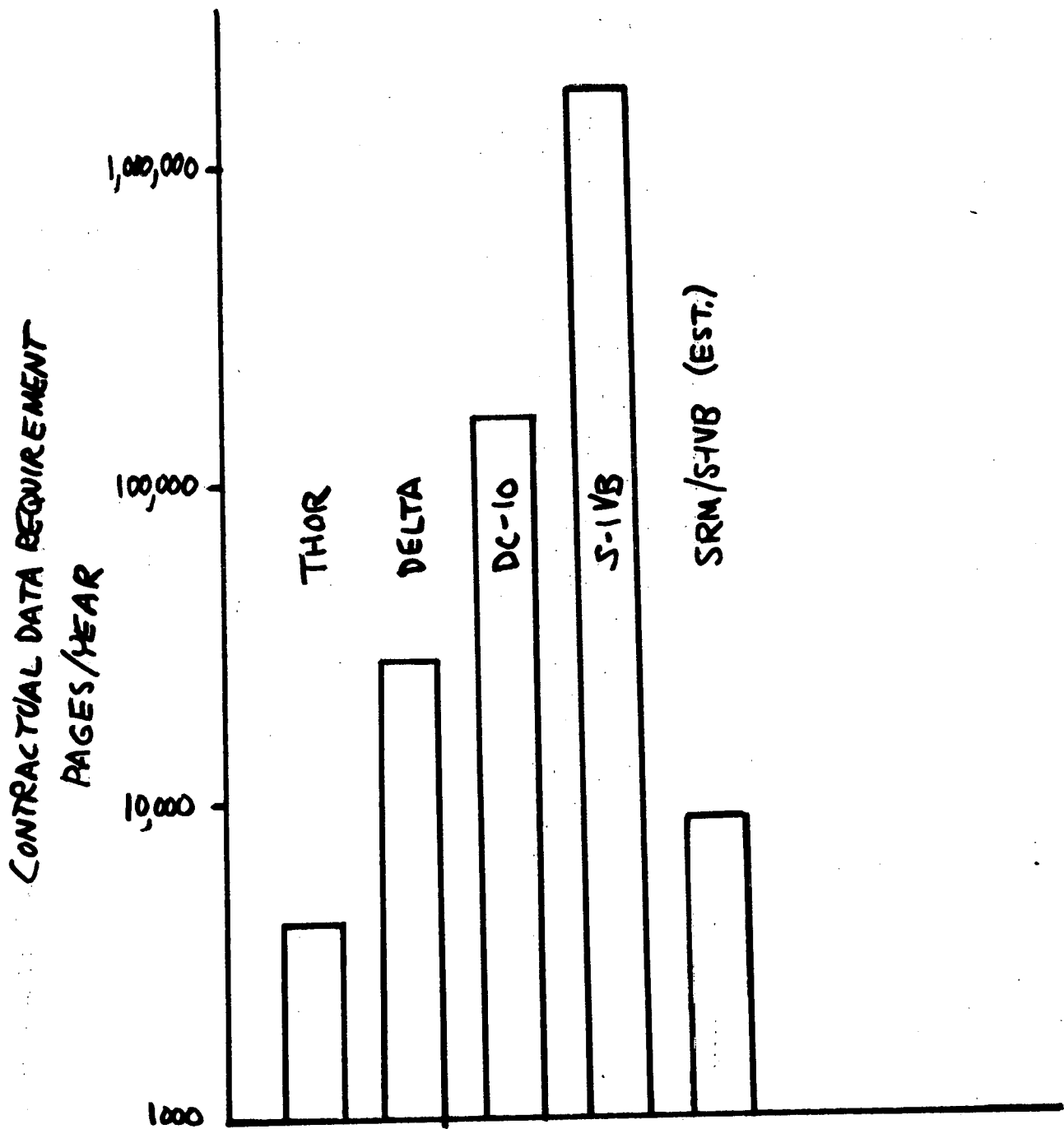
FIG 3-3
CONTRACTUAL DATA REQUIREMENTS

does not involve itself with the details of the design, it is limited by the basic design approaches and philosophies available to it. There are three approaches which are worth consideration, but which will require for their implementation an entire new philosophy of design that cuts across individual spacecraft programs to obtain its cost advantage. By their very nature, they are not available to the planner of an individual spacecraft project, but must be implemented at a broader, and higher level than the individual project. These are the standard modular subsystem, the standard spacecraft, and the cluster spacecraft, and they are discussed in the following paragraphs.

Standard Modular Subsystems. A space program involving 100 missions over a period of ten years may involve something like 1,000-2,000 individual subsystem developments. Many similarities may exist among these individual subsystems so that there is in some sense a duplication of effort involved. The Standard Modular Subsystem approach attempts to select subgroups from among this multiplicity of subsystems which can be developed as modules with applicability to more than one program. Because there are fewer developments to undertake, this permits concentrated attention on the design of these few modules for low cost. In addition, since the production runs may be larger, and there are more individual units for each fixed investment, economies of scale will also result in lower costs. Certain subsystems may not lend themselves as easily to this sort of standardized development, but such things as telemetry, command and control, electrical power, and attitude control were found in Ref. 16 to be suitable for standardized module development. Of course, even with modularization carried to the extreme, there would still be missions such as the outer planet missions whose special coding requirements, etc., for long distance communications would require special subsystem design.

Applying this concept to a 45-mission model* in the 1980's with a baseline RDT&E cost of $7 billion, Lockheed Missiles and Space Company

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* Ref. 17, Aerospace Corp., January 1972. Note that "mission" as used here means a "program" having several individual flights.

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identified a savings of $0.7 billion for the modular subsystems, or $15.6 million per mission, which extrapolates to a 91-mission model savings of $1.6 billion, or $17.6 million per mission.

There are many advantages claimed for the modular approach beyond the ones just mentioned. We have mentioned reduction in total design costs. However, it should be mentioned that the cost of designing and developing a single standard module will probably be considerably more than the development of a single mission peculiar subsystem--the savings come from the fact that new developments need not be done so many times in total.

We have mentioned specifications as a high cost item and it appears likely that the standard module approach will reduce the quantity and types of specifications required. Standardized tests may be applied on all programs using a single module; in addition, the accumulated testing time will be greater for that standard module than could be afforded on a single program. All modules of the same kind could be made in a long single production run. Besides the economies of scale already mentioned, this would permit identifying and correcting production anomalies and would take advantage of the "learning" curve effect on workmanship skills. One could also expect more homogeneity in a process having larger numbers of similar hardware items so that process anomalies and corrections will be fewer.

Logistics lead times may be reduced for standard modules versus one-of-a-kind. Batch lots of replacement parts may be ordered with resultant economies in purchase cost and inventory control. Modules may be delivered and used on a first in/first out basis rather than on a serial number basis. The use of a smaller total number of hardware items may reduce training, field maintenance, launch operations, support, and may simplify data acquisition and data reduction. It may also permit a great standardization of test equipment and facilities.

Standard Spacecraft. The concept of modularization and standardization may be carried one step further for certain missions. The

development and implementation of standard subsystems and modules may be extended by also standardizing the remaining mission-peculiar hardware such as the spaceframe, special mechanisms and devices, thermal control, and integral wiring. For example, there might be a standard earth observation spacecraft, a standard astronomical observatory spacecraft and a standard communication spacecraft. Either the standard modules satisfying the most demanding mission of the group are carried every time whether or not they are needed, or there may be standard alternate modules so that each mission to be flown has modules selected to most closely match the mission characteristics.

Table 3-2 shows the savings that were identified by LMSC in Ref. 16 for 15 low earth orbit NASA and non-NASA projected programs for 1979-1990 spacecraft programs using the standard spacecraft approach. From this chart, it can be seen that all the savings in unit costs are due to the use of standard subsystems alone and that on the order of $400 million of RDT&E savings could be obtained by using standard spacecraft in addition to standard subsystem modules. The savings are due to the fact that fewer new developments must be undertaken for a fixed number of flights. LMSC estimates that by extrapolating these results to the total 91-mission model, an additional $1 billion may be saved by using the standard spacecraft approach.

Table 3-2

Savings Due to Standard Subsystems and Spacecraft

Cost $ Billion

	Baseline Expendable Payloads	Low Cost Standard Subsystems	Low Cost Standard Spacecraft	Savings with Standard S/C
RDT&E	3.6	1.8	1.4	2.2
Unit	4.0	1.8	1.8	2.2
Operations	.5	.5	.5	--
Payload Total	8.1	4.1	3.7	4.4

Cluster Spacecraft. One of the standard approaches that is always considered for lowering costs is commonality. The cluster spacecraft is a good example of a commonality concept. The idea of commonality is to combine multiple related functions so that the cost of performing them in combination is less than the aggregate cost of performing them individually. In the case of the cluster spacecraft concept, it is observed that low earth orbit missions fall into two types of orbit: 30° inclination at 600 km and 97.4° orbit at 500 km. The principal savings for this commonality concept is that the shuttle transportation costs for placing and servicing payloads, as well as the in-orbit payload repair and refurbishment, are shared among multiple missions. The shuttle can visit a number of such experiments without maneuvering. One of the cluster spacecraft studied by LMSC, for example, combined an Astronomy explorer, OSO, and Large Space Telescope, and another combined Polar EOS, TIROS, and Polar ERS.

There is one caution that should be observed concerning commonality concepts. Each mission is best served if the spacecraft is precisely optimized for the special requirements of the mission. Attempts to exploit commonalities usually result, at some point, in compromises of mission requirements, so that not the precise requirements of the mission, but an alternate set of compromise requirements, are met. Just as, in the past, low cost design has been ignored in the pursuit of the ultimate degree of performance, so it is possible in the pursuit of the ultimate in low cost design to ignore performance to too great an extent. The exploitation of commonality is a common sense way to achieve cost reductions but it must be done cautiously and with due regard to mission effectiveness.

Table 3-3 summarizes the cost savings found by LMSC for low cost refurbishable designs, standard subsystems, standard spacecraft, and cluster concepts combined in the most optimal way for the total mission model of 91 programs. This table is based on a $10.5 million shuttle. The table starts with the expendable vehicle baseline on the first

line. The incremental effect on program cost of going through successive incremental low cost design steps is given in the following lines. The total payload savings and total program savings for each concept is given in the column following "payload cost" and the column following "program cost," respectively.

Table 3-3

Savings Due to Low Cost Design Techniques

$ Billion

	Payload Cost	Payload Saving	Total Program Cost	Total Savings
Expendable Payload (baseline)	35.8	- -	46.0	- -
Low Cost Refurbishment	23.4	12.4	36.32	9.68
Standard Subsystems	21.8	14.0	34.72	11.28
Standard Spacecraft	20.7	15.1	32.92	13.08
Cluster	20.3	15.5	31.11	14.89

Constraints

The effect on program costs of constraints such as weight, volume, etc., has already been discussed. Because of the fact that weight and volume will not be at such a premium in the shuttle era, particularly for low earth orbital spacecraft, there is an opportunity for new low cost design approaches that take advantage of the relaxed constraints. One such approach, the "big dumb" approach, is discussed here. It should be noted that this technique is not limited merely to the shuttle but would be available even for expendable systems provided that the launch costs and volume constraints were sufficiently relaxed.
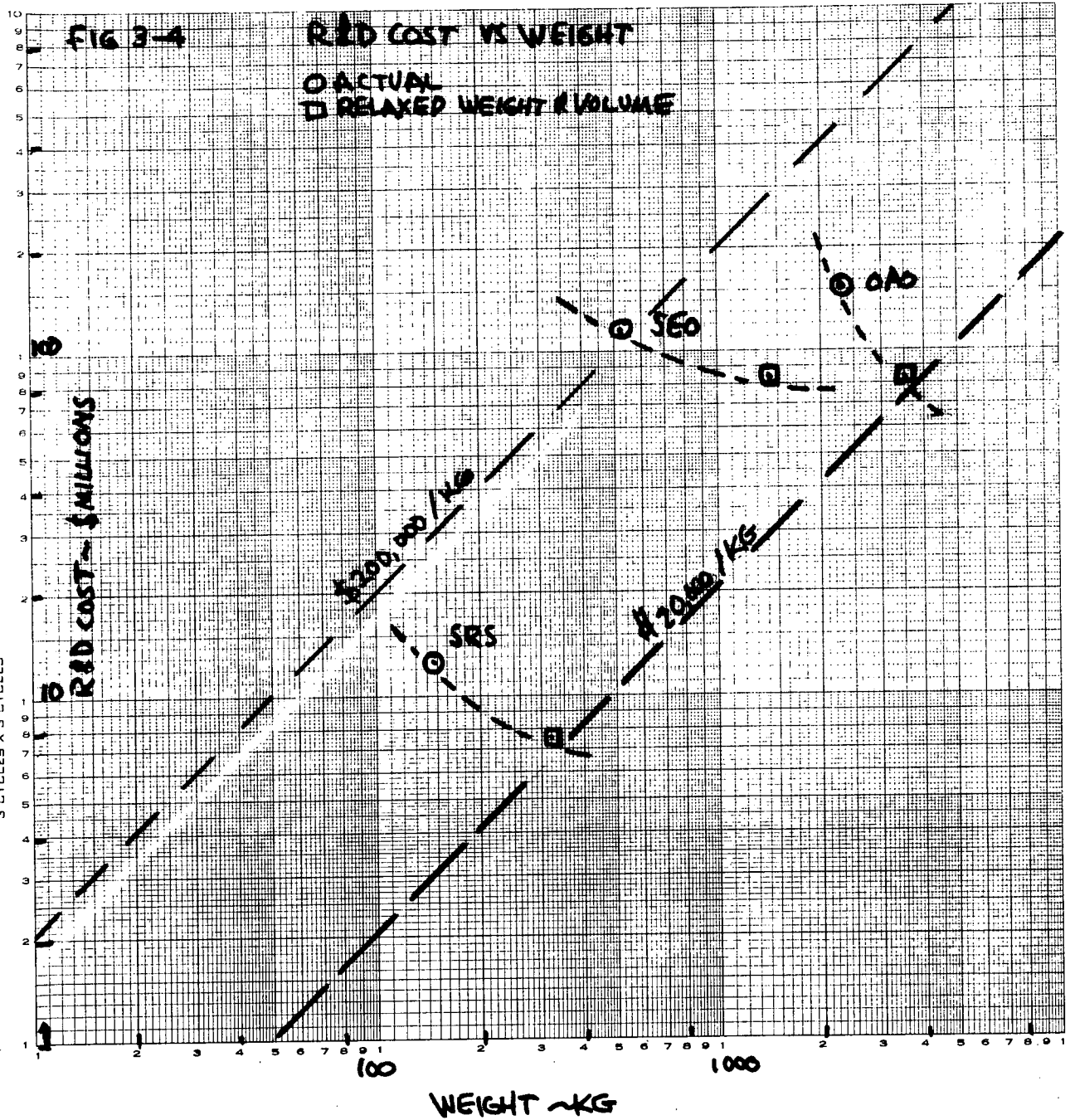
"Big Dumb" Design Approach. The effect of weight and volume constraints on increasing the cost of space programs has been mentioned. One of the proposed low cost solutions that will become possible as a
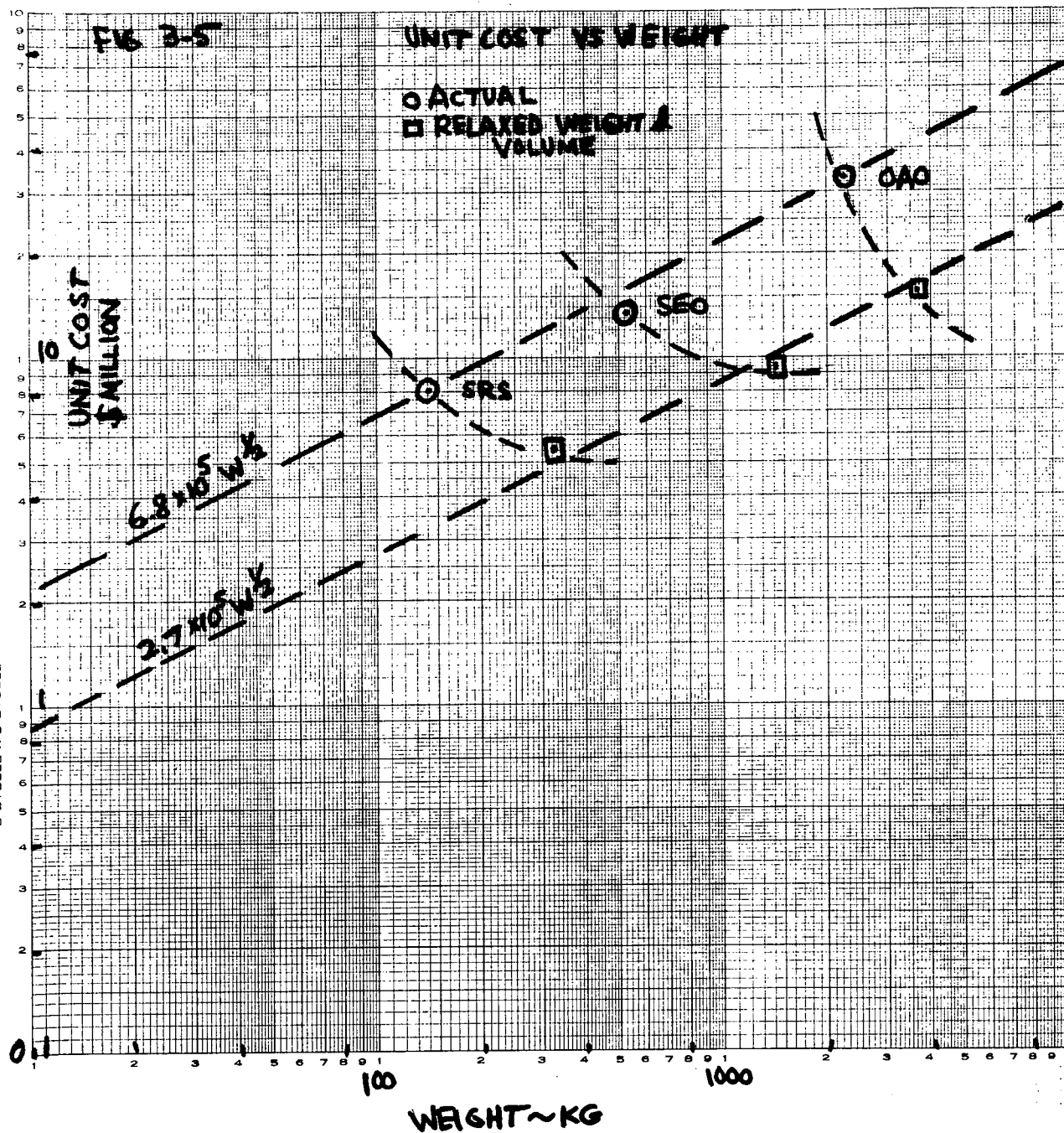
result of the shuttle is the so-called "big dumb" approach to design. In this approach, at every point where a design decision can be made based on a tradeoff between cost, weight, and volume, it is always simply decided in the way that results in the lowest cost. This approach doesn't help in all areas, such as electronics, in which the more advanced memory, circuit, etc., is sometimes lighter and smaller than the less advanced one, but in most instances relaxing the constraint on weight and volume will reduce the cost.

In their Payload Effects Study initial phase (Ref. 18), LMSC reviewed in detail the design of three typical spacecraft to determine the cost savings that might be obtained by using this approach. Figures 3-4 and 3-5 illustrate the point. Figure 3-4 shows that the RDT&E cost of the original designs was on the order of $100,000-200,000 per kg, which is in the typical range of unmanned spacecraft. By relaxing the weight and volume constraints, the reference estimates that a cost relationship on the order of $20,000-50,000 per kilogram could be achieved. However, in achieving the reduction in specific cost, it will be necessary to increase the weight considerably so that the total cost savings would be reduced to 25-50 percent.

Figure 3-5 shows a similar result for unit costs except that here the typical square root law relationship for unit costs versus weight obtains.

The various approaches to low cost design are interrelated and it is difficult to isolate their effects. For example, the "big dumb" approach is closely related to the standard modular system approach and the standard spacecraft approach. The economies of the modular approach would be much smaller if weight and volume could not be relaxed. The "big dumb" approach should probably be defined to include all techniques such as standard modules and standard spacecraft that depend on increased weight and volume for their economies.

FIG 3-4   R&D COST VS WEIGHT

○ ACTUAL
□ RELAXED WEIGHT & VOLUME

FIG 3-5

UNIT COST VS WEIGHT

○ ACTUAL
□ RELAXED WEIGHT
VOLUME

UNIT COST $ MILLION

$6.8 \times 10^5 W^{\frac{1}{2}}$

$2.7 \times 10^5 W^{\frac{1}{2}}$

○ OAO

○ SEO

○ SRS

WEIGHT ~ KG

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