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ECONOMIC ANALYSIS OF THE SPACE SHUTTLE SYSTEM

Prepared for

National Aeronautics and Space Administration

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ECONOMIC ANALYSIS OF THE SPACE SHUTTLE SYSTEM

Study directed by

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for the

National Aeronautics and Space Administration
under Contract NASW - 2081

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Volume I

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Dr. Klaus P. Heiss, Director of Advanced Technology Economics and Dr. Oskar Morgenstern, Chairman of the Board of MATHEMATICA, Inc, have been fully responsible for the overall conception, approach and implementation of the economic analysis of the Space Shuttle System.

The Space Shuttle Study Group included also the following members:

- Dr. Kan Young, who contributed Chapter 7.0 on macro and micro-economic considerations affecting the Space Shuttle System decision. The results of his work were a very important contribution to this study.
- Edward Greenblat, who contributed Chapter 8.0 and was responsible for the running of the benefit-cost evaluation programs developed by the Space Shuttle Study Group. His participation in the economic analysis effort covered all aspects of this study.
- J. Preston Layton and his technical work group who contributed Chapters 4.0 and 5.0, the technical description of satellite payloads as well as space transportation vehicles.
- Martin Wagner, who contributed Chapter 6.0 of this report on launch vehicle and payload costs and had the difficult task to reconcile the vast amount of industry and NASA data for purposes of our analysis.
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The report also benefitted from the advice and guidance of Dr. Courtland D. Perkins, a member of our Technical Advisory Group.

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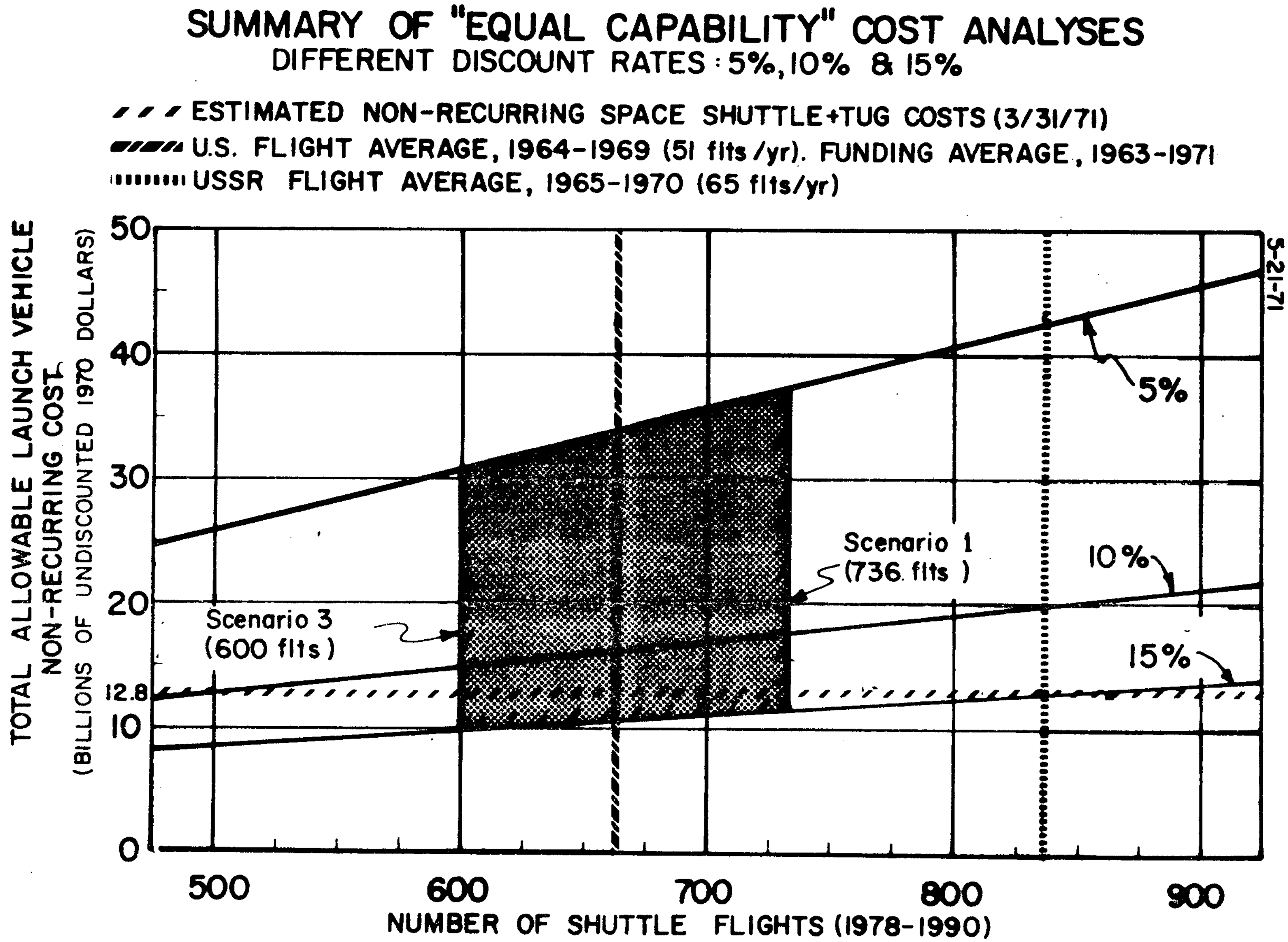

Figure 1.1
Results of May 31, 1971 Economic Study

CHAPTER 1.0

RESULTS OF THE ECONOMIC ANALYSIS

1.1 The Economic Worth of a Space Shuttle System

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SUMMARY OF "EQUAL CAPABILITY" COST ANALYSES

DIFFERENT DISCOUNT RATES: 5%, 10% & 15%

ESTIMATED NON-RECURRING SPACE SHUTTLE+TUG COSTS (3/31/71)
U.S. FLIGHT AVERAGE, 1964-1969 (51 flts/yr). FUNDING AVERAGE, 1963-1971
USSR FLIGHT AVERAGE, 1965-1970 (65 flts/yr)

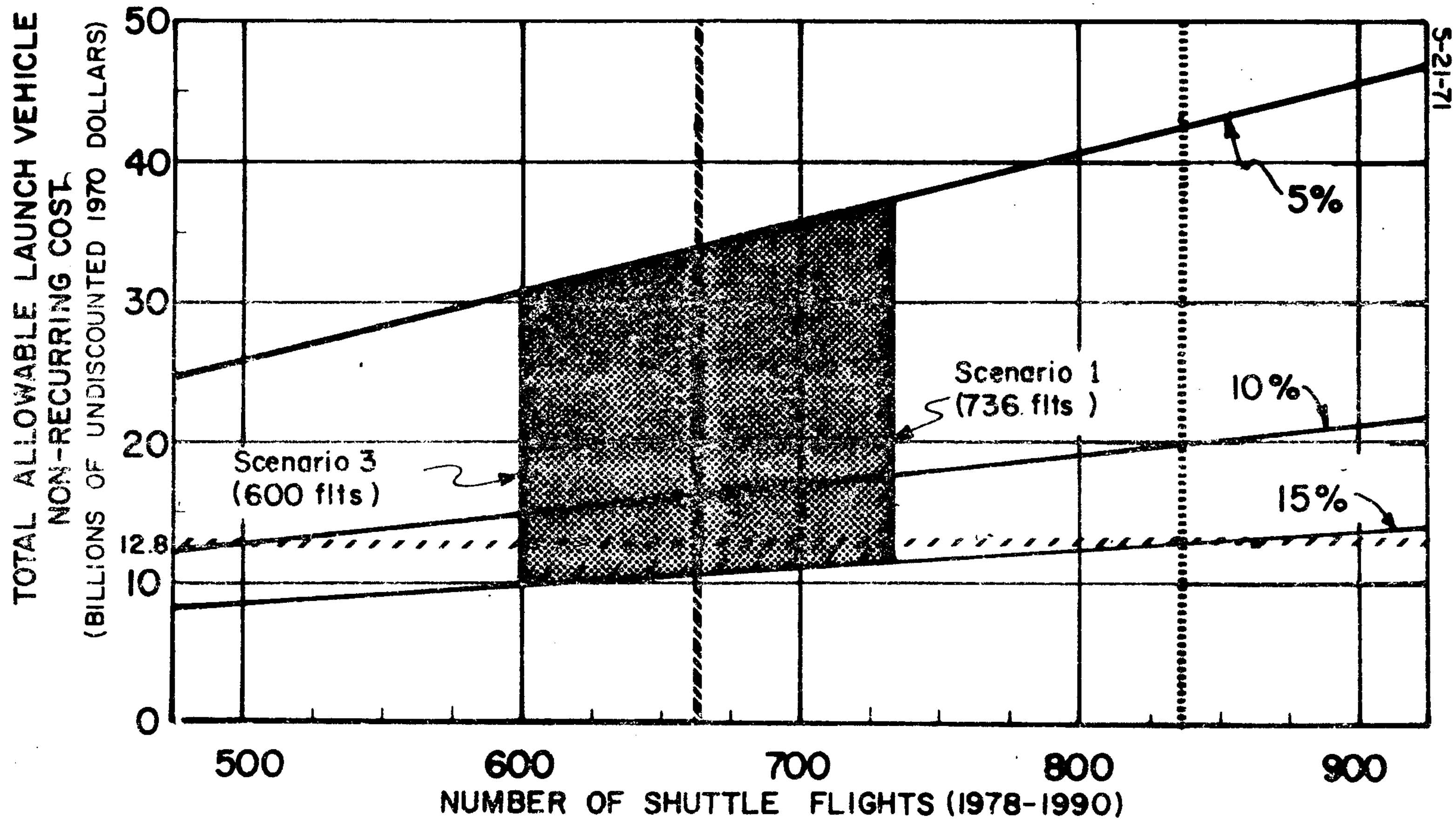


Figure 1.1
Results of May 31, 1971 Economic Study

real interest rates which do not include elements of inflation. As shown at a 10% rate of interest, the allowable non-recurring cost would vary from about $12.8 billion around 500 Space Shuttle flights in the 1980's, up to $20 billion at a flight level around 850 flights for the same period. The shaded vertical lines in Figure 1.1 show, first, the average U. S. flight level in terms of Shuttle flights between 1964 and 1969 (61 flights per year) and reflect also the funding average between the years 1963 and 1971. Also shown are the average USSR flights for the period 1965 to 1970 (65 flights per year). Furthermore, the baseline mission model of 736 flights, at that time, is shown on the right side of the darkly shaded area where the left boundary of that area is defined by a reduced mission model of around 600 flights for Space Program 3 in that analysis. Since then, we have used in our present analysis a reduced baseline mission model of 514 flights with a potential overall level of 624 space flights. Thus, in the last six months the analysis of the Space Shuttle System has been extended downwards to cover substantially the region between 450 and 600 flights. Also shown in Figure 1.1 are the then estimated non-recurring costs of $12.8 billion for a two-stage fully reusable Space Shuttle System* as well as the Space Tug and the required installations. We show the estimated economic potential of a reusable Space Transportation System in terms of allowable non-recurring costs as a function of several economic variables, among them the expected space activity level, the social rate of discount, and the type of cost-effectiveness analysis. The major findings of that effort are:

The major economic potential identified for Space Transportation Systems in the 1980's is the lowering of space program costs due to the reuse, refurbishment, and updating of satellite payloads. The fully reusable, two-stage Shuttle is the major system considered in the May 31, 1971 report, but not the only system to achieve reuse, refurbishment and updating of payloads. Payloads were assumed to be refurbished on the ground, with refur-

*The selected Space Shuttle System is no longer a two-stage fully reusable system and has substantially reduced non-recurring costs [see section 1.2].

bishment costs varying between 30% and 40%. The launch costs of the Space Shuttle and Space Tug needed to recover and place the refurbished payloads are also allowed for. We strongly recommended in May that other systems be studied to determine the extent and the cost at which they can achieve reuse, refurbishment, and updating of payloads.

The cost reductions identified originate in three distinct areas:

(a) The research, development, test and evaluation (RDT&E) phase of new payloads (satellites);

(b) The construction and operating costs of payloads (satellites) for different space missions;

(c) The cost of launching payloads into orbit.

The projected non-recurring cost associated with developing the Space Shuttle and Tug as configured in May, 1971, (a two-stage system) is shown by the economic analysis to be covered by the identified benefits provided the United States intends to operate a space program with the number of flights equal to the unmanned space program activities of the United States in the 1960's. The direct costs (payload and transportation) of space activity carried out by a Space Shuttle System are expected to be about one-half of the direct costs of the current expendable transportation system.

Manned space flight options -- for example, a manned lunar option -- are also analyzed. They show that a Space Shuttle System offers economic advantages also in terms of transportation costs for some large lunar and planetary (or defense) space flight options for the 1980's. These advantages were not considered when formulating the basic conclusions of the economic study, due to the great uncertainty of these options being adopted by the United States.

The choice of the social discount rate has a major influence on the economics of a new Space Transportation System. Differences in the rate applied to the analysis outweigh many other important issues usually raised -- and analyzed -- in the context of large scale RDT&E projects, including uncertainties in the cost data. As shown in this report, the social rate of discount influences not only the overall worth of a new Space Transportation

System, but also the choice of specific technical configurations in deciding among alternative technical approaches to bring about a reusable Space Transportation System.

The May 31, 1971 report concludes that the economic justification of a reusable Space Transportation System is not tied to the question of manned versus unmanned space flight. Space programs used and analyzed are in line with the activity and funding levels of the unmanned United States space program of the 1960's (NASA, DoD, and commercial users included). If substantial manned space flight were to be undertaken in the 1980's, a Space Shuttle System would also contribute significantly to lowering the costs of such missions and activities.

The May 31, 1971 report analyzes the economically allowable non-recurring cost of a reusable Space Transportation System. It is the task of the present report to identify the economically best reusable Space Transportation System among all the possible required alternatives.

A major point of the May 31st report is: any investment can only be justified by its goals. This applies to business as well as to government, hence also to NASA. A new, reusable Space Transportation System should only be introduced if it can be shown, conclusively, what it is to be used for and that the intended uses are meaningful to those who have to appropriate the funds, and to those from whom the funds are raised, as well as to the various government agencies that undertake space activities. The space goals can be political (rivalry with the space programs of other countries), military (to meet military space efforts of other countries who use the potential of space to meet needs of national security), scientific (for example, astronomy), or commerical (for example, earth resources applications). All these goals will, of course, be mixed into one national space program, representing to various degrees a joint demand for space transportation with a varying mix of payloads.

1.1.2 Updated Economic Results On The Economic Worth of A Space Shuttle System

Since May 31, 1971 our efforts concentrated on two major questions:

first, to what extent is the overall economic worth of a Space Shuttle System modified by new inputs given to our study; and, second, which of the many alternative Space Shuttle configurations is the most economical.

The new inputs reflect a substantially modified NASA and DoD Baseline Mission Model for the 1980's, and make a new assessment of payload effects for different missions; very importantly, new alternative Space Shuttle Systems that still promised the achievement of most of the objectives of the Space Shuttle program but at considerably reduced non-recurring costs in the 1970's, were considered.

On each of these changes a substantial set of alternative calculations was made, in keeping with the analyses and methodology already developed.

The results of the updated economic analysis are shown in the next three figures. These figures and the back-up data are described in more detail in Chapters 6 and 8 of this report. In Figure 1.2 the estimated non-recurring costs of alternative Space Shuttle Systems are shown on the horizontal axis. These non-recurring costs include the full non-recurring costs of the Space Shuttle System with at least the same capabilities as those given by the expendable Space Transportation System. Where the economic analysis of a space program indicated the continued use of expendable rockets -- e.g., Scout Rockets -- then these system costs have been included as Space Shuttle System costs. Similarly, in the time of the Space Shuttle System phase-in -- to replace expendable Space Transportation Systems -- the cost of expendable systems, as required, is also included as a Space Shuttle cost. Most important, the non-recurring costs of the Space Tug, which gives the Space Shuttle System the capability to deploy and bring back payloads from all earth orbits when economically justified, are fully included. Finally, the non-recurring costs, as used in our analysis, also include the costs of two launch sites, (ETR and WTR). It is on the basis of these non-recurring costs that the economic evaluation of the Space Shuttle System has been carried out.

The estimated non-recurring costs also include fleet investment. An estimated five Space Shuttles will be required to fulfill the NASA and DoD Baseline Mission Models for the 1980's. Fleet investment includes the orbiter procurement cost for all configurations considered,but reusable booster

SPACE SHUTTLE AND TUG

ESTIMATED TOTAL NON-RECURRING COST (BILLIONS OF 1970 DOLLARS)
RDT & E AND INVESTMENT (5 VEHICLES EACH)

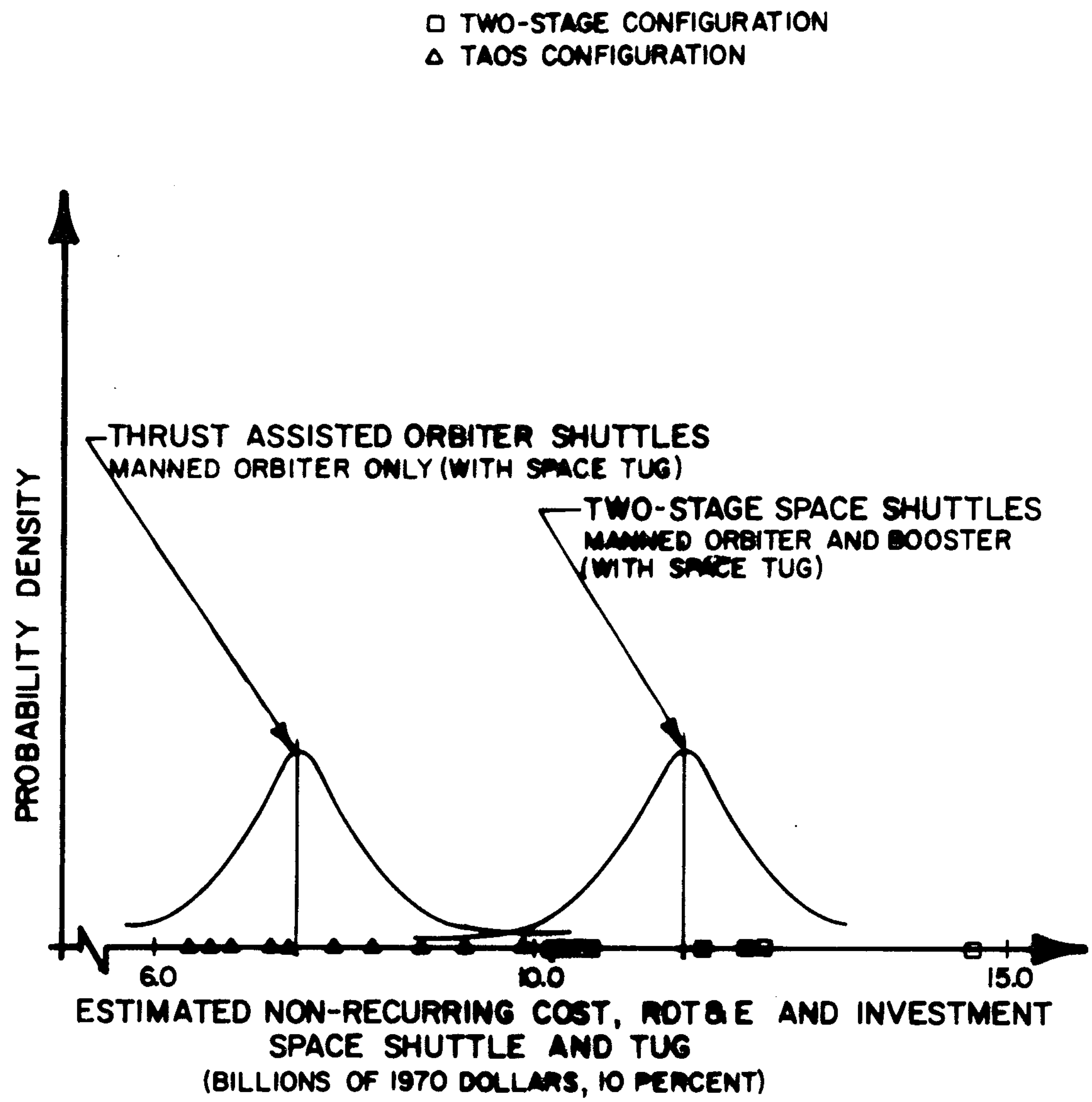


Figure 1.2

costs have been amortized as a recurring cost except for the manned flyback booster case.

Not shown in Figure 1.2 are the RDT&E and investment costs to the First Manned Orbited Flight (FMOF) of the Thrust Assisted Orbiter Shuttle (TAOS), estimated now by NASA at $5.5 billion. The estimates of alternative Space Shuttle Systems in Figure 1.2 are grouped into two classes: first, the modified two-stage reusable Space Shuttle Systems that were investigated in the past months as alternatives to the two-stage fully reusable Space Shuttle System of May 31, 1971. These systems all have associated with them lower non-recurring costs than the estimate for the original fully reusable Space Shuttle System. The technical reasons for this are described in detail in Chapter 5 and the cost considerations are given in Chapter 6. Considerable variation existed with regard to the non-recurring costs of these modified two-stage (manned booster) systems. In addition, therefore, we show the mean of these estimates as well as the standard deviation (σ) of the non-recurring cost estimates of these systems. As shown in Figure 1.2, the mean of the non-recurring costs of such modified two-stage Space Shuttle Systems is $11.5 billion, the standard deviation is $1.44 billion.

Similarly, also shown in Figure 1.2 are estimated total non-recurring costs of Thrust Assisted Orbiter Space Shuttle Systems (TAOS) that include a wide variety of technical choices, all having in common that only the orbiter is manned, with external hydrogen/oxygen tanks and all are assisted at take-off by either solid rocket motors or pressure fed rocket systems. Again, these technical alternatives are described in great detail in Chapters 5 and 6. The mean of the non-recurring cost estimates of such systems is $7.5 billion. These include about $1.6 billion for the non-recurring costs of the Space Tug and the additional required launch site. They also include a fleet of 5 Space Shuttles, each estimated at about $300 million. When Space Tug and WTR costs are excluded ($1.6 billion), as well as 3 Space Shuttle vehicles (about $900 million), then the estimated non-recurring costs in the 1970's (comparable, roughly, to FMOF costs) are estimated to be $5.0 billion (1970 dollars). The standard deviation of this estimate is $900 million, again in 1970 dollars.

Using these alternative Space Shuttle Systems, a comprehensive set of economic analyses was performed along the lines of the May 31, 1971 report to determine the economic benefits of a Space Shuttle System. The particular calculations performed are reported in Chapters 6 and 8.

In Figure 1.3 the results of the equal capability cost-effectiveness analysis are shown, at a 10 percent social rate of discount, directly comparable to the results of May 31, 1971. The benefits are again expressed in Allowable Non-Recurring Costs, thus making the benefits shown directly comparable to the estimated non-recurring costs of Figure 1.2.

Major variations were introduced in the space program activities of the 1980's, concentrating on the lower role of expected space activities of the 1980's and beyond. While in the May 31st analysis the area of interest -- based on historical, unmanned activities of the United States (and the Soviet Union) -- was confined to between 500 and 900 Space Shuttle flights in the 1978 to 1990 period, the present analysis was confined to look at the range of Space Shuttle flights between 400 and 650 Space Shuttle flights, with major variations in the analysis at 514 and 624 flights.

Two separate benefit lines were arrived at and are shown in Figure 1.3: first, the analysis concentrating around 514 Space Shuttle flights shows the economic results with the exclusion of some DoD missions that are particularly suited for Space Shuttle operations; second, the analysis concentrating at around 624 Space Shuttle flights takes the same NASA mission model, now, however, including on the DoD side the missions omitted in the first analysis.

With regard to the lower benefit line, we conclude that at 514 flights in the 1979-1990 period, the estimated benefits of a Space Shuttle System are $10.2 billion in 1970 dollars with a variance of $940 million -- expressed in allowable non-recurring costs. The economic "break even" point is reached at an annual space activity level of about 30 Space Shuttle flights, carrying satellite payloads. This annual level of NASA and DoD space activity in the 1980's and beyond will justify the development of the TAOS Space Shuttle at a social rate of discount of 10 percent.

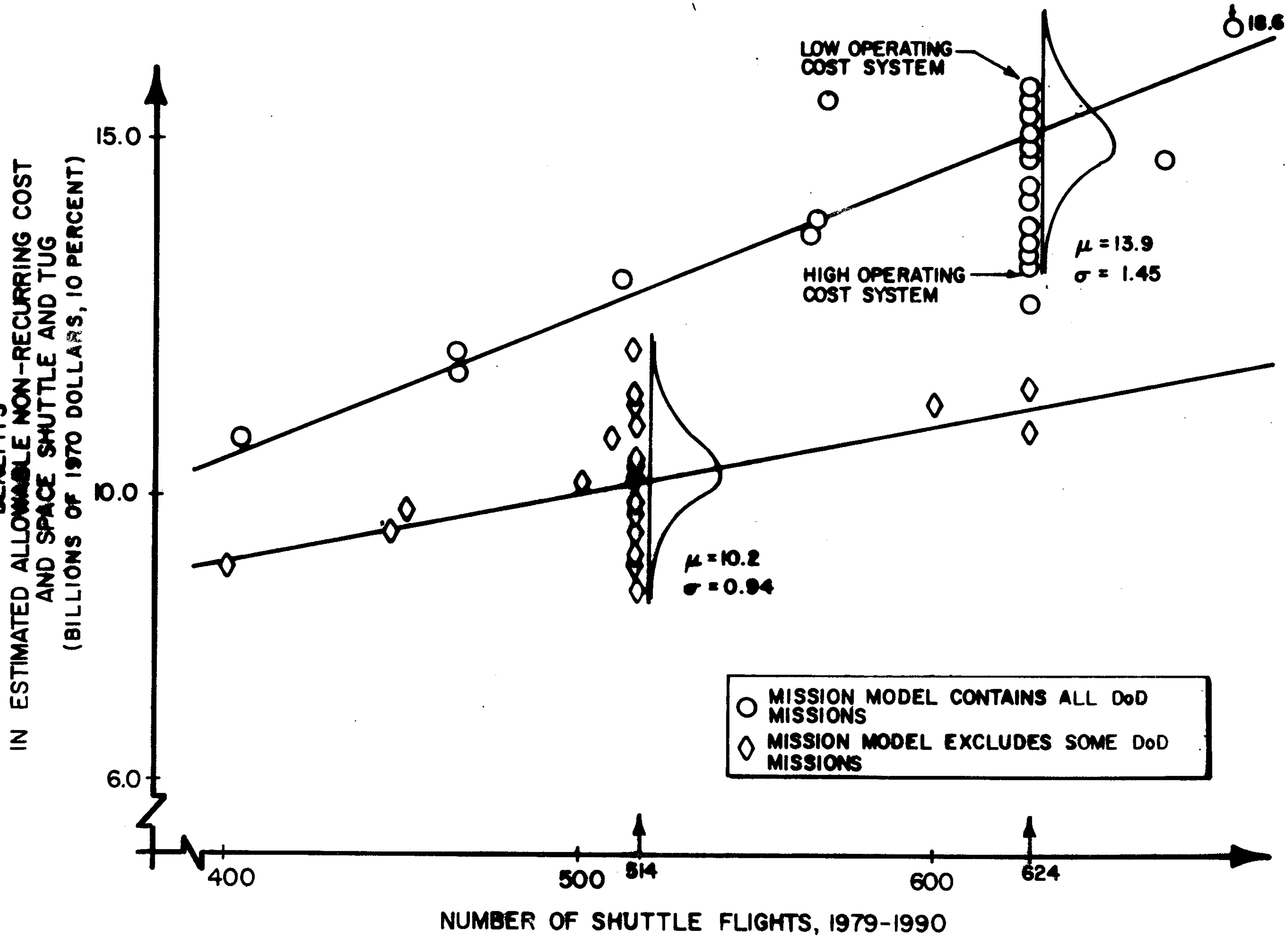


Figure 1.3

The Economic Benefits of a Space Shuttle System

When, on the other side, Space Shuttle related DoD missions are included, the economic analysis shows, at 624 Space Shuttle flights in the 1979 to 1990 period, an estimated benefit of \$13.9 billion of allowable non-recurring costs, with a standard deviation of $\pm$ \$1.45 billion. As activity levels are increased or decreased around these space programs, the expected benefits of a Space Shuttle System increase or decrease as shown by the two benefit lines in Figure 1.3. The backup of these results is given in Chapter 8. The TAOS Space Shuttle System will "break even" at an annual activity level of about 25 Space Shuttle flights, carrying satellite payloads, when the "624" mission model is taken as representative of U. S. space activities in DoD and NASA for the 1980's.

Again, we want to emphasize that these results reflect the benefits of a Space Shuttle System when applying a 10 percent real social rate of discount to the complete economic analysis.

By combining Figures 1.2 and 1.3, we can directly judge the results of the economic analysis of a Space Shuttle System.

In Figure 1.4, we show on the vertical axis the estimated non-recurring costs -- as developed in Figure 1.2 -- and also the benefits of a Space Shuttle System in terms of "allowable non-recurring costs" as developed in Figure 1.3. The estimated non-recurring costs of the TAOS Space Shuttle Systems are emphasized and the expected standard deviation of these costs is shown by the shaded area around the non-recurring cost estimate of TAOS. Similarly, the benefit lines as developed in Figure 1.3 are shown; the standard deviation around these estimates is indicated again by the shaded areas.

From the results as shown in Figure 1.4 WE CONCLUDE THAT THE DEVELOPMENT OF A TAOS SPACE SHUTTLE SYSTEM IS ECONOMICALLY JUSTIFIED, within a level of space activities between 300 and 360 Shuttle flights in the 1979-1990 period, or about 25 to 30 Space Shuttle flights per year, well within the U. S. Space Program including NASA and DoD. If the NASA and DoD mission models are taken at face value (624 Space Shuttle flights in the 1979-1990 period), the estimated benefits of a Space Shuttle System are estimated to be \$13.9 billion with a standard deviation of $\pm$ \$1.45 billion expressed in 1970 dollars (at a 10% social rate of discount). If

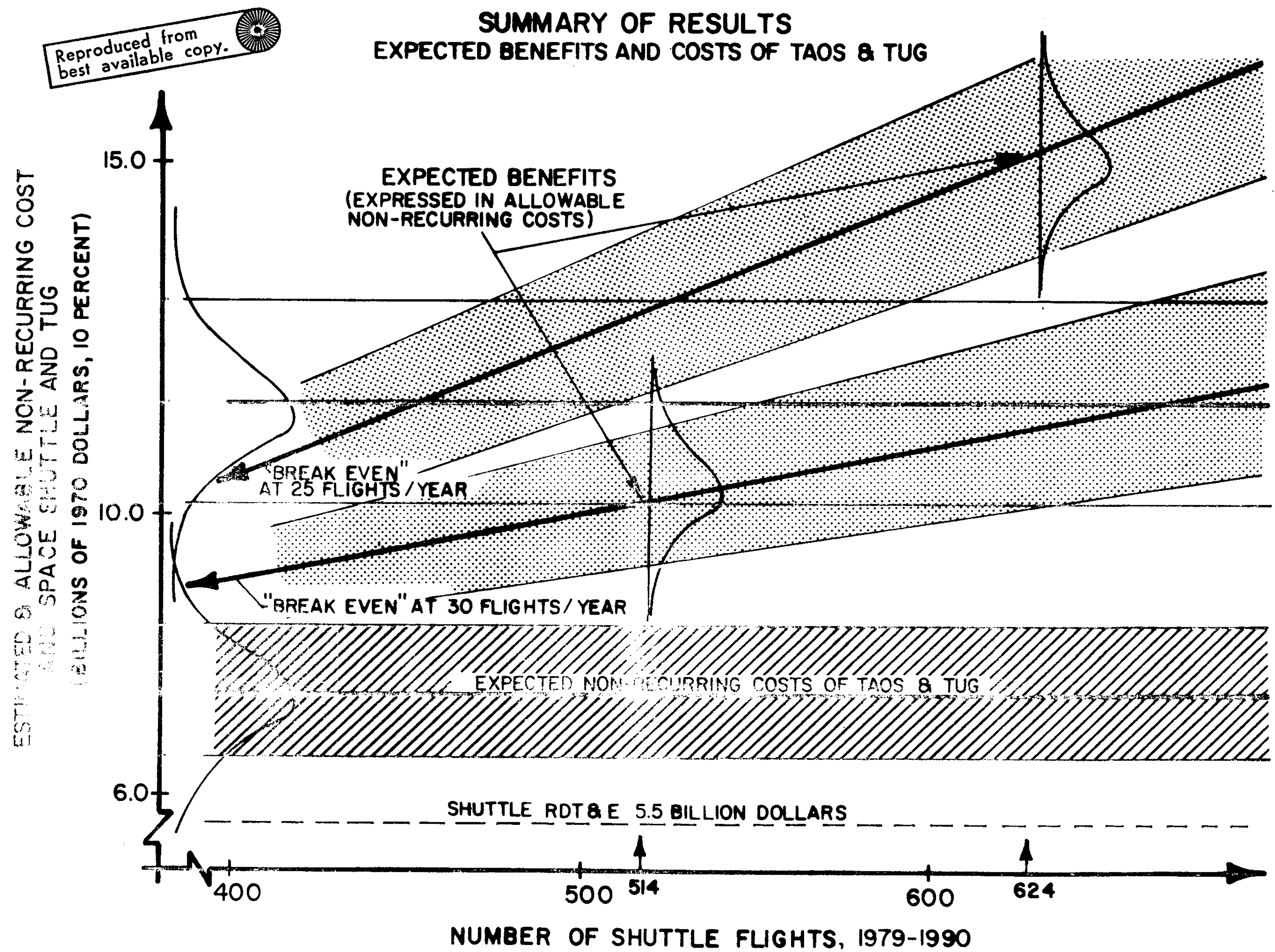


Figure 1.4

Expected Benefits and Costs of a TAOS Space Shuttle System parts of the expected U. S. Space Program are substantially modified (514 Space Shuttle flight level in the 1979 to 1990 period), the estimated benefits of a Space Shuttle System are \$10.2 billion, with a standard deviation of \$940 million (at a 10% social rate of discount).

The estimated non-recurring costs directly comparable to the benefits expressed in "allowable" non-recurring costs of a TAOS Space Shuttle System are \$7.5 billion with a standard deviation of \$960 million.

Since the complete economic evaluation of the Space Shuttle System as summarized here reflects the results when using a 10 percent real social rate of discount, the economic results in support of the TAOS Space Shuttle development have to be regarded as very strong in the context of United States national priorities.

1.2 The Most Economic Space Shuttle Configuration

As shown in Figure 1.2 there exists a great variety of alternative Space Shuttle configurations that have been studied in the past months and years to achieve the ultimate goal of a reusable Space Transportation System. If all of the Space Shuttle Systems had the same recurring costs (roughly the cost per flight) and differed only in the expected non-recurring costs, as shown in Figure 1.2, then the economic problem of choice among the proposed systems would be straightforward: find the system with the lowest non-recurring costs (RDT&E and investment).

However, the economic task is not that simple: most of the reductions in non-recurring costs are achieved by increasing, in one way or another, the operating costs of the Space Shuttle System in the 1980's and beyond. It is the economic tradeoff between non-recurring cost savings in the 1970's versus expected increases in operating costs in the 1980's and beyond that becomes the subject of economic analysis when determining the most economic Space Shuttle configuration. It is only through such an analysis that a single system or family of systems can be identified with confidence among the wide variety of alternative choices. This was done extensively by our group.

The economic methodology of determining the most economic Space Shuttle System has been put forth in detail in Chapter 3. This effort will have to take into account a variety of economic factors. Foremost among these are (1) the objectives to be achieved by an investment like the

Space Shuttle System, (2) the identification of cost-effective Space Shuttle configurations, (3) the identification, among the cost-effective configurations, of a single most economic Space Shuttle System which again will depend on (a) the activity level to be expected in the 1980's and beyond, (b) the social rate of interest to be applied to the investment decision and, (c) the anticipated payload effects of the Space Shuttle System in the area of reducing payload costs, and making possible the reuse, refurbishment and updating of payloads. The estimates of the economic benefits are also dependent on the type of cost-effectiveness analysis used within the range of equal capability and equal budget analyses. Most important are the objectives within which the analysis is carried out. We, therefore, state these here explicitly.

1.2.1 The Objectives of a Reusable Space Transportation System (STS)

In the economic analysis of this report the principal objectives of a Space Shuttle System are considered to be:

(a) A new capability of meeting all now foreseeable space missions in NASA, DoD and elsewhere, including manned space flight capabilities. Thus, whenever a proposed system cannot meet all requirements, the costs of the required expendable systems are fully included as part of that Space Shuttle System.

(b) Reduction of space program costs (manned, unmanned, NASA, DoD, commercial users) over the present expendable Space Transportation costs through reuse, refurbishment, maintenance, and updating of payloads. The Space Tug is therefore included as an integral part of a reusable Space Transportation System.

(c) Reduction of space transportation costs for all missions (low energy, high energy, manned).

(d) Option of later transition to a fully reusable system.

The above four objectives were considered to be the principal motivations for the investment in a reusable Space Transportation System. Additional objectives supporting the major objectives were considered to be:

(e) A low non-recurring cost to meet funding constraints.

(f) Assurance of a low cost per launch. Launch costs of up to about $10 million are justifiable when payload costs and effects are considered.

It is with these objectives in mind that the results of this report hold. Had the objectives been different, for example, to maintain a manned space flight capability only, or to undertake a limited technology program in support of future Space Transportation only, then a different economic analysis would have to be made, since the benefits of the Space Shuttle development -- the promised capabilities -- are analyzed here within the context of overall Space Transportation capability.

1.2.2. Space Transportation Systems Considered

Over the last two years, but particularly in the effort of the past six months, many alternative Space Shuttle concepts have been considered. It is difficult to follow and appreciate all the different ideas proposed to achieve the objectives listed in the previous section. Several basically different approaches were investigated, among them two-stage fully reusable systems, two-stage systems with some external (expendable) tankage, manned orbiters with a variety of unmanned boosters, single orbiters with parallel burn and rocket assists, single stage to orbit concepts, stage and one-half concepts, and others. When variations of technical options within each of these approaches are considered, then literally hundreds of different Space Shuttle Systems have been studied by NASA, the Phase B Study contractors and other interested parties. It can be affirmed that seldom, if ever, before has a single investment program of the scope and size as the Space Shuttle System been studied in such detail -- both technical and economic -- as to alternative approaches to achieve the objectives listed. The configurations listed and discussed in the subsequent pages are already the result of an extensive technical and economic elimination process. Some of these systems are described in detail in Chapter 5. Nevertheless, large economic differences still exist between these configurations.

This study examines in detail the economics of the following alternative Space Transportation Systems for use in the decade of the 1980's:

A. The Current Expendable System

The system envisages continuing use of the types of expendable launch vehicles presently in the United States inventory.

B. The New Expendable System

As its name implies, this envisages use of a new family of expendable vehicles designed to have better (economic) performances than the Current Expendable vehicles. Where economically justified, payloads were redesigned to take advantage of the New Expendable System performances.

C. Space Shuttle Systems

Systems considered within this category differ in concept from the previous systems in implying reusable rather than expendable launch vehicles. Two major elements are employed in each of these: a Space Shuttle which operates between the earth's surface and earth orbits of at least 185 kilometers; and a Space Tug which can be transported within the Space Shuttle and which can operate from the relatively low orbit of the Space Shuttle to high earth orbits such as the synchronous equatorial orbit (35,500 kilometers). Only the combined Space Shuttle and Tug systems provide a reusable launch system able to place payloads into all widely used earth orbits, and also able to recover payloads from these orbits. The capabilities, performances and operations of the Space Tug were assumed as given and fixed for purposes of this study, which concentrates on identifying the most economic Space Shuttle among the alternative configurations. The following systems were analyzed extensively across a wide variation of expected mission models and levels of demand for Space Transportation in the 1980's:

a. The two-stage fully reusable Space Shuttle. The baseline used also in the evaluation of the May 31, 1971 report aimed at determining the economic potential of a reusable Space Transportation System.

b. Two-stage Space Shuttle Systems with external hydrogen tanks on the orbiter.

c. Two-stage (F-1) Flyback Space Shuttle System also known as the Reusable SIC. The orbiter used in this version is the present baseline orbiter (with external hydrogen and oxygen tanks, a 60 x 15 payload bay); the ultimate capability of this system was considered to be 40K pounds to polar orbit of 185 by 185 kilometers.

d. Series Burn Pressure Fed Booster (SPFB) Shuttle System, with the present baseline orbiter.

e. Series Burn Solid Rocket Motor Boosters (SSRM) Shuttle System, with the present baseline orbiter.

f. (Twin) Pressure Fed Booster (TPFB) Shuttle Systems, with the present baseline orbiter and parallel burn at takeoff. (TAOS)

g. (Twin) Solid Rocket Motor Boosters (TSRM) with the present baseline orbiter with parallel burn at takeoff. (TAOS)

h. Identical Vehical Space Shuttle System, with two identical orbiters and three drop tanks sandwiched between them.

Each of these systems has associated with it a considerable amount of non-recurring costs, (research and development costs as well as initial fleet investment costs), and substantially different cost per flight of the systems varying from \$4.5 million per launch to over \$15 million per launch. The total non-recurring costs, including the cost of the Space Tug and two launch sites varies from a low of \$6.9 billion to a high of \$14 billion (see also Figure 1.2).

D. A Space Glider Combined with a New Expendable Space Transportation System

The Space Gliders considered had payload bays of 60 x 15 feet and 40 x 12 feet; they would be launched on expendable vehicles. Costs per flight of these systems are in excess of \$30 million per launch.

In addition to the above configurations, other variations in the Space Shuttle were also considered as alternatives. One such alternative is a 40 x 12 payload bay with 30K pounds of equatorial launch capability for the Space Shuttle System.

The cost estimates and breakdowns for the alternative Space Shuttle configurations are given, in detail, in Chapters 6 and 8.

In Figures 1.5 to 1.7 the major alternative Space Shuttle configurations are shown as identified and recommended by the Phase B study contractors in their reports of September 1, 1971 (Figure 1.5), November 3, 1971 (Figure 1.6) and December 15, 1971 (Figure 1.7). The non-recurring costs of the alternative Space Shuttle configurations are shown on the vertical axis of each of these figures, while the contractor estimated costs per flight of each alternative configuration are shown on the horizontal axis of each of these figures, all expressed in constant dollars. Chapter 6 gives more details on the cost estimates.

In Figure 1.8, all of the systems are shown that were studied and proposed in the past six months. Among these the most economic Space Shuttle configuration has to be identified.

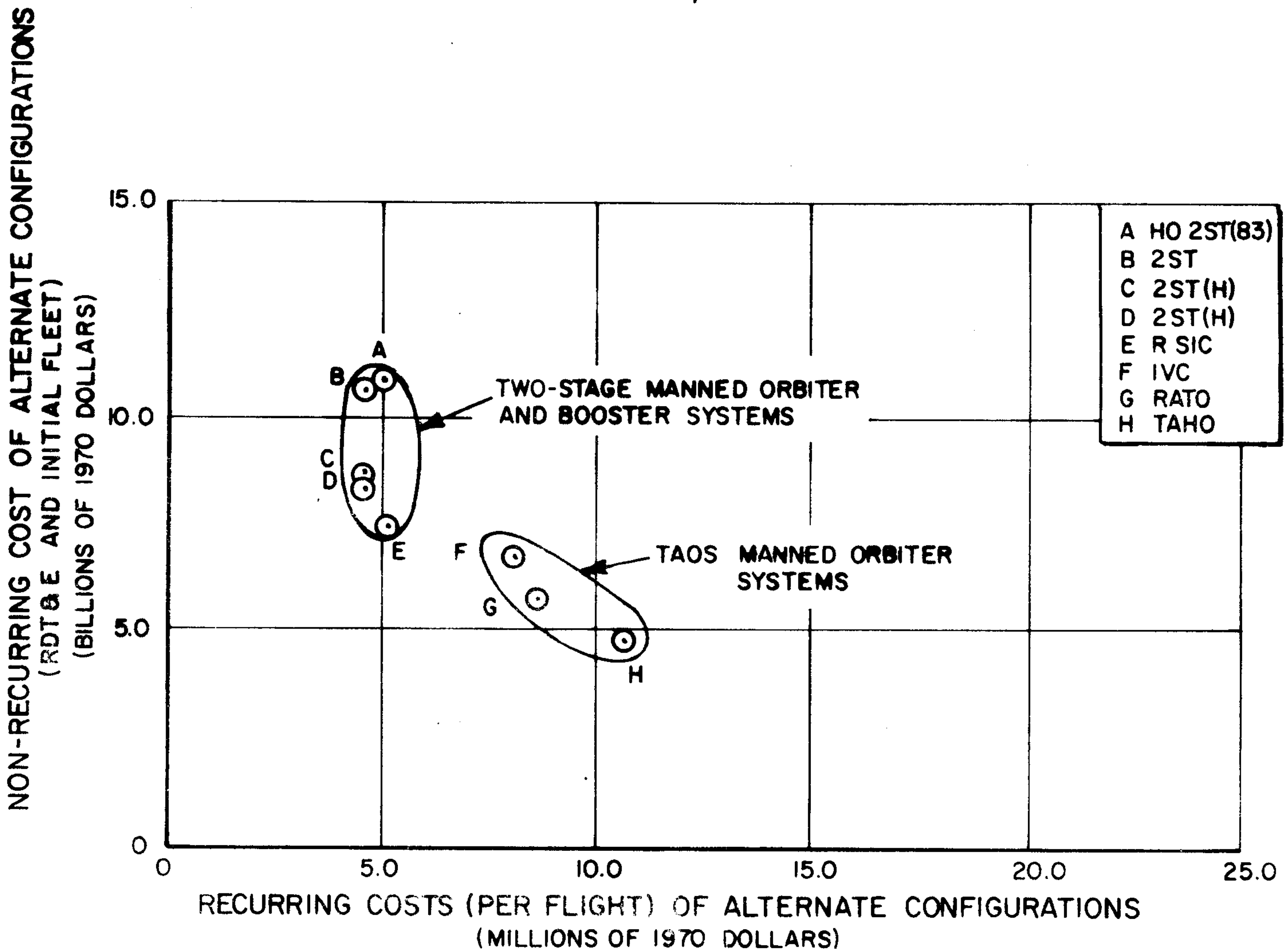
1.2.3 Results of the Economic Analysis on Alternative Space Shuttle Systems

The methodology for the determination of cost-effective systems, the meaning and significance of the economic tradeoff line, as well as the theoretic identification of the most economic systems among cost-effective systems is described in Chapter 3. Chapters 6 and 8 give the corresponding backup and actual calculations for the alternative Space Shuttle Systems and space programs of the 1980's and beyond. Here the results are represented in convenient diagrammatic form in the next figures.

In Figure 1.8 we show two important results: first, among the different concepts investigated and reported on by NASA and Industry there emerge the following families of systems as cost-effective: the original two-stage fully reusable Space Shuttle System at an estimated non-recurring cost of $12.8 billion and the lowest expected cost per flight of $4.6 million, a family of cost estimates associated with F-1 Booster technology, also known as the Reusable SIC, and shown by the shaded area in Figure 1.8 reflecting December 15 variations in industry estimates; a family of cost estimates associated with series burn and parallel burn pressure fed

RECURRING COSTS (PER FLIGHT) vs NON-RECURRING COSTS OF ALTERNATE CONFIGURATIONS

SEPTEMBER 1, 1971 DATA



RECURRING COSTS (PER FLIGHT) vs NON-RECURRING COSTS OF ALTERNATE CONFIGURATIONS

NOVEMBER 3, 1971 DATA

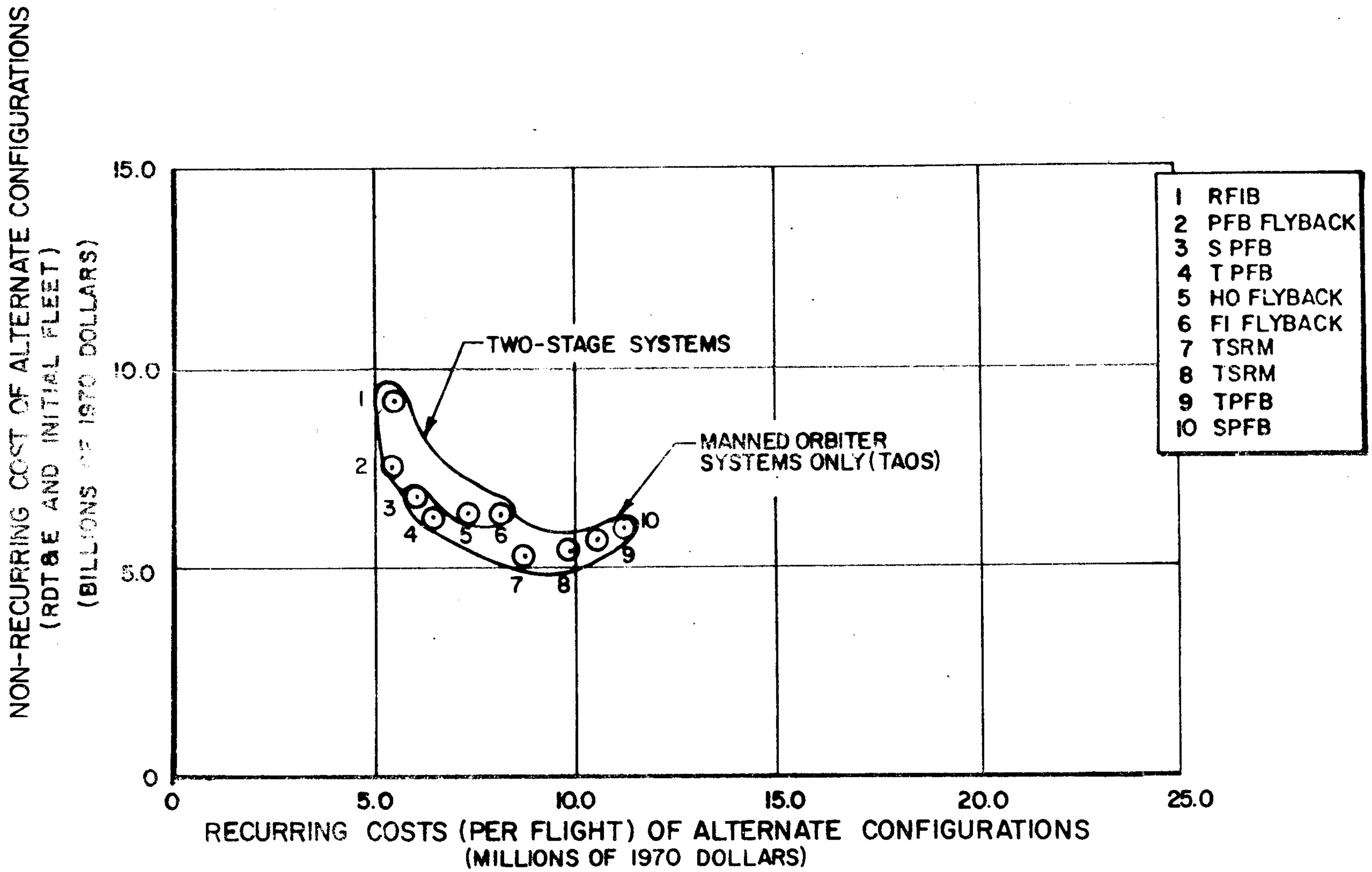


Figure 1.6

RECURRING COSTS (PER FLIGHT) vs NON-RECURRING COSTS OF ALTERNATE CONFIGURATIONS

DECEMBER 15, 1971 DATA

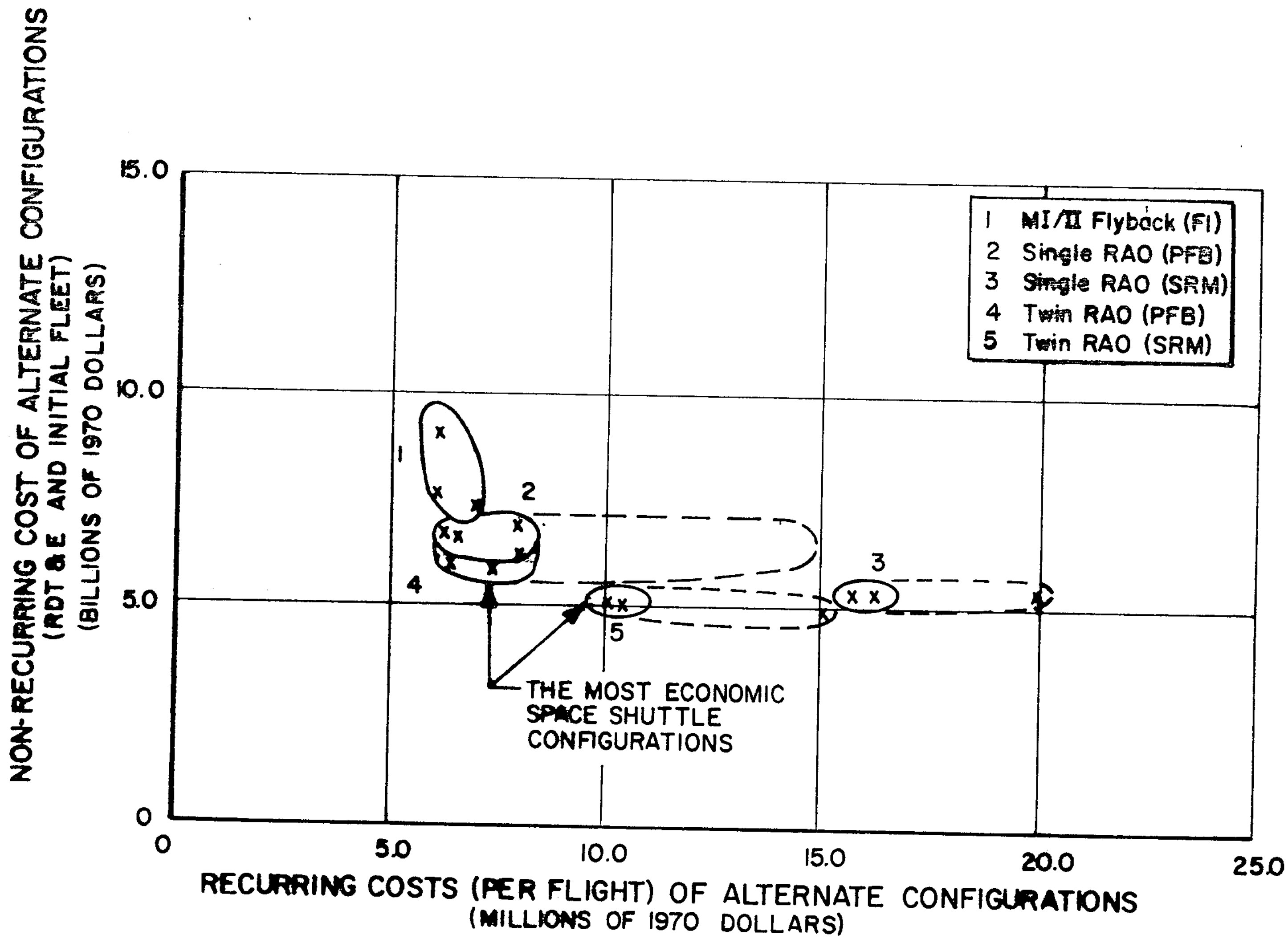


Figure 1.7

COST-EFFECTIVE SPACE SHUTTLE SYSTEMS DEFINED BY EXPECTED NON-RECURRING & RECURRING COST ESTIMATES

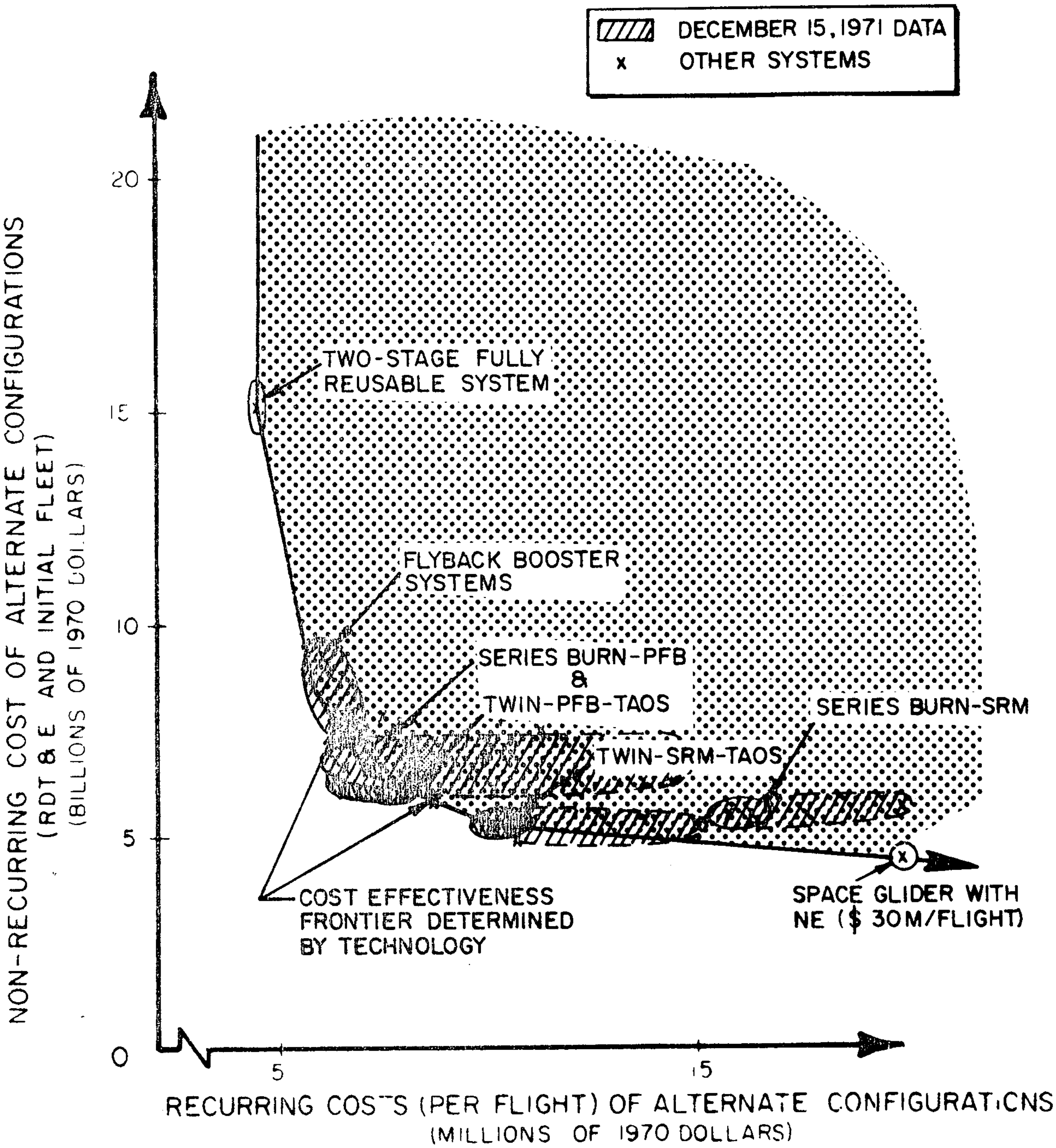


Figure 1.8

Space Shuttle Systems, all having in common the new baseline (manned) orbiter and unmanned recoverable pressure fed booster systems; a family of cost estimates associated with Solid Rocket Motor boosters and the new baseline orbiter, using parallel burn operations (i.e., orbiter engines are ignited at take-off); and a family of cost estimates for series burn solid rocket motor boosters, again using the new baseline orbiter. Also shown are all the other cost estimates since September 1, 1971 of alternate Space Shuttle configurations. And not quite accurately shown, due to the high cost per launch, is the Space Glider concept discussed by different agencies and NASA with a cost per flight of $30 million or more and a non-recurring cost of between $2.8 and $4.1 billion. Within the economic analysis and the objectives of the Space Shuttle program stated in the previous section, the Space Glider is a cost-effective system, but clearly not the most economic system among the alternative devices as the further economic analysis will show.

The black-shaded areas in Figure 1.8 show, with emphasis, the likely cost estimates for the two most interesting alternative Space Shuttle Systems, the "twin pressure fed parallel burn booster" Space Shuttle and the "twin SRM, parallel burn" Space Shuttle concepts, emphasizing the most recent and frequently quoted recurring and non-recurring cost estimates for these systems in industry. Closely associated, economically, with the "twin parallel burn PFB" Space Shuttle are the alternative, series burn pressure fed booster systems, as shown in Figure 1.8.

Finally, also shown in Figure 1.8 is the cost-effectiveness frontier as defined by these alternative technological choices: systems above and to the right of this cost-effectiveness frontier are all possible and feasible; many of these have been studied in Phase B of the Space Shuttle study effort, and some of these are indicated in Figure 1.8. The existence of systems to the left and below the cost-effectiveness frontier as shown in Figure 1.8 can, by now, be excluded with some confidence; their existence would imply that, within the range of the defined objectives of a Space Shuttle program lower non-recurring <u>and</u> recurring cost combinations were feasible; although the existence of such systems can never be excluded with complete certainty by anybody, it seems highly unlikely that such opportunities were missed in the effort of the past months and years (within the present state of technology and know-how).

The economic analysis was carried out within the cost estimates -- and their uncertainty estimates as shown in Figure 1.8. The next three figures, Figures 1.9, 1.10 and 1.11, summarize the results of the economic analysis: within the expected activity levels of space programs in the 1980's, a reasonable variation in the social opportunity cost of investment funds in the 1970's and a considerable variation in the expected payload effects due to repair, reuse, refurbishment and updating of payloads the "SRM-PARALLEL BURN BOOSTER", and the "PRESSURE FED-PARALLEL BURN BOOSTER" CONCEPTS (TAOS) EMERGE CLEARLY AS THE MOST ECONOMIC SPACE SHUTTLE ALTERNATIVES, with the "SERIES BURN PRESSURE FED BOOSTER" SPACE SHUTTLE AS A POSSIBLE THIRD ALTERNATIVE CHOICE.

In coming to this conclusion, the "Economic Tradeoff Function," measuring the tradeoff between non-recurring cost variations in the 1970's versus recurring cost changes in the 1980's and beyond, is of decisive importance. The Economic Tradeoff Function is defined and calculated in Chapters 3 and 8. Figures 1.9 to 1.11 show the results of these calculations combined with the non-recurring and recurring cost estimates of Figure 1.8.

In Figure 1.9, the position and slopes of the Economic Tradeoff Function is shown as it varies with different activity levels in the 1979-1990 period at a 10 percent social rate of discount. Systems above the Economic Tradeoff Function are not economic when compared to an Expendable Space Transportation System in the 1980's; systems below and to the left of the Economic Tradeoff Function are, economically, better than an Expendable Space Transportation System in the 1980's at a 10 percent social rate of discount. The three activity levels shown for the 1979 to 1990 period correspond to three basic space program alternatives that were used by us in the economic analysis, with considerable further variations (see Chapters 6 and 8): the NASA and DoD Baseline Mission Model for 1979-1990 (624

COST-EFFECTIVE SPACE SHUTTLE CONFIGURATIONS

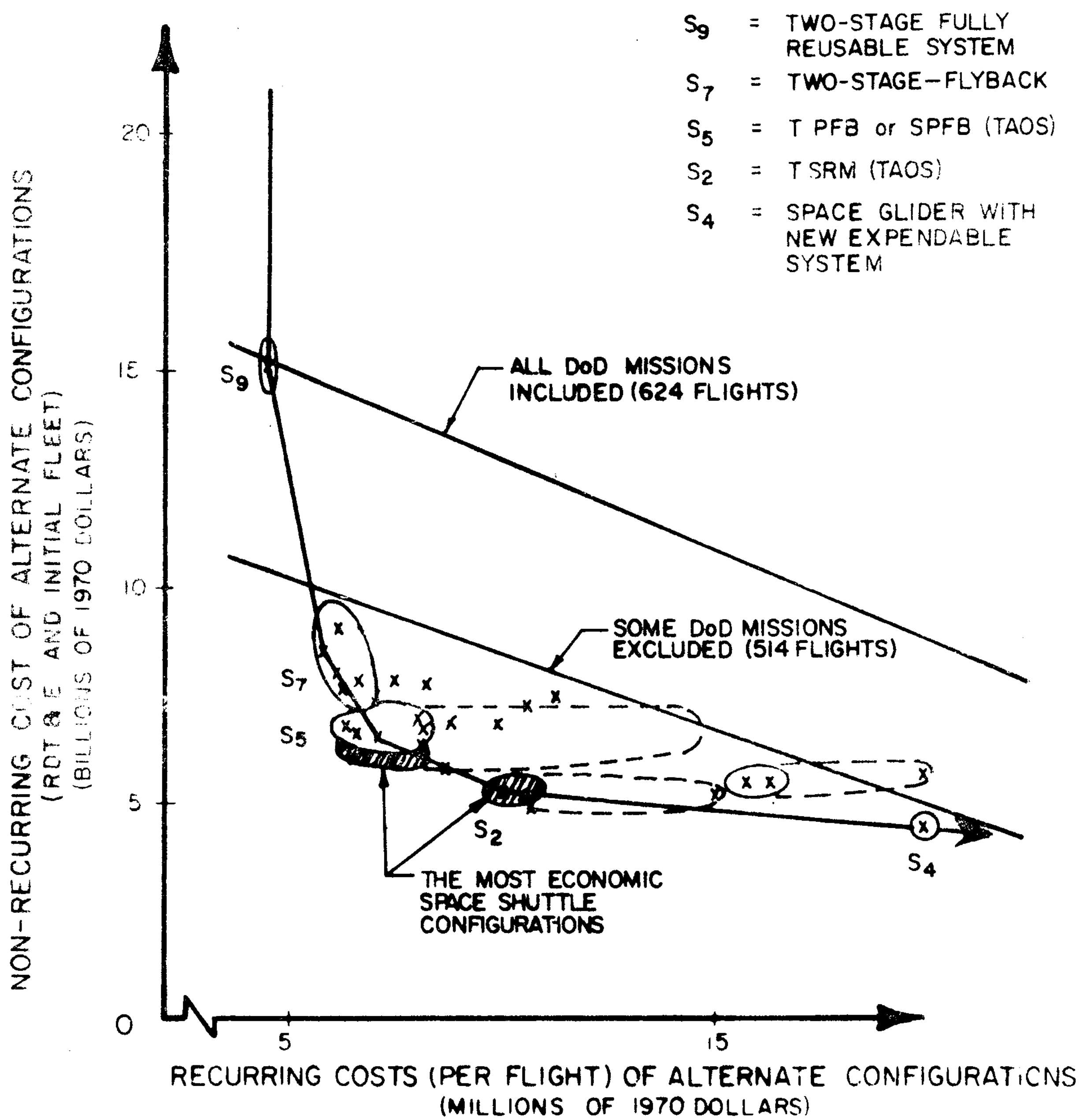


Figure 1.9

Economic Trade-off Function for Space Shuttle System with 514 Shuttle Flight Space Program (1979-1990) and 624 Shuttle Flight Space Program

Space Shuttle flights), the modified NASA and DoD Mission Model (514 Space Shuttle flights, modified in the DoD part under exclusion of some missions particularly suited for Space Shuttle operations) and the former (May 31, 1971 report) NASA and DoD Baseline Mission Model (about 736 Space Shuttle flights). With each of these activity levels the slope of the Economic Tradeoff Function does not change significantly over the range of interest. The most economic Space Shuttle System is then defined as the System along the cost-effectiveness frontier where the Economic Tradeoff Function is tangent to the cost-effectiveness frontier; it is the Space Shuttle System most distant from the Economic Tradeoff Function, when measured orthogonally to that function. In this case, both TAOS systems (TPFB and TSRM) are equally preferred over any of the other systems proposed; with higher activity levels the advantage of the TPFB-TAOS system increases, as the slope of the Economic Tradeoff Function increases slightly, and at activity levels below 624 Space Shuttle flights the advantage of the TSRM-TAOS system increases slightly. In each case the series burn PFB system is a third best alternative.

In Figure 1.10, three alternative Economic Tradeoff Functions are shown (for a 514 flight space program from 1979 to 1990) for three different social rates of discount: a 5 percent rate, a 10 percent rate and a 15 percent rate. At a 5 percent social rate of interest and accepting the non-recurring and recurring cost estimates as given by industry, the TPFB-TAOS is the most economic choice among all the technical alternatives. It means that at the relatively low social opportunity costs for investment funds (as expressed by the 5 percent rate) it may be indicated to spend the additional funds on more advanced booster programs in the form of pressure fed reusable systems with the promise of a lowering in the cost per flight in the operating phase of the Space Shuttle System. (Again, the point of tangency determines the most economic Space Shuttle System along the cost-effectiveness frontier).

At a 10 percent rate of social interest, recommended by the Office of Management and Budget, the TSRM-TAOS and TPFB-TAOS are about equally preferred to all other systems with a slight economic advantage of the TSRM-TAOS; both lie close enough to the slope of the Economic Tradeoff Function that one cannot be preferred to the other based solely on economic criteria. The TPFB-TAOS involves higher risks but promises lower operation

COST-EFFECTIVE SPACE SHUTTLE CONFIGURATIONS

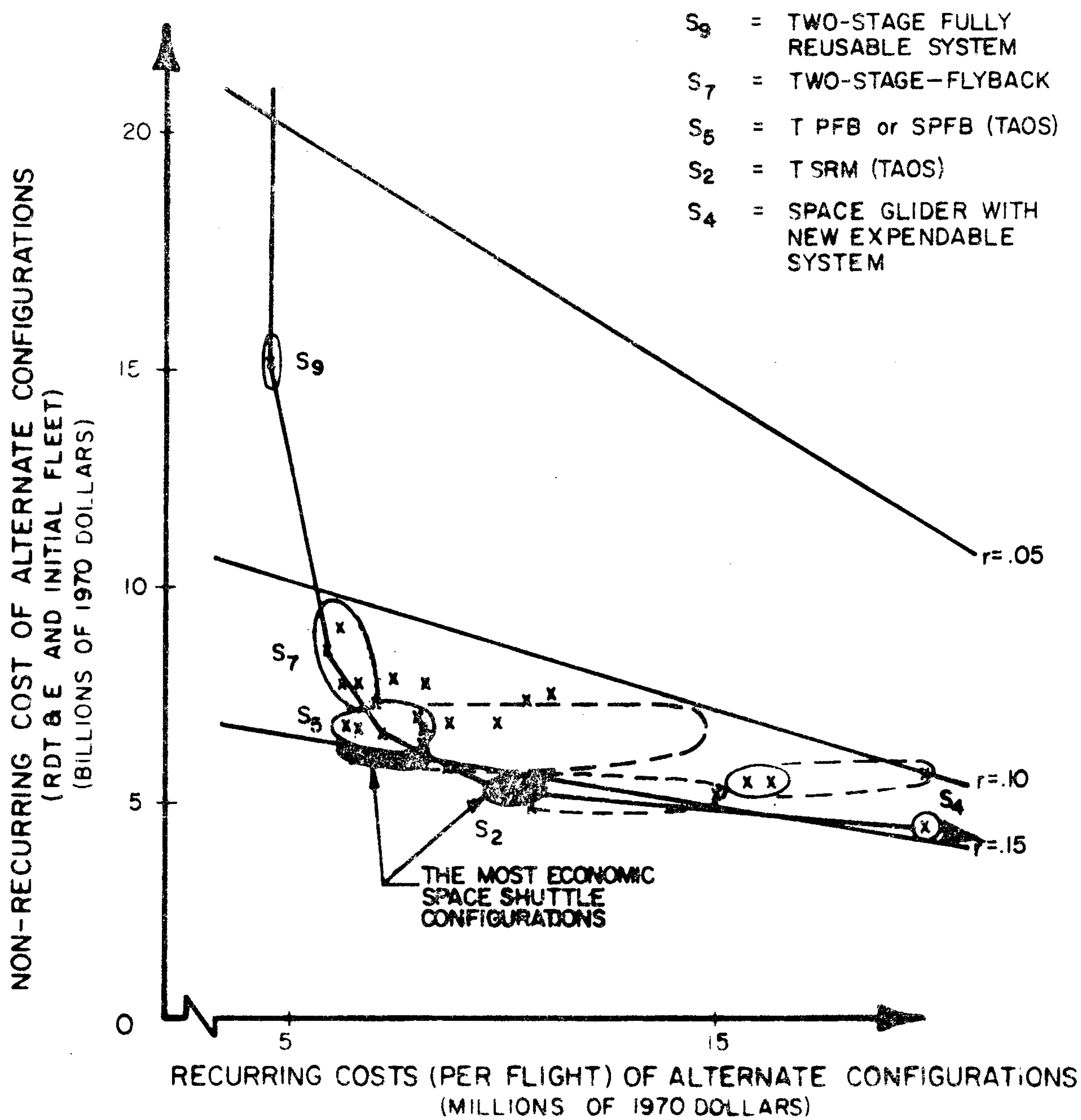


Figure 1.10

Economic Trade-off Function for Space Shuttle System when Social Rate of Discount is Varied from 10% to 5% and 15% (514 Shuttle Flight Space Program) costs. The TSRM-TAOS involves lower risks and non-recurring costs but possibly higher costs per flight. At a 15 percent social rate of discount, that is with high social opportunity costs for investment funds in the 1970's, clearly the TSRM-TAOS system emerges as the preferred Space Shuttle configuration and possibly the only system, the development of which is justified on economic grounds.

Finally, in Figure 1.11 alternative Economic Tradeoff Functions are shown, as the payload refurbishment and updating costs are varied from 30 percent of satellite unit costs to 50 percent of satellite unit costs, the band of variation within which alternate payload refurbishment costs were estimated by LMSC (Lockheed) and Aerospace Corporation as part of this economic study. The Economic Tradeoff Functions all reflect a 10 percent social rate of discount and an activity level of 514 Space Shuttle flights in the 1979 to 1990 period. As shown in Figure 1.11, again, the TSRM-TAOS and the TPFB-TAOS emerge as the preferred economic systems over any other Space Shuttle configuration.

Thus, the results of the economic analysis indicate that: "Parallel Burn Solid Rocket Motor Booster" Space Shuttle System (TSRM-TAOS) and the "Parallel Burn Pressure Fed Booster" Space Shuttle Systems are economically the best Space Shuttle choices. Insofar as the "series burn pressure fed booster" Space Shuttle offers nearly the same advantages as the TPFB-TAOS, it has to be considered as a third viable economic choice among the many alternative system configurations. At very high social opportunity costs for investment funds, the TSRM-TAOS is the clearly preferred choice, at lower social opportunity costs for investment funds the TPFB-TAOS is preferred.

Insofar as a Space Shuttle development program can be defined, the economic choice facing NASA seems to be between the development of the Parallel Burn Solid Rocket Motor TAOS or a TPSB-TAOS, with the TSRM-TAOS as a technical fall back position, at some additional cost. A mixed development strategy by NASA may be the best development choice, and particularly if a fixed funding limit were imposed on the Space Shuttle development in the 1970's. Yet insufficient detailed information was available to us to make any such recommendation between these two choices.

The TAOS concepts forego the development of manned booster stages in the Shuttle System. With the use of thrust assist of either solid rocket motors or pressure fed systems -- which can be made in part reusable for low staging velocities -- the TAOS concept promises a reduction in the non-recurring costs (RDT&E and initial fleet investment, Space Tug included) from about $10 billion or more (two stage systems, including reusable SIC's) to about $7 billion or less, with an acceptable recurring cost increase in the operating phase of the TAOS systems. The decision between the twin pressure fed and the series burn pressure fed TAOS Space Shuttle System is basically a tradeoff function between the higher non-recurring costs as well as higher risks in the development of the series burn pressure fed booster as against the lower non-recurring cost, lower risk, but possibly higher recurring cost per launch of twin pressure fed systems.

The detailed economic justifications of the TAOS concepts -- when compared to any two-stage reusable system are:

1. The non-recurring costs of TAOS are estimated by industry to be $7 billion or less over the period to 1979 or to 1984-1985 depending on the objectives and choices of NASA.

2. The risks of the TAOS development are in balance lower but still substantial. Intact abort with external hydrogen/oxygen tanks is feasible; lagging performance in the engine area can be made up by added external tank capability. A large reusable manned booster is not needed.

3. The TAOS's that were analyzed promised the same capability as the original two-stage shuttle, including a 40,000 pound lift capability into polar orbit and a 60 x 15 payload bay.

4. The TAOS can carry the Space Tug and capture high energy missions from 1979 on.

5. The most economic TAOS would use the advanced orbiter engines immediately. Our calculations indicate that among the alternative TAOS

COST-EFFECTIVE SPACE SHUTTLE CONFIGURATIONS

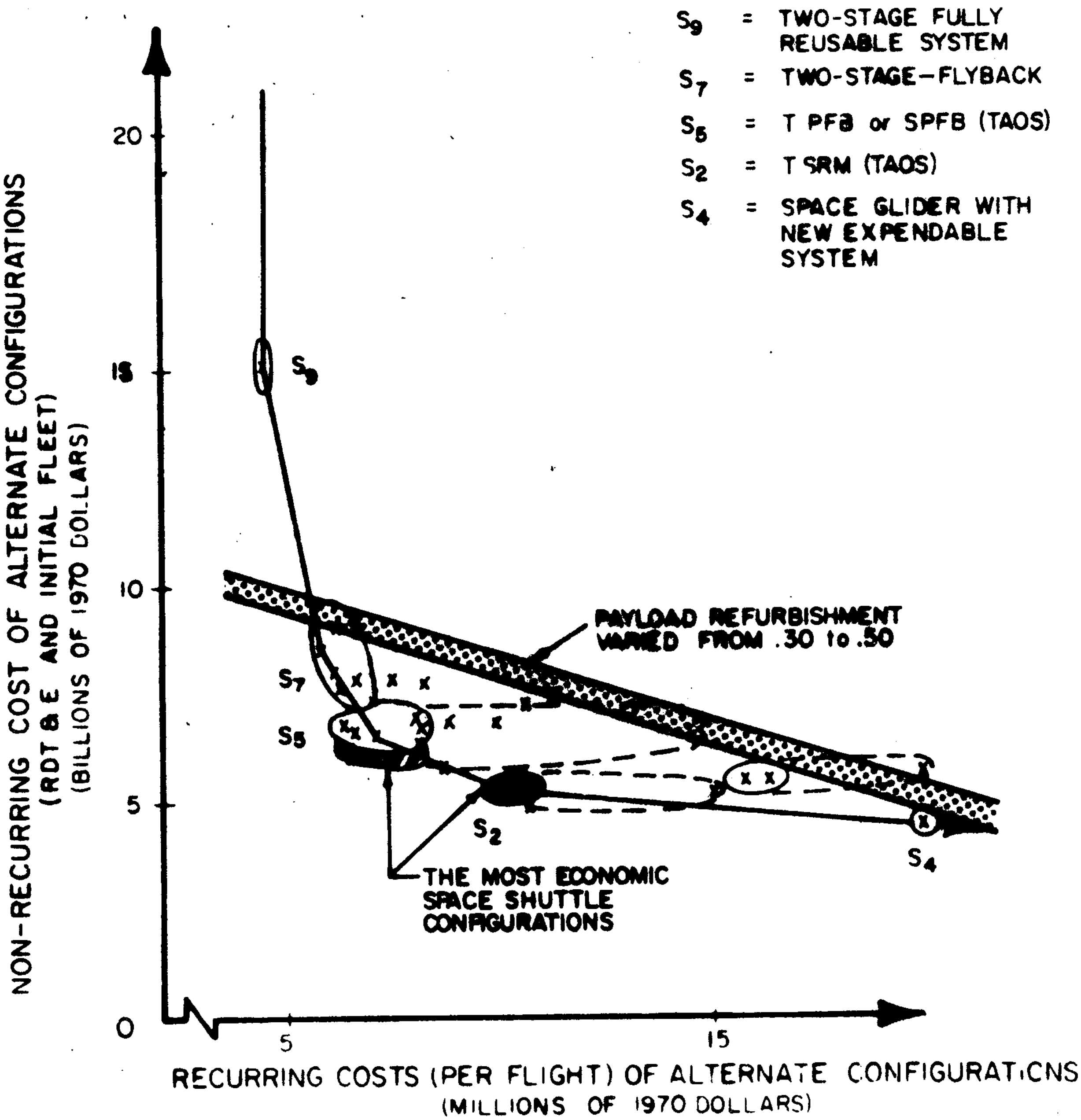


Figure 1.11

Economic Tradeoff Function for Space Shuttle System when Payload Reuse and Refurbishment Costs are Varied from 30% to 50% (expected: 39%)

configurations an early full operational capability and high performance engines on the orbiter are economically most advantageous and feasible within budget constraints of $1 billion peak funding or less. (Also, see next section).

6. The TAOS avoids the immediate need to decide on a large reusable booster and allows postponement of that decision without blocking later transition to a fully reusable system, if and when desired. Thereby, a TAOS eliminates or lowers the risk and potential cost overruns in booster development.

7. The TAOS would use "parallel burn" concepts which, if feasible, may change the reusable booster decision. Of course, a TAOS orbiter with a series burn pressure fed booster is also possible.

8. Technological progress may make the expendable parts of the TAOS system (involving mainly tank costs, and thrust assisted rocket costs) less expensive thus further aiding TAOS concepts when compared to two-stage concepts or fully expendable concepts.

9. The TAOS funding schedule makes an early Space Tug development possible. The Space Tug is an integral part of the Space Shuttle System and may be developed by Europe.

10. The TAOS assures NASA the major objectives stated previously of a reusable Space Transportation System.

1.3 Funding Constraints: The Development of the Space Shuttle System and the Projected Budget for NASA

The space programs analyzed in both the May 31, 1971 report as well as in this report are well within the budgetary limitations of the U.S. space program of NASA and the Department of Defense in the 1960's for the unmanned space program as well as some reasonable, conservative extensions of these activities for the 1980's. The particular mission model provided by NASA, which includes a set of missions for the Office of Space Science, the Office of Manned Space Flight, and the Office of Applications of NASA, as well as for the Department of Defense, are described later in this report as well as in the work of Aerospace Corporation in support of the present study. As in the earlier May 31st report, wide variations were applied to the mission model and programs supplied to us by NASA and the Aerospace Corporation. In all, close to 200 different mission models were examined over the past six months.

Underlying the conclusions of this analysis are first, funding requirements for a thrust assisted shuttle with an Initial Operating Capability (IOC) date of 1979 as identified in the selection of the most economic Space Shuttle System, and second, the mission model of 514 Space Shuttle flights in the 1980's including NASA, the DoD, as well as commerical applications. For each of the major alternative systems, that is, the competing expendable systems versus the most economic Space Shuttle System, i.e., the thrust assisted orbiter shuttle, a detailed analysis of the life cycle costs of each of the systems was undertaken. Tables 1.1, 1.2, and 1.3 describe the detailed life cycle cost summary data for the period of 1972 to 1990 (fiscal years) for the current expendable, the new expendable and the thrust assisted orbiter shuttle transportation systems. The thrust assisted orbiter shuttle system considered was a typical system among the TAOS systems identified earlier.

In each of these tables, annual total costs of a given typical Space Transportation System are divided into non-recurring costs and recurring costs. Both of these costs are then sub-divided into launch vehicle and payload costs. Furthermore, for non-recurring launch vehicle costs of expendable systems, the RDT&E costs and the investment costs are identified separately. For the current expendable and new expendable systems reported in Tables 1.1 and 1.2, the RDT&E costs, the investment costs for the launch vehicles were identified separately year by year for a 1979-1990 space program. The research and development costs basically concerned the development of a space program to maintain the option of manned space flight in the 1980's. The investment costs are the costs associated with producing the necessary vehicles for launch operations in the 1980's. The actual launch costs are shown under the recurring costs. In obtaining these cost estimates the payload costs for NASA (the Office of Space Science, the Office of Applications, the Office of Manned Space Flight) as well as the DoD and commercial applications were separately identified and costed. Notice

Table 1.1

LIFE CYCLE COST SUMMARY DATA
SCENARIO 32 - TYPICAL TAOS AND TUG, 1979 IOC
CURRENT EXPENDABLE SYSTEM
(MILLIONS OF UNDISCOUNTED 1970 DOLLARS)

FISCAL YEAR	NON-RECURRING COSTS LAUNCH VEHICLE RDT&E	NON-RECURRING COSTS LAUNCH VEHICLE INVEST.	NON-RECURRING COSTS PAYLOAD RDT&E	RECURRING COSTS LAUNCH	RECURRING COSTS PAYLOAD	TOTAL
1971	0	0	0	0	0	0
1972	0	0	0	0	0	0
1973	0	0	0	0	0	0
1974	0	0	0	0	0	0
1975	50	0	38	0	0	88
1976	160	10	114	0	1	285
1977	290	62	450	114	303	1219
1978	250	105	1018	302	989	2644
1979	140	145	1163	643	1221	3312
1980	60	135	1193	896	1320	3804
1981	5	125	1364	912	1456	3862
1982	5	75	1264	899	1700	3945
1983	0	0	1273	882	1698	3853
1984	0	0	929	948	1796	3673
1985	0	0	632	954	1592	3178
1986	0	0	476	1020	1872	3168
1987	0	0	418	1008	1716	3142
1988	0	0	365	982	1781	3128
1989	0	0	242	743	1282	2267
1990	0	0	64	292	327	683
TOTAL	960	657	11003	10595	18834	42049

Table 1.2

LIFE CYCLE COST SUMMARY DATA
SCENARIO 32 - TYPICAL TAOS AND TUG, 1979 IOC
NEW EXPENDABLE SYSTEM
(MILLIONS OF UNDISCOUNTED 1970 DOLLARS)

FISCAL YEAR	NON-RECURRING COSTS LAUNCH VEHICLE RDT&E	NON-RECURRING COSTS LAUNCH VEHICLE INVEST.	NON-RECURRING COSTS PAYLOAD RDT&E	RECURRING COSTS LAUNCH	RECURRING COSTS PAYLOAD	TOTAL
1971	0	0	0	0	0	0
1972	0	0	0	0	0	0
1973	0	0	0	0	0	0
1974	0	0	0	0	0	0
1975	60	0	38	0	0	98
1976	190	10	114	0	1	315
1977	355	80	441	81	308	1265
1978	315	194	978	240	883	2610
1979	195	193	1121	460	1163	3132
1980	60	135	1133	605	1311	3244
1981	5	125	1285	812	1423	3650
1982	5	75	1212	758	1639	3689
1983	0	0	1241	751	1649	3641
1984	0	0	905	806	1750	3461
1985	0	0	606	799	1580	2985
1986	0	0	455	837	1656	2948
1987	0	0	409	856	1684	2949
1988	0	0	362	834	1739	2935
1989	0	0	242	653	1261	2156
1990	0	0	64	269	328	661
TOTAL	1185	812	10606	8761	18375	39739

Table 1. 3

LIFE CYCLE COST SUMMARY DATA
SCENARIO 32 - TYPICAL TAOS AND TUG, 1979 IOC
SPACE SHUTTLE SYSTEM
(MILLIONS OF UNDISCOUNTED 1970 DOLLARS)

FISCAL YEAR	NON-RECURRING COSTS LAUNCH VEHICLE RDT&E INVEST.	PAYLOAD RDT&E	RECURRING COSTS LAUNCH	PAYLOAD	TOTAL
1972	17	0	0	0	17
1973	230	0	0	0	230
1974	504	0	0	0	504
1975	756	28	0	0	784
1976	978	90	0	0	1068
1977	973	411	93	252	1729
1978	939	944	294	814	2991
1979	740	1049	358	976	3122
1980	631	1048	299	1128	3106
1981	466	1136	260	960	2822
1982	420	1089	279	1021	2809
1983	344	1104	269	1057	2774
1984	211	841	234	1195	2481
1985	127	558	315	1028	2028
1986	90	422	414	859	1785
1987	27	400	495	952	1874
1988	0	362	495	1038	1895
1989	0	241	495	989	1725
1990	0	66	495	419	980
TOTAL	7453	9879	4795	12687	34724

that the estimated costs provided in the tables are based on a particular space program known as the reduced baseline mission model with 514 flights, covering the period 1979-1990. The costs of all space missions for the period before 1978 have not been included. Since the new Space Shuttle System is not expected to be available before 1979, these earlier missions would have to be accomplished by an expendable system regardless of whether a new Space Shuttle System is to be developed or not.

The current expendable system exemplified a typical space program along the lines of present knowledge and reflects the potential of space applications in the 1980's. The cost data of such a system are presented in Table 1.1 . In our cost effectiveness analysis, the other systems were required to compete against this known technology. The major systems considered are a new expendable launch system, that includes major modifications and adaptations of payloads to better provide for the needs of space transportation in the 1980's, and the Space Shuttle System, in this case particularly, the TAOS. Table 1.2 shows the comparable life cycle costs, non-recurring costs as well as recurring cost data for the new expendable transportation system which basically represent an extended Titan III system adopted for both lower payloads as well as very large payload launch requirements. Finally, in Table 1.3, the cost data of a thrust assisted orbiter shuttle system (TAOS) are provided. It must be pointed out that many alternative space programs were also analyzed on a mission by mission and a launch by launch basis, each implying different budget levels and activity levels for the 1980's. We believe that these tables represent a likely, and possibly, somewhat conservative, outlook for the space activities in the 1980's.

In Figure 1.12 the annual launch and payload costs of the new expendable system and the Space Shuttle System are shown for the period from 1972 to 1990 for a typical space program of the period 1979 to 1990. As one can see from Figure 1.12, a considerable part of the space program costs for the space program after 1979 has to occur with either system before the IOC date of 1979. This is due to the fact that payloads to be flown from 1979 on have to be developed and built in part before that time with a usual lead time of between 3 and 5 years for individual payload programs. Similarly, the

SPACE PROGRAM COSTS FOR 1979-1990 OPERATIONS WITH AND WITHOUT SPACE SHUTTLE DEVELOPMENT

(TAOS-CONFIGURATION, REDUCED MISSION MODEL-514)

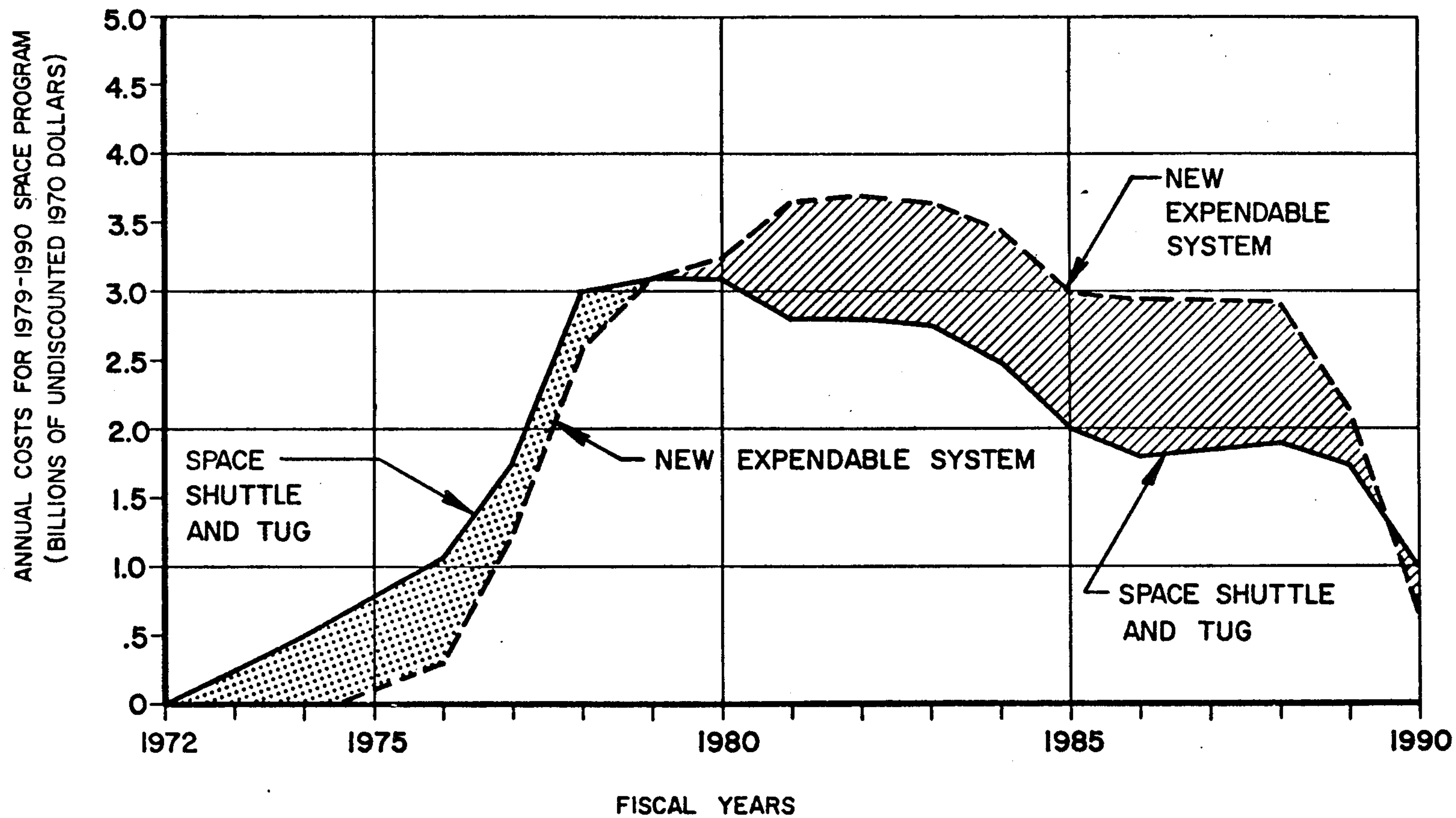


Figure 1.12

necessary launch site as well as new expendable or shuttle payload fleets have to be developed. It is therefore only the shaded area representing the budget difference between the new expendable system and the Space Shuttle System in the period before 1979 that shows the potential net budget impact of the Space Shuttle decision on the NASA budget requirements in 1970 dollars. On the other side, the shaded area of the 1980's shows the net cost difference that a Space Shuttle System would imply for a national space program in the United States along the activity lines outlined in a 514 flight program. It is the expected cost savings in the 1980's and beyond that have to justify the net investment cost outlay implied by a Space Shuttle System, in this case the TAOS system of the 1970's. The overall economic margin within which such a decision will have to be made was fully reported in the May 31, 1971 report.

However, by inspection of Figure 1.12, it is also apparent that all the costs shown are only related to a space program after 1979. Between 1972 and 1979 a continuing space program of NASA is of course planned and will take its course within very limited and very restricted budget considerations. The overall question was, as formulated in the May 31, 1971 report, whether the additional expenditures, or "hump" problem of the Space Shuttle decision could be important with regard to the NASA budget. As a result of this effort, we have undertaken an analysis of the net impact of a Space Shuttle decision. In Table 1.4 the cost differences between a Space Shuttle System and a new expendable transportation system are shown from the years from 1972 to 1990, in terms of millions of 1970 dollars. In Figure 1.13 the net cost differences between the Shuttle System and the new expendable system are shown again for the years 1972 to 1990. We take into account that considerable expenditures, mainly associated with the development of new payloads, are also associated with the new expendable or a current expendable system for a space program starting in 1979 and lasting until 1990. A fully operational space program (launch vehicles, payloads and operations) from 1979 to 1990 implies substantial expenditures before 1979 and a gradual tapering off of expenditures for the period 1988 to 1990, as shown in Figure 1.12. This tapering off of costs and benefits

Table 1.4

TOTAL FUNDING REQUIREMENTS UNDER ALTERNATIVE STS, AND DIFFERENCES FOR 1979 - 1990 U. S. SPACE PROGRAM (NASA AND DOD) (MILLIONS OF UNDISCOUNTED 1970 DOLLARS)

	Space Shuttle	Current Expendable		New Expendable	
	Budget	Budget	Difference = SH-CE	Budget	Difference = SH-NE
1972	17	0	+ 17	0	+ 17
1973	230	0	+ 230	0	+ 230
1974	504	0	+ 504	0	+ 504
1975	784	88	+ 696	98	+ 686
1976	1068	285	+ 783	315	+ 753
1977	1729	1219	+ 510	1265	+ 464
1978	2991	2644	+ 347	2610	+ 381
		IOC DATE OF SPACE SHUTTLE SYSTEM			
1979	3122	3312	- 190	3132	- 10
1980	3106	3604	- 498	3244	- 138
1981	2822	3862	-1040	3650	- 828
1982	2809	3943	-1134	3689	- 880
1983	2774	3853	-1079	3641	- 867
1984	2481	3673	-1192	3461	- 980
1985	2028	3178	-1150	2985	- 957
1986	1785	3168	-1383	2948	-1163
1987	1874	3142	-1268	2949	-1075
1988	1895	3128	-1233	2935	- 947
1989	1725	2267	- 542	2156	- 431
1990	980	683	+ 297*	661	+ 319*
TOTAL	34,724	42,049		39,739	

* The costs shown in this table refer to the complete life cycle costs of a 1979 to 1990 Space Program. From 1988 to 1990 this program comes to an end. In 1990 no payloads are refurbished or updated, nor are new payloads developed (for 1990!), thus showing again an advantage for expendable systems. Of course, if we have a Space Program also in the 1990's, the advantage of the Space Shuttle would continue to hold.

around 1990 makes the data for these years somewhat misleading. The true expenditures in these later years would be at about the same level as the mid 1980's, but most of them would be associated with flight programs in the 1990's and can therefore not be included in 1979 to 1980 Space Program costs and benefits. The overall net cost impact between a Space Shuttle System and an expendable system is considerably less than the overall development cost and investment cost of the Space Shuttle alone would indicate. It is this net cost impact that is really associated with the option of developing or not developing a Space Shuttle System and not the absolute costs of the Space Shuttle System as shown in the life-cycle cost of Table 1.3. Notice that cost streams as shown in Tables 1.1 to 1.4 as well as Figures 1.12 and 1.13 do not include any allowance for space expenditures in the 1970's that are related to the space program of the 1970's.

In order to assess the impact that a Space Shuttle investment might have in addition to the potential NASA expenditures for the 1970's, we attempt a completely new approach in order to determine or project what the likely NASA budget might be in the 1970's. As reported already in the May 31, 1971 report, there are many factors that affect the budget of an agency like NASA and that determine the amount of space activities that a nation like the United States can carry on. The past NASA budget and the development of the trends of the appropriations for its individual offices are only some of the many variables that influence such a decision and outlook. There are several other very important economic variables that also determine the overall level of NASA budget projections and of the national space activities in the United States. Among these, general economic conditions and, in particular, the overall level of federal purchases of goods and services as well as monetary conditions (e.g., the rate of inflation) have important, though indirect, effects on the ultimate budget that NASA may expect. In addition, there are political decisions (as for example the decision to land a man on the moon in the 1960's) and institutional considerations. Nevertheless, in Chapter 7 we tried to develop a macro-economic explanation of the expected NASA budget if only economic conditions were to determine

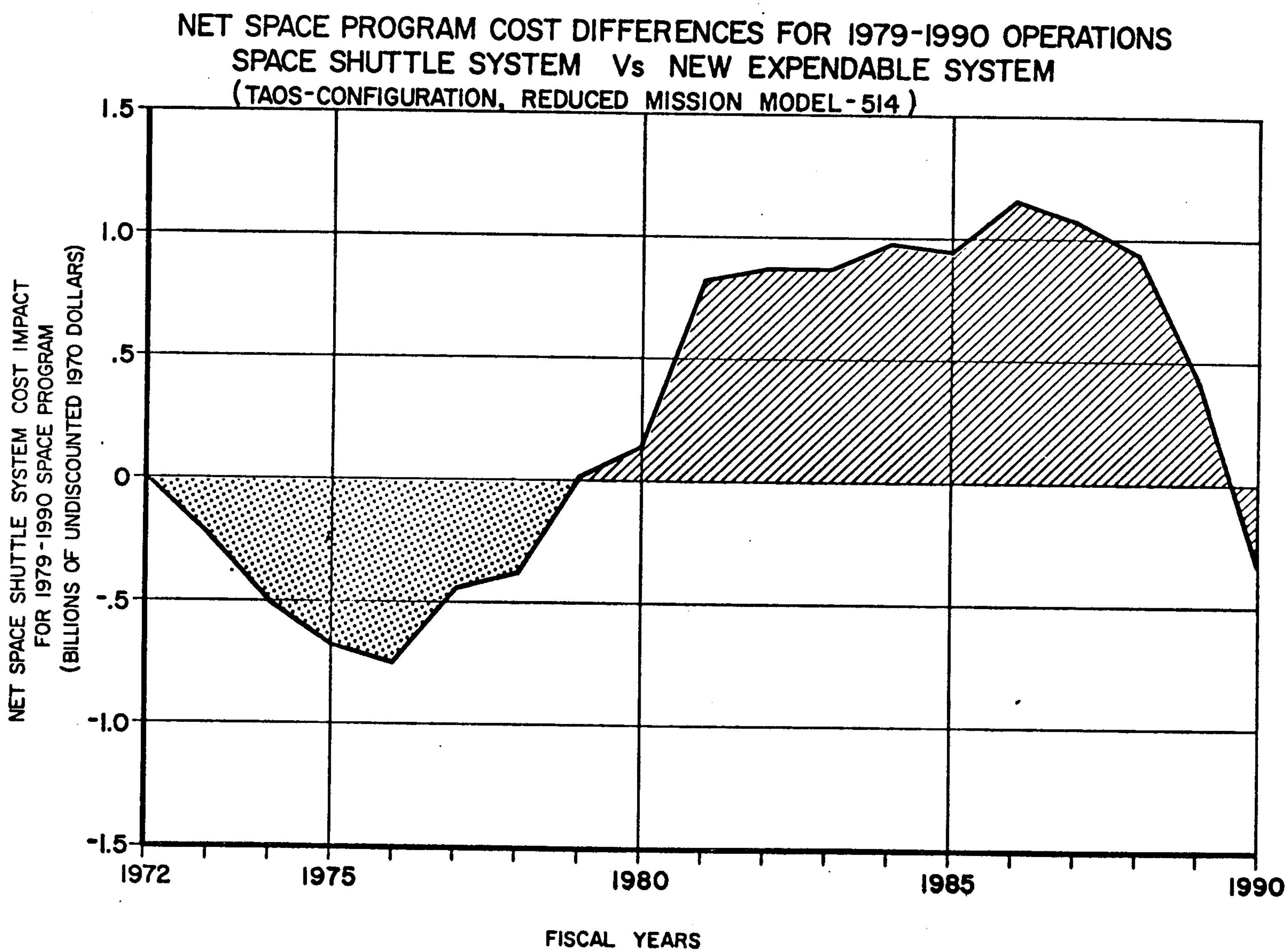

NET SPACE PROGRAM COST DIFFERENCES FOR 1979-1990 OPERATIONS
SPACE SHUTTLE SYSTEM Vs NEW EXPENDABLE SYSTEM
(TAOS-CONFIGURATION, REDUCED MISSION MODEL-514)
NET SPACE SHUTTLE SYSTEM COST IMPACT
FOR 1979-1990 SPACE PROGRAM
(BILLIONS OF UNDISCOUNTED 1970 DOLLARS)
1.5
1.0
.5
0
-.5
-1.0
-1.5
1972
1975
1980
1985
1990
FISCAL YEARS

Figure 1.13

the NASA budget in the 1970's, taking into account the past history of the NASA budget in the 1960's.

To a large extent, the formulation of a long-range program, like that of NASA's space program, must necessarily rely on our knowledge of the two-way relationship between the national economy in general and space activity in particular. Furthermore, whether a particular long-range space program can be successful depends largely on our ability to gain such knowledge and to apply it to obtain reliable forecasts of economic conditions and space activity. If plentiful resources are available, space activities can be expected to increase. If on the other side, the demand for national resources is high when compared to their availability due to the existence of many other national priorities, the general level of space activity can be expected to be less than under the first hypothesis. It must be realized however, that an economic analysis would naturally have certain limitations since it does necessarily involve numerous simplifications.

Despite these limitations, we hope to have demonstrated that macro-econometric approaches to projecting national space expenditures can provide useful information for a rational long-range planning of space exploration. In order to project expected space expenditures, as a function of economic conditions in the 1970's, a macro-econometric model has been formulated. Emphasis has been placed on the possible influence of economic conditions of the level of the space budget. Furthermore, we have also attempted to show how the future economic conditions may be affected by different fiscal and monetary policies. By investigating the possible relationship between the level of the space budget and economic conditions, which to some extent may be affected by governmental fiscal and monetary policies, we hope to have demonstrated that a suitably formulated micro-econometric model can be useful for investment decisions in long-range planning for various agencies of the federal government such as NASA.

The macro-econometric model implemented in the present report is a dynamic system of 28 equations which includes 8 equations for the government sector dealing with both receipts and expenditures. In addition, this system of equations includes not only the relationships of production, consumption, and investment activities, but also the relationship of wage and interest determination and personal income as well as corporate profit. The econometric model with the parameters estimated from annual observations from 1929 to 1941 and 1947 to 1964 was evaluated by comparing several alternative simulations with the observed values from the period 1965 to 1970 and found to be reasonably satisfactory. In particular, the simulation results of the government sector were found to be significantly superior to those of trend extrapolation of a more conventional single equation model. Following the evaluation of the model, several alternative simulations were made for the period 1971 to 1980. Both short term and long term projections as well as the implications of alternative fiscal and monetary policies appear to be quite reasonable.

Finally, the alternative simulations for the period 1971 to 1980, representing expansionary, neutral, and restrictive policies, respectively, were then used to project the future space expenditure. In order to achieve this purpose, we demonstrated that the level of current space expenditure may be explained not only by the level of past space expenditure but also by the level of government spending in general and other economic conditions such as the rate of inflation. Based on such an additional empirical relationship obtained from the annual observations of 1958 to 1969 together with alternative simulations of the econometric model, several alternative projections of the level of space expenditure were provided for the period 1971-1980. It is found that under the expansionary policy with relatively high rates of inflation the projected level of space expenditure is generally lower than that of the alternative restrictive policy. According to the neutral policy, the level of space expenditure is expected to rise gradually from $3.3 billion in 1971 to $4.1 billion in 1980 (in terms of 1970 constant dollars). According to the expansionary and restrictive policies, the level of space expenditure is projected to rise from $3.2 billion in 1971 to $3.7 billion and $4.6 billion respectively in 1980 (again, in terms of 1970 constant dollars). Among the alternative projections, the results of the most conservative projection (in 1970 dollars) from 1972 to 1980 are shown in column 1 of Table 1.5.

Table 1. 5

IMPACT OF SPACE SHUTTLE DEVELOPMENT ON
NASA BUDGET OR ACTIVITIES
1972 - 1980
(IN BILLIONS OF UNDISCOUNTED 1970 DOLLARS)

FY	Projected Space Expenditures, (1970 dollars) (1)	Difference SH/NE (2)	Maximum Expected NASA Exp. (3) (1) plus (2)	Budget of Rest of NASA if (1) is max. (4) (1) minus (2)	Projected Inflation Rates
1972	$ 3.20	$ .02	$ 3.22	$ 3.18	3.22 %
1973	2.91	.23	3.14	2.68	3.46
1974	2.88	.50	3.38	2.38	3.56
1975	2.91	.69	3.60	2.22	3.55
1976	3.02	.75	3.77	2.27	3.48
1977	3.10	.46	3.56	2.64	3.56
1978	3.30	.38	3.68	2.92	3.44
1979	3.48	-.01	3.47	3.48	3.51
1980	3.70	-.14	3.56	3.70	3.48

As seen from these projections, the budget of NASA would not vary substantially around an average of $3 billion in the 1970 period with initial projections of slightly below $3 billion using 1970 dollars ($2.91 for 1973 and $2.88 for 1974). We once again stress that this restricts itself to economic factors. However, the inclusion of several possible economic futures will hopefully account for political considerations implicitly.

In analyzing the impact that a Space Shuttle System would have on such a projected NASA budget level, two alternate extreme approaches are possible within which the decision would have to lie: first, the total net cost impact of a Space Shuttle development may be added to the projected NASA budget, considering the previous projections as the levels that one could anticipate without such a major decision like the Space Shuttle System development. Column 2 of Table 1.5 shows the cost difference of the Shuttle over the new expendable development in the 1970 period for the space program between 1979 and 1990 as shown in the previous tables. This column, when added to column 1, gives the maximum expected NASA expenditures in column 3 of Table 1.5 . This would be the maximum expected budget even with a Space Shuttle development of the type of a Thrust Assisted Orbiter Shuttle analyzed and identified in the previous sections. As shown, any of the projected budgets for the 1970 period would not exceed $3.77 billion. Of course, the closer one gets to the year 1979 the more of the total NASA budget will be taken up by activities that go to the planning, preparation and initiation of programs beyond 1979 as shown in the previous tables. On the other side one could also take the other extreme view regarding the projected space expenditures shown in column 1 of Table 1.5 as the absolute maximum that NASA can expect with or without a Space Shuttle System. In this case, the net cost impact of the Space Shuttle would have to be subtracted from the projected space budget as shown in column 1 in order to arrive at the remaining resources that NASA will have after an affirmative decision on the Space Shuttle is made. The remaining budget for other operations, therefore, is shown in column 4 of Table 1.5 . It also implies the margin that NASA is giving up for the period before 1979 with a development of a Thrust Assisted Orbiter Shuttle. Again, a substantial part of this budget will be taken up in the later years of the 1970's for activities and missions that have to do with space programs in the period of 1979 and beyond. The net impact of the Space Shuttle decision, however, is again only the net cost difference between the Space Shuttle and the new expendable system since both of these try to meet equal capabilities as projected for the 1980's.

The economic projections of the NASA budget as well as the mission model used to analyze the Space Shuttle decision lend themselves to surprisingly strong conclusions. Since the mission model analyzed for the 1980's was done with activities of the 1960's of the unmanned space program as a baseline, one would have expected some agreement among the projected space budget activities of NASA and the activities in the 1980's. Yet the close agreement and relative stability of the NASA budget for the 1970's which were arrived at on an econometric statistical basis and the 1980's budget under the new expendable system which were arrived at by a mission by mission and launch by launch planning basis lend very strong support to the economic conclusions drawn here. Figure 1.14 shows on one side for the 1972 to 1980 period the projected budget level under the new expendable system of space transportation and the activity and mission models as given to us from the space program of the United States for use in this analysis.

Of course, many external factors will influence the overall level of the NASA budget in the 1970's as well as the level of U.S. space activities of the United States in the 1960's. If a decision is made to go ahead with a substantial manned program for the exploration of the moon or the planets in the 1980's, then these manned space flight activities would have to be added to the projected alternative space budgets (Shuttle versus New Expendable) for the 1980's as shown in Figure 1.14 . Similarly, other factors could influence the projected U. S. space activities in the 1980's either through new technological developments, international developments, or a decision to forego any manned space flight. Within these projected alternatives, we regard the space budget shown in Figure 1.14 to be conservative.

If alternative one in the previous discussion of the impact of the Space Shuttle were taken as the baseline, i. e., the net impact is added to

MACRO-ECONOMETRIC BUDGET PROJECTIONS, 1972-1980
Vs
LEVEL OF SPACE ACTIVITY IMPLIED BY 514-FLIGHT MISSION MODEL

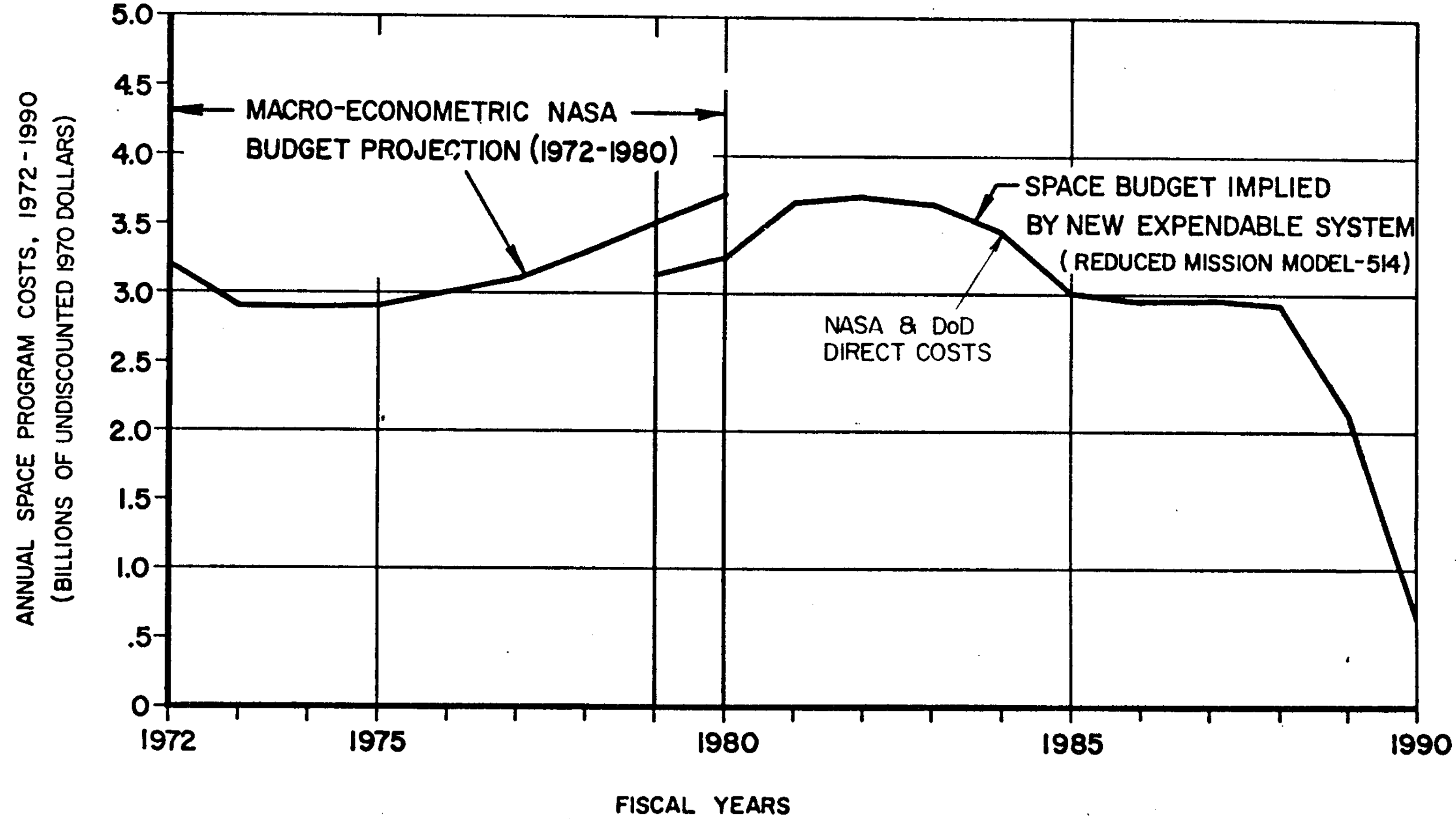


Figure 1. 14

the original projections of NASA budget, then Figure 1.15 clearly shows such a consequence. The figure shows first, the projected space budget for the period from 1972 to 1990; second, the net impact by adding the differences of the Space Shuttle System over the new expendable cost system for the period of 1972; and third, the part of the NASA budget taken up, in the 1970's, by the Space Shuttle System and payload development required for the space program for the period 1979 to 1990. As shown in Figures 1. 15 through 1. 18 a decision to build the thrust assisted orbiter shuttle in the 1970's would not impact dramatically on the overall level of space expenditures, as was previously the case with the two-stage Space Shuttle System analyzed in the May 31, 1971 report. In Figure 1.16 , the total of the funds taken up in the 1972 to 1980 period by the Space Shuttle development as well as the payloads for the 1979 to 1990 period are shown separately. In no case do the anticipated program costs in both the launch vehicle developments as well as payload cost developments exceed the econometrically projected space budget for NASA in this period.

If the other view were taken, that is, the economic projections of the NASA budget are the maximum funds that NASA can expect within the present environment of the United States economy, a hypothesis not at all unreasonable, then the net cost impact of the Space Shuttle decision on the NASA budget is shown by Figures 1. 17 and 1. 18. The total net cost difference is subtracted from the projected space budgets of NASA for the period of 1972 to 1980. Again, the dotted line in Figure 1. 18 shows the total funding that the Space Shuttle as well as the development of the payloads for the 1979 to 1990 period would take up out of this total. Again, a compatibility is found between the econometric projections of the possible NASA budget in the 1970's as well as the detailed cost estimates for the Space Shuttle System and the required payload development for the 1979-1990 period. All the other activities of NASA, of course, would have to be financed out of the remainder between the total projected NASA budget and the total Space Shuttle development funds as shown in Figure 1. 18. In each case, that is either Figures 1.15, 1.16, 1.17, or 1.18, the projected budget for the 1980's is shown for the New Expendable System and the Space Shuttle System assuming an

IMPACT OF TAOS SHUTTLE DEVELOPMENT WHEN NET COST DIFFERENCE IS ADDED TO PROJECTED NASA BUDGET FOR 1972-1980 PERIOD — 1970 DOLLARS

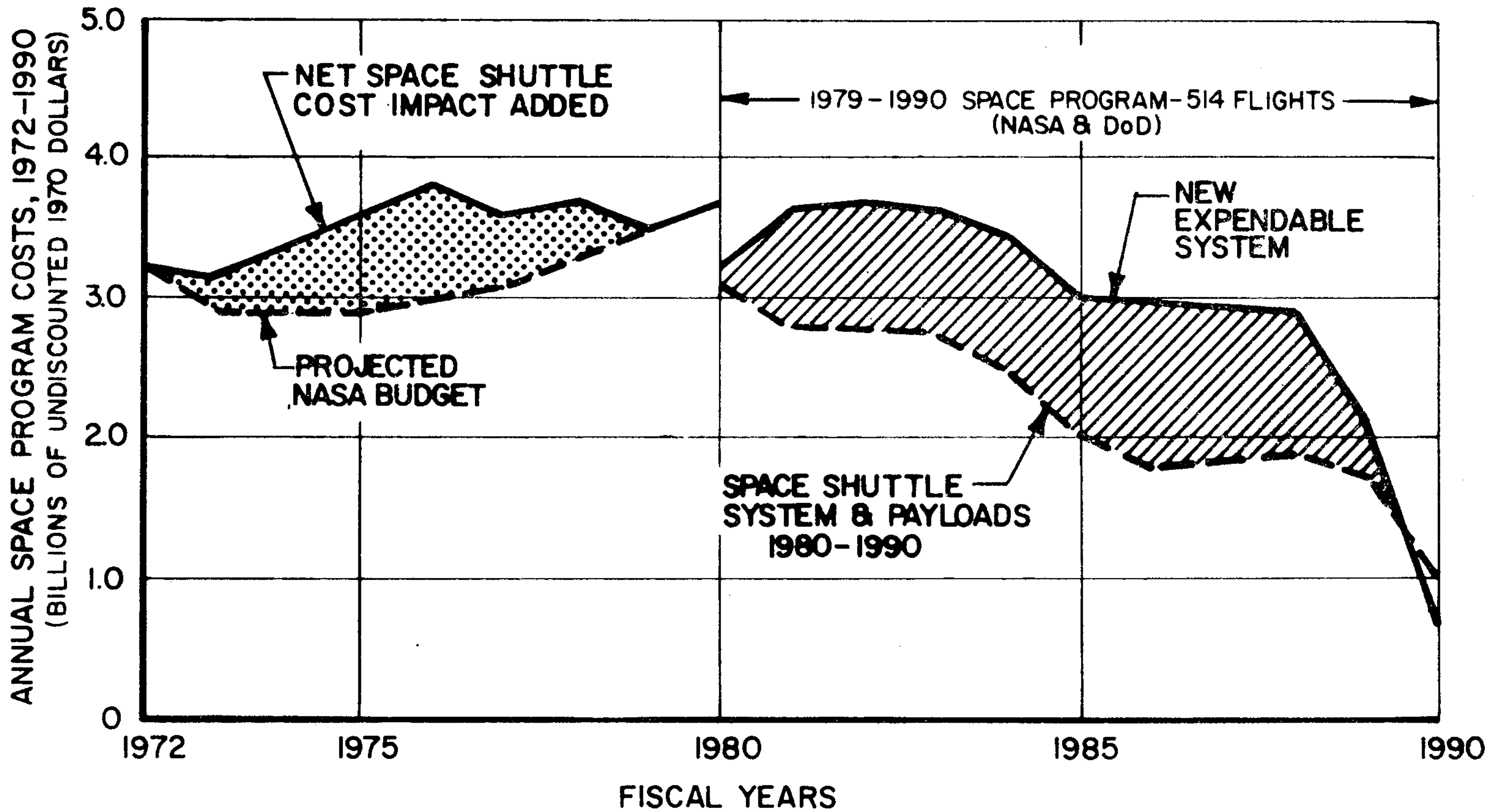


Figure 1.15

IMPACT OF TAOS SHUTTLE DEVELOPMENT WHEN NET COST DIFFERENCE IS ADDED TO PROJECTED NASA BUDGET FOR 1972-1980 PERIOD— 1970 DOLLARS

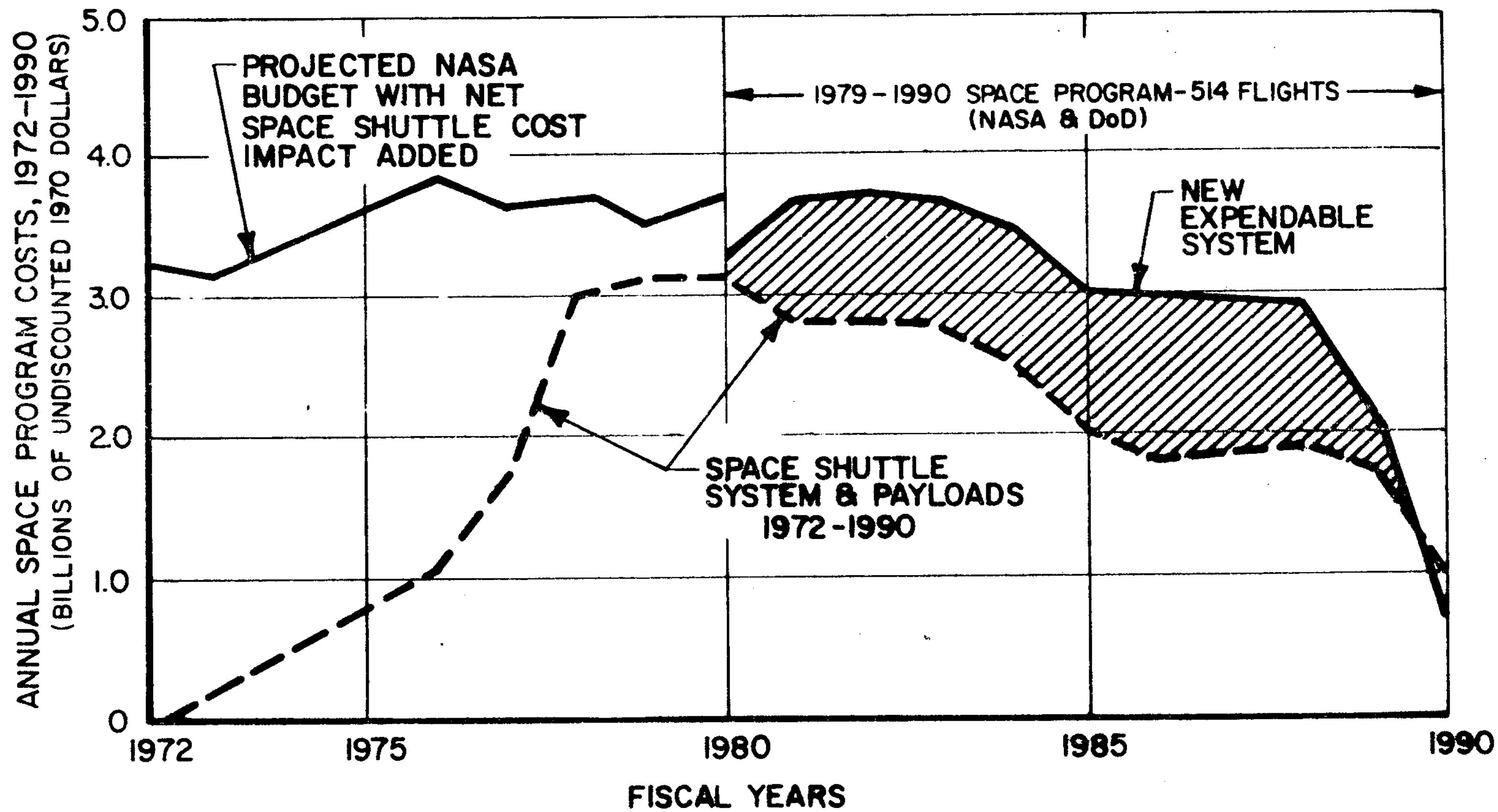


Figure 1.16

IMPACT OF TAOS SHUTTLE DEVELOPMENT WHEN NET COST DIFFERENCE IS FINANCED <u>WITHIN</u> PROJECTED NASA BUDGET FOR 1972-1980 PERIOD-1970 DOLLARS

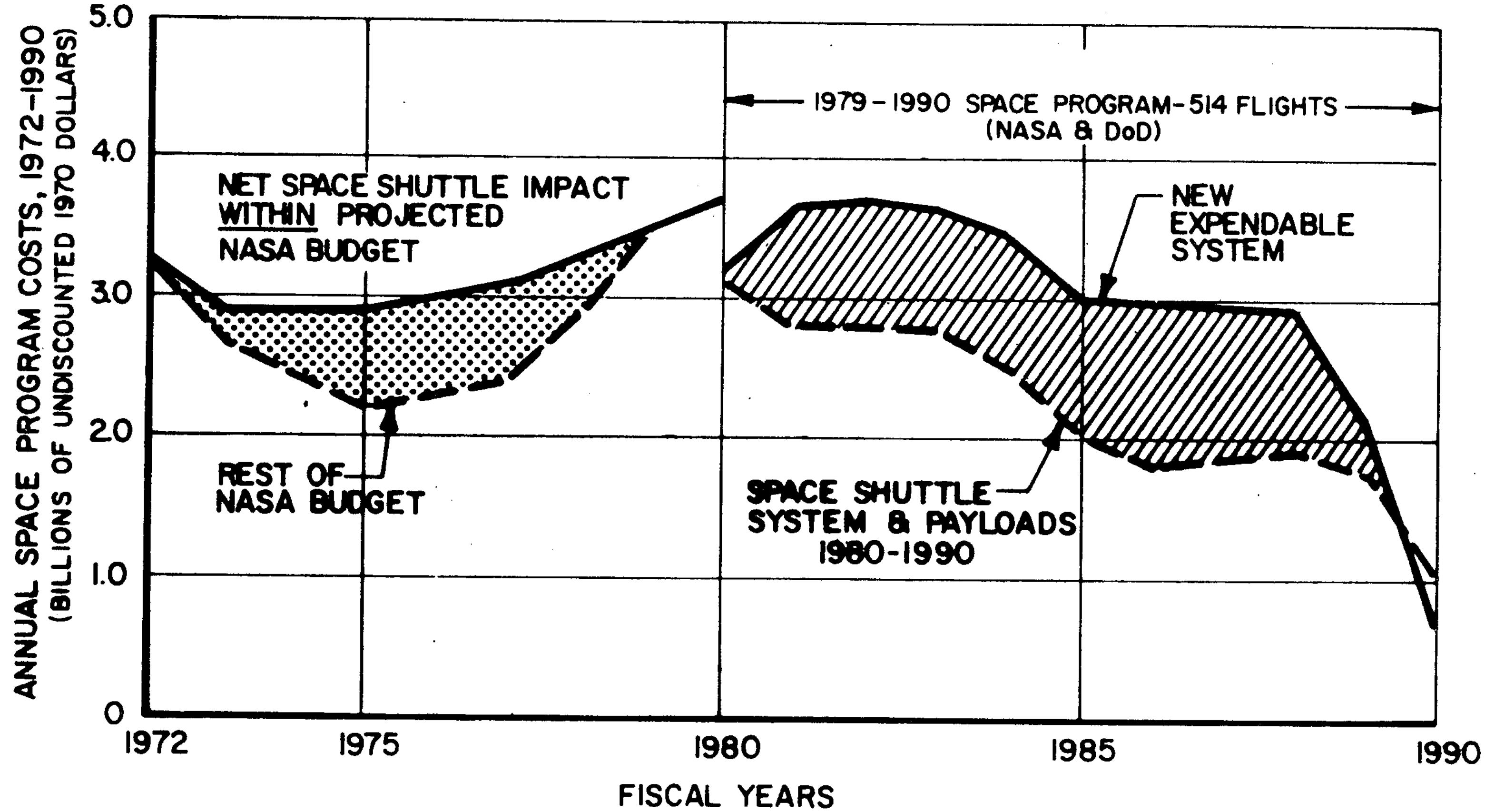


Figure 1.17

IMPACT OF TAOS SHUTTLE DEVELOPMENT WHEN NET COST DIFFERENCE IS FINANCED WITHIN PROJECTED NASA BUDGET FOR 1972-1980 PERIOD -1970 DOLLARS

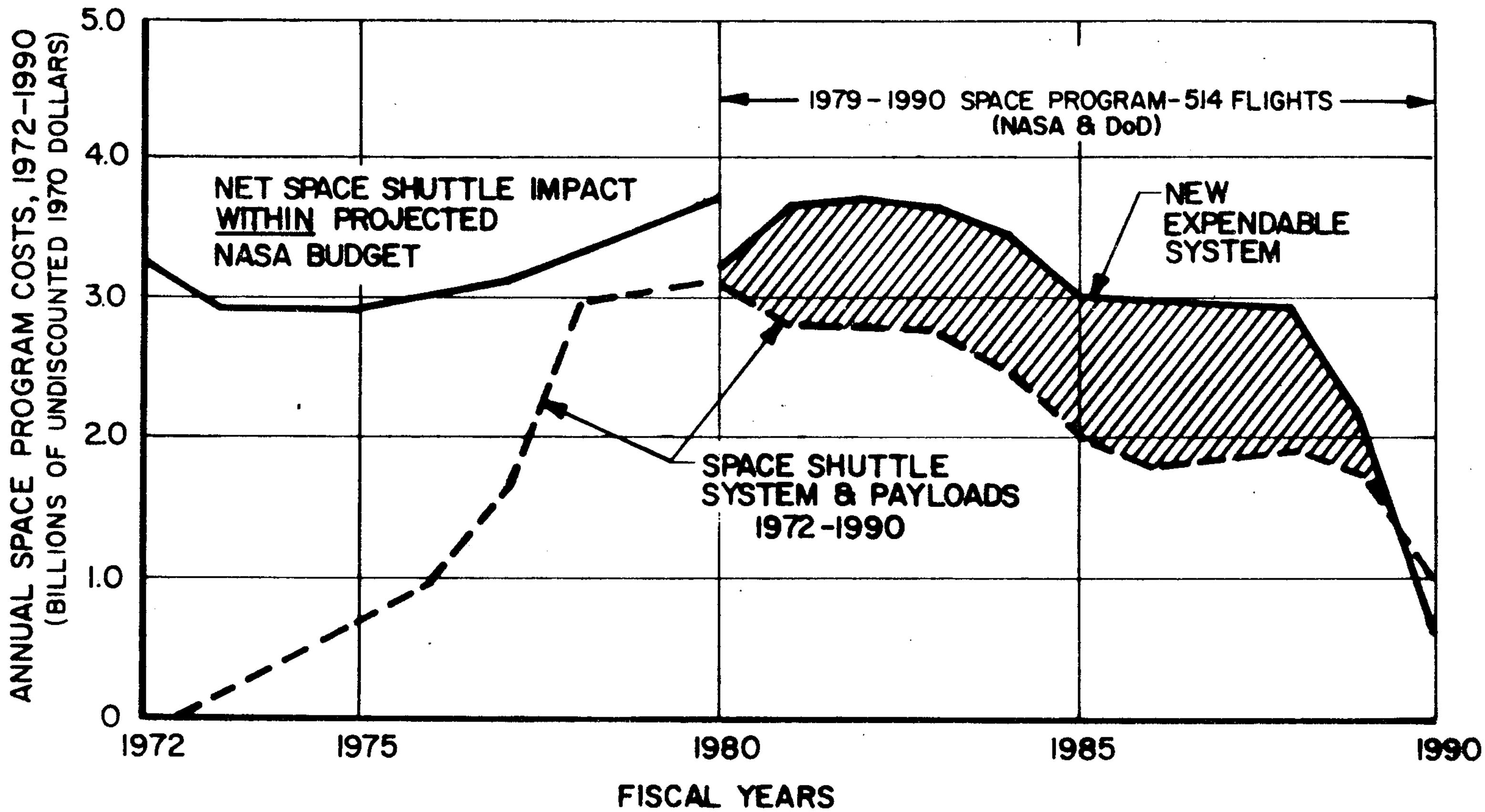


Figure 1.18

equal capability approach. The difference, i.e., the direct cost savings expected from a Space Shuttle development is shown by the shaded area. It is the cost savings that justify the added outlays and expenditures in the 1970 period for the Space Shuttle development.

While in the May 31, 1971 report, the total non-recurring cost of a Space Shuttle System development of $12.8 billion or more was a considerable problem with regard to the NASA budget required in the 1970's, it now seems that a development of a TAOS Space Shuttle System, including a Space Tug and the required launch sites, may well be within reasonably projected budgets for space activities in the 1970's and 1980's.

Thus, the crucial questions that remain are:

First, what are the expected levels of space activities in the 1980's beyond or possibly below those projected in the present mission models for NASA (The Office of Space Science, the Office of Applications, the Office of Manned Space Flight), the Department of Defense, commercial applications and potential foreign demand for United States space transportation services. It is ultimately these objectives as exemplified by past as well as future expected space activities that go to justify the development of a new, reusable Space Transportation System. If the activity level in the 1980's or beyond were to increase substantially, the development of a fully reusable Space Transportation System(i.e., using a reusable Flyback booster) in the 1980's or 1990's may be justified, again on a cost-effectiveness or benefit-cost basis.

Second, the choice of the most economic booster assist remains open. Among the alternate configurations identified to lie within the region of the most economic Space Shuttle configurations, there remain uncertainties as to the most economic booster that should go with the development of the orbiter. The choice seems now to lie between three alternate, substantially different systems, all of which should not influence the basic orbiter decision: (1) a (Twin) Parallel Burn Solid Rocket Motor Booster System, (2) a (Twin) Parallel Burn Pressure Fed Booster System, (3) a Series Burn Pressure Fed Booster.

Overall, it seems that a minimum non-recurring cost program and minimum technological risk program for the 1970's will favor a Solid Rocket Motor Thrust Assisted Orbiter Shuttle System. On the other side, pressure fed systems of either the twin pressure fed type or the series burn pressure fed boosters may be justified if the technological risks as well as the higher non-recurring costs are justified by confidence in the estimated lower costs per flight and higher activity levels in the 1980's. Thus, the ultimate decision among these boosters is an economic tradeoff decision among non-recurring costs, development risk, activity level, and the level of the social rate of discount (the opportunity cost of economic funds) in the 1970's and 1980's.

CHAPTER 2.0

THE INVESTMENT DECISION PROCESS OF NEW SPACE TRANSPORTATION SYSTEMS

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CHAPTER 2.0

THE INVESTMENT DECISION PROCESS OF NEW SPACE TRANSPORTATION SYSTEMS

2.0 Preface

This chapter is a revised version of Chapter 3 of the May 31, 1971 report, "Economic Analysis of New Space Transportation Systems". Some of the quoted numbers have been changed in this revision. In particular, the Space Shuttle System identified as the most economic version -- or the Thrust Assisted Orbiter Shuttle (TAOS) -- has substantially reduced non-recurring costs in the research and development phase as well as the initial investment phase. Yet, the major points made in the May 31, 1971 report remain valid, and are therefore quoted again, with emphasis. The substance of this chapter remains unchanged and gives the framework within which the economic analysis was carried out.

2.1 Goals of the Space Program

In this chapter we propose to raise a number of fundamental issues which present themselves in connection with the task assigned to MATHEMATICA. The task is to determine with reasonable reliability the probable economic costs and benefits of various new forms of Space Transportation Systems (STS's) which may become technically available during the next decade and beyond. The problem is one of decision making for large scale government investment in a new technology under conditions of uncertainty. The decision-making process is long and complicated. There are many forces at work representing conflicting interests and attitudes. Information about future costs and benefits is difficult to establish, but a sincere effort has been made to arrive at as good figures and numbers as can be had. However, uncertainty, being one of the fundamental characteristics of existence, can never be fully removed, either here or elsewhere. To make a decision is to choose among alternatives. These were exhaustively enumerated for the Space Shuttle System and those not rejected outright must each be examined in proper detail prior to a final decision.

The techniques for evaluating the costs and benefits of feasible alternative systems have been described and were used in the economic analyses in our May 1971 report. The intent there was to find that Space Transportation System which will accomplish certain well-defined missions at minimum costs. The present report extends these earlier analyses and attempts to examine various configurations of several alternative Space Transportation Systems in much greater detail. In particular, many possible configurations of the Space Shuttle Transportation System have been evaluated and the most economical ones identified. The Space Glider System which was not covered in our earlier analysis has also been evaluated in the present effort but proved uneconomical when compared to the TAOS.

Since the time spans over which research and development costs for the Space Shuttle arise -- eight to ten years -- are great by any standard, and since benefits (i.e., the fulfillment of missions at reduced costs) begin to accrue only in an even more distant future and are spread out over many years, it is necessary to bring both costs and benefits to a common point, the so-called Net Present Value (NPV), by using social interest or discount rates. The rates used in discounting may vary significantly from low (4% or less) to high (10% or more) and have a great influence upon the results of the computations as was shown in earlier MATHEMATICA reports [1]. Opponents of a project will want to use high rates; advocates, low rates. Also, high rates indicate a relative scarcity of resources, while lower rates indicate relatively fewer claims made on public monies. In addition, a high discount rate can reflect relatively greater urgency than does a lower rate. In business such differences in the rate selected are less pronounced because of the information provided by the investment market which largely determines when an investment is rational. But in government the rates used often differ substantially from one public investment (agency or department) to another. The choice of rate is thus frequently the outcome of a game played by the various parties involved in the decision-making process. Such are the procedures that accompany the objective evaluation of cost and benefit calculations. The impact of these differences is clearly shown in Chapters 1, 3 and 8.

Whatever the result of computations of the above nature, they do not suffice by themselves to arrive at decisions as to what is to be done. That would only be possible if the whole problem would reduce to the question of finding the most economic Space Transportation System. But this question can only be posed when the preliminary questions leading to the alleged need for new systems have been formulated and answered positively.

The principal question is this: <u>What are the goals of space activities</u>? Does their fulfillment require a new transportation system, and, if so, when is it needed? To what extent does the system to be chosen match the goals? In the usual benefit-cost analysis or cost-effectiveness analysis it is difficult to consider such issues adequately. The tacit assumption is that the goals are given, at least within broad limits, and that the choice is only between alternative technical systems implying that all systems under discussion are equally fit to accomplish the given tasks, i.e., to produce the same benefits.

It is true that in both our earlier and the present reports a wide variety of different space programs of the 1980's were analyzed. The programs (Scenarios) ranged from extremely low-level NASA and Department of Defense activities -- well below the levels of the 1960's -- to programs in line with major projections for these agencies. They sometimes included -- and at other times excluded -- manned-space-flight activities although the option of undertaking manned-space flights was maintained in each case. Some programs also included a lunar program allowing for nuclear rocket technology in the operating costs. The analysis was also put into the historical framework of 1965 to 1970 space activities of both the United States and the USSR.

The results of our analyses show a substantial economic margin for reuse, refurbishment and updating of payloads with the new STS. However, even if this were assumed to be true, it does not follow that there is no further interplay between space goals and supporting systems. For example, a given system may reach its optimal point in costs only when a certain use-intensity is postulated, and that intensity may be either too low or too demanding as far as the general goals of the space program are concerned. Also the goals should be spelled out quantitatively, and their economic justifications documented wherever possible.

Certain goals involve entire systems which are embedded in still wider systems so that the capability of these may have to be altered as a result of adjustments in the former brought about by the STS, thereby inducing costs not directly related to transportation. For example, it is conceivable that, in order to make a Transportation System "cost effective", it may be necessary to place so many satellites into orbit that, possible production and scheduling difficulties for satellites notwithstanding, the ground data processing facilities would have to be enlarged far beyond anything now contemplated. These costs must also be considered part of the new venture, particularly in evaluating the potential commercial demand for space transportation. In other words, the Transportation System is only part of the larger system within which it must function. Rigorous cost estimates for this kind of joint supply should therefore also include the interaction of the Space Transportation System with the larger system, and ultimately with the entire United States space program under whose scope fall NASA, the Department of Defense, and many other users. This interaction will tend to be very complicated and thereby requires a thorough analysis that is largely beyond the scope of this assignment. Within the limits of unmanned U. S. space acitivites in the 1960's and early 1970's we have dealt with these complete systems costs. If, as a result of the Space Shuttle development space activities were to expand considerably more, then such additional system effects will have to be allowed for. The detailed NASA mission model used for our analysis is described in Chapter 4.

We state here with emphasis: <u>any investment can only be justified by the goals</u>. This applies to business as well as to government, hence also to NASA. A new STS should not be introduced unless what it is to be used for can be conclusively shown and that these intended uses are meaningful both to those who must appropriate the funds and also to those from whom the funds are raised. These space goals can be political (rivalry with the extensive Soviet Space Program), military (competitive with Soviet military space efforts, and/or for other new U. S. military purposes), or specifically space oriented (scientific space exploration and/or commercial uses of space). All these will, of course, be mixed into one program to various degrees representing a joint demand for space transportation with a varying mix of payloads.

Whatever the true situation may be, it is the direction from the goals downward that must be pre-eminent in the decision process. The economic analysis was carried out strictly within the limits of 1965-1971 U. S. space activities.

However, it should also be recognized that when the possibilities of such a new technology are made known, new goals can come into sight and reach. This may very well be the case with the new Space Shuttle System, but this too requires a demonstration.

Thus, the present goals -- if they are well and clearly formulated at all, will also undergo shifts. Future space activity cannot be judged adequately on the basis of our present technology alone; new goals will have to be projected as well. In many cases even this will be inadequate, since new goals will arise from the scientific discoveries which will surely be made both during the anticipated lengthy development period or perhaps even more so during the first few years of the new Space Shuttle System. Even when this happens, the ultimate justification is always on the basis of the goals, be they recognized or only anticipated, but never solely by technological possibilities. Finally, with a drastic decrease in the incremental (marginal) costs of space transportation, as well as an increase in the reliability of space-based systems, the demand for commercial as well as scientific and military applications of space technology may increase substantially, thereby feeding back into the decision on systems choice and reinforcing the decision to develop a Space Shuttle System.

2.2 Characteristics of Space Programs

The fundamental requirement for the justification of introducing any new Space Transportation System -- and even for maintaining the present one at whatever level of use -- is that there be a clearly formulated space program characterized by the missions. While this is obvious, the task is very difficult to fulfill. We shall not describe or analyze here the various reports (which were used in part in our analyses) in which efforts were made to accomplish precisely this. The goals formulated in those reports were often stated in too general terms and without ranking as to their relative importance, which is insufficient for our purposes, at any rate. We note, however, that the problem of ranking is a very difficult one, both from the analytical as well as from the political point of view. One input needed and provided to us is a detailed program stating, e.g., the number of observation satellites, their expected lifespans, the number of launchings, their spacing over time, the expected costs of satellites, and the scheduling of the different missions. For the purposes of this study, several such programs (the Baseline mission model) without any further ranking -- were given to MATHEMATICA for NASA, the Department of Defense, and other users.

Applied to the Space Shuttle System this means that there must be specific information about the correspondence between the required rate of STS use (i.e., the rate of Space Shuttle use to be cost-effective when compared to the Current Expendable Systems) and the possibility of matching these activity requirements with the number of flights demanded by space exploration. For example, if the Space Shuttle were to require at least 45 flights per year in order to achieve cost effectiveness, is the space program capable of using this many flights in a sensible manner? This is a difficult matter since the Space Shuttle vehicle is precisely that: a vehicle that can accommodate a great variety of satellites, propellants, men, etc., in many combinations. The space program must require at least that many flights, and this requirement must be fulfilled optimally. It is not sufficient that the Space Shuttle makes them possible. In other words, it must be demonstrated that the overall United States Space Program as such demands that many flights at given alternative costs. It would not be proper to justify the Space Shuttle on the grounds that, "it makes so many flights possible". Of course, if there should be a drastic cost reduction per flight for a particular STS -- including the cost of payloads -- new demand may appear as was stated previously and therefore the demand for space flights (and applications) is not independent of the STS choice.

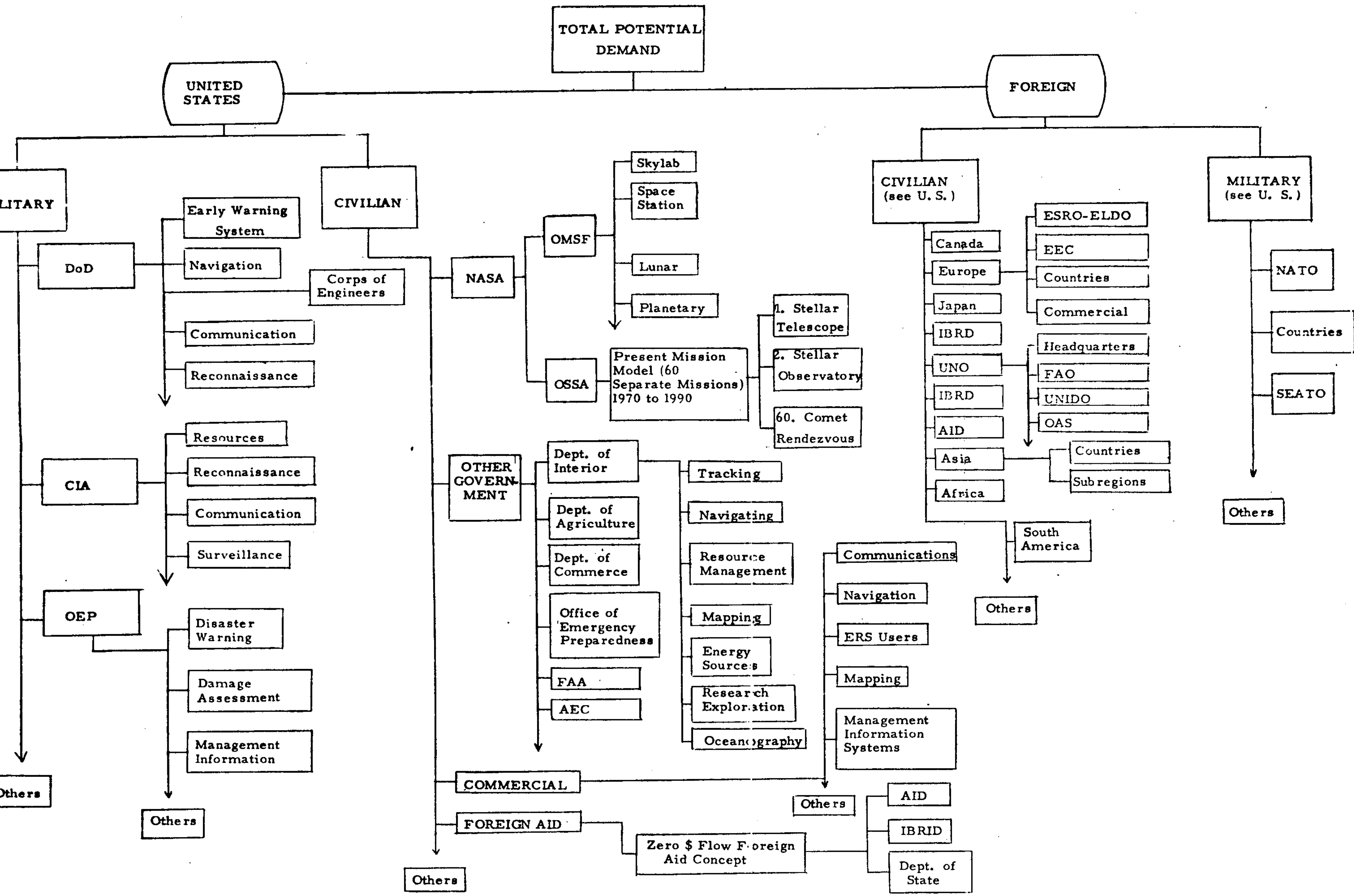
There is some specific information of this kind available. There is also the historical evidence of what the United States, the USSR and other nations did in the 1960's. But more detailed information will help in deciding what reasonable space activities can be expected in the 1980's and beyond in the United States (civilian and defense) and to confirm the reasonable, if not conservative, activity levels used for purposes of our study -- with a low of 400 Space Shuttle flights in the 1979-1990 period, or 34 flights a year. This issue has to be faced squarely as it will unquestionably be raised by those involved in the whole process of decision making and, in particular, for purposes of funding.

The present report, therefore, operates on the basis of the assumption that demands exist for space transportation. This assumption expresses the conservative belief that patterns of the 1960's will at least persist on that level in the 1970's and 1980's, not allowing for the Apollo program. Even in the absence of more information, it is possible to estimate in a general manner what demands might be made and to study their impact on the economics of the Space Shuttle System.

Figure 2.1 on the following page is a classification of prospective uses. This broad classification is clearly incomplete and only intended to be illustrative since by, say, the year 1985, entirely new uses of satellites (and possibly of man) may have appeared. Thus, it is not only a question of the projection of the intensity of the present demands over time (with possibly great fluctuations), but also of predicting new kinds of demand, particularly with the existence of a Space Shuttle System. There may be no new kinds of demands, or there may be some that could overshadow those now listed, leading even to the abandonment of these new kinds of demand since they would be superceded by better uses of the Space Transportation System.

A case in point for the latter possibility is the role of man in space. At present his role is neither proven nor disproven; it is being argued about forcefully, but as yet not conclusively. It is possible that, as instrumentation for automated spacecraft becomes more refined and powerful, there may be less need to have men in space. On the other hand, man in space is a decision maker and active experimenter, with perhaps a special importance for biology. It is also possible that, as technology develops, man may have an easier life in space than he has had so far and that, therefore, his scientific and technological values will increase. There are, at

Figure 2.1 The Potential Demand for U. S. Space Transportation (1971-1990)



present, insufficient indications that either tendency is strong enough so as to advocate with proof that an STS choice should be closely tied to manned operations or should not be so tied.

This is a dilemna, but the Space Shuttle can easily be modified in either direction or be independent of both. Clearly, this will again be a question of costs; they were not considered significant in the present study. In this and the previous MATHEMATICA reports, we have included, therefore, a minimal manned space flight program when analyzing the economic margin for the development of the Space Shuttle System.

At any rate, a new STS should not be tied one way or the other to any present position regarding the role of man in space. This is in full consideration of the fact that the Space Shuttle is frequently even identified (at least by the public) with the construction and operation of large, manned space stations as its primary goal. We exclude the possibility that "man in space" will become once more a political prestige goal in competition with similar activities of the Soviet Union or other countries. In that event normal cost-efficiency calculations are of little avail as the decisions then are of a strictly political character, pushing considerations of costs, as well as scientific benefits, into the background. Such decisions, of course, also have financial bounds but they are of a less significant nature, as was the case when the Apollo program was approved.

The successful development of the Space Shuttle may even do away with the need for a single, large manned space station, given the great orbital flexibility the Shuttle would bring to the space program. On the other side, if Skylab holds exceptional promise, as some scientists think, the Space Shuttle can serve a large space station or several small space laboratories well. However, proof of the advantage of one over the other is needed.

It is not our task to comment even briefly on each of the items included in the above classification. This list serves only to indicate some activities which, when run at different intensities, will have an impact on any future STS. The fundamental point we make, and shall make over and over again, is that the justification of the Space Shuttle System depends solely on the power with which these demands make themselves felt. In viewing the previous classification of the prospective uses of any Space Transportation System, we may note also the fact that there are essentially four categories of users:

(1) Scientific activities (government or civilian)

(2) Government operations (either for civilian, other than scientific, or for military purposes)

(3) Private business

(4) Foreign users (government or business)

Space science involves government operations into which there are private inputs apart from the dominating non-governmental demands of the scientific community to which the government yields. There are also scientific activities that are wholly reserved for the government. Operations under (3) are carried out by NASA though they may be paid in part or fully by private interests or other government agencies (Department of Interior, Department of Agriculture, etc.). Though their importance will rise over the years, especially as the price for missions goes down, they are at present of minor significance. The military uses are secret, though obviously primarily concerned with surveillance; the placement of nuclear weapons into orbit being forbidden by international treaty.

The Department of Defense missions of the 1980's used for the purposes of this analysis cover the major options that the Department of Defense is contemplating for the 1980's. They are not documented in this unclassified report in the detail that would be needed for a full insight into the work done by MATHEMATICA, in cooperation with two other contractors. MATHEMATICA did look at the cost-effectiveness and benefit-cost comparison of alternate STS's of programs in the Department of Defense, as well as those of NASA. In doing so on a mission-by-mission basis, MATHEMATICA confined itself to inputs provided directly or indirectly by the Department of Defense. Essentially, the military planning followed strictly the capabilities of Expendable Space Transportation Systems. Being both military and secret, the Department of Defense's activities may carry comparatively little weight in the present political climate, although they do contribute towards justifying the creation of a Space Shuttle System requiring large investments. On the other hand, the military is usually greatly concerned with marginal differences in established technology, even though these may be very costly to obtain, claiming these differences to be crucial relative to the capabilities of a potential enemy.

This passive -- i.e., financially non-contributory -- participation through highly secret activities of the military is thus a decided drawback for NASA as long as this participation is of major importance and the military makes no contribution to the initial investment. It is reasonable to open up a new general STS to all kinds of users: domestic, foreign, civilian and military. However, the excessive secrecy of military missions is a complicating factor of the first order. It is not easy to determine whether these missions could also be carried out by other methods, whether they are needed at all, or whether these activities should be increased substantially. This leaves a gap in the series of arguments which may speak for or against the Space Shuttle. Not knowing the value of such missions further impairs the justification. In the economic analysis we, therefore, substantially varied the mix and activity levels of the Department of Defense space mission programs for the 1980's. This is also reflected in the results of the economic analysis as presented in Chapters 1 and 8.

It is also possible that, for example, very important civilian earth resources inspection might be able to use the same devices and information the military employs, but cannot do so because of the secrecy shrouding DoD hardware. Thus, there might conceivably be expensive duplications of efforts and there is here a potential undesirable inefficiency. If there are no differences, then there is no need for secrecy. This matter ought to be most carefully analyzed. We do not propose now to develop the various arguments any further.

So there remains the mixed scientific, military and applied fields all in government hands. Here it is a question of how important the government, Congress and the public think pure science is, especially space science. The prospects are not good. It suffices to look at the budget of the National Science Foundation which over the last five years (1964-1970) moved from

$310 million to $490 million, in which last figure allowance should be made for inflation. At the same time, the Federal Budget rose from $119 billion to $185 billion and GNP allegedly from $632 billion to $932 billion. In terms of the proposed budget for Fiscal Year 1972 the basic imbalance is continued: though the proposed budget for the National Science Foundation was increased by $149 million to a total of $516 million, this still represents less than the cost of two Apollo missions of about $350 million each. This cost compares, similarly, with total funds for basic and applied research by the U. S. Atomic Energy Commission of $411 million ($423 million in Fiscal Year 1971). The total proposed government budget for research and development, though, increased in Fiscal Year 1972 by 7.6% to $16.7 billion, a figure slightly above the previous peak funding in Fiscal Year 1967 of $16 billion in current dollars (i. e., before allowing for substantial inflation). If space science activities are ranked purely within this pool of government research and development programs, there may appear to be an overemphasis on space science; if seen in the context of the overall economic resources of the United States, science, research and development may be underfinanced. The total NASA budget, including <u>all</u> of manned space flight, amounted in 1970 to hardly 0.3% of GNP.

The undeniable undercurrent of hostility against science in the country, and to some extent even in Congress and the government, will make it particularly necessary to put forward a strong and convincing case for space science. For NASA, science is -- other pronouncements notwithstanding -- in many ways a side issue, though it should be a primary concern since in the last analysis science is NASA's chief business. Most scientists will not need to be convinced, though, that their relationships with NASA could be greatly improved; they are aware of the enormous debt science owes to astronomy. The recent astonishing astronomical discoveries are heightening further expectations. The mood of the public, however, cannot be turned around very quickly.

A strong case can be made successfully for general benefits derived from communications, mapping, navigation and, in particular, earth resources and other activities. All have potentials that have so far hardly been described and quantified, let alone exploited. We know of no exhaustive, carefully determined economic estimates of probable benefits, or of their distribution over time for different economic activities, regions, countries, etc. For example, NASA services might easily be integrated in United States foreign aid programs via weather forecasting, crop reports, mapping, etc. Such often vital services would not burden the American balance of payments, or even involve noticeable additonal money outlays. A better understanding of these magnitudes -- and they would likely be considerable -- would contribute significantly towards a better evaluation of NASA's activities, especially if they were integrated with a sound estimation of expected uses of future scientific achievements which in their turn would open up new applications so far not calculated or even envisaged.

These operations involve an intertwining of government and private interests, the intricate nature of which ought to be understood and clarified. This would significantly contribute towards a better ordering of NASA objectives and the setting of priorities within the overall NASA program. It is clear that this would influence the NASA budget possibilities within the framework of the Federal budget. If there were clarification in that respect and if it can be shown conclusively how the new Space Shuttle System can be used to take care of the projected goals, the outlook for obtaining the necessary continued funding would be greatly improved.

The determination and ordering of goals thus far discussed relates principally to goals within NASA; i.e., the space agency has to determine what it wishes to do with a fixed amount of money, or how it can claim specific funds from Congress presenting an ordered array of projects. Even when Congress has set an overall amount for NASA, there is the alternative of either letting NASA settle within the organization how various programs should be treated given this total amount, or for Congress to approve individual projects leading up to the same total. The first alternative may be a desirable way for the country to treat NASA. But even then the total amount has to be determined, and it is exceedingly unlikely that any sizable amount -- several billion dollars -- could be fixed without Congress demanding prior information about specific programs and without wanting to decide upon them separately whenever any individual ones are sizeable. The new Space Shuttle System certainly falls into this category. The economic analysis used by MATHEMATICA separated the issue of specific NASA programs for the 1980's and the economic decision on the new STS. The space programs analyzed and evaluated by MATHEMATICA more than cover the expected lower range of space activities by either NASA, the Department of Defense or other outside users. The results of the economic analysis were summarized in a fashion that leaves the issue of what specific programs NASA, DoD, or Congress will decide upon completely open. No built-in bias or assumptions were made by MATHEMATICA with regard to future specific programs. Rather, the economic summary results lend themselves to rational decisions by NASA, and by Congress on whether the Space Shuttle System is justified once the President and Congress, in cooperation with NASA, have decided on a space program for the 1980's.

The range within which an economic justification for a new STS lies is well within very low estimates of space activities in the 1980's, and actually below the level of either United States or USSR space flights in the 1970's. Yet, even this fact does not detract from the ultimate need to be very specific about the goals which the STS is to support. It is our considered opinion that no such firm program of sufficient detail has yet been worked out by NASA. This is by far the weakest point in the entire NASA effort, overshadowing the uncertainties in costs and timing of the new Space Shuttle System.

2.3 Limitations of "Benefit-Cost Analysis"

It must be pointed out that what has been called in our reports a "benefit-cost analysis actually uses the term "benefit" in a very specific and restricted manner: savings in the cost of space programs, both in the launch costs and the cost of payloads. Furthermore, the time pattern of the different missions and their interrelation are crucial in many respects and, a fortiori, this information is also wanting in certainty. MATHEMATICA did use in its economic calculations very specific payload programs for the period 1979-1990. What we question is the accuracy and finality of these specific projections. Furthermore, not only is there considerable uncertainty associated with these specific projections of space programs, but the reliability of the cost data as provided to us by the Aerospace Corporation cannot be determined with complete confidence. It is understood that the Aerospace Corporation has made a considerable effort to obtain the cost estimates which were provided to MATHEMATICA. Despite their best efforts, in view of the difficulty of such a task, we must expect considerable uncertainty to remain in the cost data.

One possible source of uncertainty in the cost data is related to the estimation of the reliability of launch vehicles and payloads. To take the effects of the possible failures of either launch vehicles or payloads into account, the Aerospace Corporation had to increase the operating costs of launch vehicles or payloads by a certain percentage or by a given amount to some space programs. In general, with respect to launch vehicles, the Space Shuttle System was regarded as more reliable than the Expendable System, since the percentage cost increases were from 6.5% to 9% for the Space Shuttle System as compared with 9% for the Expendable System. The treatments regarding the uncertainty of payloads were somewhat different. For the Expendable System, additional costs due to possible payload failures were allowed for all programs without backup payloads and all programs with less than 3 payloads. For the Space Shuttle System, additional costs due to possible payload failures were allowed for all planetary programs, but not for others [2]. To the extent that the estimates of the reliability of launch vehicles and payloads may be subject to errors, the resulting cost data would also involve some considerable uncertainty.

All economic analysis has to be based on the fundamental fact of economics that value does not derive from costs and expenditures embodied in objects or services. <u>Value derives solely from use within a system of preferences.</u> These have to be established and must fit into the overall system of preferences of the nation. In other words, a rational NASA value system must be assumed to exist or must be created. History serves as a useful guide. Contained within the system must be a part which requires and justifies a new STS which when identified as far as its missions are concerned, must then fulfill minimum cost requirements or maximum capability levels for a given budget. This is the only correct way of approaching any economic analysis of a proposal for a Space Shuttle System. There is no way of justifying expenditure on anything, no matter what or where, merely because it is technically possible or otherwise becomes achievable. The system of preferences is not easy to establish and the process of building one is usually subject to many influences. Even when established it may have a complicated structure which may also be subject to change over time.[1]

When there is an open market for services, it is easier to determine the value of new government services. But only a few space applications have a market price, though one must hope that their domain will increase [3]. Public investment for, say, water resources can more easily be evaluated because the need for the water is clear and market prices also exist for different uses.

In the absence of an appropriate measure of benefit, our "benefit-cost analysis" has to measure the "benefit" solely by savings in the cost of space programs. The results of the economic analysis show that the cost levels are nearly proportional to the activity levels. In other words, the return to space activity when comparing Space Shuttle operations to Expendable (Rocket) operations can be characterized by constant returns to scale. By restricting the measurement of "benefit" solely to cost savings of activities planned for (more expensive) Expendable Systems, we have implicitly assumed in effect that no benefits can be attributed to the capabilities and activities peculiar to the Space Shuttle. There are other possible limitations of a benefit-cost analysis which are more technical in nature. A discussion of some of these limitations has been provided in Chapter 3 of this report for readers who may wish to pursue this matter further.

2.4 The Process of Budgeting for Space Expenditures

Figure 2.2 describes the interrelationships among the different phases through which the Space Shuttle System has to pass before receiving final

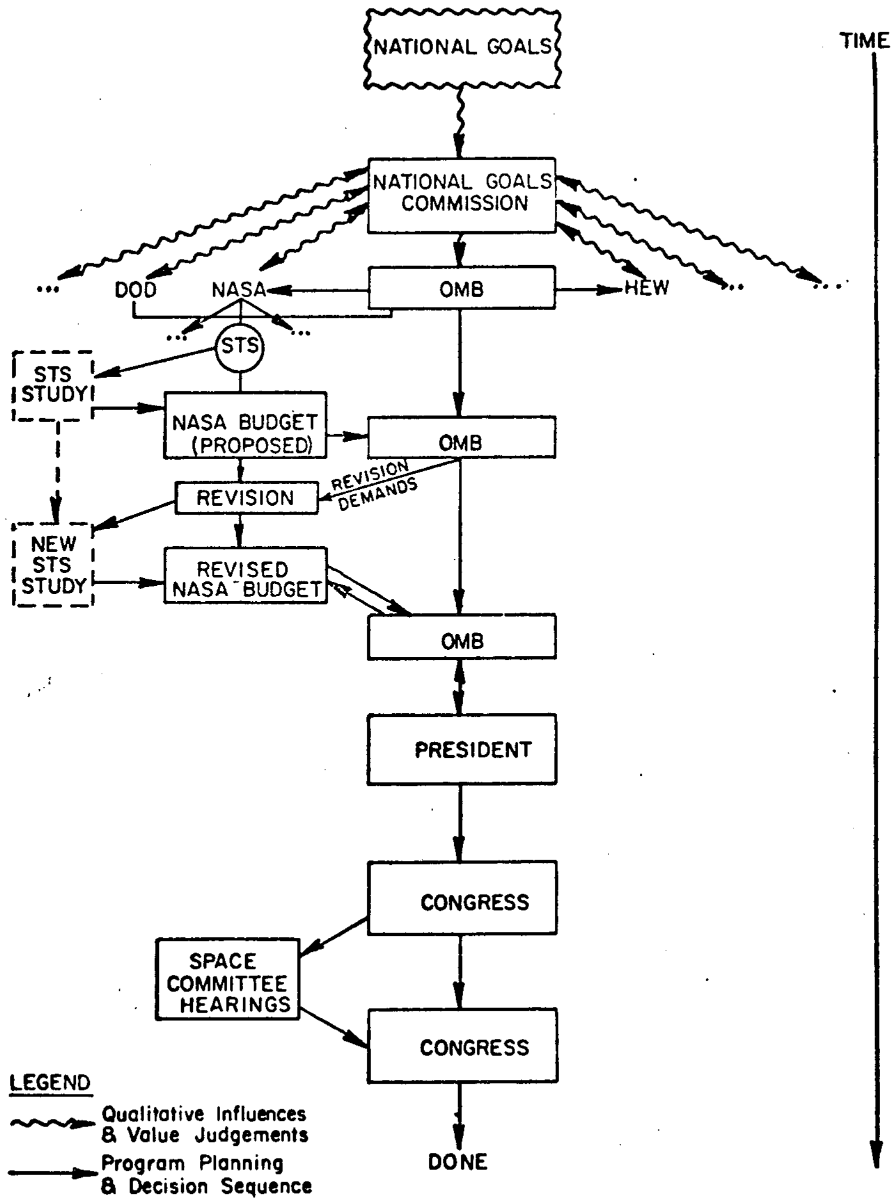


Figure 2.2 The Budget Process

approval or rejection. There are both a time sequence with several feedback loops as well as a logical structure. Inspection of this figure will show where MATHEMATICA's final report does fit the analyses.

The figure shows that national goals must be set. They are, or were, as a rule not very clearly and explicitly formulated, though the National Goals Commission (since dissolved) was charged with this difficult task. It would be absurd to expect NASA to have a clearer picture and better interpretation of national goals than other government agencies. Rather, as with all others, there will be an approximation leading to the sharp formulation of specific NASA programs. In the present study, we must assume that national goals are sufficiently definite to allow the establishment of a preliminary Federal budget. The real process of arriving at a Federal budget is, of course, very complicated. The budget is not the result of a simple direct translation of goals into money terms. Rather, it is the result of a strategic game played among all those who believe they have claims on the nation's resources. The final outcome of that game is reflected in the Federal budget. It approximates what Congress thinks is a fair representation of national preferences and thus a reasonable allocation of national resources. We shall not enter here into the difficult analysis of these processes, although understanding them would be of crucial importance when the various departments and agencies of the government wish to determine their optimal strategies in budget making.

Having stressed the game nature of budget formation one can nevertheless attempt to reflect government policies to some extent by means of an econometric model. Such models allow some projections to be made of government budgets and, also, of NASA budgets. We consider these matters in the following section.

It is apparent that the better the preliminary analyses of alternative STS's, the better is the chance to anticipate and conform to the ideas of the Office of Management and Budget in whose attitude should be seen the financial reflection of national goals and preferences. The fact that probabilities of mission success have to be included, as well as projections of outside demand (other agencies, commercial and foreign) which also have a high degree of uncertainty, makes it clear that stochastic elements (other than those in the cost estimates) prevail throughout. The present report merely points out their existence; however, the stochastic factors in the internal NASA program, as far as the costing and the historical demand for the STS is concerned, are considered numerically.

2.5 Potential Future Space Expenditures and Budget Requirements of New Space Transportation Systems

We sketched out earlier how the Federal budgets are determined. In spite of political factors, the effects of many government policies can be explicitly evaluated by an econometric model. In an effort to arrive at alternative forecasts of future NASA budgets, we have constructed such an econometric model by substantially modifying the widely accepted Klein-Goldberger model of the United States economy to incorporate the relationships of both government receipts and expenditures. The new model consists of a system of 28 simultaneous equations describing the development of production, consumption, and investment activities, as well as the determination of profits, wages, and interest rates. Several important policy variables, controllable by the government, have been included in the model. These include not only monetary policies regarding the discount rate and reserve requirements, but also fiscal policies relating to corporate and individual income taxes as well as compensation to government employees, etc.[2]

In this section, we consider some implications of the overall budget constraints which NASA must take into consideration when introducing a New Space Transportation System such as the Space Shuttle. Specifically, it covers:

(1) The future level of NASA budgets as a function only of NASA's past budgets;

(2) The future level of NASA budgets as a function of several economic variables in the context of the U. S. economy in the 1970's; and

(3) The required budgets of the Expendable and Reusable Space Transportation Systems as well as their feasibility given in (1) and (2).

Were one simply to project the expected NASA or space budgets[3] of the 1970's based only on the trends of NASA and other space appropriations of the 1960's and early 1970's (see Figure 1.3 for the 1955 to 1971 Fiscal Year budgets), the level of space expenditures can be projected to fall from approximately \$3.9 billion in 1971 to only \$2.0 billion in 1980 (in 1971 constant dollars). Such projections, in fact, have been made by NASA. The projections of space expenditures were obtained simply by first extrapolating the expenditures for manned space flight, science applications and military purposes separately and then summing up these separate extrapolations. These projections, failing to take into consideration the national economic conditions and the level of government expenditures in general, appear to be very unrealistic. Making a forecast based only on trends in past space budgets of different agencies leads to very drastic extrapolations over a 10-year period; e.g., the decline of budgets for manned space flight from approximately \$1.6 billion in 1971 to merely \$0.1 billion in 1980. It must also be noted that while our projections of potential space expenditures (as all other dollar values in this analysis) are expressed in billions of constant 1970 dollars, the particular NASA projection is expressed in billions of constant 1971 dollars.

In Chapter 7 we shall demonstrate that the level of space expenditures during the past decade has been influenced significantly by economic variables other than NASA's past budgets. These variables include the level of government expenditures in general and the condition of the national economy, such as the rate of inflation or the rate of unemployment. In order to forecast NASA budgets or space expenditures, we must therefore be able to forecast each of these influencing factors which may be simultaneously determined with many other factors in an econometric model of the national economy.

As an exploratory investigation, an econometric model has been constructed which is capable of generating reasonable forecasts of the future national economy, including government receipts and expenditures. The resulting forecasts were then used to project the future level of expenditures

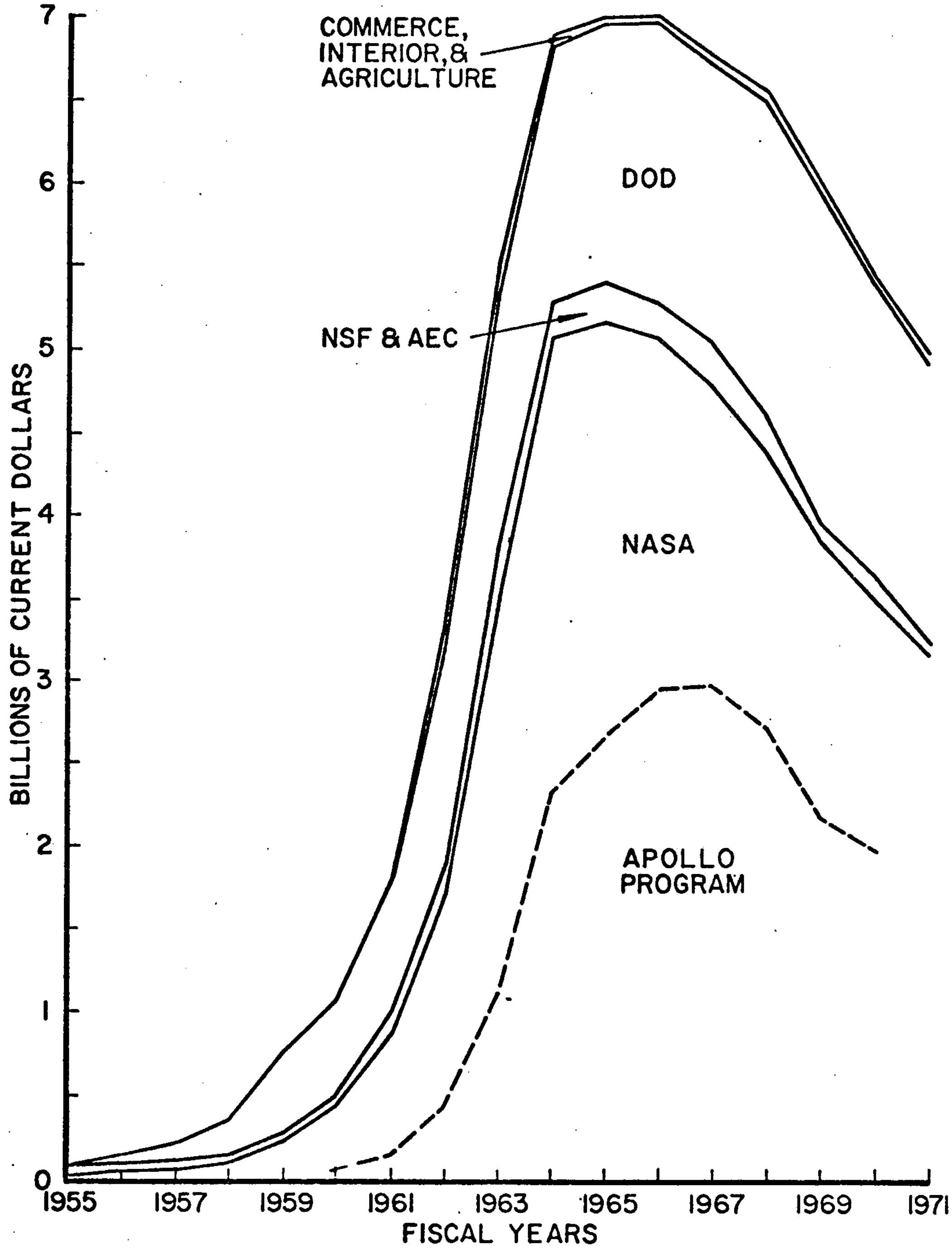


Figure 2.3 **Federal Budgets for Space Expenditures.**

for space research and technology. Several alternative projections of the national economy representing expansionary, neutral and restrictive policies respectively, were obtained for the period 1971-1980. The projected results of the levels of government expenditures and economic conditions, such as the rate of inflation, were then used to project potential future space budgets for the same period. One of these projected levels of potential future space expenditures, reflecting the neutral monetary and fiscal policies, is presented in Table 2.1. For comparison, the funding levels of the three options recommended by the Space Task Group Report (1969) are also provided in the same table. In general, the levels of our projections are lower than those of all three options, but are very close to those of the third option.

The projected space expenditures are based on the national income account concept of "government expenditures for space research and technology". This concept closely approximates the appropriations of NASA budgets. For some purposes, however, a broader concept of space expenditures which includes not only NASA expenditures for space activities but also the expenditures of the Department of Defense and other government agencies for space activities may be more meaningful. The relative importance of NASA's and other government agencies' expenditures for space activities are shown in Figure 2.3 for the period from 1955 to 1971.

A comparison can be made between the different forecasts of space budgets for the 1970's. A surprising result of the work done so far is the close agreement of the Space Task Group Report projections of NASA's budget and the independent forecast made by MATHEMATICA for the late 1970's. These contrast sharply with the budgets projected for NASA and other space applications based on simple trend extrapolations. The *a priori* positing of any arbitrary *fixed* budget level for space activities, say, $4 billion, would be dangerous for a rational economic choice of the best Space Transportation System of the 1980's. For historical purposes, if nothing else, the Space Shuttle and Tug funding requirements for nonrecurring costs in the 1970's are compared to the activities of NASA in the 1960's in Table 2.2. Compared with an earlier estimate, the present estimate of *nonrecurring*

Table 2.1

Projected Levels of Potential Future Space Expenditures, 1971-80

(Billions of Current Dollars; i.e., with expected inflation)

Year	Projected Total*	Recommended Totals - STG**		
(1)	(2)	Option 1 (3)	Option 2 (4)	Option 3 (5)
1971	3.40***	4.25	3.95	3.95
1972	3.20***	4.85	4.05	4.05
1973	3.47	5.85	4.25	4.25
1974	3.71	6.80	5.00	5.00
1975	3.94	7.70	5.45	5.45
1976	4.18	8.25	5.50	5.50
1977	4.47	8.75	5.50	5.50
1978	4.78	9.10	5.65	5.50
1979	5.15	9.35	6.60	5.50
1980	5.55	9.40	7.65	5.50

* Projections based on the econometric model (calendar year), except 1971, 1972.

** The Post-Apollo Space Program: Direction for the Future. Space Task Group Report to the President, September 1969, p. 22.

*** Budget figures, January 1971.

Table 2.2

NASA Budgets: The 1960's Versus the Space Shuttle Non-Recurring Costs

(Billions of Current Dollars, except Budget Requirements for Space Shuttle which are expressed in Constant 1970 Dollars)

Years 1959-1970 (1)	Space Expenditure* (2)	NASA Appropriation (3)	Manned Space Flight** (4)	Apollo*** (5)	TAOS-Space Shuttle and Tug**** (1970 Dollars)	Years 1971-1980
1959	0.26	0.33	0.05	0.01	--	--
1960	0.57	0.52	0.12	0.04	--	--
1961	0.89	0.97	0.30	0.19	--	--
1962	1.80	1.83	0.54	0.45	0.02	1972
1963	3.37	3.67	1.50	1.19	0.23	1973
1964	4.63	5.10	2.72	2.28	0.50	1974
1965	5.59	5.25	2.96	2.63	0.76	1975
1966	5.95	5.18	3.17	2.97	0.98	1976
1967	4.86	4.97	3.02	2.99	0.97	1977
1968	4.55	4.59	2.81	2.81	0.94	1978
1969	3.95	4.00	2.18	2.18	0.74	1979
1970	3.57	3.75	2.03	2.03	0.63	1980

* National income account concept of "government expenditures for space research and technology" (calendar year).
** Includes R&D funding only.
*** Includes R&D funding to Apollo Program and Apollo Applications
**** Includes RDT&E and Initial Fleet Funding

costs of the Space Shuttle program as represented by a typical TAOS is substantially lower. According to the present estimate, the annual non-recurring costs of the Space Shuttle System are at no time expected to exceed $1 billion (constant 1970 dollars).

Having compared our projections of space expenditures with simple extrapolations and with alternative options recommended by the Space Task Group Report, we may now consider how these projected overall space expenditures compare with the required budgets for the three major alternative Space Transportation Systems throughout the 1970's. Since the ability to project the overall space expenditures beyond 1980 is obviously very uncertain, we shall confine our comparison to the period from 1971 to 1980. For the purpose of this comparison, we shall select only the Reduced Baseline Model (Scenario 32) though many other mission models have also been examined in the present report.

In order to avoid the uncertainty associated with the possible inflation, the budget requirements of alternative Space Transportation Systems are expressed in undiscounted 1970 dollars. Furthermore, the costs associated with the military missions for the Department of Defense are excluded. For comparison, the projected overall space expenditures were also converted into 1970 dollars. Table 2. 3 shows such a comparison together with the percentage of the overall budget that would be absorbed if one of the three alternative Space Transportation Systems were selected.

The budget requirements of the Space Shuttle System reach their peak in 1979 at $2. 36 billion, and the budget requirements of the Current Expendable and New Expendable Systems reach their peaks in 1981 at $3. 14 and $2. 97 billion respectively. Furthermore, the Space Shuttle System would absorb more than 50% of all space expenditures from 1978 on.[4] The same is also true for the Current Expendable and the New Expendable Systems. Notice that the budget requirements of the Space Shuttle System for 1979 and 1980 are lower than those of the alternative Expendable Systems.

It must be pointed out that all of the foregoing conclusions have been

Table 2. 3

NASA Budgets Requirements of Alternative Space Transportation Systems, 1971-80

(Billions of 1970 Dollars)*

		Space Transportation Systems** (DoD not included)		
Year (1)	Potential NASA Space Expenditures (2)	Space Shuttle (3)	Current Expendable (4)	New Expendable (5)
1971	3.32	0	0	0
1972	3.04	0.02 (1%)***	0	0
1973	3.19	0.23 (7%)	0	0
1974	3.31	0.50 (15%)	0	0
1975	3.40	0.78 (23%)	0.09 (3%)***	0.10 (3%)***
1976	3.50	1.07 (31%)	0.29 (8%)	0.32 (9%)
1977	3.62	1.46 (41%)****	1.00 (28%)****	1.06 (29%)
1978	3.75	2.14 (58%)	1.96 (53%)	1.97 (53%)
1979	3.91	2.36 (61%)	2.58 (66%)	2.46 (63%)
1980	4.08	2.36 (59%)	2.99 (75%)	2.67 (67%)

* In billions of (constant) 1970 dollars, i.e., without inflation for all figures shown in the table. Rates of inflation were predicted, based on a neutral economic policy, by year from 1971 to 1980. These rates were used to obtain "Potential NASA Space Expenditures" in Column (2).

** Including costs of payload, based on the Reduced Baseline Model (Scenario 32) constructed by MATHEMATICA.

*** Column (3) as percent of column (2)
Column (4) as percent of column (2)
Column (5) as percent of column (2)

**** DoD funding not included.

based on our projections of potential space expenditures and a particular space mission model. While the reliability of the projected space expenditures cannot be easily assessed, they are quite consistent with the alternative recommendations of the Space Task Group Report. As to budget requirements, it was found that the budget requirements in the 1970's of alternative Space Transportation Systems relative to one another would not change significantly when the modified space mission model of 514 Space Shuttle flights of the 1980's is taken as the basis for evaluation. For these reasons, the conclusions regarding the peaks and scheduling of alternative Space Transportation Systems should generally be true, even if the predictions of potential space expenditures and the particular set of budget requirements for alternative Space Transportation Systems are more tentative in nature. The question of required Space Shuttle fundings in the context of the overall NASA budget of the 1970's is discussed in more detail in Chapter 1..

2.6 The Impact of Space Expenditures

In the previous discussion of the goals and nature of space programs, we have stressed that the fulfillment of space goals cannot be considered separately from that of many other national goals. The reason lying behind this argument is the intrinsic nature of joint supply and joint demand associated with any space program. Therefore, the goals of space programs must be carefully coordinated with other national goals, which may either be economic, political, or military. Although it is extremely important to consider all of these goals, this is beyond the scope of the present report. which deals mainly with economic issues of Space Transportation Systems. Frequently one may encounter an apparently reasonable argument to the effect that space programs can greatly contribute to economic growth and full employment. This assertion, however, is very difficult to support by a careful analysis, once it is realized that the funds provided for space exploration can have other alternative uses which are not necessarily less -- or more -- beneficial to economic growth and full employment. Until very recently there have been few rigorous studies of the economic impact of space expenditures or of new Space Transportation Systems.[5] To fill this gap, we have undertaken a task of investigating the spending impact of space expenditures on various industries or groups of industries by using input-output analysis techniques. Specifically, we have attempted to evaluate the impact of the reallocation (not simple elimination) of a $3 billion space expenditure to some alternative uses in terms of the effects on production and employment. The results of this investigation have been reported elsewhere. Since the study has provided useful information for decision-making in space exploration, some of the significant findings are summarized below.

The analysis of the spending impact of space expenditures on the national economy has been based on the most recent (1963) input-output tables. The relative impact was, however, computed by comparing the estimated effect to an estimated 1970 level of production and employment. We had conducted a similar analysis by using the earlier 1958 input-output tables and found that most results were not significantly different from those based on the 1963 tables. Therefore, no effort has been made to update the 1963 input-output tables to a 1970 basis. In fact, whether an updating can improve the results of our analysis is somewhat doubtful.

Besides the spending impact of space expenditure on production and employment, four other alternative expenditures have been considered. These include new construction, communication and transportation equipment, medical and educational services as well as research and development in general. The impact of the reallocation of a $3 billion space expenditure into each of the four alternative uses was evaluated first in terms of production levels then in terms of employment level.

The spending impact of a reallocation of $3 billion from space expenditures to each of the four alternative uses was found to be relatively unimportant, except for those industries which are directly affected. This is shown to be true both in terms of the production levels and the employment levels of various industries. In fact, except for those industries which are directly affected by the reallocation of $3 billion, almost no industry would be affected either beneficially or adversely by more than 1% of the 1970 production or employment level.

As to the impact on the industries which are directly affected by the reallocation of $3 billion in space expenditures, while it is true that ordnance and aircraft industries together would decrease their production by nearly $4 billion annually, it must also be recognized that the alternative industry would increase its production by more than $3 billion (though it may not be as high as $4 billion). Similarly, in terms of employment, while it is true that transportation equipment and ordnance industries would lose about 170 thousand man years of employment, it must also be recognized that the alternative industry would gain more or less the same level of employment, depending on its labor intensity.

As an example of the foregoing conclusions, we may mention only the major impact of the reallocation of $3 billion from space to communication and transportation equipment. According to our analysis, such a reallocation may be expected to decrease the annual production of ordnance and accessories by $1. 2 billion (about 11% of 1970 level) and the annual production of aircraft industries by $2. 6 billion (also about 11% of 1970 level). At the same time such a reallocation may be expected to increase the annual production of communication equipment by $2. 1 billion (about 10% of the 1970 level) and the annual production of transportation equipment by $1. 0 billion (about 12% of 1970 level). The only other industry which may be expected to be affected either beneficially or adversely by more than 1% of its own 1970 level is manufacturers of machine shop products. Its annual production may be expected to fall by about 3% of 1970 level, which is only $0. 1 billion. In terms of employment, the group of transportation equipment and ordnance industries may be expected to lose 125 thousand man years (about 10% of 1970 level). At the same time, the group of electrical machinery industries may be expected to gain 118 thousand man years (about 6% of 1970 level). Therefore, on balance the net long-term effect on the whole economy, both in terms of production and employment is largely negligible. Therefore, the spending effect and employment argument should be used neither for nor against the development of a Space Shuttle System. It must be recognized, however, that some significant effects can be found for those industries and locations which are directly affected by a reallocation of the fundings, both in terms of production and employment.

2.7 Final Remarks

From our analysis there emerges an important lesson: the Space Shuttle would have to be "drastically" better and cheaper in operation, and would have to accomplish approved tasks that are out of reach of existing and/or modified existing systems, in order to be considered. This applies particularly if the new system requires large initial investments, long lead times and is a long term commitment from which it would be very hard to return. Only such "drastic" improvements make it at all likely that the new system can stand the test of economic analysis, in particular with a relatively high social rate of discount -- say, 10% -- measuring the social opportunity cost of investment funds. The results of our analysis show that the new Space Shuttle System does significantly improve NASA's operations, not by orders of magnitude, but more than sufficiently when a 10% social rate of discount is applied in the analysis. The report does clearly document the substantial savings in payload costs due to reuse, refurbishment, updating and on-orbit check-out of payloads. Whether the Space Shuttle System, and which particular Space Shuttle configuration, is technically suited to best achieve reuse, refurbishment, and updating of payloads, as well as check-out on orbit, is strictly an engineering task, which again can be subject to economic analysis, however, in a different context. We believe this technology to be feasible. MATHEMATICA did estimate the maximum RDT&E outlays that could be justified on economic grounds to develop such capability. The typical Space Shuttle System currently under consideration appears to lie well within that region.

The entire question of the size of the future NASA budget is sharply illuminated in Figure 2.3. Although one should always be wary in trying to predict the future from the past, it is clear that it will take strong arguments and a significant change in the environment in which decisions regarding NASA's share in national resources -- small as it is, especially when allowing for the expansion of the economy -- are made, in order to achieve a sudden turn-around in appropriations such that on top of the current expenditure pattern a new large investment is authorized, one which commits funds in a rigorous manner into a rather distant future. That is, the Space Shuttle, once started, takes a number of years to construct and then requires operation for a substantial period of time in order to be "amortized". However, the TAOS System promises substantially reduced nonrecurring costs in the 1970's when compared to the Two-Stage Fully Reusable Shuttle System of May 31, 1971. As shown in Chapter 1, many of the "peak funding" constraints have thereby been alleviated.

It is, unfortunately, not normally the policy of Congress to budget important and complicated long-range programs for several years ahead of time. It will be particularly difficult to obtain firm funds of this nature at present even though the new Space Shuttle System (TAOS) proves to be strongly cost-effective. The fact that this type of funding -- and indeed funding on a substantially larger scale -- was once obtained for Apollo was due to a combination of circumstances which do not now hold. At that time, President Kennedy had announced a goal that was nationally acceptable, exciting, and in competition with expected Soviet efforts. We are now far from this. Even under the most favorable circumstances the Space Shuttle -- startling as the concept is and with a much further ranging potential than Apollo ever had -- cannot compete with the drama of placing men on the Moon and doing this for the first time in human history. In addition, when that goal was announced and the decision made, there was no war to cope with (or to liquidate), and the awareness of grave problems now felt by the public such as pollution, destruction of the environment, population increase (all with the additional factor of unrest, e.g., among the young), was insignificant. Yet, in terms of economic analysis, and promise of future technological, scientific and economic opportunities, the development of the Space Shuttle is by orders of magnitude more important!

The Space Shuttle is a means of achieving lower space transportation and space payload costs. If, and only if, this is documented to the satisfaction of NASA and Congress should this investment be made. Present economic data so far show the Space Shuttle -- and particularly TAOS -- to be cost effective.

A few remarks have to be made regarding the STS investment decision when compared, for example, to the development of the Supersonic Transport (SST). It may appear that the proposal for a new STS is similar to that for a supersonic transport plane for which Congress denied funds in March 1971. However, the two are fundamentally different, both technologically as well as economically. The SST would have used and developed well-known technology further, since many supersonic planes -- mostly military -- have been built by many nations. It would have been a private effort merely underwritten by the government. The SST would serve no scientific purpose in its uses; the planes would merely transport persons able to pay the fare, at any rate only a small fraction of the travelling public.

The Space Shuttle, on the other hand, can never be a private enterprise. Its construction and operation is a government matter, though its services may be made available to domestic and foreign business. Its dimensions are far larger, both in investment as well as over time; indeed, it would be the largest technological effort of the country, comparable only to the Manhattan and the Apollo projects.

In concluding we list a number of problems which must be settled, but which are beyond this assignment:

(a) The expected demand for Space Shuttle services has to be studied in detail, nationally and internationally, as a function of launch costs and payload costs. This is a complicated undertaking which will also involve a fair amount of field work.

(b) The cost analysis of payloads in orbit in our analysis did include the costs of developing the payloads for alternative STS (the Current Expendable System, the New Expendable System and the Space Shuttle System). The costs of satellite data handling and distribution of the space program for the 1980's were not included in the analysis in sufficient detail. These costs should be similar for the three systems, though the Space Shuttle System may lead to important reduction of these costs in some areas. Information about these matters is needed, but estimates will be hard to make and to evaluate.

(c) There is a need to quantify the benefits to the nation of more and more space applications. As in cases where numbers have to be obtained from qualitative or mixed qualitative-quantitative information, this is a difficult matter as anyone who has ever attempted to do so will attest. Yet, it is clear that rational decision making would be aided if more meaningful numbers could be arrived at to quantify the benefits and the prospective uses of space. When a proposed investment is very large, this effort is, indeed worthwhile though there is no guarantee of success in all respects.

REFERENCES IN CHAPTER 2.0

[1] MATHEMATICA, Inc., Economic Analysis of New Space Transportation Systems, May 1971 and "On the Principles of Public Project Evaluation" in Cost-Benefit Analysis of New Launch Systems, July 1970, both prepared for NASA.

[2] The Aerospace Corporation, Integrated Operations/Payload/Fleet Analysis Final Report, Volume III, Table A-8, page III-A-12, prepared for NASA, Washington, D.C., August 1971.

[3] K.P. Heiss and C. R. Frank, Cost-Benefit Study of the Earth Resources Satellite Program: Grazing Land Applications, prepared for Radio Corporation of America, August 1968.

FOOTNOTES IN CHAPTER 2.0

1. Preferences of values may be incomparable to each other (i.e., be only "partially" ordered), or they may be easily and clearly "completely") ordered according to importance, yet some, so ordered may lack the so-called "Archimedian property" of continuity. The problem of optimal allocation of scarce resources is in each of these cases a different one and sometimes is only settled by complicated political processes. It would lead too far to discuss these matters here, vital though they are. (For more detail and illustrations cf.: O. Morgenstern, "The Economic Worth of the Space Program," in Astronautics and Aeronautics, Vol. 6-No. 2, (1968) pages 45-51).

2. For more detailed discussion see K. H. Young, "A Macro Econometric Model for Projections of National Economy and Space Expenditure", Working Paper, MATHEMATICA, October 1971, in part incorporated in Chapter 7 below.

3. Space budgets include the Department of Defense space appropriations as well as other non-NASA space activities.

4. At the peak of the Apollo Program, the comparable ratios were approximately 50% and 60% for 1966 and 1967 respectively.

5. During the preparation of this report, two technical papers prepared by North American Rockwell have come to our attention. They are: C. M. Merz, T. A. Gibson and Ward Seitz, "Impact of the Space Shuttle Program on the National Economy", SD 71-478, March 1971 and T. A. Gibson and C. M. Merz, "Impact of the Space Shuttle Program on the Economy of Southern California", SD71-762, September 1971.

6. K. H. Young, "The Impacts of Space Expenditure on the National Economy in the United States", Working Paper, MATHEMATICA, October 1971. See also Section 7.2 of Chapter 7 which includes some materials based on this paper.

CHAPTER 3.0

THE THEORY OF BENEFIT-COST AND COST-EFFECTIVENESS ANALYSIS

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CHAPTER 3.0

THE THEORY OF BENEFIT-COST AND COST-EFFECTIVENESS ANALYSIS

3.1 The Approach Used in This Analysis

In trying to apply economic principles when determining the most economic Space Transportation System, the analysis is hampered by one major drawback when compared to the economic evaluation of other transportation systems: there does not at present exist in the United States economy any "free" market where the demand for space transportation and supply of space transportation services are determined by the interplay of many consumers and many producers. Rather, we find a situation similar to that of Department of Defense decisions where two major consumers are two government agencies, the Department of Defense and the National Aeronautics and Space Administration. On the supply side, we find at most ten to twelve major companies competent to compete for major aerospace hardware systems. Thus, huge investment expenditures are decided on the basis of technical criteria, political processes, national priorities, etc. Most important, instead of a market value the costs of systems is frequently used as a substitute for the measurement of economic value, a very questionable economic practice.

This does not mean that economic decisions made in such an environment have to be less rational than those made in the free market. The means of arriving at economic decisions is different. The basic assumption of an economic analysis in the absence of market indicators is, and has to be, that the decisions on the actual budgets -- the budgets for the 1960's and the 1970's -- do reflect in effect national priorities. One has to assume further that within each agency the programs outrank in priority projects not undertaken by the agency. In other words, we have to make the assumption that the resources allocated to space activities in the United States, both by NASA and by the Department of Defense, are efficient in an economic sense: that the needed resources of NASA and of the Department of Defense are minimized to achieve a given capability demanded by Congress or the Administration -- i.e., cost minimization is achieved -- or, given the resources allocated to NASA and to the Department of Defense a maximum capability is developed with these funds within NASA and DoD. Given that the agency funds, particularly within the Department of Defense, compete with other programs within the same agency, the assumption of economic efficiency within each agency is not completely unreasonable. In this analysis we do not have to assume that the budget level is optimal.

Given this basic assumption, cost-effectiveness analysis, in a strict sense, is only concerned with identifying technically feasible systems that assure either a maximum of space transportation capability at any given budget level or a minimum cost for any given space transportation capability. Although in economic theory this is a rather straightforward task, in practice it proves very difficult to determine the cost-effective systems, either for the present technology or for the projected new Space Transportation Systems. Figure 3.1 shows a hypothetical example of the cost efficiency frontier for the space program in terms of space missions to low earth orbit for 1970 technology (i.e., expendable rocket technology). The vertical axis in Figure 3.1 represents the capability measured in terms of numbers of payload missions flown to low earth orbit, and the horizontal axis measures the costs (the budgets required) to deliver that payload to low earth orbit. The figure is basic to an understanding of cost-effectiveness calculations for analyzing the economics of new Space Transportation Systems. The shaded area in Figure 3.1 shows the region of possible costs of payloads in low earth orbit. That is, a given space program capability of, say, k_1 can be delivered to low earth orbit certainly for a budget of b_1 -- about 46 space missions -- can be lifted to low earth orbit for \$3.0 billion, including payload costs. The same capability, i.e., 43 payload missions, can also be lifted up and delivered to low earth orbit for more than \$3.0 billion, e.g., for \$3.5 billion or \$4.0 billion. Such a cost to capability combination would lie to the right of k_1 in the shaded area shown in Figure 3.1 below the efficiency frontier (cost curve). Similarly, for the same budget of \$3.0 billion, we could have a smaller space program, for example, a capability k_0 (35 flights). Again, these combinations would lie below the efficiency frontier within the shaded area of Figure 3.1. As we move from one point within the shaded area -- the feasible region of space project/cost combinations -- toward the left and upward, we improve

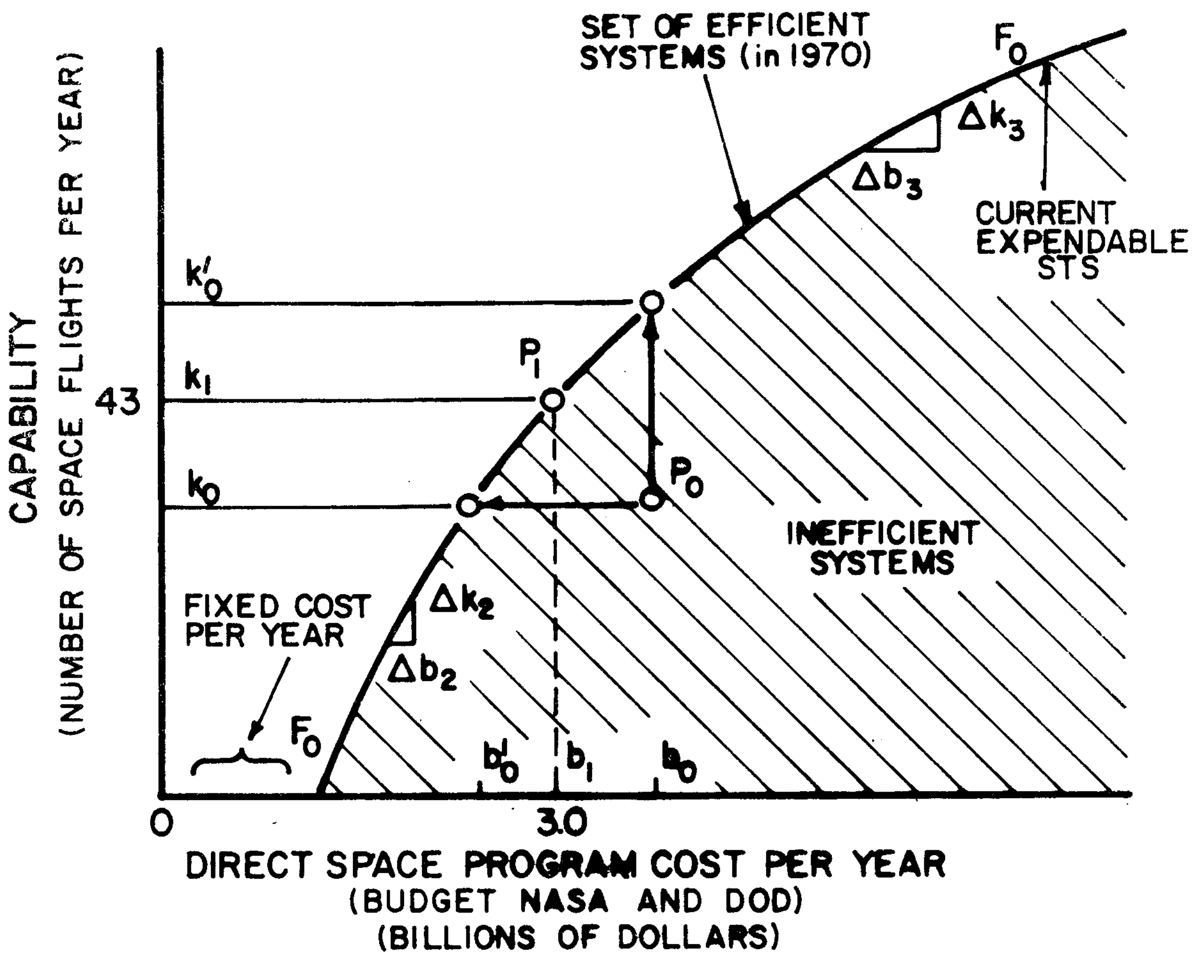


Figure 3.1 The STS Cost-Efficiency Frontier

the economics of systems choice. Cost-effectiveness analysis is concerned with finding space transportation programs where no increased capability (more payloads in low earth orbit) is possible without a corresponding increase in budgetary funding. Also, for systems that are cost-effective, no further decrease in cost is possible without a corresponding decrease in capability. The set of cost-efficient points -- the cost curve -- is shown by the boundary of the shaded area, F_0F_0, in Figure 3.1. By inspection, we see that P_0 -- a point not on the frontier -- is not cost-effective. The system P_0 requires a budget of b_0 and promises a capability of k_0. We can find other space transportation programs different from P_0 that offer more capability in terms of payloads delivered to low earth orbit or less cost or both. One of such programs is shown at P_1, with a budget requirement of b_1 (smaller than b_0) and a capability of k_1 (larger than k_0).

From the shape of the cost efficiency frontier, we also observe that by increasing the budget of the space program we add -- along the cost curve -- capabilities. But as we move out to larger and larger funding levels, any additional funding yields smaller and smaller increments in capability. In other words, the shape of the efficiency frontier reflects increasing marginal costs as the capability requirements of space transportation expand. In Figure 3.1, two cases are shown to illustrate this point. The change in capability of Δk_2 is equal to the change in capability of Δk_3 -- at a higher funding level. But the absolute increase in capability is bought at an increased incremental cost ($\Delta b_3 > \Delta b_2$). In many large-scale, advanced technologies, this efficiency frontier may well be a straight line over a considerable range of the cost efficiency frontier. The intercept of the efficiency frontier with the horizontal axis does indicate the minimum (fixed) costs of buying any amount of capability of space transportation. Thus, a straight line efficiency frontier with a positive intercept at the cost (budget) line would indicate a Space Transportation System with constant marginal (incremental) costs and decreasing average costs. This is what we actually find to hold for Space Transportation Systems, the Current Expendable and the new, fully reusable. The case shown in Figure 3.1 is more general and includes, in principle, the more specific case of the new Space Transportation Systems as we will see later on.

The task of benefit-cost analysis is more demanding. While cost-effectiveness analysis tries to identify the systems (for space programs) along the "efficiency frontier" (the cost curve), benefit-cost analysis attempts to select a single space program from all possible cost-effective candidates. To do this, however, we have to use a benefit (utility or value) measure of all the conceivable space programs within the range of technology -- a task we do not propose to solve and which may be an intractable task. Given information on the economic value of these programs, we can then, in theory, select an optimum space program.

This choice process can be illustrated with the aid of Figure 3.2 which shows the cost curve and the benefit curve confronting the decision maker and the actual capability and cost levels of several space programs. It should be noted, first of all, that the cost curve in Figure 3.2 differs from that shown in Figure 3.1. The latter denotes "recurring costs per year" as a function of "capability per year." The cost curve in Figure 3.2, on the other hand, refers to "total program costs over the entire planning horizon." Since "total program costs" are incurred over time, it must be assumed that all costs are adjusted for the time value of economic resources. The time stream of space program benefits, summed up in the benefit curve, also is assumed to have been discounted appropriately.

Figure 3.2 illustrates the general relation between space program costs and space program benefits. Observe that at higher and higher levels of capability, an additional (marginal) space mission becomes increasingly more costly in our example -- the same cost curve as in Figure 3.1 -- the marginal cost of space mission increases while, at the same time, the marginal benefit derived becomes increasingly smaller.[1] The assumption of progressively decreasing marginal benefits is based on the notion that successive additions to space programs will perform successively less valuable missions and, at some point, may well reach a saturation point, which means that the benefit curve in Figure 3.2 will eventually become vertical.

At a given level of capability, say k_0, "net program benefit" is measured by the horizontal distance between the benefit and cost curves.

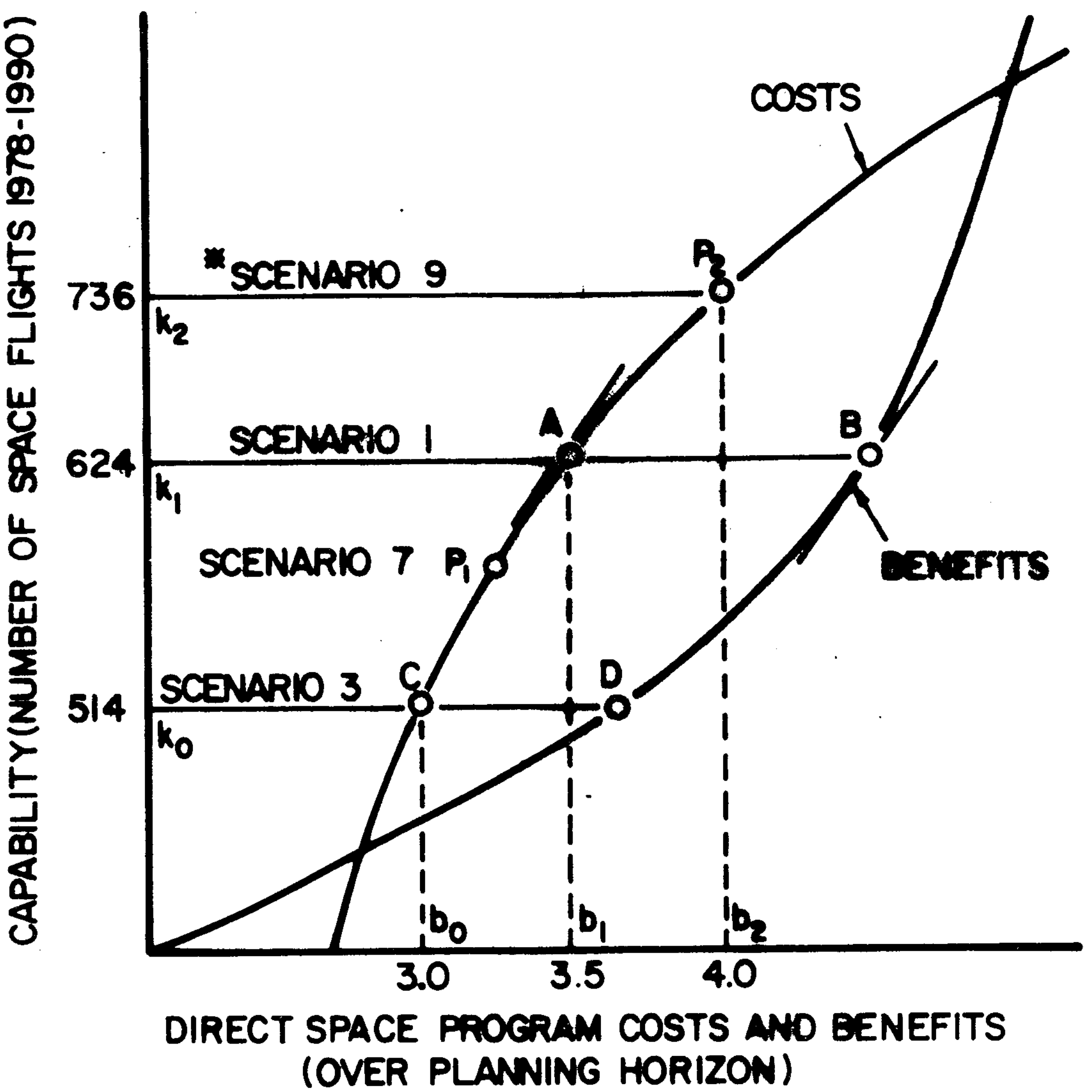


Figure 3.2 The Cost Benefit Analysis of the STS

B

In Figure 3.2, the net benefit at k_0 is given by the distance CD; at k_1, it is given by AB. Recall that the cost curve is really an efficiency frontier associating a given level of capability with the least cost Space Transportation System which, with given technology, will provide that capability. The optimal space program therefore is the one corresponding to the scenario at which the distance between the benefit and the cost curves, i.e., the net benefit, is maximized. It is the capability level at which the cost curve and the benefit curves have the same slope, i.e., at which marginal (incremental) benefits are just equal to marginal (incremental) costs. In Figure 3.2 this optimum space program is k_1.

Some cost analysts prefer to define the optimum capability level (and the corresponding optimum space program) as that level at which the ratio of program benefits to program costs is maximized. In Figure 3.2, that level might be capability k_0 at which, however, the net program benefit is seen to be suboptimal.[2] It was shown in the earlier MATHEMATICA report that the so-called benefit/cost ratio is not a reliable criterion of program evaluation while the "net-program-benefit" criterion generally leads to the economically correct choices. The economic implications of a full benefit-cost analysis of the space program are illustrated in Figure 3.2.

Having established these fundamental points we notice that the benefit (value) relationship of space programs within the range of technology cannot be measured quantitatively at present -- if it can ever be. The next section explains the economic analyses possible within the confines of cost-effectiveness analysis.

3.1.1 Equal Capability and Equal Budget Analysis of the Space Transportation System

The above general definition of cost-effectiveness analysis has to be applied to the analysis of a large breakthrough promised by a new technological system -- the fully reusable Space Transportation System -- where all the space transportation programs of the past may become cost inefficient once the new system is available. Technological innovation -- the new, fully reusable, two-stage Space Transportation System -- will change the efficiency frontier (cost curve of space programs). In general, technological change will shift the efficiency frontier F_0F_0 of Figure 3.1 upward and towards the left -- i.e., it will lower costs or increase capabilities. Figure 3.3 shows that shift from F_0F_0 to F_1F_1 and represents in our case the change in expected recurring costs of the space program before the fully reusable Space Transportation Systems becomes available. If technological change occurs throughout the range of interests (the likely space transportation budgets in the 1980's or likely space program requirements in the 1980's) then the shift will take place along entire F_0F_0 as shown in Figure 3.3. If the New Space Transportation System brings about increased efficiency at larger scales of operation only, then the shift in F_0 F_0 will take place only at larger cost/budget levels and leave the lower points of F_0F_0 more or less unchanged.

If one evaluates an efficient space program for expendable space transportation technology, for example, P_0, one sees that the space program P_0 is not any more cost effective with regard to the new, fully reusable technology F_1F_1. Given the new Space Transportation System, we can find other space programs (low cost payloads, reusable Space Transportation System vehicles) that provide the same capability at less cost (space program P_1) or a larger space program with more flights and a larger number of payloads at the same budget level (space program P_2).

Therefore, within the confines of cost-effectiveness analysis (strictly defined), one may ask the following two questions:

(a) Equal capability efficiency for a given capability level: What are the net cost savings that can be achieved by adopting new technology and are these cost savings (for example, the distance P_0P_1), large enough to justify the initial (non-recurring) outlay on RDT&E and new hardware over the uselife of the new system? (Figure 3.4)

(b) Equal budget efficiency: What increases in the capability

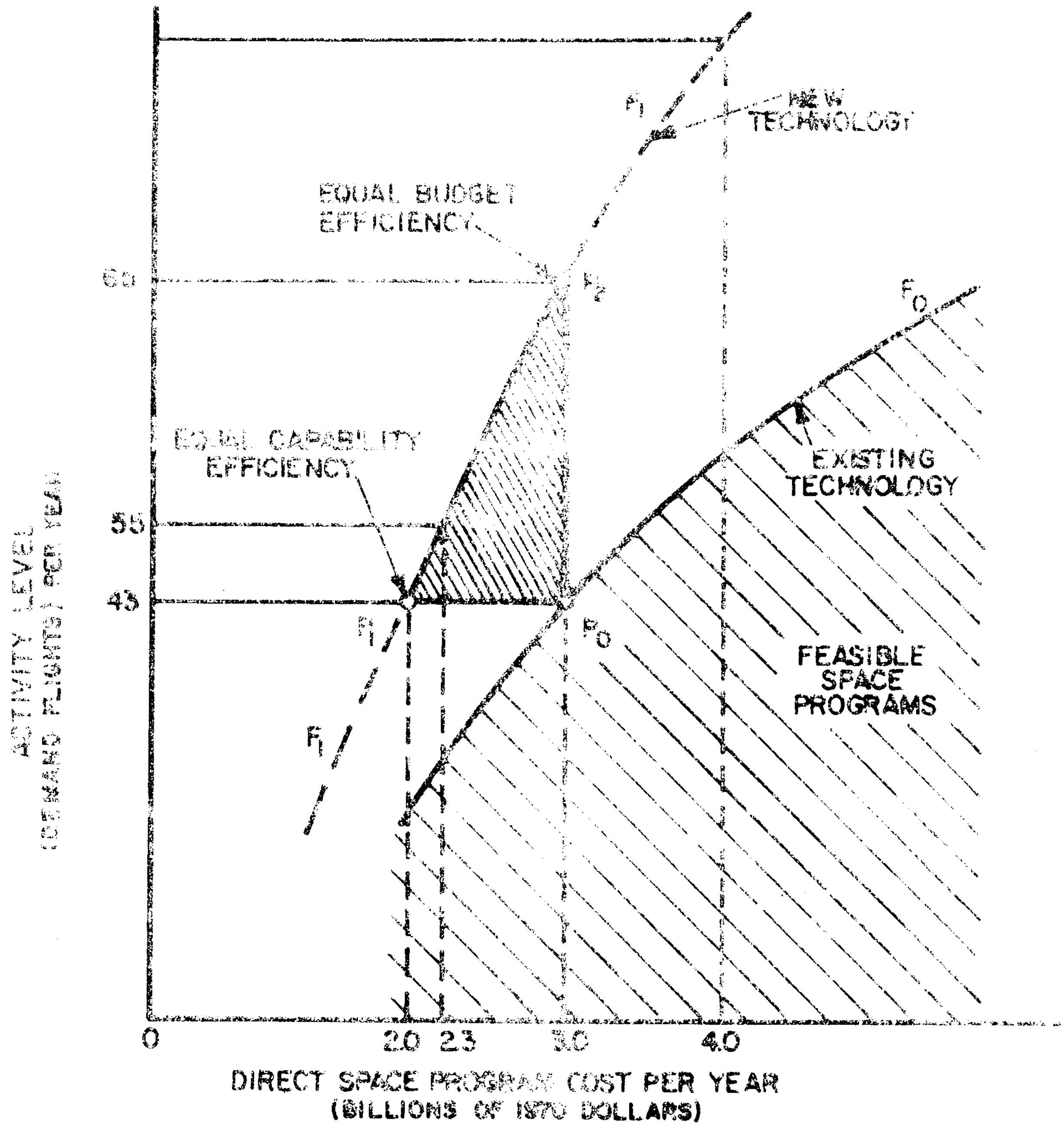


Figure 3.3 Cost-Effectiveness Analysis of [illegible] Change. The Case of the New S[illegible]S

of payloads in low earth orbit are brought about by technological change, the new Space Transportation System, <u>at the same budget level</u> after the new system has been introduced, and will the <u>economic value</u> of this added capability through the reusable Space Transportation System justify the required, initial outlays on RDT&E and new hardware over the useful life of the new system? (Figure 3.5)

Question (a), illustrated in Figure 3.4 on the basis of Scenarios 3 and 23 by MATHEMATICA, is by far the easier one to answer from an empirical point of view in the context of the new Space Transportation System. In answering that question, one need only make the assumption -- prior to the development of the new Space Transportation System -- that society is willing to spend \$3.0 billion to place 43 payload flights into low earth orbit per year. The reader should notice that the only, and <u>crucial</u>, assumption is that the \$3.0 billion allocated to space transportation by the Department of Defense and NASA jointly (average over the years from 1963 to 1970) are being spent in an efficient way, that is, no sizeable cost cutbacks could be achieved for the same program capabilities either in the Department of Defense or in the science and applications programs of NASA -- that is, excluding for the moment any question of manned space flight efficiency. We do not assume, and do not have to assume, for the purposes of our analysis that the <u>flight level</u> or the size of the space program -- the particular space transportation capability -- is an optimal one. The only assumption is that the \$3.0 billion capability/cost program really lies on the cost efficiency frontier of space technology in 1970. On that assumption, a very conservative and objective estimate of the benefits from the new Space Transportation System is the annual cost savings (\$2.0 billion in absolute dollars at the activity level of the present space program, Scenario 23, of our overall economic analysis).

A whole set of equal capability analyses has been made along a varying level of budget activities, for a variety of about twenty-four different space programs for the 1980's.

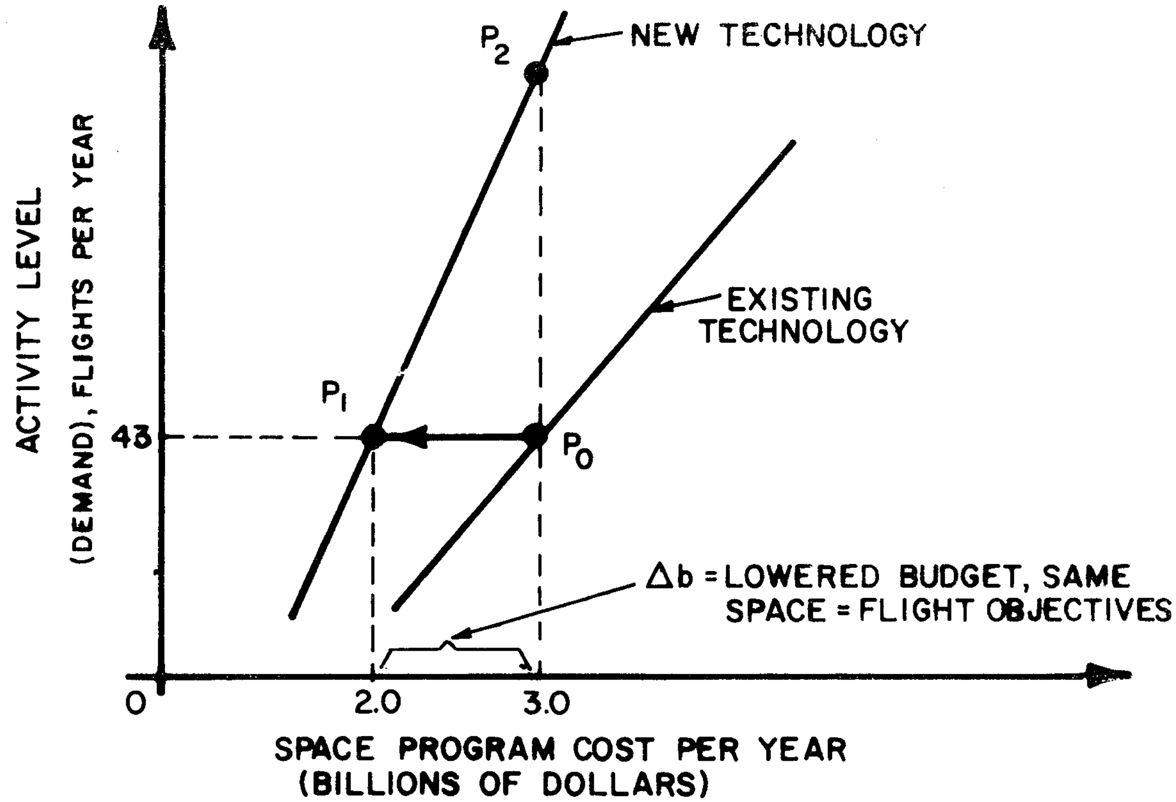


Figure 3.4 Equal Capability Analysis, 1979-1990

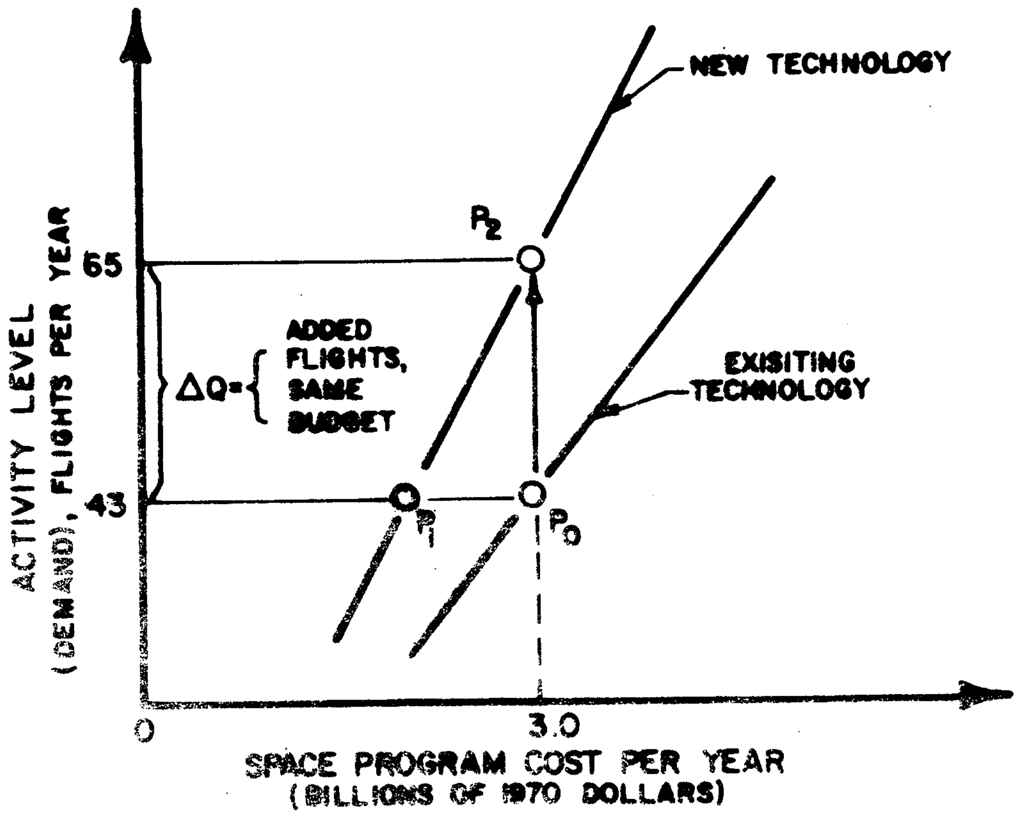


Figure 3.5 Equal Budget Analysis, 1979-1990

It is much more difficult, in practice, to ask question (b) above and illustrated in Figure 3.5. The question really amounts to asking:

(b') Given the fact that we could fly a total of 43 payload flights per year to low earth orbit annually at a cost of \$2.0 billion, does the economic value of additional payloads which could be placed in orbit by spending an extra \$2.0 billion annually -- that is, a total of \$4.0 billion with an additional set of about 43 flights per year -- justify the additional expenditure?

Clearly, this question cannot be answered unless one can, in fact, place a value on the additional 22 payloads per year placed into orbit. In other words, question (b) really requires one to know society's demand curve for space missions. The assumptions necessary for such a cost-effectiveness analysis of the new Space Transportation System are spelled out in the next section.

3.1.2 The Measurement of Induced Benefits from Incremental Space Activities

In measuring the economic benefits of additional flights for "equal budget" analyses (beyond those already undertaken under the Current Expendable System), one has to take into account one basic axiom of economic theory: as additional missions are added to the existing space program, they will increase the total utility received by society, by the agency, or by the scientific community; however, the increment in utility received by society or the consumer will be decreasing as the number of missions increases. This should hold for NASA, as well as other government agencies. In earlier reports, we pointed out some of the reasoning that lies behind the construction of such a relationship which ultimately leads to a negatively sloped demand curve for transportation services.

For the Space Transportation System to be evaluated in this report, the analogue to point $P_0 = (Q_0, F_0)$ is already known: it is the baseline mission model (Scenario 3) (i.e., traffic level Q_0) equivalent to roughly 46 Shuttle flights per year (see also Figures 3.1 through 3.5).

The cost per mission -- including payload cost -- under the Current Expendable System is about \$60 million. The corresponding cost per mission for the fully reusable Space Transportation System is two-thirds that amount, i.e., \$40 million. These data are depicted in Figure 3.6. One need not know the precise shape of the demand curve above section F_0P_0 in order to estimate the direct benefits from the introduction of the Shuttle for "equal capability" analyses. These benefits are defined to be the cost savings indicated by area $F_1F_0P_0P_1$ in Figure 3.6. The points P_0, P_1, P_2 correspond exactly to the same points in the earlier figures of this section. If one were to treat the direct cost savings as the only economic return from the new Space Transportation System, then one assumes implicitly that the demand curve is a straight, vertical line going through points Q_0 and P_0. This is a conservative assumption, indeed, as it assumes that only a fixed capability is to be placed into space, irrespective of transportation and payload costs. With this assumption, one can infer something closely akin to a demand curve. This inferred "demand curve" is shown as the rectangular hyperbola labeled DD in Figure 3.6. The product of any combination F and Q on this demand curve will be equal to a constant budget outlay.

In Figure 3.6, Q_0 represents the space program roughly reflecting the activity level of the 1960's for NASA and for the Department of Defense. The new capability Q_1 reflects the possible incremental capability if NASA and DoD do operate under a constant budget approach. This increment is shown in Figure 3.6 -- going from 43 space missions to low earth orbit (Q_0) to 65 missions to low earth orbit (Q_1). The increment under the equal budget hypothesis is given by the point where the costs per mission, that is F_1F_1 in Figure 3.6, intersect the "constant budget" demand curve, DD. The increment in activities ΔQ shown in Figures 3.5 and 3.6 is about 22 space missions. The induced benefits to be added on to the direct benefits is the area shown as B under the demand curve. This area was defined earlier as the "induced benefits." Given the size of the cost savings implied by the new Space Transportation System (roughly thirty-five percent for the various agencies in launch costs, payload costs, and payload research and development costs) the added activity under the constant budget

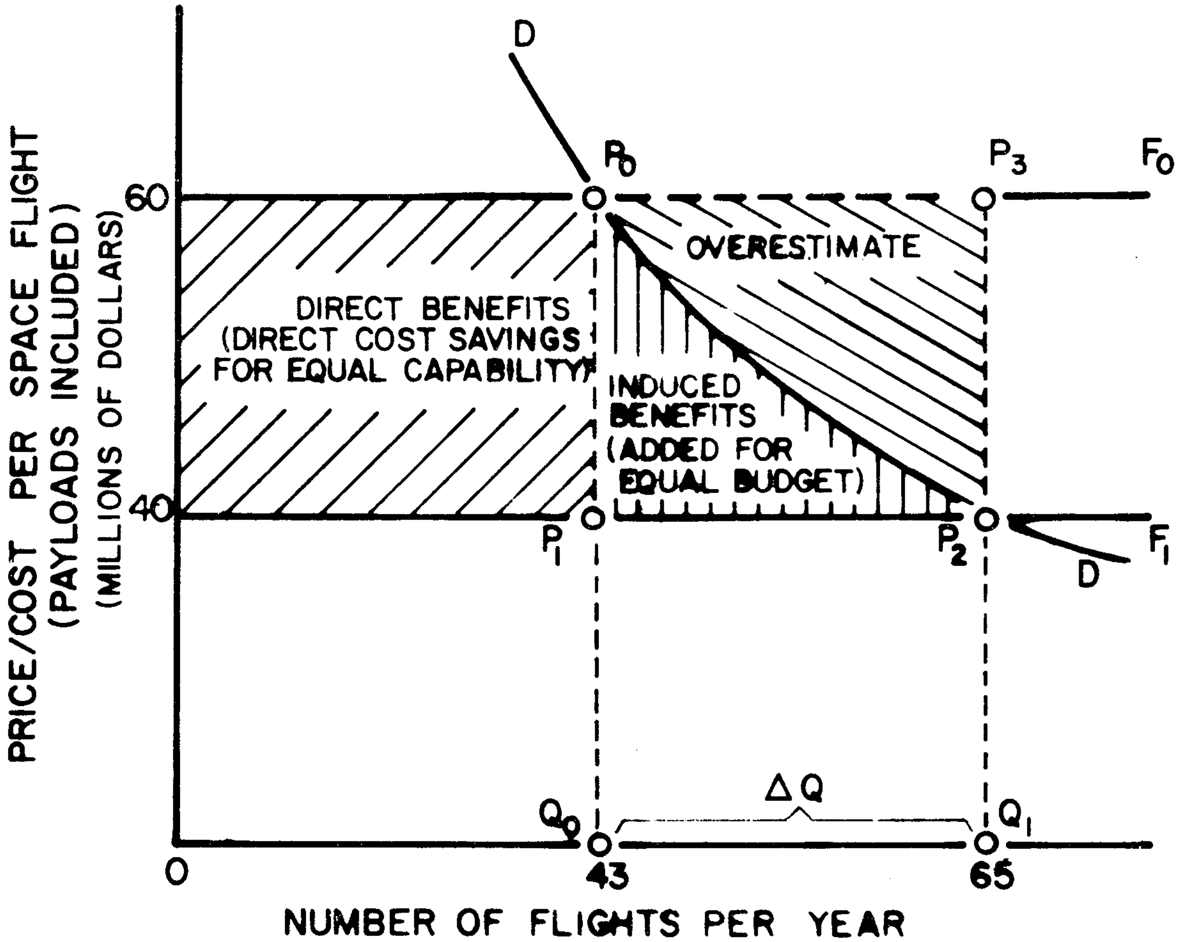


Figure 3.6 Induced Benefits of Additional Space Flights with Equal Budget Analyses

hypothesis adds up to, roughly, another 50 to 60 percent of Q_0. However, the measured benefits shown under the demand curve amount only to 25 to 30 percent of the estimate which would have been made based on a cost savings approach for the total activity level, shown as area B and C in Figure 3.6.

For the actual calculations presented in this report, we proceeded as follows: F_1 represents the cost per equivalent mission capability in orbit for the new Space Transportation System. The expression "equivalent mission capability" or "equivalent payload flight" requires some explanation. One of the major sources of cost savings provided by the fully reusable Space Transportation System is that it will permit heavier and, therefore, cheaper payloads since the absence of the weight constraints will allow the construction of less expensive payloads in a shorter time. Also, a major cost savings in the payload costs, both for research and development as well as per unit costs is derived from the reuse and refurbishment capability of the new Space Transportation System, a capability not existing for expendable systems for economic reasons. From the data that were provided by Aerospace Corporation and LMSC it is shown that, for equal capability, the Shuttle will put up payloads at a cost saving of nearly 30 percent in both OSSA and the DoD as well as application programs, with different payload weights and different numbers of actual space flights.

In order to make the two systems comparable, the cost per pound of payload in orbit or the numbers of space missions for the new Space Transportation System are changed by a factor which varies from payload to payload for our purposes, say a factor of 1.6 (for payload mass) and for number of space flights, say a factor of 0.7. The area $OF_0P_0Q_0$ in Figure 3.6 represents the baseline activity costs of the Current Expendable System. The cost of the Shuttle for a traffic level Q_0 is shown by the area $OF_1P_1Q_0$. The shaded area $F_1F_0P_0P_1$ represents the cost savings of the Shuttle over the Current Expendable System. Then we calculate the induced benefits from the increased activity level that would be stimulated by the lower costs of the fully reusable Space Transportation System for space missions.

From the mission programs, and the cost data provided, is seen from Figure 3.6 that the new, fully reusable Space Transportation System could send up roughly double the payload capability at the same total program costs. The demand curve defined in Figure 3.6 is shown for a total budget of funding level for space transportation activities, including payload costs of $3.0 billion, not including manned space flight activities. With the reduction of payload costs in orbit, the activity level would then increase to Q_1 where the cost curve of the fully reusable Space Transportation System intersects the demand curve. The added activity level in equivalent space missions to low earth orbit is, in the example chosen, roughly 22 flights a year. This amounts to a total of about 65 flights to low earth orbit for the new Space Transportation System at a cost of roughly $40 million per mission including payload costs. The induced benefits generated by the Shuttle at the additional activity level is therefore represented by the area labeled B under the demand curve in Figure 3.6. This represents the consumer surplus or the benefit to society of the new Space Transportation System for the increased activity level ΔQ. The area B is easily computed. B, the benefits due to induced activity, can be calculated as:

$$B = \$3.0 \text{ billion } (\ln Q_1 - \ln Q_0) - A = \$0.40 \text{ billion (per year).}$$

The total undiscounted benefits of the new Space Transportation System per year would therefore equal the original cost savings of $1.0 billion plus the incremental benefits of about $400 million, or together about $1.40 billion per year. It is the sum of the areas shown by A and B in Figure 3.6. In the "Equal Budget" cost-effectiveness analysis, one factor is of overriding importance: the cost per space flight under the different Space Transportation System -- the Current Expendable System and the new, fully reusable Space Transportation System. As a matter of fact, all of the RDT&E and initial investment costs of a new Space Transportation System aim at reducing the operating cost of space programs -- the larger this decrease in costs per flight, the larger the expected cost savings for NASA and DoD missions, and the greater the economic attraction of space technology for commercial ventures. The greater the reductions in the cost per space flight (including payload costs), the more we will move out along the "demand curve" for space transportation shown in Figure 3.6.

3.2 Costs and Benefits: A Unified Concept

The purpose of this section is to examine in greater detail the problem of the comparison and estimation of the benefits derived from the new Space Shuttle System. The term, benefit-cost analysis, is misleading insofar as it implies that the costs of undertaking an investment project are conceptually distinct from the benefits derived from it, and that the categories of costs and benefits must be estimated separately.

For example, suppose that one train costs the same as three buses, and that one train carries 100 passengers between points A and B, whereas one bus can carry only twenty passengers over the same route. If there are 100 passengers to be transported and providing there are no other costs to be considered, then presumably the train should be assigned to carry the passengers. The use of buses to carry the passengers will either increase the cost of carrying a given number of passengers or reduce the benefits achieved from a given expenditure in that few passengers will be carried. A cost is simply a negative benefit. A cost saved is a positive benefit. If, for purposes of estimation a distinction is made between costs and benefits, the line between the two will depend upon the particular structure of the project being analyzed. In the case of the cost-effectiveness approach discussed below, the line becomes blurred and the conceptual identity of costs and benefits emerges.

3.2.1 Problems of Definition and Measurement

The framework developed by economists for the analysis of costs involves a description of the relationship between cost and output levels. Total cost curves measure the total cost of producing each possible quantity of output, and total cost is related to fixed, variable, marginal and average cost in the following way:

Let	total cost	=	TC
	fixed cost	=	FC
	variable cost	=	VC
	marginal cost	=	MC
	average cost	=	AC

$$\text{output} \quad = \quad Q$$

then $$TC = FC + VC$$

$$\frac{TC}{Q} = AC$$

$$\frac{dTC}{dQ} = MC$$

Each value of TC, AC, MC and VC depends of course on the level of output. FC by definition does not change with the level of output. Figures 3.7 and 3.8 describe a conventional set of cost curves. The cost relationships used in economic analysis are simple but important tools for the economist. However, great problems are encountered when an attempt is made to estimate these relationships using real-world data. Cost information recorded by accountants may not conform to the definitions of economists. For example, total and average costs are useful for computing profits and therefore may be easily obtained from existing accounts, but marginal cost, which measures the additional cost which would be incurred if extra units of output were produced is not usually estimated by accountants and may be difficult to obtain. Implicit as well as explicit costs are included by economists in total costs, and these are often excluded from cost accounts.

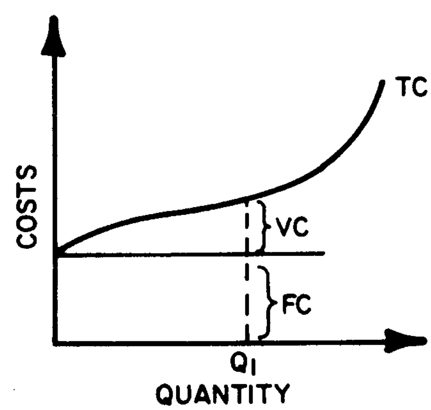


Figure 3.7

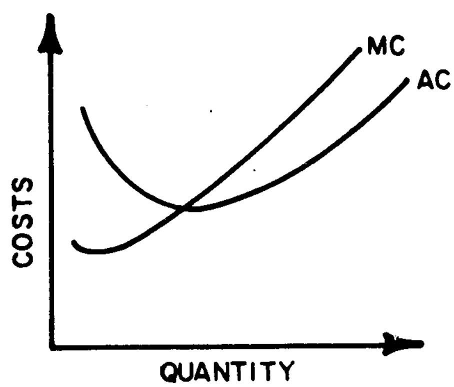


Figure 3.8

Another problem encountered in the estimation of cost curves is the determination of the units in which the volume of output is measured. For example, in connection with the estimation of costs in the transportation industry, it has been suggested that "Different cost levels are associated with different proportions of tons, miles and different velocities... Furthermore, an average length of haul may simply mask substantial diversity among specific hauls thereby obviating (or hiding) considerations of relative heterogeneity, which, of course, renders ten miles an inappropriate traffic concept from the point of view of costs."[4]

For the Shuttle project, the volume of output is variously measured as the number of flights per year (capability), the total number of flights produced by the system over its uselife, and the activity level, or the number of flights produced over the years 1979 to 1990. The shape of the total and marginal cost curves will of course depend on which output measure is used.

The conclusions of any cost-benefit analysis will therefore be sensitive to the way in which the economist chooses to define his terms. Different answers may be reached using different definitions.

The identification and estimation of benefits is subject to precisely the same kinds of complications and we begin with the simplest approach -- cost-effectiveness.

3.2.2 Cost-Effectiveness As A Measure of Benefits

The cost-effectiveness approach itself is straightforward. By means of some decision-making process it is stipulated that certain definite tangible objectives are to be attained. For example, one objective might be the attainment of a given number of space flights per year. Given the objective, the costs of the various alternative programs for achieving it are compared. The choice between programs is then based upon the criteria of minimizing the cost of achieving the specific objectives.

Cost-effectiveness analysis was undertaken for the Shuttle project in the following way. First it was assumed that for a Space Transportation System, the total cost curve could be represented by the straight line TC = F + VM, where TC = total cost, F = fixed cost, VM = variable cost and M = the total number of flights produced by the system over its entire uselife (see page 1-31 of Volume I of the May 31, 1971 Report). V is both the average variable cost per flight $\left(\frac{TC}{M}\right)$ and also the marginal cost of producing the extra flight $\left(\frac{OTC}{OM}\right)$. The assumption is, therefore, that marginal cost is constant over the relevant range of output. Figure 3.9 illustrates the total cost curve.

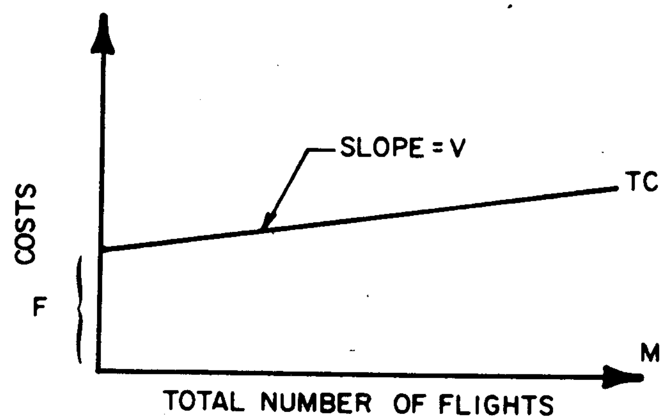


Figure 3.9

Suppose there is a choice of three possible Space Transportation Systems. System one is the current expendable system. System 2 is the proposed Shuttle System and system 3 is the proposed New Expendable System. For each Space Transportation a total cost curve can be drawn (see page 1-37, Figure 1.5 in Volume 1 of the May 31, 1971 Report).

In Figure 3.10, $TC_1^{\,1}$ is the total cost curve for the current system, TC_2 and TC_3 are cost curves for a future new system. In order to compare the three systems fixed costs (F_1) must be deducted from $TC_1^{\,1}$ at every level of output, since these would no longer be incurred if system 1 were scrapped and systems 2 or 3 chosen instead (see page 1-24 of Volume 1 for a more detailed explanation of this point). The total costs of each system are now compared at different levels of output, the objective being to choose that system which can be produced at least cost. Since at every output level TC_3

is higher than TC_1, system 3 would not be chosen. For any output level below M_2, TC_1 is lower than TC_2 and if the chosen objective is to produce output M_1, then system 1 is the cheapest. But if the chosen objective is to product a greater number of flights than M_2, then system 2 is the cheapest. In other words, if the objective is a number of flights equal to say M_3, then system 2 is said to be cost-effective; it is the cheapest (least cost) way of producing more than M_2 flights.

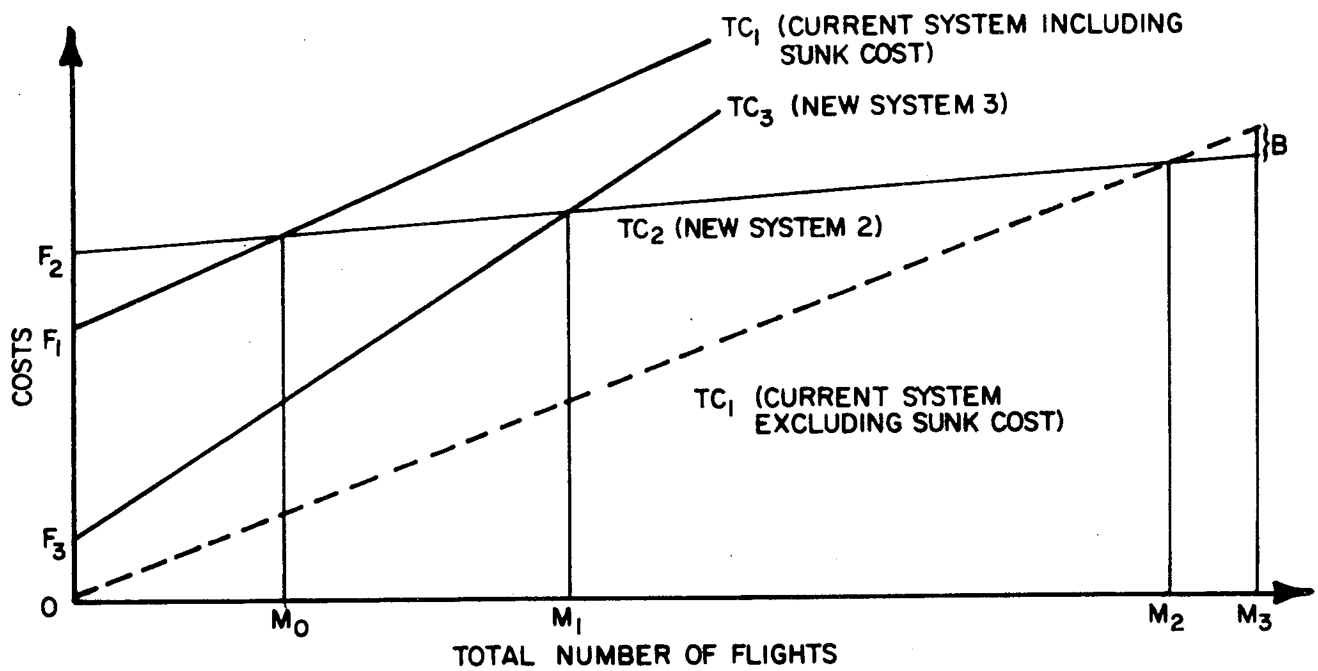


Figure 3.10

Now the question can be raised: what are the net benefits derived from employing system 2? In other words, how much do we stand to gain by employing system 2? The first part of the analysis has only indicated that system 2 is the best way of achieving the objective (say M_3) but presumably it would also be interesting to discover the extent to which system 2 is better than the other systems.

The approach in cost-effectiveness analysis is to measure the difference in total cost between system 2 and (say) system 1 at M_3. This distance, B, measures the extent to which the use of system 2 to achieve M_3 flights reduces cost below that incurred by system 1. The extent of the cost saving (negative cost) can be regarded as an estimate of benefits. The cost-effectiveness approach therefore measures benefits as the amount of cost saved in achieving the given objectives.

Some ambiguity arises, however, when, as for the NASA project, more than two systems are being compared. If the Shuttle System proves to be cost-effective at output level M_3, the question is then whether the benefits should be determined by comparing the Shuttle with the current expendable system or with the new expendable system. The economist's concept of opportunity cost is useful here. When resources are invested in the Shuttle project, they must be diverted from other uses. The cost of the diverted resources can therefore be measured in terms of what their value would have been in other uses. More specifically, the opportunity cost of the diverted resources is equal to the value which they would have had in the most efficient alternative use. The net benefits of the Shuttle System should therefore be measured as the cost saved by choosing the Shuttle over the next most efficient alternative. At output level M, the most efficient alternative was system 1, and the distance B in Figure 3.10 is therefore a correct measure of benefits.

However, since the total cost curves for each project (TC_1, TC_2, TC_3) are not parallel, the relative cost rankings of each project will change for different levels of output. For example, at output level M_0, system 1 is cost-effective and system 3 is the next most efficient alternative. Between M and M_2, system 1 is still cost-effective but now system 2 is the most efficient alternative. Above M_2 system 2 is cost-effective and system 1 is the most efficient alternative. To clarify the switches in cost ranking it was decided to record the differences between TC_1, TC_2 and TC_3 at every level of output (see page 2-37 in Volume 1).

In fact, the actual cost-effectiveness calculations were complicated by the introduction of a discount rate and a more detailed specification of the output objective. A chosen discount rate was used to reduce the total cost estimates of each different output level to their present value. Discounted total cost was then plotted against M to yield three different discounted cost curves. The shape of the cost curves was obviously dependent on the discount rate chosen.

To compare the three projects, an objective (value of M) was selected from a range of scenarios. Since M equals the number of flights per year (Q) multiplied by N, the number of years in the system's uselife, both Q and N could be altered to yield different values of the objective M. For example, scenario 1 consisted of 736 flights over a period of 13 years. M was 736, N was 13. At the level of M determined for scenario 1, the discounted total costs of each project were compared (see p. 2-20, Figure 2.6 in Volume 1) and the benefits of the cost-effective program estimated from the differences between the total cost curves at that level of M.

Before turning to an examination of the equal budget approach as a way of estimating benefits, another way of expressing the cost-effectiveness approach should be introduced. As we have stated above, the total cost of producing any level of output is the sum of the fixed or non-recurring cost and the variable or recurring cost of producing that level of output. When the total cost curve is a straight line, the variable cost per unit of output is unchanged regardless of the level of output. (See Figure 3.9). The value of the intercept of the total cost curve with the vertical axis is of course equal to fixed cost. Now for the three different programs examined the relative size of the contributions of fixed and variable cost to total cost differed. The new expendable system involved a small initial fixed outlay with high variable costs, whereas the Shuttle involved a large initial fixed outlay with rather low variable costs. It was recognized that a choice could therefore be made between having high initial fixed and low recurring costs, and low fixed and high recurring costs. Normally the researcher would only be interested in comparing the total discounted costs of each program. But if for political, budgetary, or other reasons it was expected that constraints might be placed upon the level, not just of the total cost which could be incurred, but upon either the fixed cost or the yearly recurring cost, then an analysis of the relationship between fixed and variable cost would be useful. This is the rationale behind the trade-off analysis describ ed in the report.

Suppose the total cost of achieving objective M_1 is TC_1; the objective can be achieved either by incurring a large amount of fixed cost and a relatively small amount of variable cost, or by sacrificing some fixed cost and correspondingly raising the variable costs which must be incurred. The straight line $T\text{-}0_1$ in Figure 3.11 represents the trade-off between fixed and variable costs when the total cost of achieving output level M_1 is TC_1.

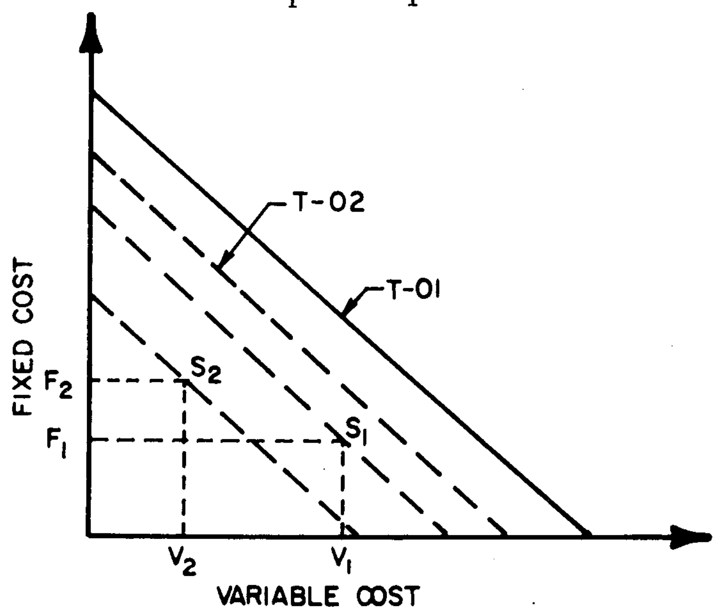


Figure 3.11

If the total cost of achieving output level M_1 were less than TC_1 the trade-off line would shift to the left -- T-02 in Figure 5. Each Space Transportation System can be represented by a single point on the graph. For example, System 2, represented by point S_2 would incur fixed costs F_2 and variable costs V_2 in the production of M_1 units of output. System 1, however, represented by point S_1, would incur fixed costs F_1 and variable costs V_1 in the production of M_1 output. The cost-effectiveness system is that system which lies on the lowest trade-off line. Since system 2 lies on a lower trade-off line than system 1, system 2 is cost-effective.

3.2.3 The Equal Budget Approach as a Measure of Benefits

The cost-effectiveness approach does not provide a method for analyzing changes in objectives. While there may be little difficulty in estimating the costs of increasing the number of space flights produced per year, the question of whether the extra flights produced are worth the extra cost needed to produce them may not be so easily resolved. In other words, since cost-effectiveness analysis assumes that each proposed program must achieve the same objective, whatever the value attached to this objective, this value or benefit will be the same for all programs. The criterion for choosing between programs is therefore to choose that program for which the total cost is least. However, when the possibility arises that each program may achieve a different objective then it is not sufficient to compare the costs of producing the different programs; a comparison of the benefits gained from the different objectives must also be made. This means that a technique must be introduced which will follow a broader evaluation of benefits than that provided by cost-effectiveness analysis.

So far, the discussion has mostly been in terms of total costs, but in economic theory the concept of marginal or incremental cost is also very important. If the government means to operate a Space Transportation System in such a way as to maximize the economic welfare of society as a whole, then it should sell the services (flights) of the system at a rate which is equal to the incremental cost per flight. For Space Transportation Systems characterized by a linear total cost function, $TC = F + VM$, the marginal cost $\left(\frac{dTC}{dM} = V\right)$ will be constant at every level of output. This means that the price per flight charged by the government should be constant and equal to the marginal cost at every output level. Using the proposition that price should equal marginal cost it is possible to describe the cost-effectiveness approach in terms of marginal rather than total cost and then to extend the analysis to include a broader definition of benefits.

As described above, the slope of the curves TC_1 and TC_2, i.e., the marginal cost curves of the current expendable and the Shuttle differ. The marginal cost for the Shuttle System is lower than that for the current expendable system. The two marginal cost curves are shown in Figure 3.12 below.

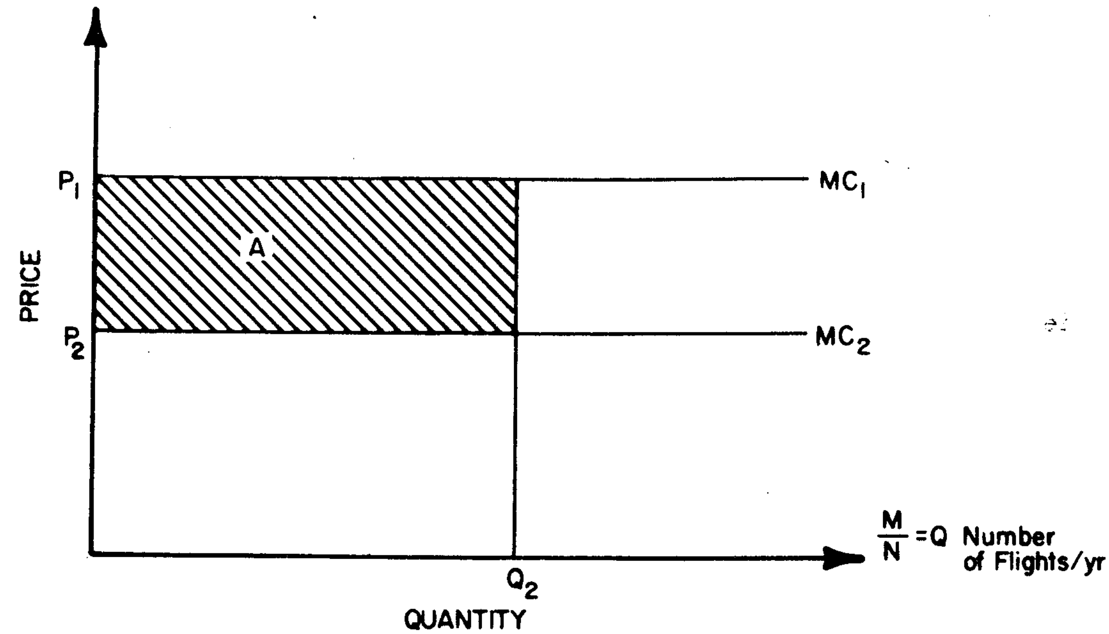


Figure 3.12

If the price charged by the government is equal to marginal cost then the introduction of the Shuttle System would mean a reduction in the price per flight which the government could charge. Suppose the fixed objective is Q_2 flights per year, the rate per flight charged for system 1 will be $P_1 = MC_1$. The rate per flight charged for system 2 will be $P_2 = MC_2$. The net benefit from the introduction of the Shuttle, system 2, is then equal to the price reduction $(P_1 - P_2)$ multiplied by the total number of flights Q_2, shown by the shaded area A in Figure 3.12.

Using this framework it is possible to extend the analysis to calculate the benefits of the Shuttle program when objectives are not fixed. The following discussion centers around the determination of the value of space flights when it is assumed that such flights can be sold to buyers. However, it should be emphasized that not all, perhaps not even a large proportion, of the benefits from Space Transportation are derived directly from the sale of space flights to those willing to buy flights. If a meterological bureau buys space flights for weather research it does so because it derives benefits from the flights. But many other people may benefit indirectly from the results of the weather research, and these benefits may not be included in the price of the space flight. In other words, non-marketable benefits from Space Transportation may be large and should be estimated separately.

The rest of this section concentrates only on the problem of estimating the value or benefits from Space Transportation which are reflected in the market price. This approach therefore yields an underestimate of benefits and should be weighted accordingly.

In order to deal with changes in objectives, it is now necessary to introduce the idea of a market mechanism and demand and supply curves. The quantity of a good demanded by a single consumer can be expressed as a function of the price of the good. Normally, given the consumer's level of income and tastes, if the price of the good falls the consumer will demand more of the good. The quantity demanded is therefore negatively related to the price of a good and the demand curve which represents this relationship graphically (DD in Figure 3.13) is downward sloping.

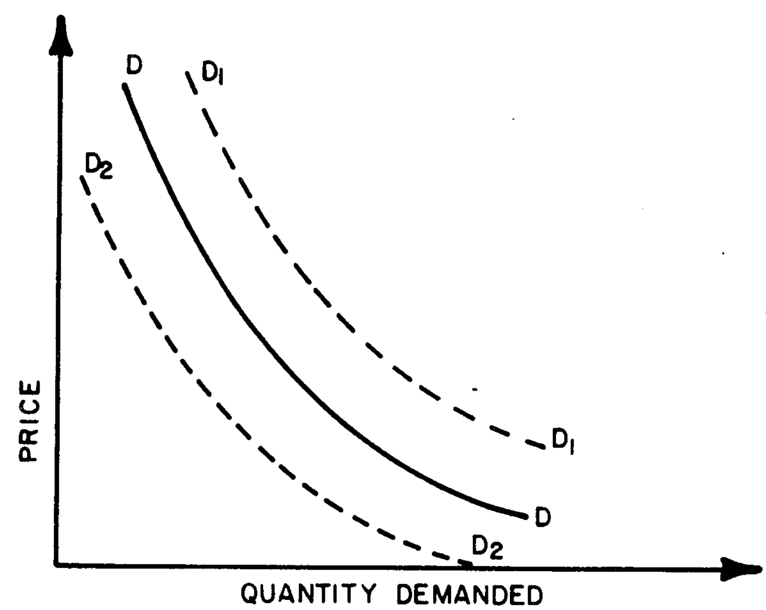


Figure 3.13

Changes in income and factors other than price which affect the consumer's demand will cause the demand curve to <u>shift</u>. The curve will shift outward if circumstances are such that the consumer wants to buy more of the good at every price (D_1D_1), and inwards towards the origin if the consumer wants to buy less at every price (D_2D_2). The total market demand curve for the good is simply the horizontal sum of all the individual demand curves.

For a competitive industry the upward-sloping market supply curve measures the amount of a good which producing firms are prepared to supply at every price. The shape and position of the supply curve depends upon current technology and the price of the inputs used in producing the good. The market mechanism or competitive bidding process will then determine that the actual price at which goods are bought and sold and also the quantity exchanged occurs at the intersection of the demand and supply curves. (See Figure 3. 14)

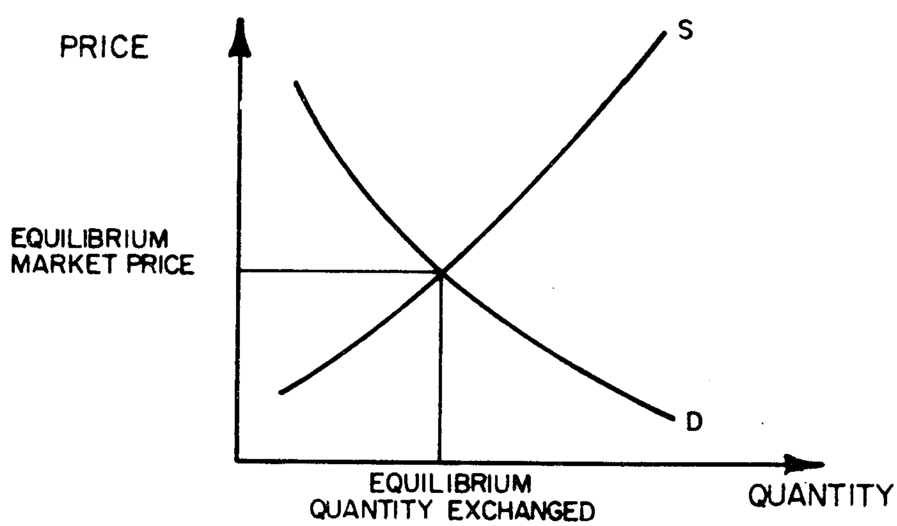


Figure 3. 14

Since, in a perfectly competitive world, the market supply curve is simply the sum of all firms' marginal cost curves, the price which is determined by supply and demand is also equal to each firm's marginal cost of producing the good. Therefore the market price is said to be efficient and to maximize social welfare.

The market mechanism and the determination of price by supply and demand dominates at least the private sector of the economy. However, Space Transportation is produced by only one producer, the government, and is sold to a few large buyers including the government, although there is no doubt that a larger number of potential buyers exists. The market for Space Transportation, therefore, differs from the competitive market structure described above in certain important ways.

Looking first at the demand side, the demand for Space Transportation can also be expressed as a function of the price of space flights, and the demand curve for space flights can be drawn as a downward sloping curve. However, another way of describing the demand curve for Space Transportation is to say that it expresses the consumer's willingness to pay for space flights.

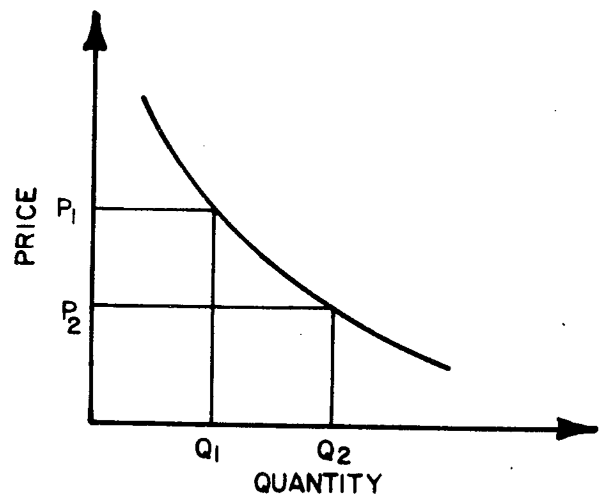


Figure 3.15

If the price charged is P_1 per flight (In Figure 3.15) only those who are willing to pay at least P_1 per flight will demand flights at that price. In other words only those to whom the value of the flight exceeds P_1 per flight will demand space flights. If the price were lowered to P_2 then those willing to pay less than P_1 but more than P_2 per flight would exhibit a demand for flights and the total number of flights demanded would go up. The demand curve therefore characterizes the value or willingness to pay of consumers for Space Transportation.

However, the demand curve for Space Transportation may not be revealed. In a competitive market situation, if producers mistakenly set a price above the equilibrium price level they would find that the amount they were prepared to supply at that price exceeded the amount demanded and bought. They would have a surplus of goods and this would be the signal for them to reduce their price towards the equilibrium level. At different price levels producers will perceive the amount demanded and therefore have an idea of the shape of the demand curve. But for Space Transportation there is only one producer, the government. Moreover, though there may be a large number of buyers who would benefit from being able to buy Space Transportation and would buy more the lower the price, they are not able to buy the good yet since the good is only for sale to certain government departments. Therefore, the total demand for Space Transportation which would reflect the total valuation put on Space Transportation by society may be said to exist but is not revealed. If the government were to quote a lower pricer per flight, those departments (such as NASA and DoD) currently buying Space Transportation might be willing and able to buy more flights thereby revealing the value which they put on the flights. However, for all those buyers who are not yet able to buy flights a value or benefit exists which is not revealed. A demand curve which reflects the response of the quantity demanded by current buyers to price changes, but does not include potential buyers is therefore an inadequate tool for the estimation of benefits and will lead to an underestimate of the social value of Space Transportation.

The equal budget approach which relies on the concept of a demand curve is based on the following hypothesis. Suppose there is just one government agency buying Space Transportation -- say DoD. That agency has a budget allotted for the purchase of space flights which is fixed for a given period -- say a year. At the quoted price P_1 (in Figure 3.16), the DoD will be able to buy as many as Q_1 flights if its budget is equal to P_1Q_1, area $0P_1xQ_1$ in the figure. Now suppose that the following year the DoD has been allotted the same budget but that the quoted price has been reduced to P_2. The equal budget hypothesis assumes that the DoD will buy as many more space flights as its budget allows; i.e., at a price of P_2 DoD will demand Q_2 space flights where the product P_2Q_2, area OP_2YQ_2 equals area OP_1xQ_1. In other words, while cost-effectiveness analysis

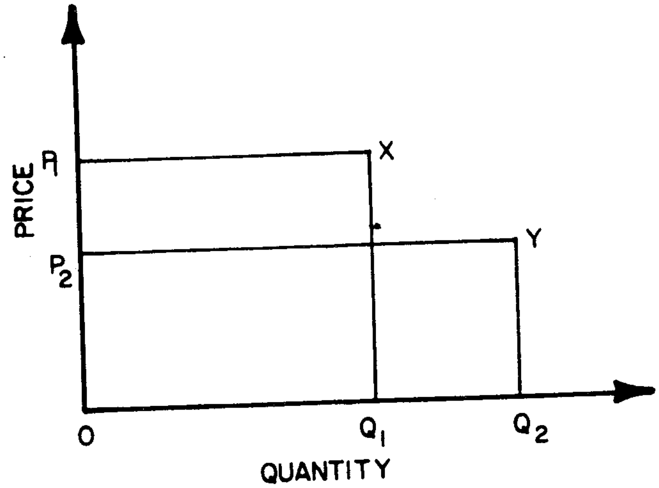


Figure 3.16

assumes that the same quantity of flights is bought regardless of the price, the equal budget approach assumes that the same quantity of money will be spent on space flights regardless of the price.

Both approaches embody an implicit assumption about the shape of the demand curve for space flights. The cost-effectiveness approach assumes that demand is completely unresponsive to price and therefore that the demand curve for flights is a vertical straight line at the level of the fixed quantity demanded. (See Figure 3.17)

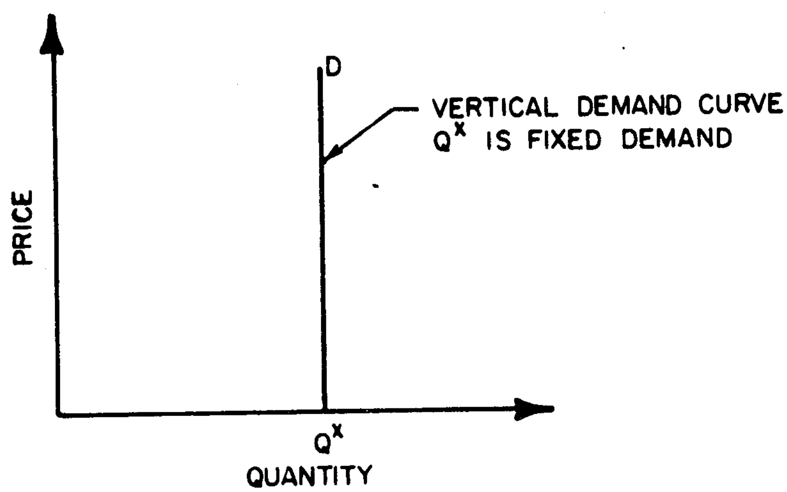


Figure 3.17

The constant budget approach assumes that at each price that quantity will be bought such that the square area under the demand curve which represents the product PQ (the total amount of money spent on flights) is always the same. Such a demand curve has the shape of a rectangular hypobola. (See Figure 3.18)

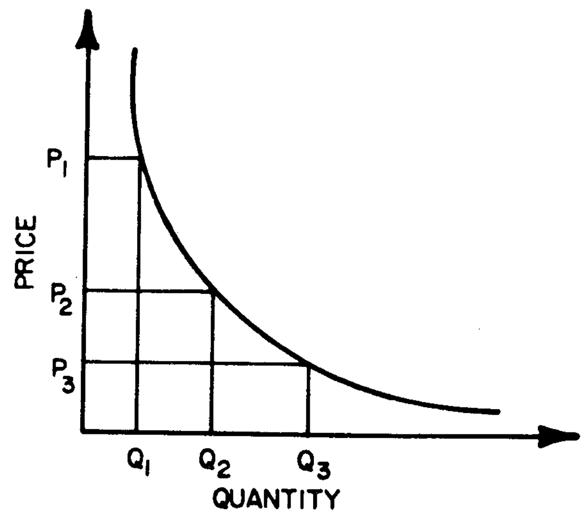


Figure 3.18

In economic terms the shape of the demand curve is described by the concept of elasticity; in the case of the constant-budget approach the demand curve has unitary elasticity.

The elasticity of demand measures the extent to which the quantity demanded responds to a change in price. The fact that the demand curve slopes downwards to the right indicates that when the price falls the quantity demanded rises. However, the elasticity of the curve measures the extent to which demand rises in response to the price fall. For example, suppose the price falls by 3%, if there is a more than 3% rise in quantity demanded, then the demand curve is said to be elastic at the point at which the measures were taken. If a 3% fall in price is accompanied by a 2% rise in quantity, then the demand curve is said to be inelastic. If a 3% price fall induces a 3% rise in quantity then the demand curve is said to possess unitary elasticity, and this is the assumption behind the constant-budget approach.

We examine below the plausibility of the unitary elasticity assumption in terms of the likely behavior of those government agencies which buy Space Transportation.

For now, the task is to show how these concepts can be used to measure the comparative benefits of two systems using the equal budget approach. The problem can be formulated as follows: suppose the government can produce two possible Space Flight Systems. For each system, the marginal cost per flight is constant, but for system 1 the marginal cost curve is higher than for system 2. (See Figure 3.19)

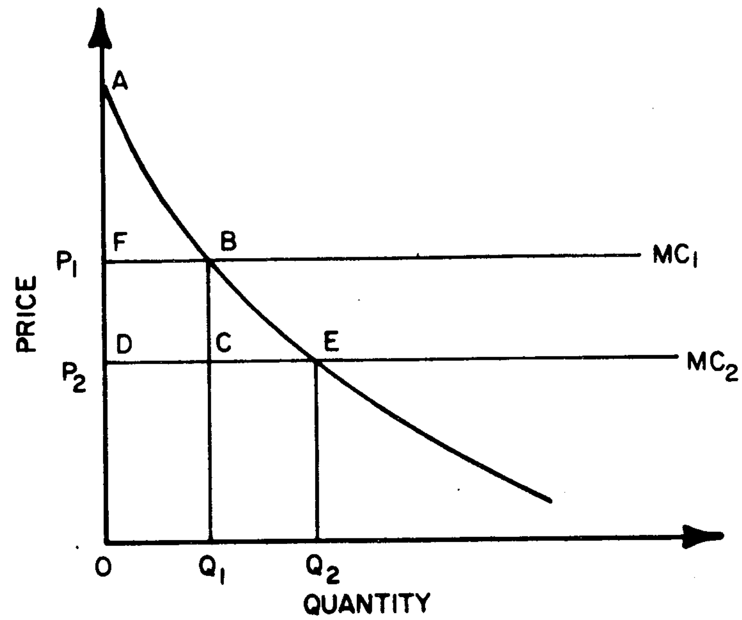


Figure 3.19

Assume that the price per flight for each system is always equal to the marginal cost for the system. If the demand curve for flights is known we can see that if system 1 is employed the price per flight will be P_1 and the quantity demanded at that price will be Q_1; if system 2 is employed the price per flight will be P_2 and the quantity demanded Q_2. What are then the benefits of employing system 2 rather than system 1? Note that the cost-effectiveness approach assumes that Q_1 is consumed for both systems and therefore that the net benefits gained from choosing system 2 equals the cost (or price) reduction (P_1 - P_2) multiplied by the fixed quantity Q_1, area DFBC in Figure 3.19.

To explain the measurement of benefits for the constant budget approach, the economic concept of consumers' surplus must be introduced. When price equals P_1 and quantity Q_1 is consumed, the value to the consumer of the last unit of Q_1 must be just equal to P_1. However, all consumers except the last were willing to pay more than P_1 for the units which they consumed; these consumers therefore experience a surplus value over and above the price P_1 which they paid for the good. This surplus value is called consumers' surplus. At price P_1 the consumer's surplus generated from the consumption of Q_1 is shown by the area CS in Figure 3.20 below. Now suppose the price falls to P_2 and the quantity demanded rises correspondingly to Q_2.

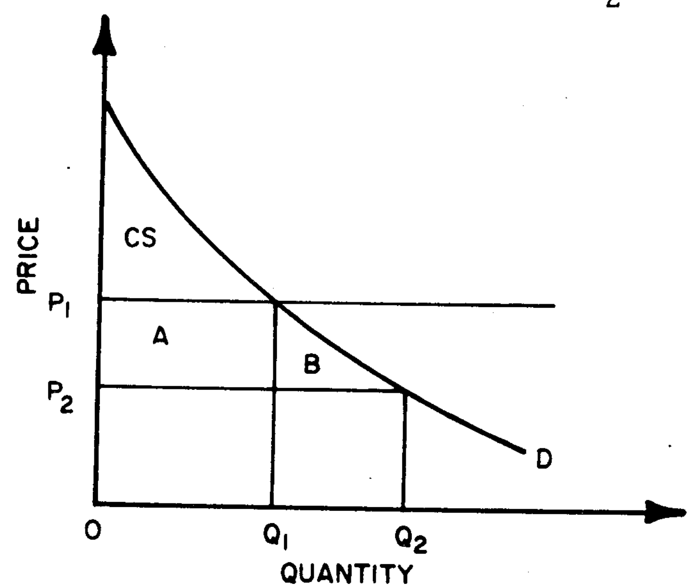


Figure 3.20

Now the value to the consumer of the last unit of Q_2 is exactly equal to P_2. But all the consumers of the intramarginal units were prepared to pay more than P_2 for the good and therefore experience a total consumers' surplus of CS+A+B. The addition to consumers' surplus which results from the fall in price is therefore equal to area A and area B. Area A represents the increase in benefits to existing consumers from the price fall, and area B represents the extra benefits which accrue to consumers from the consumption of a larger quantity. For the Shuttle project area A is referred to as Direct Benefits and equals those estimated for the cost-effectiveness approach; area B is called Indirect Benefits.

If the concept of consumers' surplus is recognized as a legitimate measure of benefits then it can be seen that the cost-effectiveness approach underestimates the net benefits of using sytem 2 where space flights are priced lower for system 2 than for system 1. The net benefits A+B gained from system 2 are then compared with the fixed-cost expenditure associated with the introduction of system 2 and that system chosen for which benefits -- costs is greatest.

Given that the use of a downward sloping demand schedule for the estimation of benefits is a more realistic and inclusive method than the cost-effectiveness approach, it is now appropriate to investigate the question of whether the unitary elastic demand curve is a plausible representation of the behavior of the current buyers of Space Transportation -- i.e., government agencies. If it can be shown that government agencies do increase the quantity of space flights they buy when the price falls, and that the percentage increase in quantity is approximately the same as the percentage fall in price, then it can be argued that the use of the constant budget hypothesis to estimate benefits is a reasonably accurate method.

Let us assume that there is only one supplier of space flights, NASA, and only one purchaser, DoD, both supplier and purchaser being government agencies. As before it is assumed that the supplier agency sells its product at a price equal to marginal cost. If the constant-budgeted approach is to be used for an estimate of benefits, evidence must be found for the following hypothesis; there is a choice between the production and sale of two systems, the current expendable (CE) system and the Shuttle System. For the CE system the marginal cost per flight is constant for all relevant ranges of output and higher than the marginal cost per flight for the Shuttle System which is also constant. Under these circumstances with the introduction of the Shuttle System the price per flight which the DoD must pay will go down and DoD will buy more flights such that its total expenditure on space flights remains constant.

The sytem of allocating funds to the various federal government agencies known as the PPB system has undergone sveral important changes during recent years, but continues to sustain criticism. Among the papers advanced as part of a Several Study of the PPB system undertaken in 1969 [5] the following have important implications for the constant-budget hypothesis.

Weidenbaum [6] discusses the extent to which agency budgets are controllable by congress. Weidenbaum argues that because of the timing of appropriation, rigidities resulting from the earmarking of funds for particular purposes, statutory constraints and the limitations of planning resulting from authorization made on a year-to-year basis, it is difficult for congress to control, and in particular, to reduce yearly the budgets of some agencies. In other words, it is only possible for congress to change some agency budgets year by year if the change is in the upward direction; it is very difficult to reduce them. This implies that it is difficult to switch funds between agencies and therefore that an efficient interagency allocation of funds in which the marginal net benefits of funds are equated between agencies is unlikely to occur. The absense of efficiency in interagency allocation of funds necessarily reduces the benefits from allocating funds efficiently within any one agency, and weakens the estimate of benefits used here.

Weidenbaum suggests, however, that a large percentage of DoD funds are controllable and able to be reduced by congress on a yearly basis.

Assume that at any given budget level the DoD demand for flights is a normal downward sloping schedule, DD in Figure 3.21.

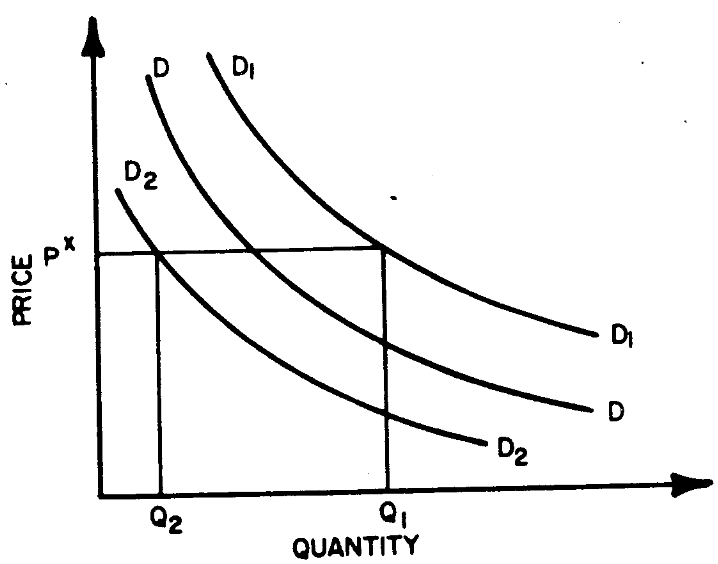


Figure 3.21

A rise in DoD's budget implies an upward shift in its demand curve for flights to D_1D_1; a reduction in its budget implies a downward shift in the demand curve to D_2D_2. If the price per flight remained constant at P^x the quantity of flights consumed would obviously be larger for the large budget (Q_1) than for the small budget (Q_2). If the DoD budget is changed every year then its demand curve will shift every year and the quantity demanded at any given price will be different every year.

One of the ways of determining the shape of the demand curve of a government agency might be to examine the quantity of flights bought and the price paid each year.

For example, in Figure 3.22 the quantity of flights bought in 1963 was Q_{63} and the price paid was P_{63}. The quantity of flights bought in 1964 was Q_{64} and the price paid was P_{64} and so on. The actual price-output combinations observed each year could be plotted and a curve DD constructed through these points as an estimate of the DoD demand curve.

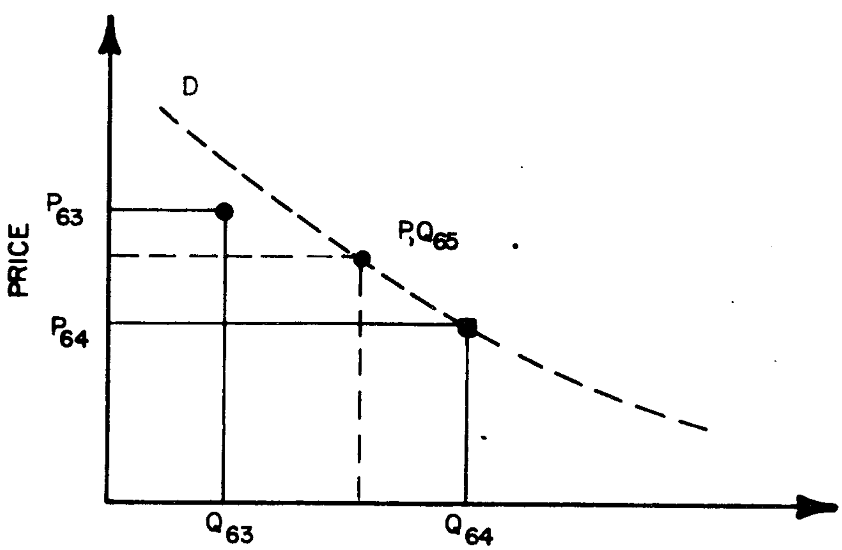


Figure 3.22

However, this analysis assumes that the demand curve does not shift from year to year. But suppose that the 1967 demand curve was D_7D_7 in Figure 3.23, and the 1968 demand curve was D_8D_8, etc. Then the estimated demand curve is a hybrid which resembles none of the true demand curves. This identification problem would arise in the space flights' case if, as we have suggested the DoD budget does not remain constant from year to year.

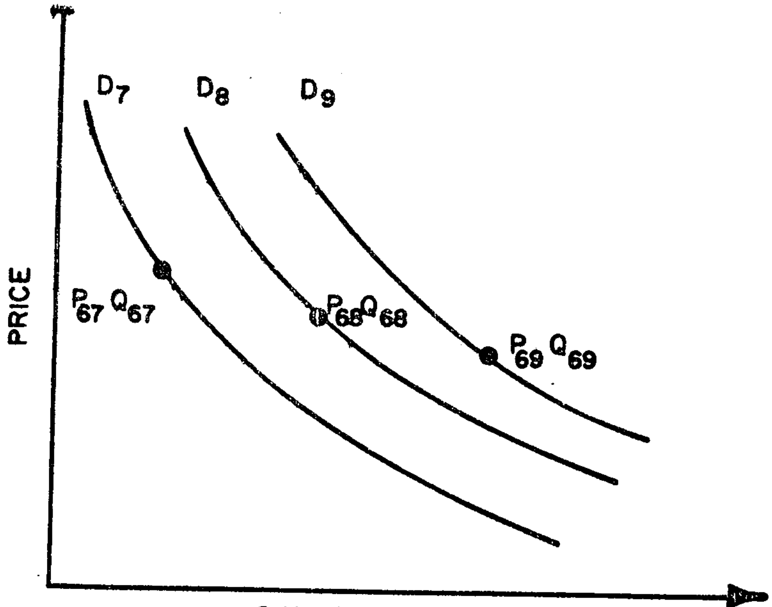


Figure 3.23

However, additional information is available in the Space Transportation case which can help solve the identification problem. It was assumed above that the supplier agency always charged a price per flight equal to marginal cost. Suppose that each year technological changes take place causing the marginal cost curve of the producing agency to shift downwards. Each year the price charged to the buying agency is reduced. Suppose, moreover, that the demand curve is relatively stable from year to year and not shifting very much. Then the price quantity points which are observed trace out the shifting of the marginal cost curve along the true demand curve. (See Figure 3.24)

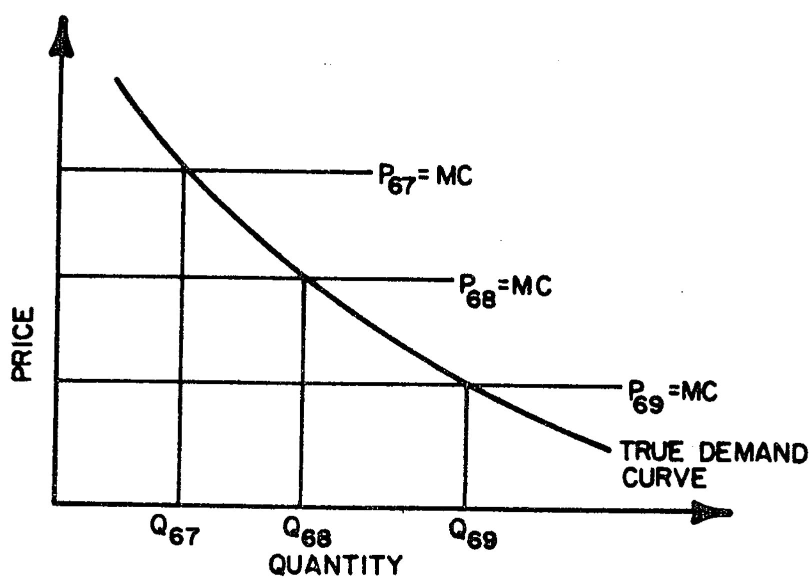


Figure 3.24

In other words, when there is information which suggests that the marginal cost curve is shifting downwards year by year then it can be concluded that the observed price quantity points trace out something close to a demand curve.

Information gathered from DoD suggests that this is the case for Space Transportation.

We can conclude from the evidence provided by the DoD that DoD does in fact buy more flights when the price of flights is reduced, and furthermore that the elasticity of its demand curve is close to 1.

A further rationale for this behavior might be found in the way budgets are used within any given agency. Both Achinstein[7] and Weidenstein[8] suggest that as is the case between agencies, within any given agency funds are rigidly alloted for certain purposes. Once allocated these funds cannot be shifted easily to another project. A reduction in the price of flights to the DoD would both increase the real value of the budget allotted to the DoD for the Shuttle project (income effect) and also make expenditures on space flights cheaper relative to expenditure on other projects (substitution effect). Because of the rigidity of fund allocation one would not expect the DoD to substitute additional space flights for other projects since the funds could not be easily shifted into the Shuttle project. However, one would expect the income effect to work in that the DoD would now buy more flights when the price of flights fell because of an increase in the real value of its budget. In fact, since it would presumably be equally difficult to shift funds out of the Shuttle project if some were left over, one would expect the DoD simply to use up its funds in buying extra flights. In other words, it would spend the same amount in space flights at every price; its demand curve would exhibit constant elasticity.

3.3 Critical Parameters in the Evaluation of New Space Transportation Systems

Up to this point our attention has been focussed exclusively on the definition of the benefits and costs of new Space Transportation Systems and their use in cost-effectiveness and benefit-cost analyses. We shall now turn to an examination of the major parameters entering the evaluation of new Space Transportation Systems, namely: the social rate of discount, the investment horizon, and the gestation period and IOC-date.

3.3.1 The Social Rate of Discount

3.3.1.1 The Theoretical Underpinnings of the Concept

In the May 1971 Report, we had introduced the technique of discounting and the concept of the social rate of discount by referring to society's so-called rate of time preference. Briefly, society's rate of time preference may be defined as a rate of interest which reflects consumer's subjective, relative evaluation of given quantities of consumables available at different points of time. For example, if in year 0, consumers assign the same value to 100 units of consumables available immediately as they do to the certain prospect of receiving 105 units of consumables one year hence, then their rate of time preference is said to be $0.05 = \left[\frac{105}{100} - 1\right] = 5$ percent. Alternatively the rate of time preference may be defined as the rate of interest which consumers would have to be offered in order to persuade them to sacrifice additional current consumption in favor of additional future consumption.

Any investment project -- public or private -- involves the sacrifice of consumables at some point in time for the sake of increased consumption at one or more subsequent points in time.[9] From the very definition of the rate of time preference, it is clear that this rate must some how be reflected in the social rate of discount used in the evaluation of public projects.

There is, however, still another side to the social discount rate. We had noted in the May Report that the social opportunity costs of a public project are the benefits foregone when the economic resources used by the project are diverted from the private to the public sector. The social rate of discount should reflect these opportunity costs as well.

Let us assume, for example, that all of the resources devoted to a public project would have been used in the private sector for investment outlays promising an annual rate of return of 10% before corporate income taxes and after an allowance for the eventual replacement of worn out equipment. Suppose \$1-billion in resources were transferred to the public project. Then the public project could be justified economically only if it also promised a benefit stream (necessarily accruing to members of the private sector at large) equivalent to an annual benefit stream of \$100-million (10% of \$1-billion). An alternative way of expressing this is that the present value of the benefit stream produced by the public project, discounted at $r = 10\%$, must be at least as high as \$1-billion, or, that the net present value (NPV) of the project must be greater than or at least equal to zero.

The interest-rate concept used in the preceding paragraph is sometimes referred to as the time productivity of economic resources. It is the rate of return which society is able to earn in the private sector by sacrificing current consumption in favor of future consumption, i.e., by investing economic resources in productive investment projects. In contrast, society's rate of time preference is the rate of return for which society's rate of time preference is the rate of return for which society is willing to sacrifice current consumption for the sake of increased future consumption. These two interest-rate concepts should not be confused: the rate of time productivity is an objective, technical concept; the rate of time preference, on the other hand, is a purely subjective magnitude.

It can be shown that, in the imaginary world of classical economics, the savings and investment behavior of society -- through the nation's capital markets -- would always drive the economy to an equilibrium position in which all individuals exhibit the same (social) rate of time preference, all investors face the same (social) rate of time productivity and in which, moreover, the social rate of time preference would be just equal to the social rate of time productivity. This overall equilibrium market rate of interest would then be the appropriate discount rate to be used for public-project evaluation.[10]

Unfortunately the real world differs significantly from the happy state of affairs in the classical model. For one, individual investors face different degrees of risk and differ in their attitudes toward risk. The rate of returns required by private investors therefore include risk premia which differs over the spectrum of investors.

Secondly, the tax system does not treat all investors in the private sector equally. Corporations, for example, force tax rates that differ from those paid by unincorporated businesses, and there are also differences in the rates paid by different unincorporated business firms. To earn the <u>same</u> after-tax rate of return, different business firms must therefore earn <u>different</u> pre-tax rates of returns on their marginal investments.

Finally, net savers in our economy typically obtain rates of return on their savings that differ from the rates faced by net-borrowers. Different consumers therefore are characterized by different rates of time preference.

<u>In short, then, in the real world there exists no single market rate of interest which can be viewed as the appropriate discount rate for public project evaluation</u>. The rate being used for that purpose must therefore be a weighted average of the various rates prevailing in the market.

In the real world, a resource transfer from the private to the public sector does not usually come solely from private investment projects: part of the resources will surely come from private consumption. It follows that the opportunity costs of the resource transfer must reflect not only the spectrum of rates of return on foregone private investments, but also the spectrum of time preference rates of those who sacrificed current consumption. This requirement confronts one with enormous difficulties in any attempt to estimate the appropriate level of the social discount rate for practical applications of benefit-cost analyses. These difficulties are discussed in detail in an earlier report, <u>On the Principles of Public Project Evaluation</u>[11] and will not be enumerated here. Suffice it to say that the fundamental idea underlying this estimation process is always the same: one seeks to estimate the magnitude of the sacrifice borne by the private sector when resources are transferred from private consumption or investment to public-sector use, and to express this sacrifice in the form of an annual rate of return, r.

3.3.1.2 Social Rates of Discount Used by Various Federal Agencies in the United States

Table 3.1 presents a sample of discount rates estimated with painstaking effort by various professional economists. It should be emphasized that the economists' estimates were made at different points in time, i.e., under different capital-market conditions. But this circumstance alone cannot explain the wide variation in these estimates; rather, the variation reflects for the most part differences in the conceptual framework used by these economists.[12]

From the surveys presented in Table 3.1 and earlier surveys[13] it is apparent that neither the various U.S. government agencies nor professional economists have so far been able to agree on an appropriate social rate of discount. The rates of discount implicity or explicitly adopted by Federal agencies span a range from 0 percent to 15 percent. (In some cases this rate actually may be less than zero when outright subsidies are given in the financing of projects with a negative return in undiscounted dollars.) The rates suggested by economists span the somewhat smaller range from 4 percent to roughly 14 percent.

In view of the prevailing uncertainty about the proper social rate of discount, some economists would prefer not to select a unique discount rate at all, but instead to evaluate public projects in terms of an entire set of alternative rates. For want of a better term, we shall call this method the flexible approach. Pushed to its logical limit, the flexible approach amounts to the derivation of the net present value curves for all projects being evaluated for a reasonable range of discount rates, say from zero to 20 percent. The overall evaluation can then be presented simply in terms of a diagram such as Figure 3.25, which depicts the discount-rate sensitivity of three hypothetical investment projects.

The advantage of the flexible approach is immediately apparent from Figure 3.25. For Project I, the approach clearly indicates acceptance of the project for the example chosen, since the project has a positive net present value over both the range of discount rates suggested by economists

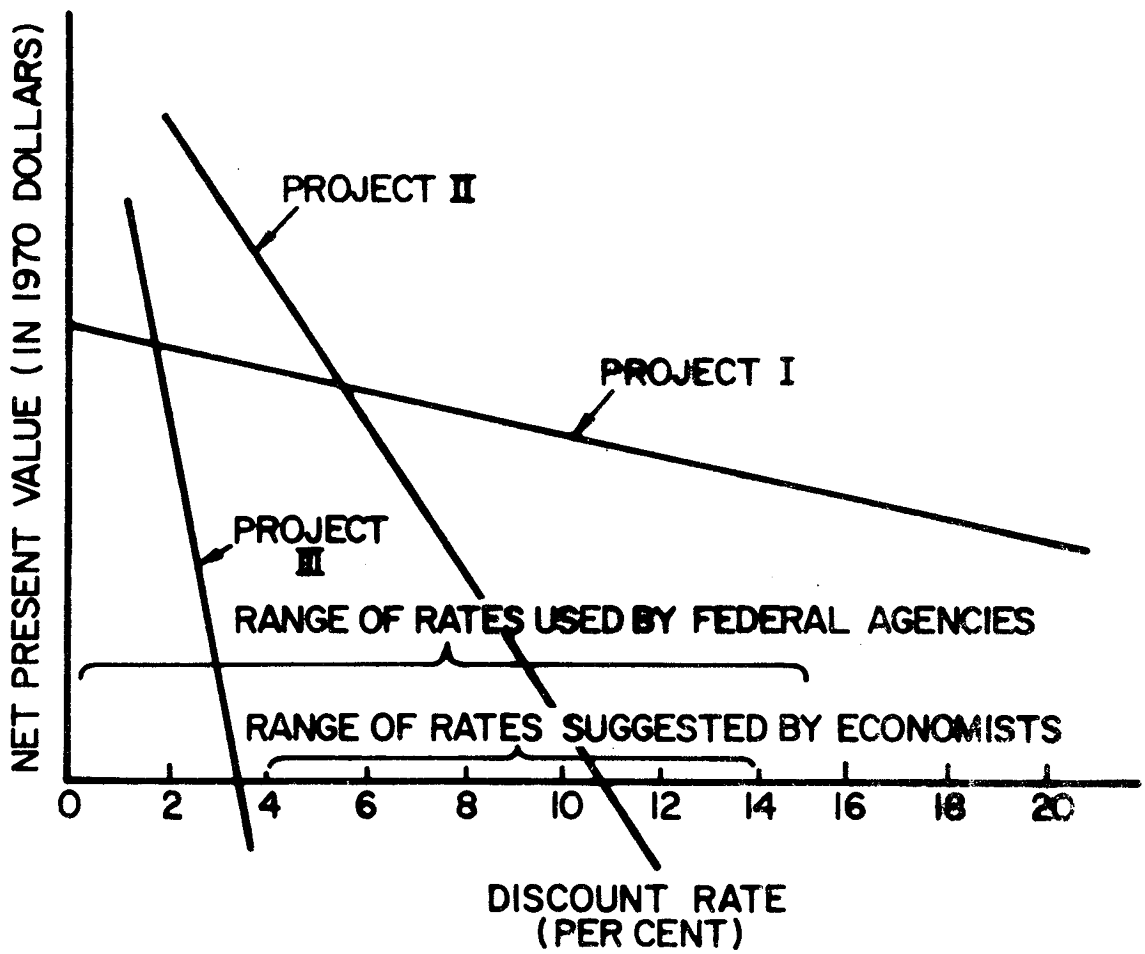
Table 3.1

Social Rates of Discount Recommended by Various Economists

Author	Year	Rate
Krutilla and Eckstein [9]	1958	5 to 6 percent
Hirschleifer, DeHaven, and Milliman [10]	1960	10 percent
Hufschmidt, Krutilla and Margolis [12]	1961	4 to 5 percent
Weisbrod [11]	1960	10 percent
Friedlaender [13]	1965	5 percent [1]
Bain, Caves and Margolis [14]	1966	5 to 6 percent
Stockfish [4]	1967	13.5 percent
Baumol [15]	1968	10 percent
Eckstein [16]	1968	8 percent
Harberger [17]	1968	10.68 percent

1 The author adjusts for risk by assuming a relatively short use life for the (highway) investment project being evaluated.

Source: J. Hirschleifer and D. L. Shapiro [2], Table 1, pp. 517, for unstarred items and author's publication for starred items.



Project Evaluation: Net Present Value As A Function Of Discount Rates Used

Figure 3.25

(4 to 14 percent) and that suggested by federal agencies (0 to 15 percent). Similarly, Project III would probably be rejected since it has a positive net present value only at rates lower than those recommended by economists. The more flexible approach thus provides one with information about the sensitivity of the acceptance criterion to the analyst's assumptions concerning the discount rate.

However, the flexible approach is not particularly helpful in one's evaluation of Project II. Clearly, it is small comfort to know that there are some rates, acceptable to some analysts, at which Project II would be acceptable, when there is also an entire range of recommended rates at which the project would be deemed to be "uneconomic." In other words, for projects such as II the flexible approach begs the question entirely.

Facing the risk of being criticized for not having taken into account any one of the particular interest rates suggested by economists, we analyzed, as a first step, all alternative Space Transportation Systems being considered in this Report for interest rates ranging from 1 to 20 percent. These discount rates, it should be noted, are real rates, i.e., they are free from any allowance for inflation.

At some stage of the evaluation of new STS's, NASA (or the final arbiter) must, of course, narrow the range of plausible social discount rates sufficiently to help him overcome the ambiguities left by the flexible approach. This narrowing of the range of plausible rates, however, cannot proceed on a rational basis unless the arbiter has at least some understanding of the conceptual issues involved in the estimation of the social rate of discount. For only on the basis of such an understanding can a government agency decide or argue that, say, 7.5 percent is likely to be a better approximation of the true social rate of discount than, say, 12 percent.

3.3.1.3 The Discount Rates Used by MATHEMATICA

For the purpose of this Report, MATHEMATICA proposes that the representative values for the evaluation of the new Space Transportation System be chosen at a rate of discount of 10 percent. For purposes of comparison, MATHEMATICA will also summarize the economic results at

5 percent and 15 percent. In making this recommendation, the following considerations are offered:

1. The 10 percent rate of discount is among the highest rates used for the evaluation of public investment projects in large scale research and development programs.

2. It is larger than the discount rate used by the Bureau of Public Roads which "does not use discounting techniques in administering Federal aid and direct Federal highway construction programs", and "in addition, does not plan to use discounting techniques in the future." [6, p. 169.]

3. The 10 percent rate is in direct agreement with the recommendation of the Department of Defense which recommended that "one way for the DoD to assure this result [i. e., to treat interest as a cost] is to adopt in public investment evaluations an interest rate which reflects the private sector investment opportunities foregone. The discount reflects the preference for current and future money sacrifices and the public exhibits in non-government transactions. A 10 percent rate is considered to be the most representative point within a range of plausible rates at a present time." [7, p. 60.]

4. The 10 percent rate exceeds the rate proposed by the U.S. Water Resources Council [6, p. 13] and that recommended by the Subcommittee on Economy and Government and by the former Bureau of the Budget which stipulated in Circular A-92 of June 26, 1969, that "a discount rate used to evaluate programs and projects should not be lower than the discount rate established by the Water Resources Council... The formula to be used to compute this rate is defined in the December 24, 1968 issue of The Federal Register, Volume 3, pp. 19, 170."

This rate was recommended as "the floor of the acceptable range [of rates]." [5 , p. 9.]

5. The 10 percent rate exceeds or equals the social rate of discount recommended by 8 out of 10 economists listed in the previous survey, a representative cross-section of the present recommendations by the economics profession. The exceptions are Harberger [17] who recommends 10.68 percent, and Stockfish [4] who recommends 13.5 percent.

6. The discount rate of 10 percent applied to real dollars (1970) dollars were used throughout our analysis of the new (STS) corresponds actually to a nominal financial market rate of at least 15 percent in the present environment of the U.S. economy, with a rate of inflation well in excess of 5 percent. This rate can be considered as one of the most conservative rates used in an evaluation of public projects.

3.3.2 The Investment Horizon

In the discussion above it has been assumed that the uselife of our hypothetical, new Space Transportation System (System 2) is a finite number of N years. That assumption is surely an oversimplification. In reality, a transportation investment consists of a variety of distinct components, each with its own physical uselife. Given this agglomeration of different, individual uselives, the question arises what the overall project horizon of a Space Transportation System should be? We shall now examine this question, using as a concrete example the two-stage reusable Space Shuttle currently being evaluated by NASA.

3.3.2.1 The Determinants of the Uselife of an Investment Project

The assumed "economic uselife" of an investment project is normally something shorter than infinite because of one or a combination of the following factors:

1. Factors inherent in the project itself:

   a. One of the physical inputs to the project depreciates over time, collapses at a point in time (one hoss-shay depreciation) or becomes unavailable at a point in time (e.g., a rented piece of land, or an exhaustible supply of raw materials).

   b. The demand for the product or service yielded by the project may drop off or disappear altogether after some time.

2. Factors inherent in the decisionmaker:

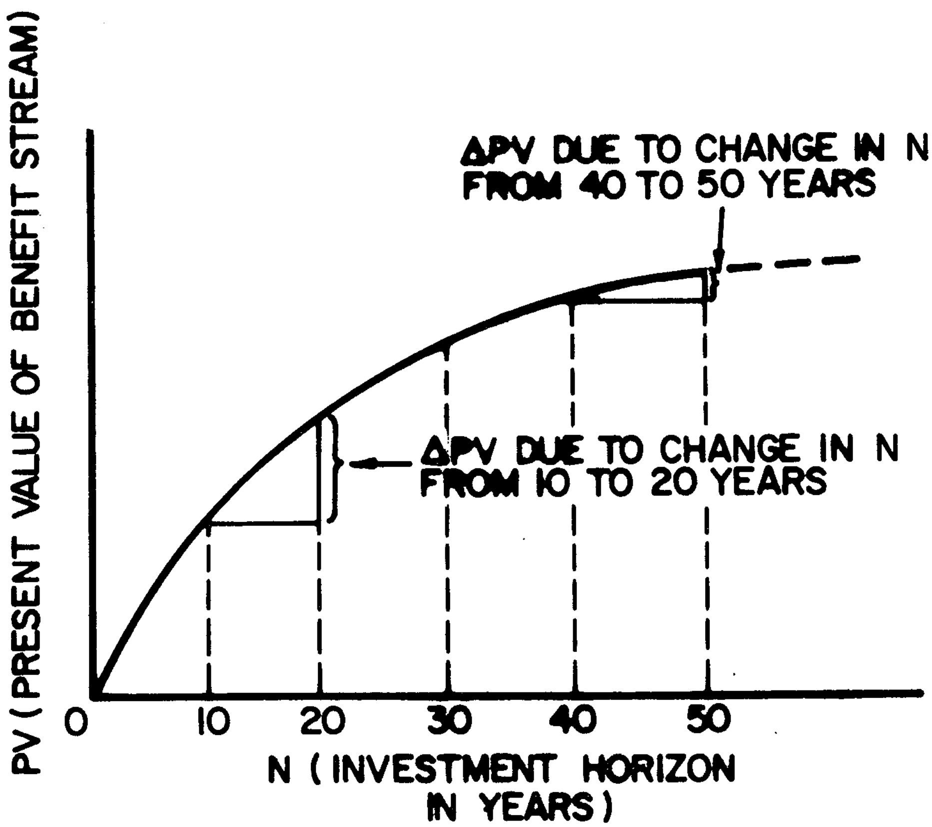
   a. The decisionmaker is risk averse and deliberately chooses a finite and possibly short investment horizon as a risk adjustment.

   b. The decisionmaker limits the investment horizon to his own life expectancy.

Since the present discussion is concerned exclusively with public investments in transportation systems, item 2(b) above can be dismissed from consideration altogether. Furthermore, it has been argued in an earlier report by MATHEMATICA to NASA [14] -- and in the pertinent economic literature at large -- that the government should not be risk averse in evaluating alternative public projects. This means that a public agency should not, because of risk averseness, shorten the investment horizon (N) of a public project arbitrarily. On the basis of this argument, item 2(a) above can be eliminated from consideration as well.

With respect to item 1(b) above, it can probably be assumed that there will continue to be a steady -- or even increasing -- demand for transporting "things" and men into low earth orbit, at least, for the next four to five decades. But at discount rates greater than, say, 5 percent, the present value of a steady stream of annual benefits increases only at a sharply diminishing rate with increases in the investment horizon, as is indicated in Figure 3.26.

In Figure 3.26, the symbol $PV(\bar{r}, N)$ denotes the present value of a steady stream of annual benefits obtained for N consecutive years and discounted at some discount rate $\bar{r} > 5$ percent. As may be inferred from Figure 3.26,



The Effect of the Investment Horizon (N) on the Present Value of a Steady Stream of Benefits

Figure 3.26

the assumption of a 40 to 50 year project horizon is almost tantamount to assuming an infinite horizon. Thus, in asserting that the demand for Space Transportation will continue into the indefinite future, one really needs to be certain only that it will continue for at least the next four to five decades.

This leaves us with point 1(a) above, i.e., with the question of whether a physical input into the Shuttle program will become unavailable at some future point in time, and if so, when.

The first - and second - stage vehicles and the launch site facilities acquired for the Shuttle do, of course, wear out, but they can be rebuilt. Engineers and astronauts wear out, but they also can be replaced. However, from society's point of view, the knowledge (blueprints) produced by RDT&E expenditures -- by far the most important component of the initial cost of the Shuttle -- does not depreciate,[16] i.e., such knowledge does not simply evaporate or become over time. One is led to wonder then, whether these RDT&E expenditures need to be recovered[17] in any finite period of time and, if so, what should determine the length of this period?

3.3.2.2 The Uselife of RDT&E Costs

One approach to the problem of determining the uselife of RDT&E costs might be to estimate the average number of years in which technologically advanced systems become obsolete and to use that estimate as the project horizon (N) for the Space Shuttle. The currently proposed horizon dated 1990 is probably based on such an approach. That approach, however, implies that the technical know-how gained during the RDT&E phase of the Shuttle project will have no further economic value after 1990! In other words, one acts as if such knowledge will, in fact, have fully depreciated by 1990.

Actually, there is a crucial difference between the concept of depreciation and that of obsolescence. Depreciation refers to the physical deterioration of an asset; obsolescence to a situation in which it is no longer expedient, on economic grounds, to use an asset further. This distinction bears directly on the problem under discussion here.

Let us suppose that, if the Shuttle were ready for operation in 1978, the initial set of vehicles (and the associated ground facilities) would have to be replaced in 1990. Let us further suppose that, by 1990, it will be found that the Shuttle is obsolete, (a circumstance which can not really be predicted in 1970). This means, presumably, that an economically superior design is available in 1990. It does not mean that the blueprints for the original Shuttle have evaporated or have been mislaid. In other words, in 1990 NASA still has the option of building replicas of the Shuttle (Model 1978), although NASA may, for economic reasons, decide not to do so.

What are these economic reasons? Consider the investment decision NASA faces in 1990. NASA has the option of spending $1- or $2-billion, or so, on replacing the old Shuttle equipment with identical new equipment, or it can go over to an entirely new Space Transportation System, presumably one involving heavy RDT&E outlays, initial investment outlays and a different future benefit stream. However, the decision whether or not to adopt any new Space Transportation System in 1990 will have to be made against the baseline furnished by the 1978 Shuttle System. This means, presumably, that NASA will go over to a new Space Transportation System only if the net present value (in 1990) of the extra costs and extra benefits associated with it will be higher than that associated with the 1978 Shuttle System. If that condition is not met, then the 1978 Shuttle System will still be the economically superior system in 1990 and should, therefore, be maintained in operation.

The gist of the preceding discussion is that the assumption of an infinite uselife for the Shuttle-related RDT&E expenditures is not as reckless as it might appear at first glance. For as we have suggested above, to limit the uselife of these expenditures to the year 1990 is tantamount to assuming that all scientific and technical knowledge produced as part of the Shuttle development will be useless by 1990, and that the development of whatever new system might be built in 1990 will not draw on such knowledge. That assumption, however, is not only unrealistic, but it is also unnecessarily restrictive. It is restrictive in that it leads to an understatement of the true economic value of RDT&E

activities and hence tends to discourage investment in such activities.

It must be emphasized at this point that, in positing an infinite uselife for RDT&E outlays on public investment projects, one presupposes that all conceivable and technically feasible alternatives are being evaluated at the time the project selection is made. Let us suppose, for the sake of argument, that in addition to the two stage reusable Space Shuttle potentially available in 1978, NASA were fully aware of a still more advanced system -- (i.e., a system offering even more substantial operating economies than the Shuttle) available for operation in, say, 1985 only. Suppose further that the net present value of the 1978 Shuttle, evaluated against the current expendable system, is positive. Suppose, next that the net present value of the still more advanced system is even larger than that of the Shuttle, if the current expendable system of Space Transportation were used as a baseline system, but that the net present value of the advanced system would turn out to be negative, if the Shuttle were used as the baseline system.[18] Finally, suppose that the Shuttle could not be justified on economic grounds if its uselife (including the uselife of the Shuttle-related RDT&E expenditures) extended only to 1985.

In the (hypothetical) situation outlined above, NASA clearly ought to decide against developing the 1978 Shuttle and chose instead the more advanced system available in 1985, since the latter has a larget net present value (in 1971) than does the Shuttle, and since the 1985 concept is in no way technically dependent on the prior development of the 1978 Shuttle.[19] It is to be noted, however, that in deriving the net present values for the 1978 and the 1985 systems, an infinite horizon should be posited for the RDT&E outlays of either system.

To summarize at this point: if a reasonable effort has been made to identify all conceivable alternatives in a benefit-cost analysis, and if the economically most attractive alternative is actually chosen from the roster of conceivable projects, then one can make a strong case for an infinite uselife for RDT&E costs. This argument will be especially strong if the knowledge produced in the RDT&E phase will carry over into whatever future system will eventually cause the obsolescence of the project now chosen, i.e., if the latter is a technical stepping stone for the future replacement.

3.3.3 The Program Start, the Gestation Period, and the IOC-Date

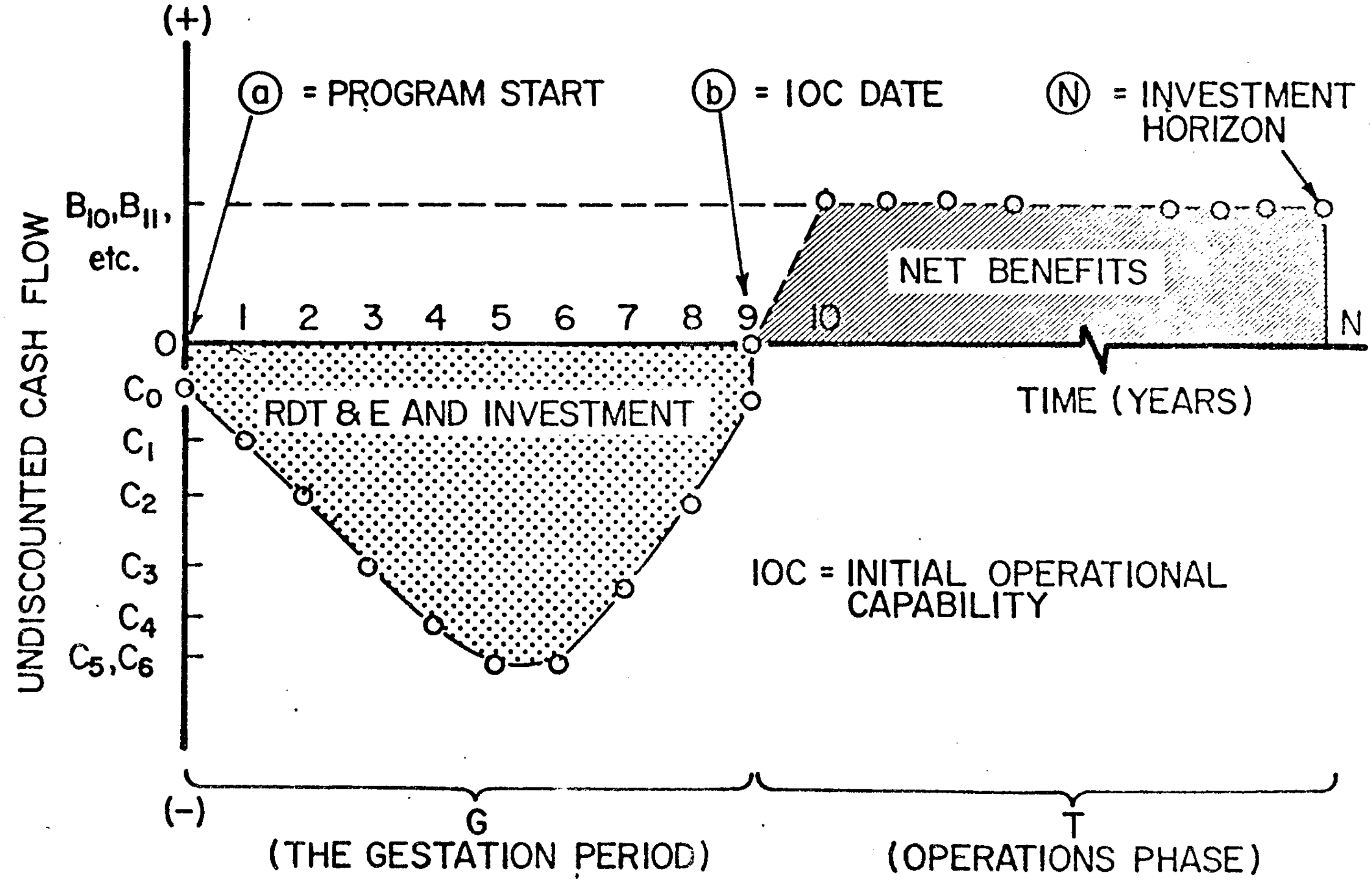
It is sometimes supposed that, if at the time a project is being evaluated, the net present value (NPV) of that project is negative, then the project should be postponed for all times. Actually, a negative net present value simply means that, for a given IOC-date (denoted by b in Figure 3.27) and for a given gestation period (G), the project being evaluated is not economically attractive. The project may appear much more favorable if the IOC-date and/or the gestation period were altered. It is a possibility which should not be overlooked in the development and evaluation of the proposed Space Shuttle. We shall now briefly examine the principles underlying this argument.

3.3.3.1 Changes in the Gestation Period

In Figure 3.27, it was simply assumed that the RDT&E and Investment Phase (i.e., the gestation period, G, in Figure 3.27) of the project being considered spanned a total of nine years. Actually the length of that period is rarely a technical datum; within limits, it can presumably be shortened or lengthened. Any lengthening or shortening of the gestation period, however, would tend to alter also the total non-recurring costs associated with the development of the project. The manner in which the present value of non-recurring costs might vary with the length of the gestation period is sketched in Figure 3.28.

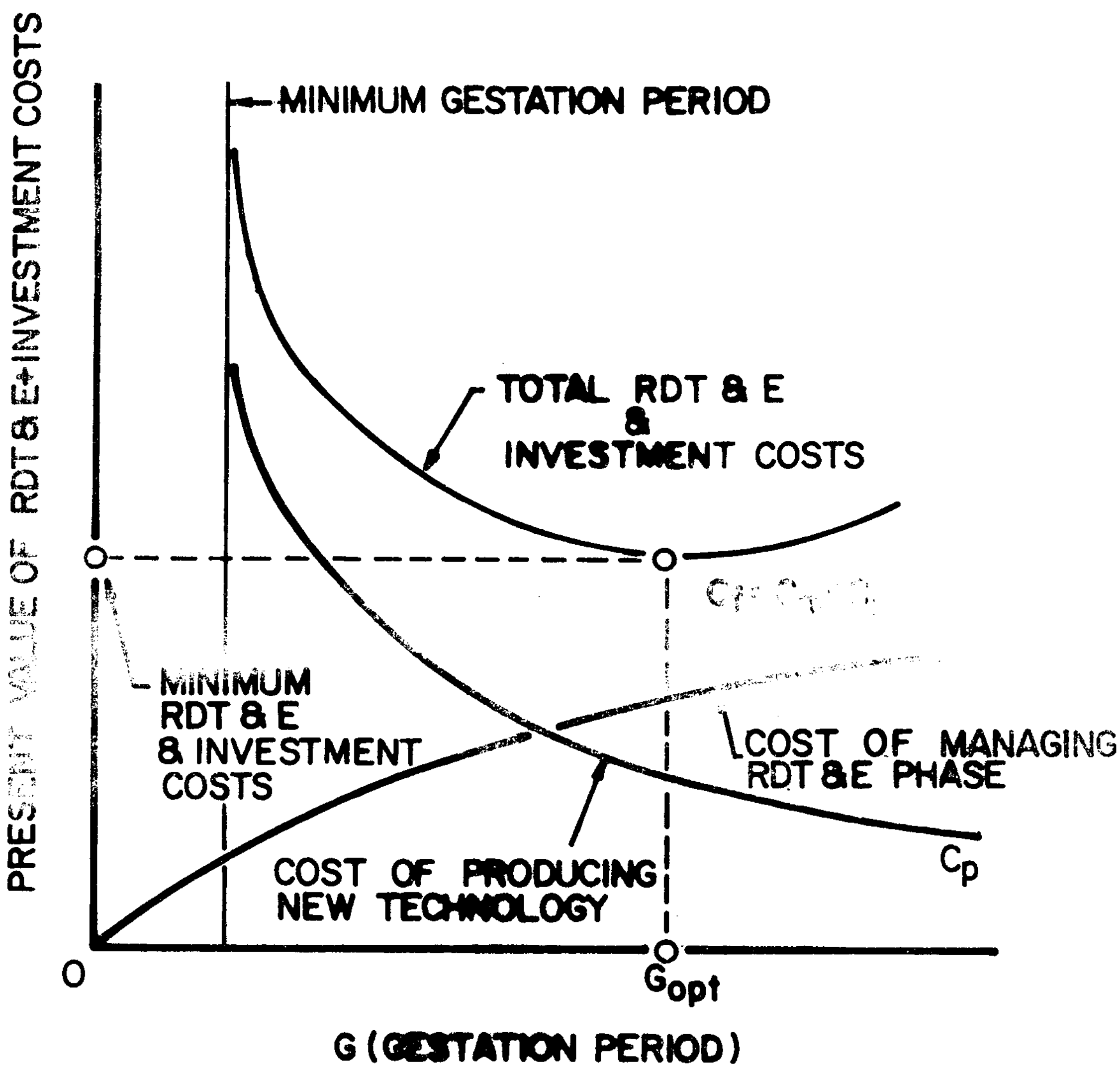
In Figure 3.28, the curve labelled C_m represents the present value of the costs of managing an RDT&E program. The curve is based on the assumption that a minimum management capability must be maintained just to keep the development phase of any major transportation improvement alive. If the annual cost of this minimum management capability is a constant amount, then the present value of these costs will increase with G as is indicated by line C_m.

One would assume that the longer the gestation period allowed for a new project is, the less costly it will be to procure the new technology, if any, required for the project. This is so because the longer the gestation period, the more technical know-how will be available to the project in the



The Time - Phased Cash Flow of a Hypothetical Investment Project

Figure 3.27



The Effect of the Length of the Gestation Period on the Non-Recurring Costs of a Project

Figure 3.28

form of "spill-overs" from other, unrelated research in the economy. From the point of view of the particular project being evaluated, such "spill-over" information is costless. Curve C_p in Figure 3.28 reflects this relationship between the cost of new transportation technology and thd time within which it is produced. The curve becomes vertical to the left, because a minimum of time will always be required to produce new technical know-how, regardless of how much is spent on that activity.

In addition to making more and more technical know-how available, virtually without cost to the project being evaluated, a lengthening of the gestation period also has the effect of shifting some RDT&E outlays from earlier to later years. Other things being equal, this postponement of RDT&E costs will, of course, reduce the present value of these costs. It is sometimes supposed that such reductions in the present value of costs (i.e., reductions obtained by reallocating a constant total of funds over time) do not represent real savings at all, but are simply the mathematical consequences of discounting.

A moment's thought makes it clear, however, that something concrete can be gained by a postponement of RDT&E costs, for that postponement does free funds, temporarily, foruse in competing projects. It is the earnings yielded by the competing projects during the period of postponement which constitute the real savings.[20]

It is seen from Figure 3.28 that the selection of an optimal RDT&E and Investment (gestation) period involves the balancing of the extra management costs associated with a lengthening of the period against the savings one achieves by a more deliberate pace of technology production. In Figure 3.28 the optimum gestation period is shown as G_{opt}; it is the point at which the extra (incremental) savings from cheaper technology production is just offset by the extra (incremental) management costs associated with a slightly longer gestation period. Alternatively, it is the cost at which the present value of total RDT&E and Investment costs (represented by the curve labelled C_f) is minimized.

Consider again Figure 3.27 above. Suppose it is discovered that, on the basis of the assumptions underlying this diagram, the net present vlaue (NPV) of the project is calculated (by way of equation (1.2)) to be slightly less than zero. This may mean that the project should never be accepted. But it may also mean that the gestation period chosen for the development of the project is too short, i.e., that the non-recurring costs associated with the project are unnecessarily high. Indeed, after optimization with respect to the gestation period, it might well turn out that the net present value of the project will be positive, i.e., that the project becomes economically attractive.

3.3.3.2 The Optimal IOC-Date

Even if the gestation period (G) were somehow given and fixed, the net present value of a proposed project can change from negative to positive, or vice versa, by a change in the IOC-date. Let us examine this proposition in the context of the choice between STS 1 and STS 2, an example already described in Section 3.2 above.

Suppose, for example that the govenment expects the demand for launches to increase at a steady rate over time. This means that the demand curve is expected to drift towards the upper right-hand corner. As a result of this drift, the annual direct and induced benefits of STS 2 will therefore increase over time.

The time profile of benefits and costs associated with the proposed STS 2 before the shift in the IOC-date will appear as the solid line in Figure 3.29 below. The corresponding time profile after the shift in the IOC-date is indicated by the broken line. It will be noted that we have assumed a constant gestation period, regardless of the IOC-date, so that postponement of the later implies a corresponding postponement of the starting date.

Suppose now that, for an assumed IOC-date of 10 years (see Figure 3.29) the net present value (NPV) of STS 2 is found to be negative. It follows that the development of system 2 as it had been originally planned must be rejected on economic grounds. It does not follow, however, that system 2 should be omitted from consideration for all times. For example, consider the possibility of starting the RDT&E and Investment Phase of system 2 not in year 1, but instead in year 6. With a constant gestation period (G), this means that the system's IOC-date is moved from year 10 to year 15. The postponement in the IOC-date, in turn, will have the following, opposite effects on the net present value of system 2 (as the NPV is calculated at time = 0):

1. The NPV of STS 2 will be reduced by the present (discounted) value of the benefits lost due to the postponement. In Figure 3.28, the undiscounted total of such cost benefits is represented by the shaded area A B C D.

2. The NPV of STS 2 will be increased by the present value of the earnings which can be earned by postponing some RDT&E and Investment outlays. Those RDT&E and Initial Investment outlays for STS 2 which are postponed to a later date are identified by shaded area labelled X in Figure 3.29. The eventual incurrence of these outlays is indicated by the area labelled Y.

It is impossible to predict, a priori, whether the postponement of the project's IOC-date (and the starting date of its RDT&E phase) will increase or decrease its net present value at time t = 0; that depends on the relative magnitude of the two effects described above. In practical applications, the delay in the starting date of the RDT&E phase itself may yield some extra savings in the RDT&E costs, since more and more of the required new technology will be available, free of cost, from research undertaken elsewhere in the economy. (We have already discussed that possibility in Section 3.3.1 above).

This discussion on the timing of Space Transportation investments has been included in the present chapter mainly to draw attention to the fact that the starting date of a project's RDT&E phase and the length of that phase (hence, implicitly, also the project's IOC-date) are economic and not merely technical decision variables. The history of technological development during the post-war period suggests that all too frequently in the past, technological advancements have been advocated and pushed for their own sake, without due regard to the relative magnitude of the costs and benefits associated with such advancements. This effort to introduce ever more advanced tehcnological "improvements" in rapid succession is sometimes buttressed by the statement: "Technical progress is inevitable, therefore, we might as well push it along." That statement is, of course, a perfect non-sequitur.[21]

The remarks contained in the previous paragraph should not be construed as an argument against <u>basic research</u>. Nor should they be taken as a criticism of NASA. Indeed, the emphasis currently placed by NASA on the role of economic analysis in the selection of alternative Space Transportation Systems is a clear-cut departure from the practices criticized above and therefore much to be commended.

3.3.4 Summary and Conclusions

As was mentioned at the outset of this section, its intent has been mainly to expose certain principles underlying the economic evaluation of alternative Space Transportation Systems. No attempt has been made to cover the entire range of problems encountered in practical applications of benefit-cost analysis; nor was the discussion always directed at the fully reusable Space Shuttle as such.

3.4 Considerations of Risk Aversion in the Evaluation of Alternative Space Shuttle Configurations

The benefit-cost analysis performed and presented in the May 1971 Report was mainly concerned with the economic evaluation of whether or not the Space Shuttle investment could achieve reduced space transportation costs in the 1980's as well as an overall reduction of the costs of space programs; the question asked was whether these expected benefits did justify the expected non-recurring cost outlay in the 1970's for the development of the Space Shuttle System. Although relatively early in the project we did raise the issue of whether or not the government should be risk averse when engaging in large scale projects such as the Space Shuttle System, we followed the accepted line in benefit-cost and cost effectiveness analysis of government projects by assuming that the government itself is risk neutral in the choice among its projects.

The notion of government risk neutrality is, in essence, based on the insurance effect when the government engages in many alternative investment projects. For the size of most investment projects undertaken by government agencies, for example, the building of a particular highway link, or the building of a hydroelectric dam, as well as many other investment projects, the assumption of risk neutrality due to the insurance effect is correct. It is based on the effect of repetitively incurring the same risk which leads to a canceling out of the possible variances in the evaluation of the benefits and the costs of such projects and leads to a convergence of the rate of return on government investment to expected values.

However, as with individual behavior, also the government and its agencies should be increasingly adverse as a particular project either uses a substantial amount of the funds of an individual agency or a considerable amount of the total resources available to the nation or to the government. Under the complete list of alternative investment projects either in research and development, as well as other investment projects, the government under the hypothesis of risk neutrality would be indifferent to both the scale of the investment project as well as the variance of the expected rate of return. If either of these assumptions is not correct, a substantially different portfolio of investment, research, and development projects will be chosen by the government than under the assumption of risk neutrality. In the case of the Space Shuttle System there are important considerations that affect the choice of system if NASA as well as the government are risk averse for a project of this size. In the following we will sketch a theory of rational behavior under uncertainty and risk in terms of expected utility. The point will be stressed of the possible justification of risk aversion by the government in the case of the Space Shuttle as against the assumed risk neutrality of the present analysis and of benefit-cost and cost-effectiveness analyses in general. The following figures may lead to a better understanding of the size of the proposed Two-Stage Fully Reusable Space Shuttle System versus the TAOS Systems (1) In years where the funding of the RDT&E costs of the original Two-State Fully Reusable Space Shuttle would have required the expenditure of $2 billion per year in the 1970's the economy could afford at the projected levels of the gross national product (GNP) only 500 such projects as a nation, assuming every single dollar be invested with no consumption and no depreciation in the economic system as well as no other services rendered. (2) On another basis, the total investment funds of a national economy and of the United States vary usually between 15 and 20 percent of Gross National Product. On that basis--since the Space Shuttle investment has to be built with such funds, the United States could, theoretically, afford at most one hundred such national projects with no other investment activity in the 1970's. (3) if the funds are more closely defined as pertaining to the research and development activities of the nation (a funding of $16 billion by the federal government in Fiscal Yar 1972), then the U.S. government could have engaged in, at most, seven other projects of similar type per year throughout the peak funding period. (4) Similarly, in terms of the NASA budget and its present funding level of about $3.2 billion or even the long term projected level of between $3.5 and $4.0* billion

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* See Chapters #2 and 7.

Two-Stage Fully Reusable Space Shuttle investment in several years would have constituted two-thirds or one-half of the total agency budget.

The analogy of the Apollo project and its expenditure of, say, $24 billion in the 1960's is not quite correct. The reason for this is that the Apollo project itself consisted of several discrete, single steps, i.e., the Mercury program, the Gemini program, the Apollo program, as well as the subsequent step-by-step development of the hardware. Each of the components could be developed separately with each advance adding to the capabilities ultimately required of the Apollo project, but also usable by themselves for other space capabilities. For one, the initially stated need for the Nova rocket proved, through some ingenuity, never to be needed in terms of the requirement of landing a man on the Moon in the 1960's.

On the other side, as proposed, the Two-Stage Shuttle System, but less so other configurations of a Fully Reusable Space Transportation System, development would have associated with it the direct outlay of between $14 billion to $15 billion over the next ten years, and both the development of the orbiter and the booster as well as all other components have to be successful to assure the economic success of the system.

Obviously, the usual notion--with or without adequate justification--for other government investment projects of risk neutrality cannot hold when such a discrete portion of funds is allocated to a single project; the notion of risk aversion ought to play an important part in determining the best portfolio of R & D investments in the nation as well as when determining the best choice of alternative Space Shuttle configurations. Here we propose one quantitative set of analyses that should take risk aversion into account in determining the best choice among the vast set of different Space Shuttle configurations, which in the end, lead up to confirm very strongly the choice of a TAOS system.

3.4.1 Expected Utility -- The Theory of Rational Behavior

Work in the 1960's has further clarified the role of risk and uncertainty in economic decisions, one of the more exciting aportions

of economic theory throughout the past centuries. A good summary of the recent state of the art can be found in Portfolio Selection, Efficient Diversification of Investments by Harry M. Markowitz [Cowles Foundation for Research in Economics, John Wiley / Sons, New York, 1959].
As Markowitz explains, portfolio analysis is characterized by:

1. The information concerning the projects upon which it is based; in the case of Markowitz, securities.

2. The criteria for better and worse portfolios which set the objectives of the analysis.

3. Computing procedures by which portfolios using the information in 1, are derived from the criterion in 2 from the inputs.

A portfolio analysis approach to the decision both, on the best Space Shuttle configuration as well as to the best mix of government research and development projects, in general is only a logical consequence of the information that is put into the evaluation of the research and development project. The inputs for the May 1971 economic analysis have been provided by Lockheed LMSC and Aerospace Corporation. There is a large ongoing effort within NASA and in industry and reported on in this report to evaluate alternative Space Shuttle configurations and their expected life cycle costs. Another important part of the evaluation and the information put into our evaluation were payload effects and their expected life cycle costs for different Space Transportation Systems. The present economic analysis as performed and presented in the May Report assumes risk neutrality by the government and NASA with regard to the size of the project and the expected variance in the rate of return of alternative Space Shuttle configurations. A unique social discount rate was posited and the summary was given at 5%, 10% and 15%. The analysis was performed from 0% to 20% for all projects and mission models based on the Two-Stage Fully Reusable Space Shuttle configuration. The question of best system choice among the alternative Space Shuttle configurations was not raised; when analyzing that problem, however, the analogies with portfolio analysis in security market operations become increasingly important.

The criteria determine how the information is used and transformed to yield conclusions regarding alternative investment projects, in our case Space Shuttle configurations and the overall worth of this project as compared to the opportunity costs of these funds within the nation.

The computing procedures are outlined in detail for the analysis done in our case under the assumption of risk neutrality of the government. A quantification of the level of uncertainty and risk was made in Section 6.3.3 of the May 1971 economic analysis in order to quantify the expected variance, for example in the operating phase of the Space Shuttle System in the 1980's. However, that information was not used to discriminate between alternative Space Shuttle configurations. The computing procedures for risk averse government investment decisions, particularly in the case of the Space Shuttle System, are the topic of this section.

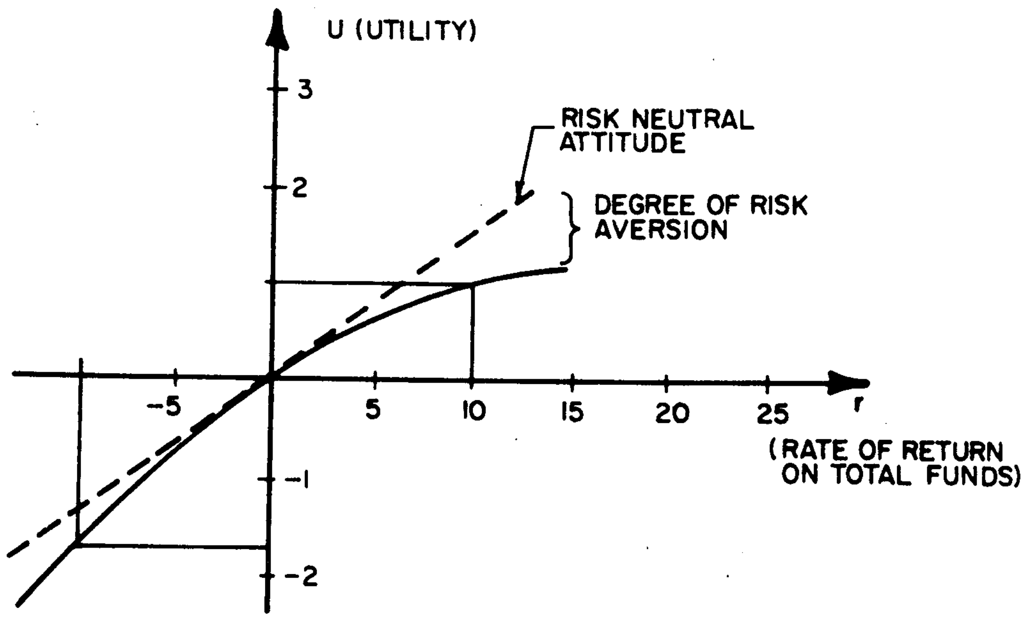
3.4.2 Expected Utility vs. Expected Money Return.

The way that the additional information of risk aversion by the government is included is by defining a utility measure of the expected return as against mathematical money expectations. The problem can best be explained along the line of the St. Petersburg paradox. The St. Petersburg paradox is a classical example dating back to the 18th Century when for the first time a paradox was described which arises with an expected money return theory of rational behavior by Daniel Bernoulli in "Exposition of a New Theory of Risk Evaluation."

The paper by Daniel Bernoulli contains numerous new ideas, among them the notion that a gamble should be evaluated not in terms of actuarial value of its alternative money payoffs but rather in terms of actuarial value of its utilities of the expected payoffs. Bernoulli then shows that the diminishing marginal utility of income implies that a mathematically "fair" bet, that is, one who's expected "actuarial" money value is zero is necessarily disadvantageous to anyone who undertakes it. The reason is easily illustrated by one example--an equal chance of gaining and losing $1,000 is disadvantageous because, with diminishing marginal utility of income, a loss of $1,000 in terms of utility is greater than the utility offered by a gain of $1,000, so that the expected utility of the gamble (one-half utility of gaining $1,000 plus one-half this utility of losing $1,000) is negative. We will present subsequently utility functions that imply exactly this principle. This classical example led to a revision over the past centuries of utility and investment theory. A similar utility function really can also be derived by the principle of <u>risk aversion</u>. Under risk neutrality one would work with the hypothesis that an expected return of, say, 30% on an investment is evaluated "indifferent" from the variance attached with the expected return. Under such behavior an investor, given his resources, would try to identify the projects that have associated with them the highest expected return irrespective of the expected variance, skewness, etc; most likely he will put all his funds into just one single project if that project promises him the highest return with such a decision rule. An investor who thought only to maximize the expected return would never prefer a diversified portfolio either. If one security had greater expected return than any other on the stock market, the investor would place all his funds into that security. If several securities had the same (greatest) expected return, the investor would be indifferent among portfolios, diversified or not, which contain only these securities. Thus, if we consider diversification a sound principle of investment, we must reject the objective of simply maximizing expected return. Or, put better, we must find the underlying rational on why in actual behavior a diversified portfolio is preferred to a non-diversified portfolio even with the expectation of identical return on investment among securities. The obvious parallel here with regard to government projects is that given the government funds for R & D money, the government can invest every year only a limited amount of funds (roughly $16 billlion government financed in Fiscal Year 1972) and the government has to make a choice on where to put this money among the many diverse R & D projects, hopefully maximizing with that also the expected return to society (the nation, national security and general welfare of the people) from these activities in the long run. With the assumption of risk neutrality the government would try to identify among the research and development projects those with the highest total expected return irrespective of the scale and possible variance (uncertainty) associated with these projects. If now the government engages in many, say, 100 or more (possibly thousands) of research and development projects, each of them requiring a relatively small portion of funding out of the total R & D funds, or the total government funds available, then through the insurance effect among different research and development projects the government effectively can claim and defend the position of risk neutrality by maximizing only the expected return for each research and development project and realizing actually this rate among projects of the same yield across the hundreds or thousands of projects undertaken.[22]

On the other side, the principle of insurance which ultimately would lead to the claimed attitude of risk neutrality in government decisions does not hold any more. When the funds needed for a single research and development project do make up a large portion of either the total funds of research and development financed by the federal government in any one year or the funds make up a sizable sum of the total funding of the government agency, insurance effects are not applicable since the government could engage in at most seven to eight projects of similar size per year in the 1970's. Thus, by looking only at the expected money return of investment without considering the possibility of a large variance in that expected return (in part already quantified in our May 1971 Report), the government would really not make a rational choice among alternative Space Shuttle Systems. It is our contention that with regard to the choice of research and development projects as they become relatively large, the principles of portfolio selection equally apply, by analogy, to investment project selection in R & D for government financed activities, particularly with regard to the Space Shuttle System choice.

The <u>expected utility rule</u> was proposed as a substitute, therefore, for the expected money return rule. (By applying a social interest rate uniformly across government projects irrespective of the scale and uncertainty of these, one adheres to the expected money return rule.) A money return of 20%, it was argued, is not necessarily twice as good as a 10% return; a loss of 20% is not necessarily only twice as bad as a loss



Money Rate of Return on Funds vs. Utility Perceived

Figure 3.29

of 10%. Perhaps there is a curve such as that in Figure 3.29, relating to various levels of return on total resources invested. According to the curve in Figure 3.29, for example, the utility of a zero return is zero a utility of a 10% gain is 1, the utility of a 10% loss is minus 1.3. Perhaps, instead of maximizing expected money return, the rational man would maximize the expected "value of the utility" return.[23] The expected utility of a bet with a 50-50 chance of a 10% loss and a 50-50 chance of a 10% gain equals:

$$U = (\tfrac{1}{2})\ (1) + (\tfrac{1}{2})\ (-1.8) = -.40$$

This is less than the utility of having zero return with certainty. Thus the individual or agency maximizing the expected value of utility, as represented by the curve in Figure 3.29, would prefer the certainty of no return rather than a 50-50 chance of a 10% loss or gain. Expected utility return is lower in the second case even though expected money return is the same in both cases.

3.4.3 The Principle of Risk Aversion Applied to NASA Decisions

In the case, for example, of the Space Shuttle investment with an underlying utility curve or risk aversion expressed in the form of a utility curve as shown in Figure 3.29, it would imply that two separate investment chunks of $7 billion, each with a return of 20% would be preferable to a single investment of $14 billion with an expected return of 20%, total assets being in each case, say, $14 billion (each $7 billion project would yield 10% on $14 billion). The application of the social discount rate across mission models of, say 5%, 10% or 20% and as constantly done at present in cost effectiveness and benefit cost analysis of government investment projects does assume risk neutrality, i.e., indifferent (i.e., "equally good") between the first two separate investment projects and the second single investment projects. The introduction of the criterion of risk aversion in government projects has profound, deep and immediate applicability to the Space Shuttle investment decision on the best choice of shuttle configuration.

The modern notion of utility avoids any hedonistic interpretation of the curve in Figure 3.29. We are not to think of the vertical axis as representing pleasure and pain. It simply represents the degree to which the individual or the government agency is willing to take risks for outcomes presented along the horizontal axis (return on "total available assets"). As to the philosophic, introspective and psychological interpretation of this varying willingness to take risks, this brings us from firm ground to conjectural areas of controversy.

The expected utility maxim stripped of any hedonistic interpretation says that the individual or agency should act as if:

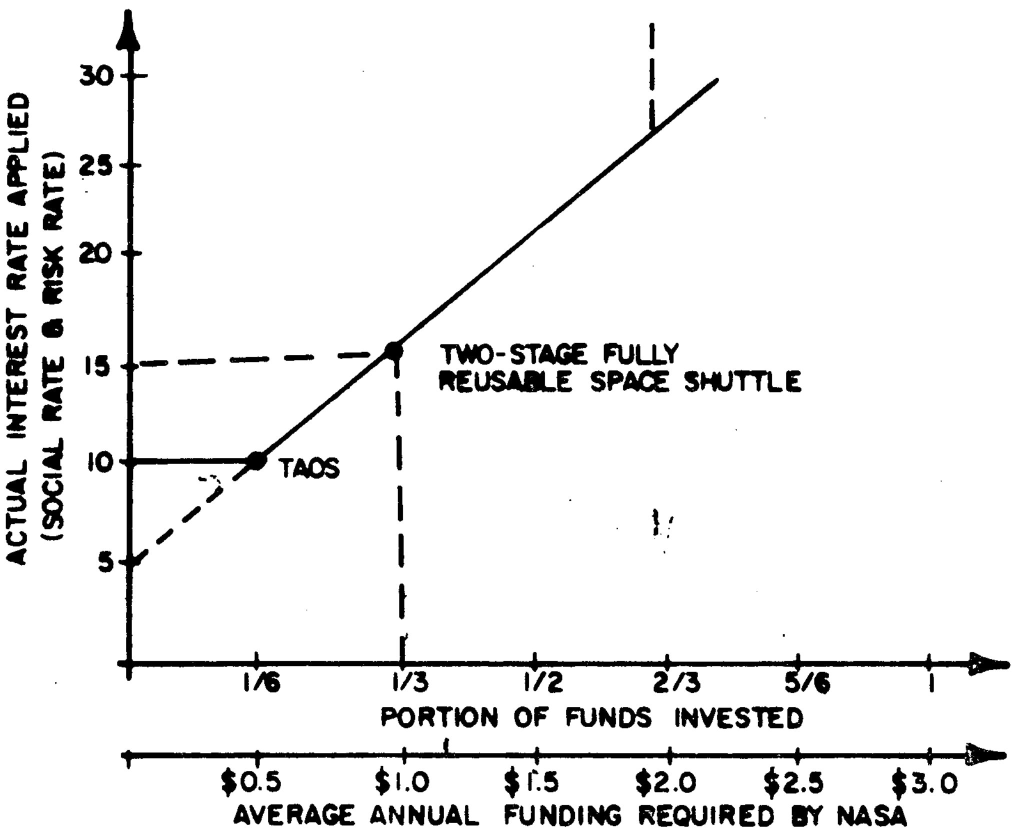
1. He attaches numbers, called their utility, to each possible outcome, which may be higher, lower or the same as the "money" numbers; and

2. When faced with chance alternatives, he selects the one with the greatest expected value of utility.

We shall refer to this formulation as the "expected utility" maxim or the "expected utility return" maxim. The expected utility maxim avoids the difficulties which condemned the expected money return maxim. If his utility curve is shaped like that in Figure 3.29, with increasingly great money returns adding less to utility return, the investor will generally prefer diversified portfolios. If, over the range of possible returns, his utility (U) depends on return (r), according to a formula of the form

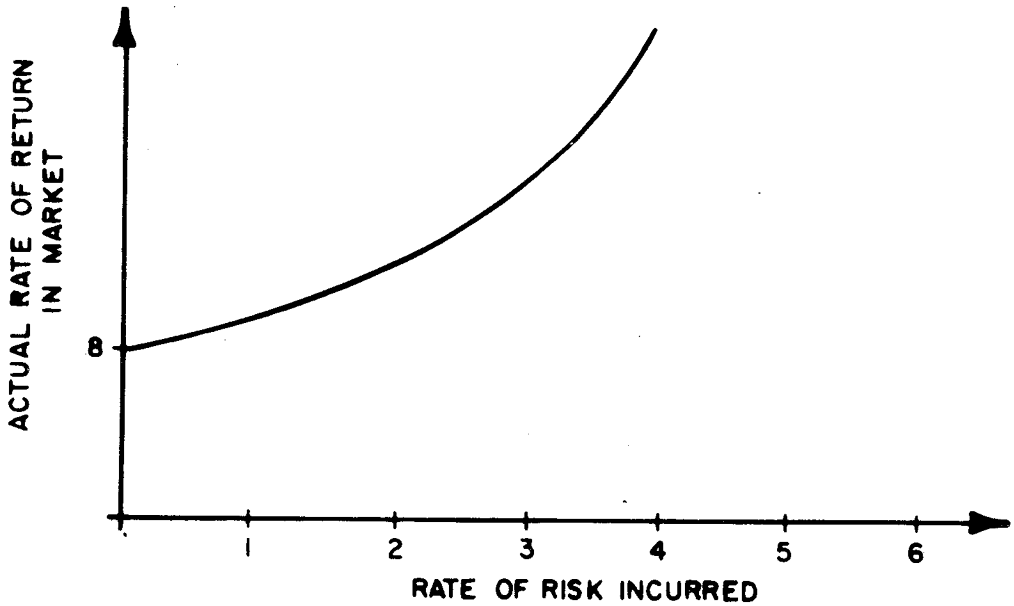
$$U = r - Ar^2$$

the investor will select the efficient portfolios through an analysis based on an expected return and variance principle. The particular portfolio preferred depends on the value of the positive number A[24], where r is the rate of return on total assets. In terms of the Space Shuttle investment we actually can find a more suitable way of incorporating risk aversion into the analysis by making the risk rate an increasing function of the portion of funds risked or invested by the agency or the government.



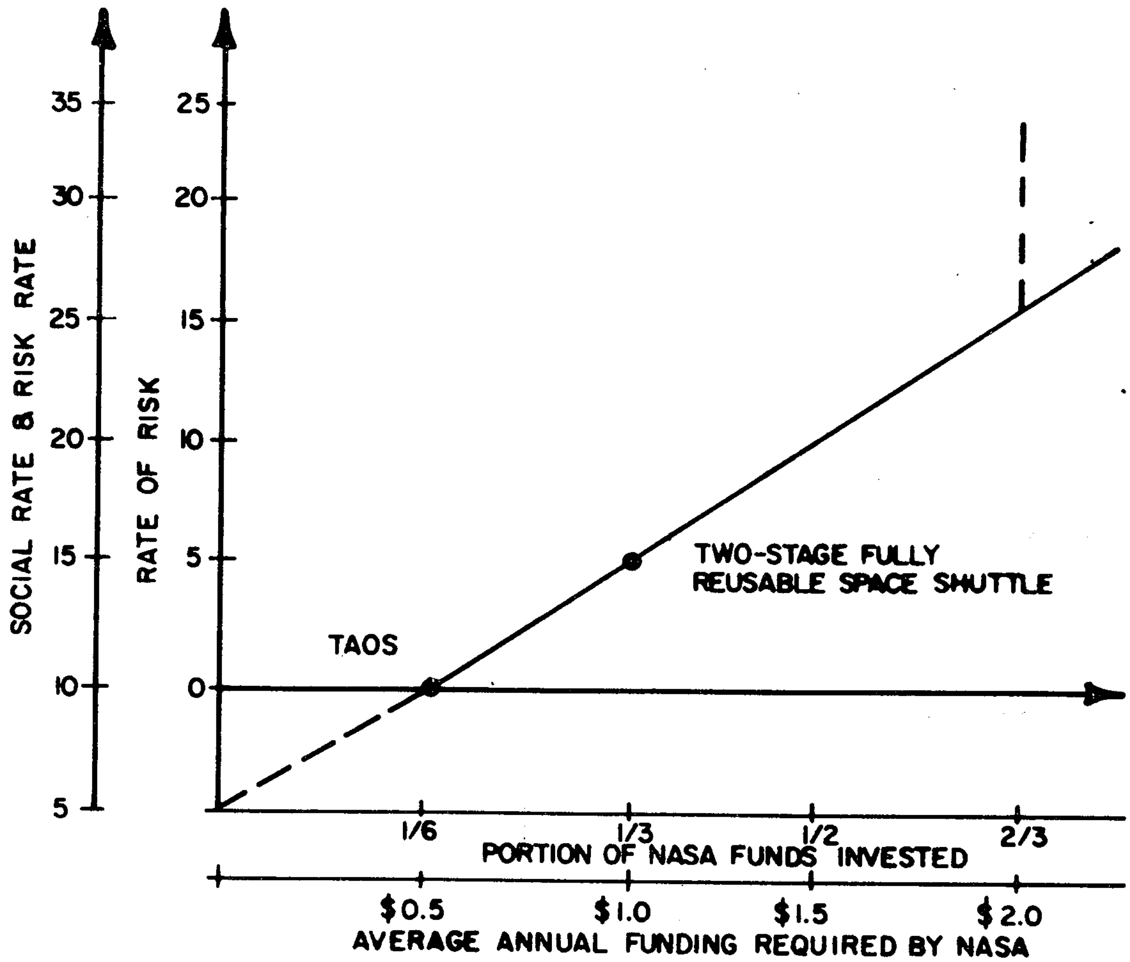
Actual Rate of Discount Applied vs. Average Annual Funding Requirement

Figure 3.30



Actual Rate of Return vs. Rate of Risk Incurred

Figure 3.31



Proposed Social Rate and Risk Rates as a Function of
NASA Funds Invested

Figure 3. 32

This principle actually corresponds to the principle expressed in Figure 3.29, now quantified for the purposes of the Space Shuttle investment as shown in Figures 3.30, 3.31 and 3.32. On the horizontal axis in Figure 3.30, we show in the case of the Space Shuttle investment the average (or peak) annual funding required for the development phase and investment phase of the Space Shuttle varying from zero to $.5 billion, $1 billion, $1.5 billion, $2 billion and $2.5 billion upwards. Also, one could plot on the horizontal axis the funds risked in the form of a fraction of the total agency funds, in this case NASA, and corresponding to the average annual funding level the values would now read 1/6, 1/3, 1/2, 2/3, 5/6, and 1 etc. Again one could plot the total funds required by the alternative projects in order to get towards a fully reusable Space Transportation System and the values would here increase from $5 billion to $10 billion, $15 billion, and $20 billion. On the vertical axis we have the rate of risk added to the social discount rate in order to evaluate now projects of different size expressed either on an annual peak funding level basis, an annual average funding level, the total project funding level or the fraction of agency funds risked by the investment project. In terms of the levels of funds risked by the agency, we think the curve (in Figures 3.30, 3.31 and 3.32) is even of general value, not only NASA but also the Department of Defense, the Atomic Energy Commission, and other government agencies engaged in investments into research and development projects. The particular slope of the line shown now in Figures 3.30 and 3.32 is, of course, very, very arbitrary, but nevertheless we think it represents, at least to us, an intuitively rational and plausible progression of risk rate added to the social discount rate for the evaluation purposes of alternative projects.[25] The risk rate (see Figure 3.32) progresses from zero for projects of up to $500 million for NASA of annual funding to 5% for projects requiring funding of $1 billion for the research and development phase, 10% for projects of $1.5 billion and progresses linearly from there on. As to the intercept between the horizontal axis and the risk aversion function, one either could assume that the government is risk neutral in the case of NASA of projects requiring annual funding levels of less than $500 million, or one could make the line proceed below the axis to intercept at the 5% level and a zero funding requirement with the actual level of the social discount rate then at 5%.

In order to evaluate different Space Shuttle configurations proposed, and reported in this report, the very important message here is that different Space Shuttle configurations do require different levels of funds to become operational and capture the payload effects effectively on an economic basis. Basically what it says is that the investment, if possible, should be split up between the fully reusable components. If any one part can be developed first and the second part developed later on, if and when require, that is if the research and development are truly separable components and each step as a cost effective project in itself than the evaluation of the joint project can be made at a relatively lower risk rate than the combined evaluation of a single project requiring for example $15 billion. The idea as quantified in Figure 3.30 is of great and immediate importance when deciding about the particular Space Shuttle investment in addition to the promise of reducing Space Transportation costs in the 1980's.

This analysis, allowing for risk, has to be integrated with two to three important, economic considerations when evaluating alternative Space Shuttle configurations and the choice then becomes much more clearer and narrower. When therefore, the principle of risk aversion were to be integrated into the full economic analysis of alternative Space Shuttle configurations, it would strongly reinforce and confirm the choice of the TAOS-System and, therein, the choice of the TSRM-TAOS System.

6

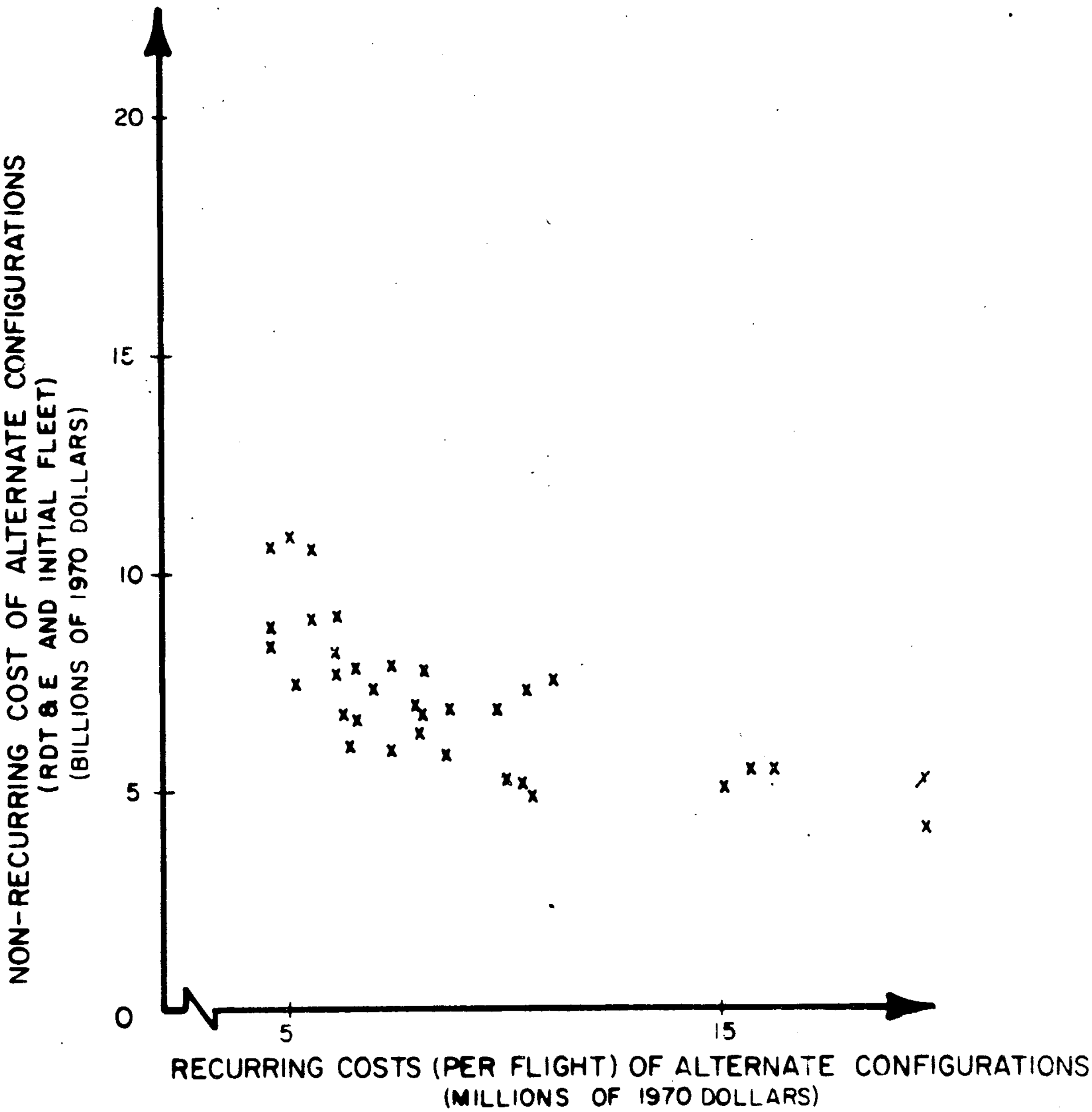
3.5 Determining the Most Economic Space Shuttle Configuration

All of the economic criteria stated in the previous sections do enter into determining the most economic Space Transportation System in a complex system of interdependent economic-evaluation procedures. These range from different types of cost-effectiveness analysis and benefit-cost analysis to, finally, the most important issue of the adjustment of benefit-cost streams for the time value of economic resources. Nevertheless, it is possible to single out the two most important parameters, namely, the expected nonrecurring cost for the alternate Space Transportation Systems in the 1970's and the expected recurring costs per launch of a space flight in the 1980's and illustrate on the basis of these two economic parameters the selection of the most economic Space Transportation System among the alternate ways of doing space transportation. The main alternatives are (1) expendable space transportation and (2) reusable space transportation. Within the reusable space transportation systems, many alternatives are available. This section describes how with all the previous economic criteria and principles in mind, the cost-effective systems as well as the most economic systems among these can, nevertheless, be determined rather easily as a function of these two economic variables only.

3.5.1 The Economic Location of Alternate Space Transportation Systems

In Figure 3.33, alternate Space Transportation Systems are shown in relation to each other as a function of two economic variables: the nonrecurring costs expected in the 1970's, shown on the vertical axis, and the expected costs per launch of these alternate systems, shown on the horizontal axis. In positioning alternate Space Transportation Systems, for example, the Two-Stage Fully Reusable Shuttle System or the New Expendable Space Transporation System, they are each shown as point estimates in regard to both the expected nonrecurring costs of the 1970's as well as the costs per launch in the 1980's. Of course, the costs per launch, for example, of a New Expendable System vary widely, depending on the payload mass to be transported to widely differing earth orbits and earth escape missions. Similarly, for some of the hybrid systems, for example, the Thrust Assisted Orbiter Shuttles, equally

RECURRING COSTS (PER FLIGHT) vs NON-RECURRING COSTS OF ALTERNATE CONFIGURATIONS



Recurring Costs (per flight) vs. Non-Recurring Costs of Alternate Space Shuttle Configurations

Figure 3.33

different costs per launch might be arrived at, again depending on the mass of payloads to be delivered and the particular earth orbit to which they are to be delivered. Therefore, on the horizontal axis the point estimates of the average cost per launch are shown; these average launch costs are determined across the space-activity models expected for the 1980's and represented in the alternative scenarios used in the evaluation of the Space Transportation Systems. In Figure 3. 33, many possible Space Transportation Systems or combination of Space Transportation Systems are shown for illustrative purposes with regard to their economic location in terms of nonrecurring and recurring costs. Any system has, of course, uncertainties attached to the expected cost per launch in the 1980's as well as to the expected nonrecurring cost in the 1970's. Thus, instead of actual point estimates as shown in Figure 3. 33, the analysis of the risks and uncertainties in the nonrecurring costs as well as recurring costs does reveal that each of the points actually is a major area extending both horizontally and vertically. Figure 3. 34 shows the position of the alternate Space Transportation Systems, now, however, reflecting some of the uncertainties as given by industry or NASA, with regard to the expected variation in the nonrecurring as well as recurring cost of alternate Space Transportation Systems. Of these systems, for example, the New Expendable System, and in particular, the Current Expendable System, have a much reduced uncertainty in present expected launch costs per flight of the system as well as the outlays for the systems in terms of nonrecurring costs in the 1970's. Yet, even these systems have substantial economic cost uncertainties attached to them, which are minor, however, when compared to uncertainties reflected in completely new systems yet to be developed by research and development. The horizontal extension of the areas shown for each system in Figure 3. 34 points out the uncertainty in the expected cost per launch for each of the family of systems identified for illustrative purposes. The vertical extent of the area reflects the expected uncertainty in the <u>nonrecurring</u> costs of the systems in the 1970's.

The more advanced a system is when compared to the present state of the art, and the more ambitious with regard to complete reusability, the larger the vertical extent of the area is expected to be in the 1970's. This

RECURRING COSTS (PER FLIGHT) vs NON-RECURRING COSTS OF ALTERNATE CONFIGURATIONS

DECEMBER 15, 1971 DATA

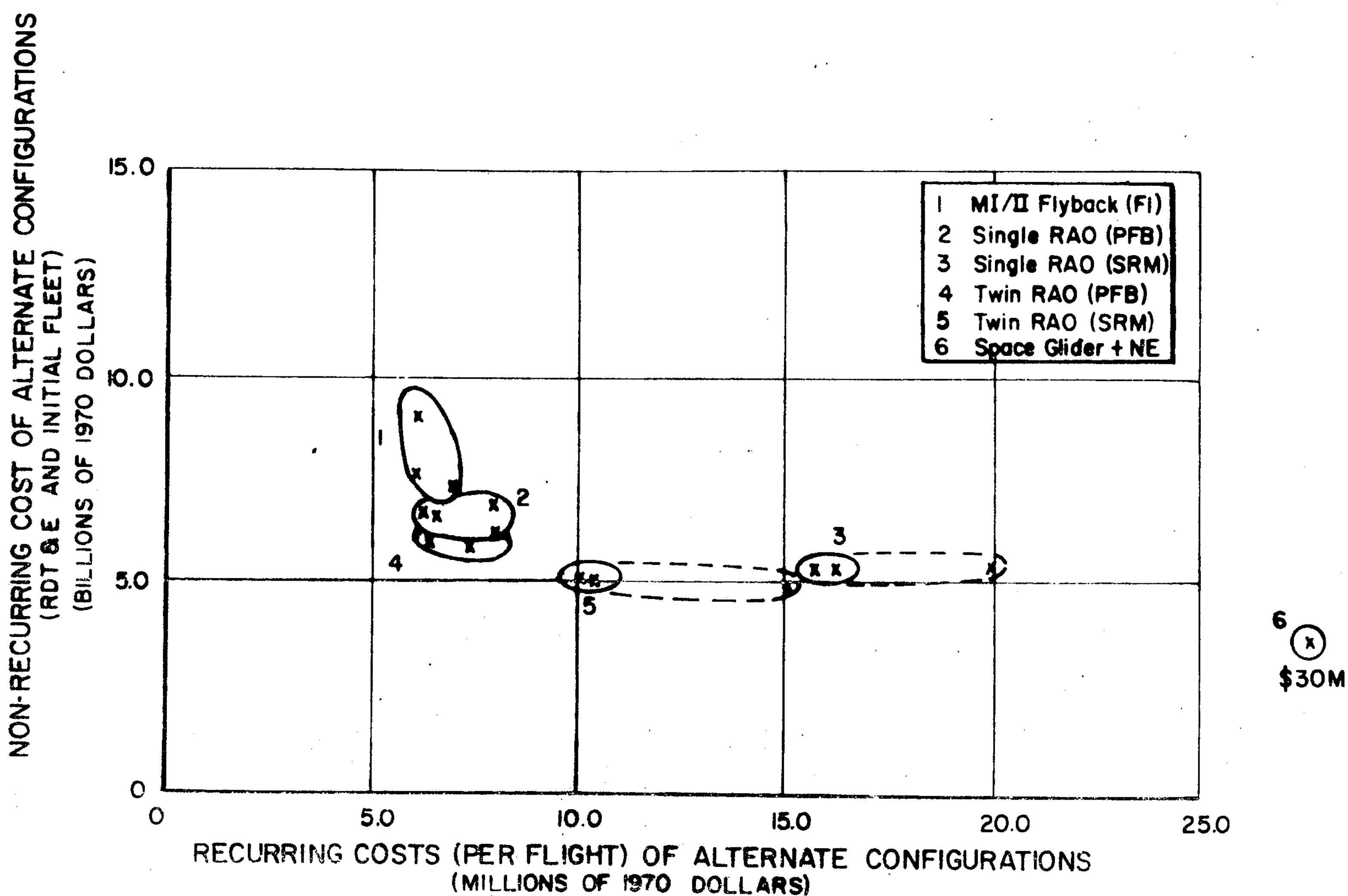


Figure 3. 34

is due to the plain fact that we cannot estimate these costs with as much accuracy as for systems which already have been built in the past. The vertical extent of the area reflects in a quantitative way the qualitative feeling that for systems that represent a larger advance over the present state of the art, the uncertainties and variability in costs in the nonrecurring cost part of the 1970's will be larger than for systems which are closer to the present state of the art.

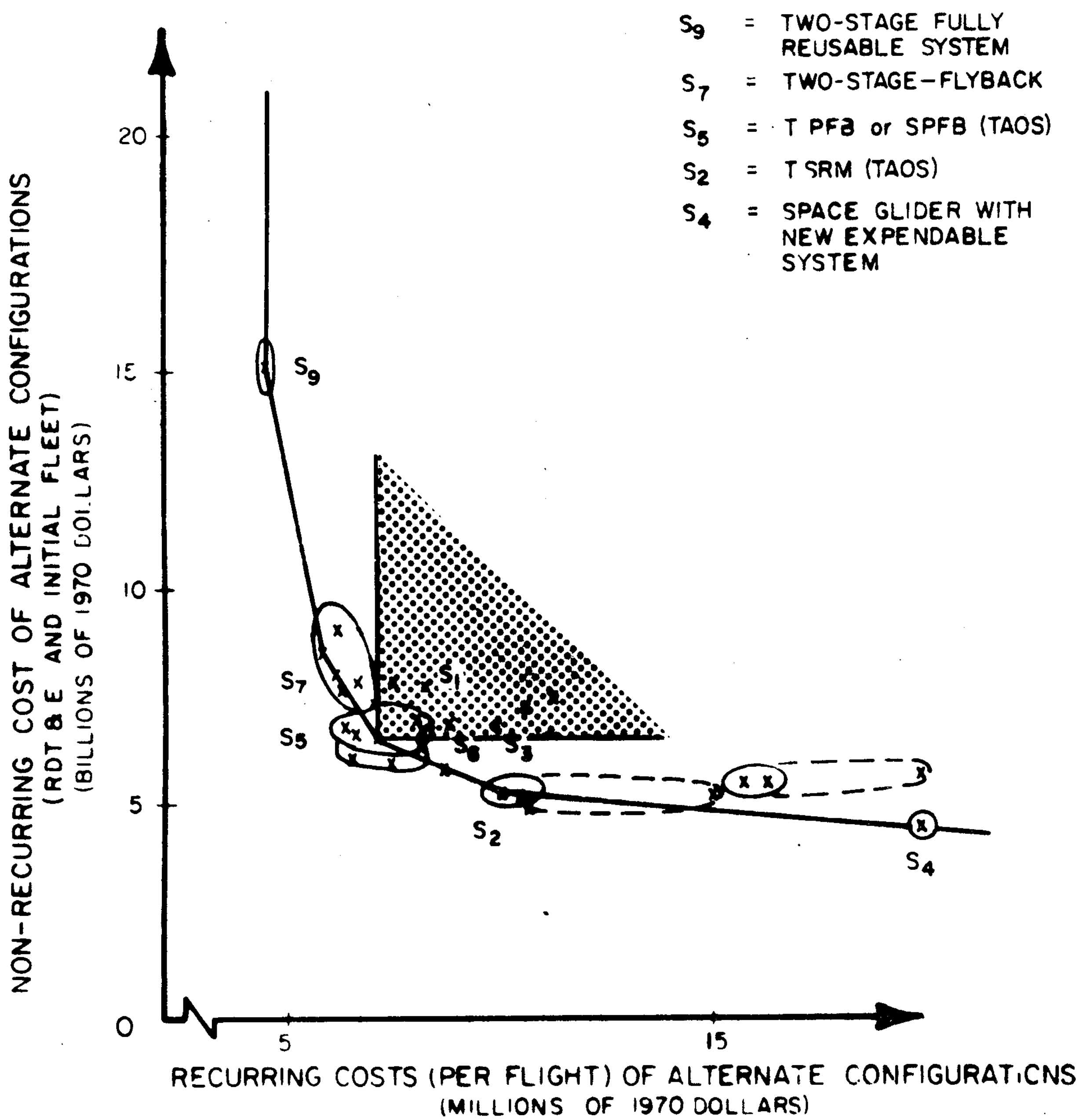
Similarly, the variation in the cost per launch reflects uncertainties, for instance, as to the expected possible turn-around time of Reusable Space Transportation Systems as well as the possibility and feasibility of integrating these systems more or less effectively with existing expendable hardware. In order to determine the actual shape of these areas for each of the family of systems a considerable effort has to be spent and each of the systems have to be evaluated on a comparable and consistent basis. This is not the case for the present cost estimates as well as the uncertainty estimates that we have been able to gather from various sources. Nevertheless, they are roughly indicative of the expected variation, at least on the nonrecurring cost side, on a consistent and comparable basis. Economic analyses were made by us within the expected range of uncertainties as given and reflected in estimates by industry and government agencies as well as our own judgment as to the uncertainty of some of these costing efforts in separate analyses.

The most important thing, however, with regard to Figure 3.33 as well as Figure 3.34 is that each of the systems as shown in these figures have a full equivalent space transportation capability to deliver payloads across the mission model for NASA, and the DoD, as well as commercial applications in the 1980's to all orbits, including earth escape missions. Therefore, in our analysis these systems include whatever expendable hardware has to go with partially reusable systems, as well as the inclusion of the Space Tug for the Fully Reusable Space Transportation System in the 1980's. The system costs also include the needed launch sites, both the ETR and WTR. All of the reusable systems do include for that matter the capability of using scout rockets for very small payload launches in the 1980's.

Analagous to the determination of cost effectiveness as explained in the first section of this chapter, we now can determine cost effectiveness in the context of the recurring versus nonrecurring cost tradeoff as shown in Figure 3.35. In Figure 3.35, the same Space Transportation Systems are shown for illustrative purposes, as in Figure 3.33. Obviously, not all systems are equally desirable from an economic standpoint. For example, as illustrated in Figure 3.35, System 5 when compared to Systems 1, 6 and 3, is obviously a better choice in economic terms. Each of these three systems (1, 3, and 6) has both higher recurring costs as well as nonrecurring costs when compared to System 5. Therefore, there exists no economic reason -- if the cost estimates also reflect technological risk and cost uncertainties as shown and exemplified in Figure 3.34 -- to choose any of these systems when compared to System 5. Without any further economic analysis, System 5 is obviously better than either of the three systems enclosed by the shaded area with its vertex at S5. In economic terms, Systems 1, 3 and 6 are inefficient systems.

On the other side, when System 5 is compared either to System 2 or System 7, as shown in Figure 3.35, we cannot state with equal assurance, or for that matter with any assurance as of now, that System 5 is better or worse than either System 7 or System 2 as long as no other additional economic criteria are introduced. When System 7 is compared to System 5, System 7 promises a further reduction in the cost per launch in the 1980's when successfully developed. This additional reduction in the recurring costs, however, has to be acquired by a substantial additional outlay of cost in the 1970's. As long as we do not know to what extent the recurring costs can be traded off economically into nonrecurring costs and vice versa, we have no way of choosing between Systems 5 and 7. Similarly, if System 5 is compared to System 2, we find that System 2 does promise a lower nonrecurring cost in the 1970's, while on the other side there is a substantial increase in the cost per launch for System 2 when compared to those expected from System 5. Again, the savings in nonrecurring costs can only be made

COST-EFFECTIVE SPACE SHUTTLE CONFIGURATIONS



Cost Effective Space Shuttle Configurations (S9, S7, S5, S2, S4)
Figure 3. 35

up by a corresponding increase in the expected cost per launch in the 1980's. System 5 does not and cannot be preferred uneconomically to System 2 without the introduction of additional economic criteria that again allows one to tradeoff recurring versus nonrecurring costs.

Among all the systems shown that are technologically feasible, and represented in Figures 3.33 and 3.34, there is a very small set of systems among these that is cost effective in the sense that these systems clearly and unequivocally dominate other technologically feasible systems; systems that are cost effective have associated with them either a lower non-recurring cost than any of the other systems considered or a lower recurring cost than any of the other systems or a combination of recurring or non-recurring costs that is lower than that of other technologically feasible and/or cost effective systems.

The cost-effective systems are shown in Figure 3.35 as the lower boundary to the technically feasible systems and for purposes of illustration are connected by straight lines between them. The lines as shown actually signify that, for instance, Systems 7, 5, 2, and 4 (that is, each of the cost-effective systems) have been studied in detail by industry. However, other systems possibly and probably can be found between, for example, systems 5 and 2, that would lie somewhere within the cost-effectiveness line connecting Systems 5 and 2, which for reasons of economy and time have not been studied in detail. It is also possible that systems between 5 and 2 are not actually possible, but in that case, at least during the operating period of these systems, a combination of Systems 5 and 2 would allow the achievement of recurring costs between points S5 and S2. However, it is unrealistic to assume that such a combined system could be achieved at the nonrecurring cost shown in these figures.

Thus, among all the technically feasible systems, a frontier of technological alternatives can be defined that economically dominates any of the other feasible systems. Systems along this boundary are cost-effective Space Transportation Systems, each of them having some advantages either singularly or by a combination of economic attributes that are not met by other systems capable of meeting the space transportation needs of the 1980's. The determination of cost-effective systems is one major task of economic analysis.

The second task of the full economic analysis is to determine among all the cost-effective systems the one single system or combination of systems that is most adequate, in economic terms, to meet the space transportation needs of the 1980's. The subsequent section shows how Space Transportation Systems are chosen as a function of all the different economic criteria and parameters that enter the economic evaluation.

3.5.2 The Determination of the Most Economic Space Transportation System: the Nonrecurring Versus Recurring Cost Tradeoff Line

As shown in Figure 3.35, one can move from System 5 to System 7 along the cost-effectiveness line only by trading off a given amount of cost per launch, the Δ recurring costs, at corresponding increase in the nonrecurring cost, shown again in Figure 3.35 by the Δ nonrecurring costs. For example, we can move from a cost per launch of $8 million for some of the Thrust Assisted Orbiter Shuttles to a cost of, say, $4.6 million per launch by incurring the development cost for a fully reusable flyback booster in the 1970's. Obviously, if there is only one launch, then even at usually high discount rates it is uneconomic under any criterion to trade off a savings of $5 million in the 1980's versus a nonrecurring cost outlay in the neighborhood of, say, between $1 or $2 billion in the 1970's. On the other side, the same cost reduction expected in the 1980's would be more than justified if in the 1980's there were an unusually high rate of launches per year, for example, 1000 launches. In this case, even applying the most strict economic criteria in the evaluation of such projects, it would be economic to incur the additional outlay in nonrecurring costs in the 1970's in order to bring about a very substantial savings per year in the 1980's. The actual level of activity in the 1980's as well as the value of other economic parameters will lie somewhere in between these two extremes.

The basic principle is that there exists some economic tradeoff, yet to be defined, between cost outlays in terms of research and development expenditures as well as investment expenditures in the 1970's for a promised reduction in costs and operations in the 1980's. In terms of the two economic variables shown in the diagram -- that is, the recurring and nonrecurring costs -- one can draw this economic tradeoff line as a straight line from some point along the horizontal to some point along the vertical axis. This line shows, with all due allowance for the different economic criteria that enter into the economic evaluation (the overall level of the social rate of discount applied in the analysis; the activity level in the 1980's to be expected for space transportation; the external effects expected for the Space Transportation System, in this case, the effects on payload costs and the costs of space missions over an extended period of time; as well as the type of economic analysis applied to evaluate the systems, foremost, the equal-capability versus the equal-budget analysis as described in the earlier sections of this analysis), the combination of recurring and nonrecurring cost systems that are economically equally desirable as the development of a New Expendable System for the 1970's. All of the economic variables mentioned will influence the exact slope of the tradeoff line to be drawn when trading off recurring versus nonrecurring costs in the evaluation of alternate Space Transportation Systems in the determination of the most economic system. We will first give a general exposition of the theory and assumptions underlying the concept of Economic Tradeoff Functions; then we will show how changes in the major economic variables do influence the location and the slope of the Economic Tradeoff Function. In Chapter 2, the actual results are shown as they affect the choice among alternative Space Shuttle configurations and in Chapter 8 the computational routines and flow diagrams are presented.

Since the development of any new Space Shuttle System must be tailored to fit NASA's budget projection, it is useful to characterize alternative system candidates in terms of the following financial parameters:

(a) the nonrecurring costs associated with the RDT&E phase;

(b) the recurring costs <u>per flight</u> or <u>per year</u>.

One can develop so called equal-net-present-value lines (also called equal-economic-benefit lines) depicting the theoretically possible tradeoff between levels of nonrecurring and recurring costs.

3.5.2.1 The Economic Tradeoff Function

Since both the recurring costs and the nonrecurring costs of a typical new Space Shuttle System are incurred over time, the problem of developing the tradeoff curves is tractable only if we are willing to make certain simplifying assumptions, the most important of which are stated below:

Assumptions:

(i) The capability to be placed into low earth orbit is the same regardless of the particular Space Shuttle being analyzed. This assumption allows us to measure benefits strictly in terms of cost savings.

(ii) It is assumed that, for any given Space Shuttle, the number of flights to be flown per year is the same from year to year. This number may, of course, vary from system to system. This assumption simplifies our presentations greatly without detracting much from their realism.

(iii) The benefits per unit of time of any candidate system are measured solely by the reduction in recurring costs, per unit of time, achieved when the new system is used and the baseline capability is maintained. In other words, we do not include in benefits any increment in capability attainable with the new system. The reduction in recurring costs may, however, include certain payload effects, i.e., cost savings in payload construction.

Notation:

We shall adopt the following notation:

B = the recurring costs, per flight, under the baseline system (i.e., the Current Expendable System).

m = the number of flights, per year, flown under the baseline system.

R_j = the recurring costs, per flight, under candidate system "j" (e.g., under the Shuttle or the hybrid system).

Z_j = the number of flights, per year, flown under STS "j".

X_j = $Z_j R_j$, the recurring costs, per year, under candidate system "j".

NR_{jt} = the nonrecurring costs incurred in period t for the RDT&E phase of STS "j".

L = the last year in which nonrecurring costs occur (RDT&E and Initial Fleet investment).

N = IOC date for the Space Shuttle System (i. e., the first year in which recurring-cost savings accrue).

r = the social discount rate.

H = the economic uselife of the entire project.

$NPV_j(r)$ = the net present value of Space Shuttle System "j" evaluated at a discount rate of r.

Other symbols will be explained as we proceed with our discussion.

Definition of Recurring and Nonrecurring Costs:

The term nonrecurring costs refers to any type of cost which is incurred only once during the economic uselife of the Space Shuttle System. All other costs are regarded as recurring costs.

Example: Consider a new Space Shuttle System requiring $5 billion for the RDT&E phase, $1. 5 billion for an initial fleet of vehicles assumed to wear out in 10 years, and certain variable costs arising solely out of the execution of flights.

We shall consider the RDT&E costs as unambiguously nonrecurring. Similarly, the mission-related costs are unambiguously recurring. A question arises, however, in connection with the initial fleet costs.

Our rule will be as follows:

1. If the project life is assumed to come to an end when the first set of vehicles wears out, then the initial fleet costs are a nonrecurring cost, as they occur only once during the project life.

2. If the project life extends beyond the uselife of the initial set of vehicles (i. e., if the first set of vehicles will be replaced with a second set, and so on then the initial fleet cost will be regarded as recurring.

In a situation where the initial fleet costs are considered recurring costs, we must, of course, include their amortization in the definition of recurring costs per year (X_j above). Assume now that the initial fleet for system "j" costs $\$C_j$ and has a uselife of M years. Then the annual equivalent fleet cost (A_j) is defined as

(1) $$A_j = \left[\frac{C_j \cdot r}{1 - (1+r)^{-M}}\right]^{*}$$

Variable A_j is something akin to straight-line depreciation of the initial fleet costs, except that A_j includes an interest component, while straight line depreciation (in the above case equal to C_j/N) does not. In sum, then, for cases where the project life extends beyond the life of the first set of vehicles, the annual recurring cost X_j includes an allowance for amortization. The allowance will have a value of A_j/Z_j, when recurring costs are expressed on a per mission basis, i.e., as R_j.

The other items assumed to be included in R_j or X_m are the launch costs, payload costs, the costs of ground facilities and, in the case of hybrids, the cost of expendable components.

The Net Present Value of Space Shuttle System "j"

We shall think of a new Space Shuttle System as a time stream of costs and benefits, the latter being thought of as cash equivalents. This stream can be depicted along a **time axis** as follows:

time:	0	1	2	...	L	L+1	L+2	...	H	→ time **
$:	NR_{j0}	NR_{j1}	NR_{j2}	...	NR_{jN}	Y_j	Y_j	...	Y_j	

* It should be noted that the expression $\left[1 - (1+r)^{-M}\right]/r$ is the present value of an M-year annuity of $1 per year, discounted at an annual interest rate r.

** Note that for illustrative purposes, the time stream above assumes recurring costs to begin one year after the last non-recurring costs have been incurred. In fact, however, the nonrecurring and recurring cost streams may overlap; i.e., N may be smaller than L.

where Y_j is defined as the net reduction in recurring costs per year associated with Space Shuttle "j". It is calculated as

$$(2) \qquad Y_j = \left[mB - Z_j R_j\right]$$

where, as will be recalled, R_j may include the amortization of depreciable vehicles.

The net present value of the stream of benefits and costs, evaluated at a discount rate r, is then given by

$$(3) \qquad NPV_j(r) = -\sum_{t=0}^{t=L} \left[\frac{NR_{jt}}{(1+r)^t}\right] + \left[mB - Z_j R_j\right]\left[\frac{(1+r)^{H-N} - 1}{r(1+r)^H}\right]$$

It should be noted that if the initial set of vehicles wears out precisely at the end of period H (and, since H is the assumed end of the project life, it is not replaced with a second set of vehicles) then the initial fleet costs are assumed to be included in the nonrecurring costs NR_{jt}, and R_j is exclusive of amortization of vehicle costs. If H extends beyond the uselife of the first set of vehicles, then the NR_{jt} do not include vehicle costs and R_j includes an amortization allowance.

In equation (3), it is assumed that the project horizon is a finite number of H years. Actually, society does have the option of retaining system j indefinitely. Presumably, society will do so until a better system comes along. There is, then, no compelling reason to use a project horizon of less than infinity for the benefit stream Y_j.

If one uses an infinite horizon, then equation (3) becomes

$$(3a) \qquad NPV_j(r) = -\sum_{t=0}^{t=L} \left[\frac{NR_{jt}}{(1+r)^t}\right] + \left[mB - Z_j R_j\right] \cdot \left[\frac{1}{r(1+r)^N}\right]$$

where R_j now definitely includes amortization of depreciable vehicles and NR_{jt} excludes initial fleet costs.

The Desired Economic Tradeoff Functions

We can use equations (3) and (3a) to derive the Economic Tradeoff Functions between nonrecurring and recurring costs. These functions can then be depicted on a two-dimensional graph with recurring and nonrecurring costs as the abscissa and ordinate, respectively. But before we can derive these functions, we must first of all decide precisely how we wish to represent the nonrecurring and recurring costs.

The Nonrecurring Costs

Since we wish to depict the tradeoff functions in only two dimensions, the vector of nonrecurring costs (NR_{j0}, $NR_{j2}, \ldots$, NR_{jL}) must somehow be collapsed into a scalar. Here we have three options:

Alternative 1:

We can assume that the relative amounts to be spent, per year, on non-recurring costs over the period 0 to L will remain constant, and that a "given "percentage change in nonrecurring costs" is interpreted to mean that each year's nonrecurring expenditures change by that percentage.

On this approach, we can normalize all nonrecurring expenditures NR_{jt} on those of some given year, e.g., on NR_{j0}, and write the vector of non-recurring costs as

$$NR_{j0}\,(1,\ n_{j1},\ n_{j2},\ n_{j3},\ \ldots,\ n_{jL})$$

where $n_{jt} = NR_{jt}/NR_{j0}$. The trade-off curve between non-recurring and recurring costs will then be

$$(4) \qquad \left[NR_{j0} = \frac{1}{\sum_{t=0}^{t=L} \frac{n_{jt}}{(1+r)^t}} \right] \left[\frac{(mB - Z_j\ R_j)\ \left[1+r\right]^{H-N} - 1}{r(1+r)^H} - NPV_j(r) \right]$$

and

$$(4a) \qquad NR_{j0} = \left[\frac{1}{\sum_{t-0}^{t=L} \frac{n_{jt}}{(1+r)^t}} \right] \left[\frac{(mB - Z_j\ R_j)}{r\,(1+r)^N} - NPV_j\ (r) \right]$$

for the finite-and infinite-horizon cases, respectively.

Alternative 2:

We can develop the tradeoff simply between the nonrecurring costs in a particular year (e.g., NR_{js}), and the recurring costs (R_j), holding the nonrecurring costs in any other year $t \neq s$ constant. The tradeoff curves will then become

$$(5) \quad NR_{js} = (1+r)^s \left[\frac{(mB - Z_j R_j)\left([1+r]^{H-N} - 1 \right)}{r(1+r)^H} - NPV_j(r) - \sum_{t=0}^{t=L} \left(\frac{NR_{jt}}{(1+r)^t} \right) \Bigg|_{t \neq s} \right]$$

and

$$(5a) \quad NR_{js} = (1+r)^s \left[\frac{mB - Z_j R_j}{r(1+r)^N} - NPV_j(r) - \sum_{t=0}^{t=L} \frac{NR_{jt}}{(1+r)^t} \Bigg|_{t \neq s} \right]$$

Alternative 3:

We can develop the tradeoff curve in terms of the present value of all nonrecurring costs and the recurring costs. On this alternative, we obtain the tradeoff curves

$$(6) \quad NR_j(r) = \frac{(mB - Z_j R_j)\left([1+r]^{H-N} - 1 \right)}{r(1+r)^H} - NPV_j(r)$$

and

(6a) $$NR_j(r) = \frac{(mB - Z_j R_j)}{r(1+r)^N} - NPV_j(r)$$

where $NR_j(r) = \sum_{t=0}^{t=L} \frac{NR_{jt}}{(1+r)^t}$. This definition of the non-recurring-cost parameter is, of course, dependent upon the discount rate (r). It follows that a diagrammatic representation of equations (6) and (6a) can be given only for a single, assumed interest rate (r). Aside from this restriction, however, Alternative 3 is probably the preferred definition of the non-recurring-cost parameter.

Equation (6a) has been plotted in Figure 3.36 below for the case $NPV_j(r)=0$ and $NPV_j(r)>0$. It will be recalled that equation (6a) is based on an infinite project horizon.

Each of the tradeoff curves in Figure 3.36 depicts a continuum of alternative combinations of nonrecurring costs and recurring costs per flight, each combination representing a distinct hypothetical Space Transportation System differing, however, from any other system only with respect to the nonrecurring and recurring costs. In particular, in this simplified case we assume that the number of flights flown per year is the same number (Z) for any Space Transportation System plotted in Figure 3.36 except for the baseline system for which the number of flights per year is assumed to be m. All such systems (with the same Z) located on the same tradeoff curve have the same net present value ($NPV_j(r)$) if their distinct cost-benefit streams are discounted at r.

We assume that the Current Expendable System, denoted by j=CE, is located on the horizontal axis with nonrecurring costs ($NR_{CE}(r)$) for that system being zero and recurring costs per mission being R_{CE}. Let us now examine a possible new Space Transportation System "X" with positive,

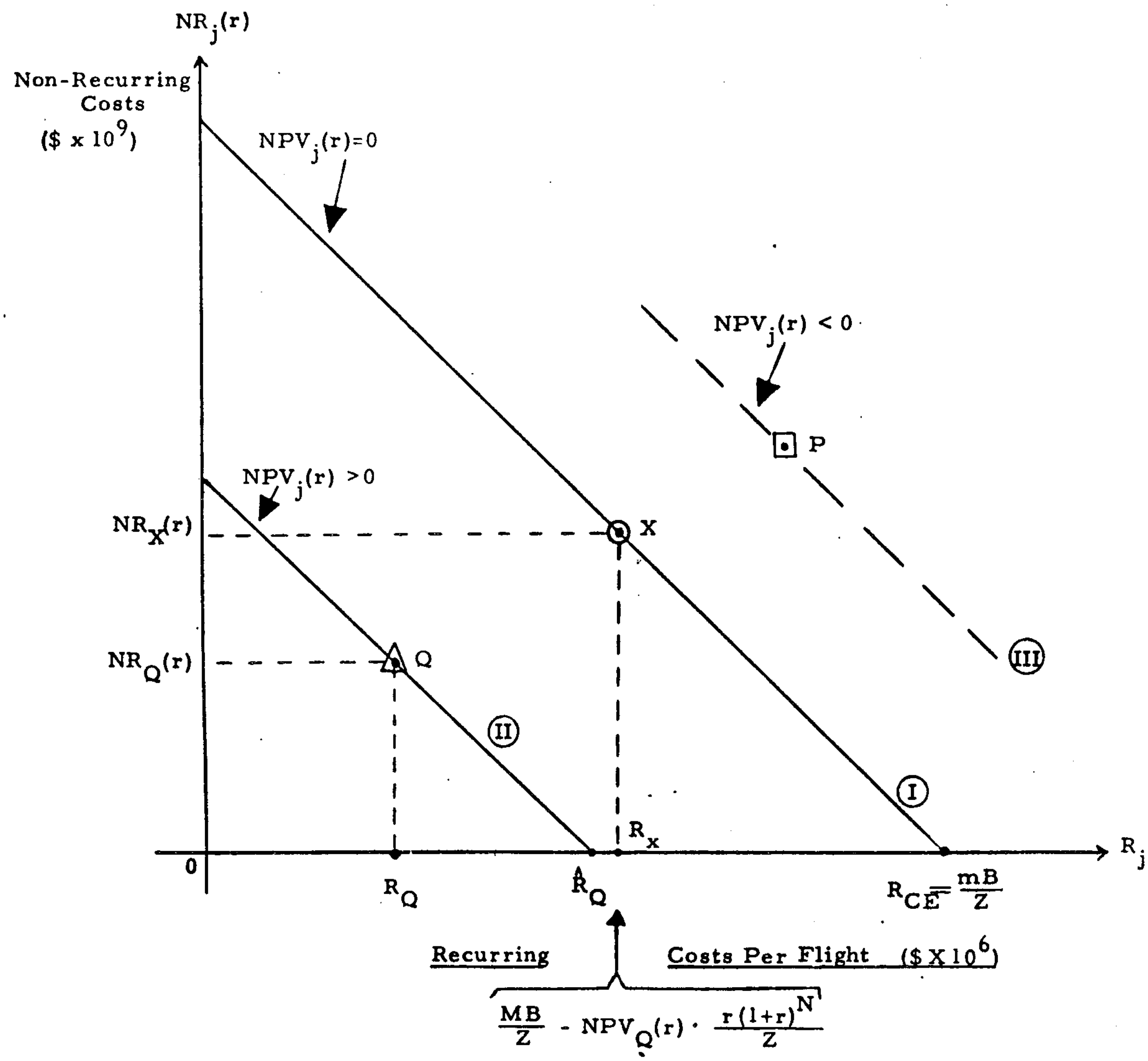


Figure 3.36
Nonrecurring vs. Recurring Cost per Flight
Tradeoff Function: Simplified Model

nonrecurring costs equal to $NR_X(r)$ and recurring costs per flight equal to R_X and flights per year equal to Z. This system, if evaluated at a discount rate of r is just equivalent to our assumed baseline system CE. In other words, any new system located on the line (I) is no better and no worse than the current baseline system.

Consider now a system Q characterized by the nonrecurring costs $NR_Q(r)$ and the recurring costs per flight R_Q and flights per year equal to the same Z we assumed for system X. If evaluated at r, this system would be equivalent (in terms of net present value, NPV(r)) to another hypothetical system characterized by zero nonrecurring costs, hypothetical recurring costs per mission of $\hat{R}_Q$, and the same number of flights per year (Z) as systems Q and X. It is clear that system Q is superior to both system X and the (current-expendable) baseline system CE. For at a discount rate of r, system Q must have a net present value greater than zero as otherwise $\hat{R}_Q$ could not be smaller than R_{CE}.* Similar reasoning will convince the reader that system P is inferior to both system X and the baseline system, since P must have a negative net present value ($NPV_P(r) < 0$.

We may therefore draw the conclusion that, for all conceivable Space Transportation Systems characterized by the same number of flights per year, those systems located below line (I) are preferred to the baseline system CE, those located on line (I) are no better and no worse than the baseline system and those located above line (I) are inferior to the baseline system. This is the precise meaning of graphs such as Figure 3. 3 6.

A Closer Look at the Recurring-Cost Dimension:

Figure 3.36 has one major weakness: it is the requirement that, with the exception of the baseline system, all Space Transportation Systems plotted in the figure are characterized by the same number of flights per year.

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* Note that $\hat{R}_Q = R_{CE} - NPV_Q(r)/r(1+r)^N$. It follows that $\hat{R}_Q < R_{CE}$ is possibly only for $NPV_Q(r) > 0$, if $r > 0$.

Actually there is no reason to suppose that the number of flights to be flown per year will be a constant over all alternative systems being considered. In view of the variability of Z_j, it is therefore best to express the recurring-expense parameter not on a per-flight basis (i.e., as R_j), but rather on a per-year basis (i.e., as $X_j = Z_j R_j$). The graphic presentation of the tradeoff curves will then appear as in Figure 3.37.

In outward appearance Figure 3.37 differs from Figure 1 only in that the abscissa now represents X_j, the recurring costs per year associated with Space Shuttle System "j". (Moreover, as Figure 3.38 is drawn, the scales of the axes are obviously not the same as those in Figure 3.36; but this change has been made only for expository convenience.) The great advantage of Figure 3.38 over Figure 3.36 is that we can represent in it any conceivable Space Shuttle System, regardless of the number of flights the system requires per year.* Moreover, part of the exercise is surely to see how alternative systems are likely to affect NASA's annual budgets, and that is possible only if recurring costs are on a per annum basis.

Figure 3.37 still has the property that any Space Shuttle System located above line (I) is inferior to the (current expendable) baseline system, any system located on line (I) is equivalent to the baseline system and any system located below line (I) is superior to the baseline system.

Figure 3.37 can be made more informative still if it is accompanied by a net present value scale as in Figure 3.38 below. The reader will have noticed that to every point ($X_j \geq 0$, $NR_j(r) = 0$) corresponds a unique net present value $NPV_j(r)$. Consider, for example, system R in Figure 3.38 with nonrecurring costs of $NR_R(r)$ and recurring costs per year equal to X_R. We know that this system is equivalent to another hypothetical system with zero nonrecurring costs and annual recurring costs equal to $\hat{X}_R > X_R$.

* The reader should note, however, that the trade-off curves in Figure 3.37 all have the slope $1/r(1+r)^N$, i.e., all systems evaluated with reference to these curves are assumed to have the same IOC date. We shall consider the treatment of variable IOC dates in Figure 3.39.

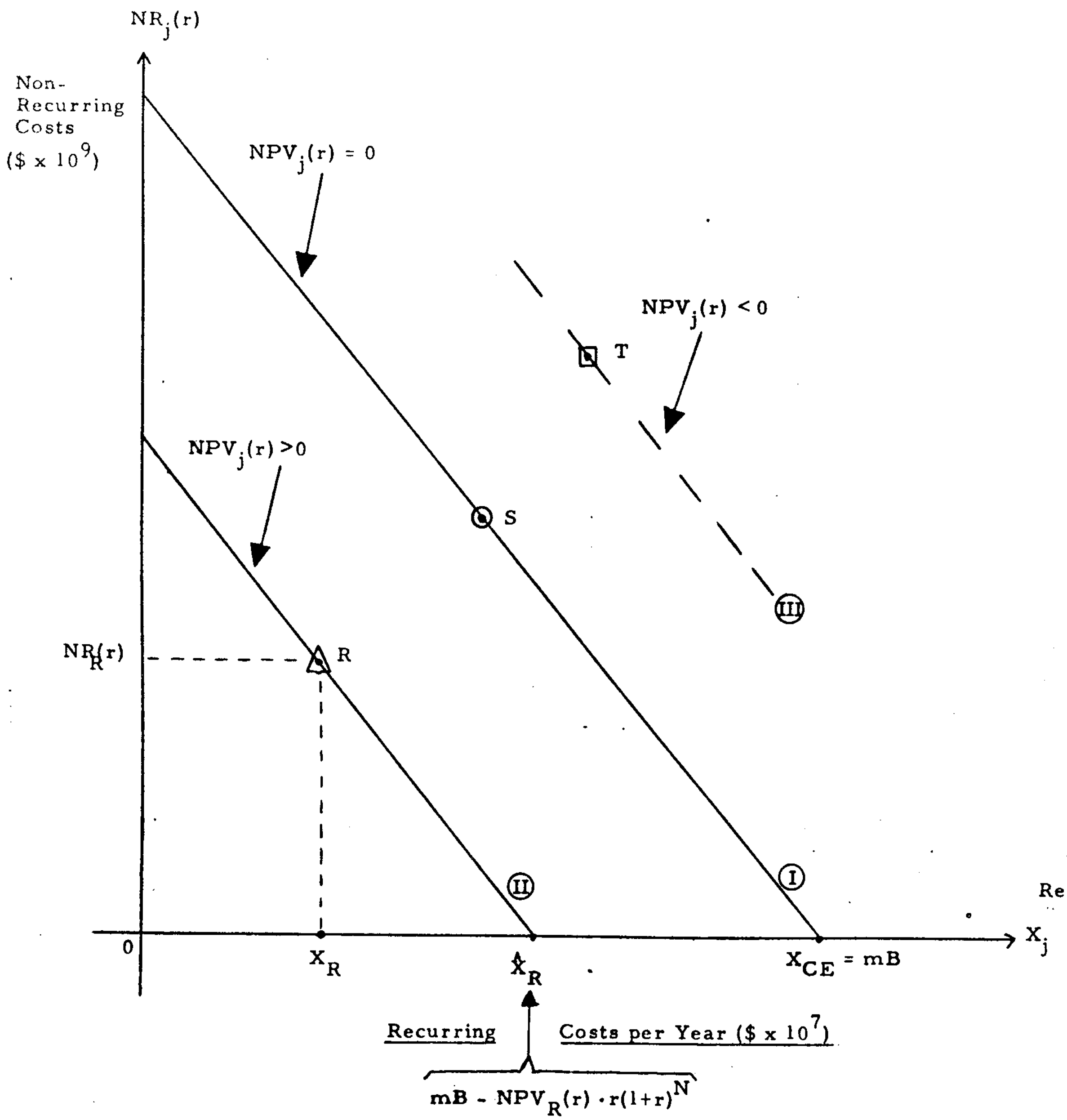

Figure 3.37
Nonrecurring Costs of the New Space Shuttle System
Vs. the Recurring Costs per Year

Now this $\hat{X}_R$ has the value of

$$\hat{X}_R = mB - r(1+r)^N \cdot NPV_R(r), \tag{7}$$

which can be solved for

$$NPV_R(r) = \frac{mB}{r(1+r)^N} - \frac{\hat{X}_R}{r(1+r)^N} \tag{8}$$

The values of $NPV_j(r)$ corresponding to any other $\hat{X}_j$ (where, to repeat, the ^ signifies that we are talking about a hypothetical system with zero non-recurring costs) can be obtained via equation 8.

Figure 3.38 enables one to rank the project plotted in the nonrecurring--recurring cost space with relative ease. Consider, for example, project T. To find its net present value, simply move along the tradeoff curve (line III) on which T is located up to the point where the tradeoff curve cuts the horizontal axis at $X_j = \hat{X}_T$. From there, drop a perpendicular to the net-present value scale and read off the net present value, $NPV_T(r)$, of system T. If all systems under consideration have been properly located in the NR-X space, the system with the left-most position on the net present value scale is the most desirable one. (Recall, again, that all systems considered are assumed to satisfy a given capability.)

While the X_j-axis in Figure 3.38 increases from left to right, the net present value scale increases from right to left, and its zero-point is located just where the X_j-axis has the value of mB. Finally, in terms of absolute dollar values, one unit of distance on the X_j-axis corresponds to $1/r(1+r)^N$ units of distance on the net present value scale.

It is well to keep in mind, however, that the net present values shown in Figure 3.3.8 do not make any allowance for incremental benefits. Any system on that graph with a positive net present value is therefore

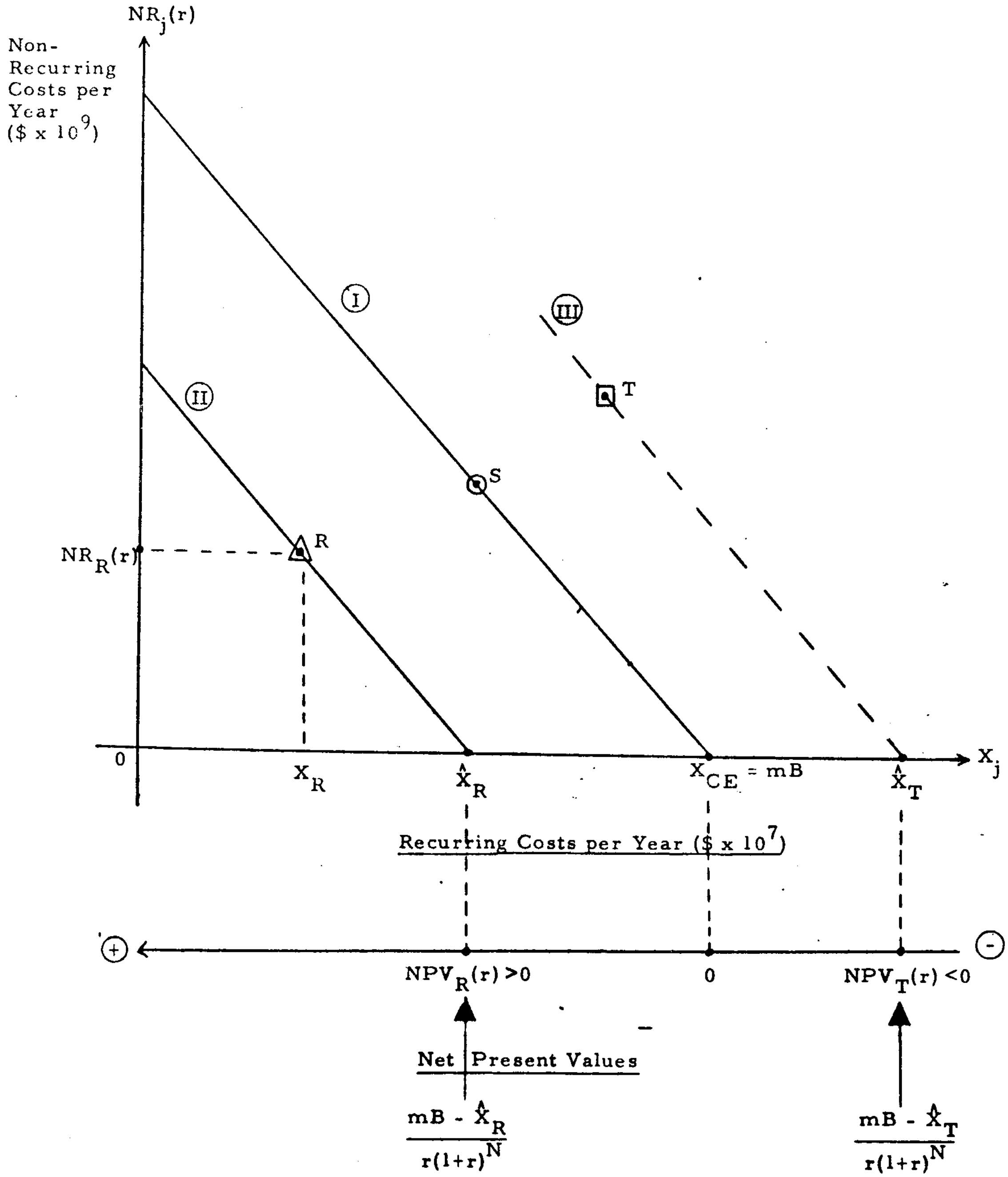

Figure 3.38
Nonrecurring Costs of New Space Shuttle System vs. the Net Present Value of Recurring Costs

definitely superior to the baseline system (assuming costs to have been predicted accurately). On the other hand, even a system such as T in Figure 3.38 might be better than the baseline system if all potential future benefits associated with the system are accounted for.

Economic Tradeoff Functions when the IOC Date varies among Systems

It will have been noted that the slopes of the tradeoff functions in Figure 3.36 are

$$\frac{\partial NR_j}{\partial R_j} = \frac{-Z_j}{r(1+r)^N}, \tag{9}$$

and those of the trade-off curves in Figures 3.37 and 3.38

$$\frac{\partial NR_j}{\partial X_j} = \frac{-1}{r(1+r)^N}. \tag{10}$$

In other words, all of the functions shown in these diagrams are based on the assumption that the systems to be evaluated have the same IOC date N years hence.

Suppose now that we wish to evaluate two alternative systems, U and V, against the baseline system CE. Assume further that for U, nonrecurring costs are incurred for L years while for system V nonrecurring costs occur for $K \neq L$ years. Finally, assume that system U has an IOC date of N, while system V has an IOC date of $M > N$.

It is clear from the slope equations (9) and (10) above, that the location and possibly the slope of the Economic Tradeoff Function will be different for each of the IOC dates. This is shown in Figure 3.39. Since "U" has an IOC date of N, its position must be evaluated with reference to line I. And, as may be seen from the net present value scale, system U is clearly better than the current baseline system CE. If system V were

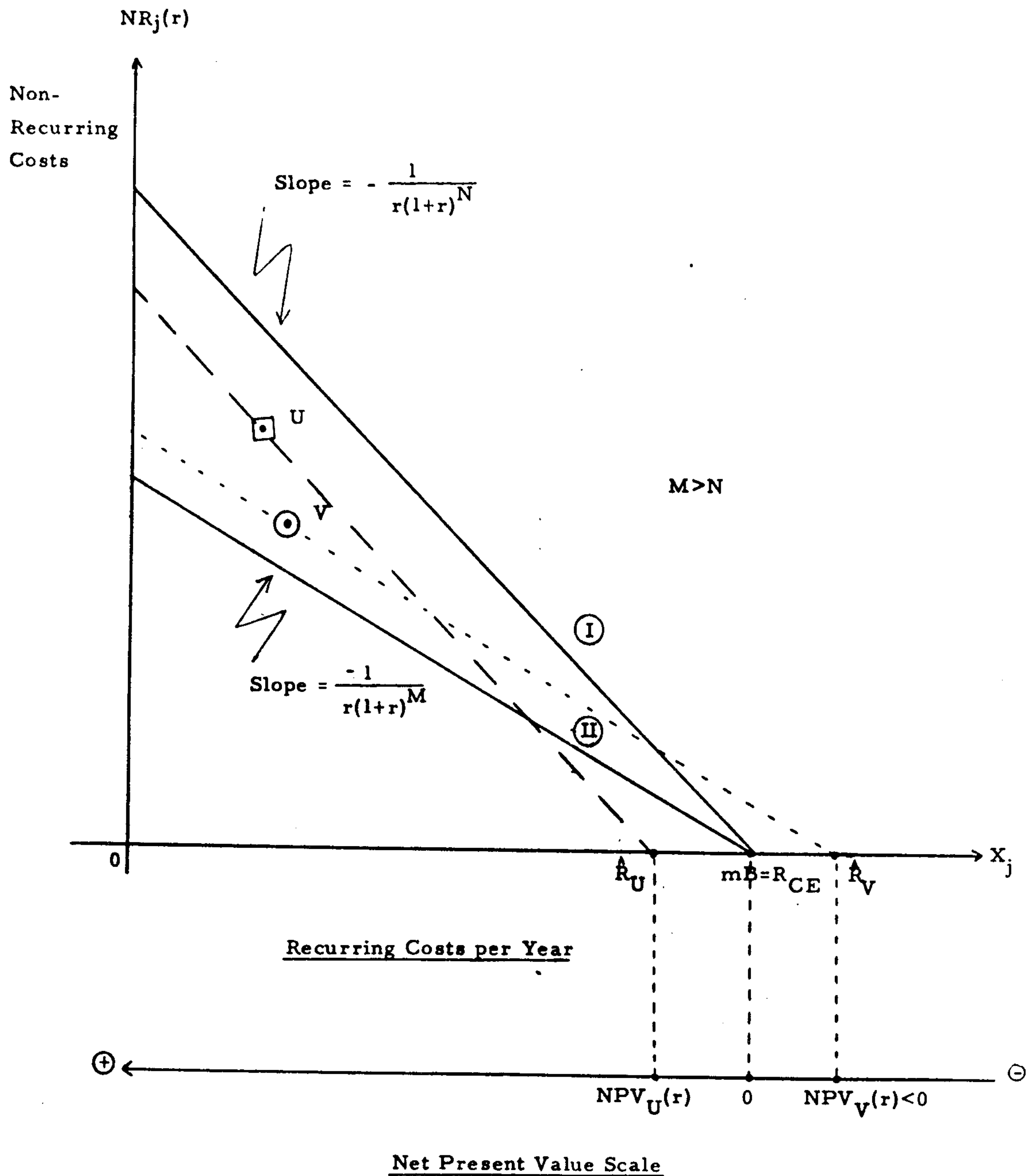

Figure 3.39
Effect of Changes in Major Economic Variables (e.g., IOC Date) on Location and Slope of the Economic Tradeoff Function

evaluated with reference to line (I) as well, it would appear to be better than both the baseline system CE and candidate U. However, it will be recalled that the IOC date for system V was M >N. This means that V must be evaluated in terms of its position vis-a-vis line (II) (having a slope of $-\frac{1}{r(1+r)^M}$). And it is apparent from Figure 3.39 that system V, far from being better than the baseline system, is clearly inferior to it, because the net present value ($NPV_{CE}(r)$) of the baseline system is zero, while that of system V ($NPV_V(r)$) is negative.*

It is seen, then, that Economic Tradeoff Functions, such as Figure 3.38 can easily be adapted to the case in which the IOC date varies among the alternative Space Transportation Systems being evaluated. Any other changes in the major economic variables can be incorporated equally well and represented easily in the Economic Tradeoff Function (ETF), each significantly influencing the exact location or slope of the ETF. But it is equally clear from our discussion that one must be careful in making explicit one's assumptions implicit in the use of the Economic Tradeoff Function. For, as was illustrated with Figures 3.36 and 3.39, failure to be conscious about the assumptions underlying particular tradeoff functions can easily lead one to make erroneous choices.

The actual Economic Tradeoff Functions are arrived at in Chapter 8 and the major empirical results are summarized in Chapter 2. However, the impact on Space Shuttle System choice of changes in the major economic variables identified in the economic analysis are brought out in the next four figures. In Figures 3.40, 3.41, 3.42, and 3.43 it is shown how the actual slope of the tradeoff line does influence the choice of the Space Transportation System in the case of new space transportation alternatives.

In Figure 3.40, three alternate tradeoff lines are shown which reflect the influence of the level of different economic variables on the tradeoff line. Tradeoff line A shows how the cost per launch expected for a New Expendable System in the 1980's can be traded off -- at increased research and development expenditures -- by moving toward a reusable Space Trans-

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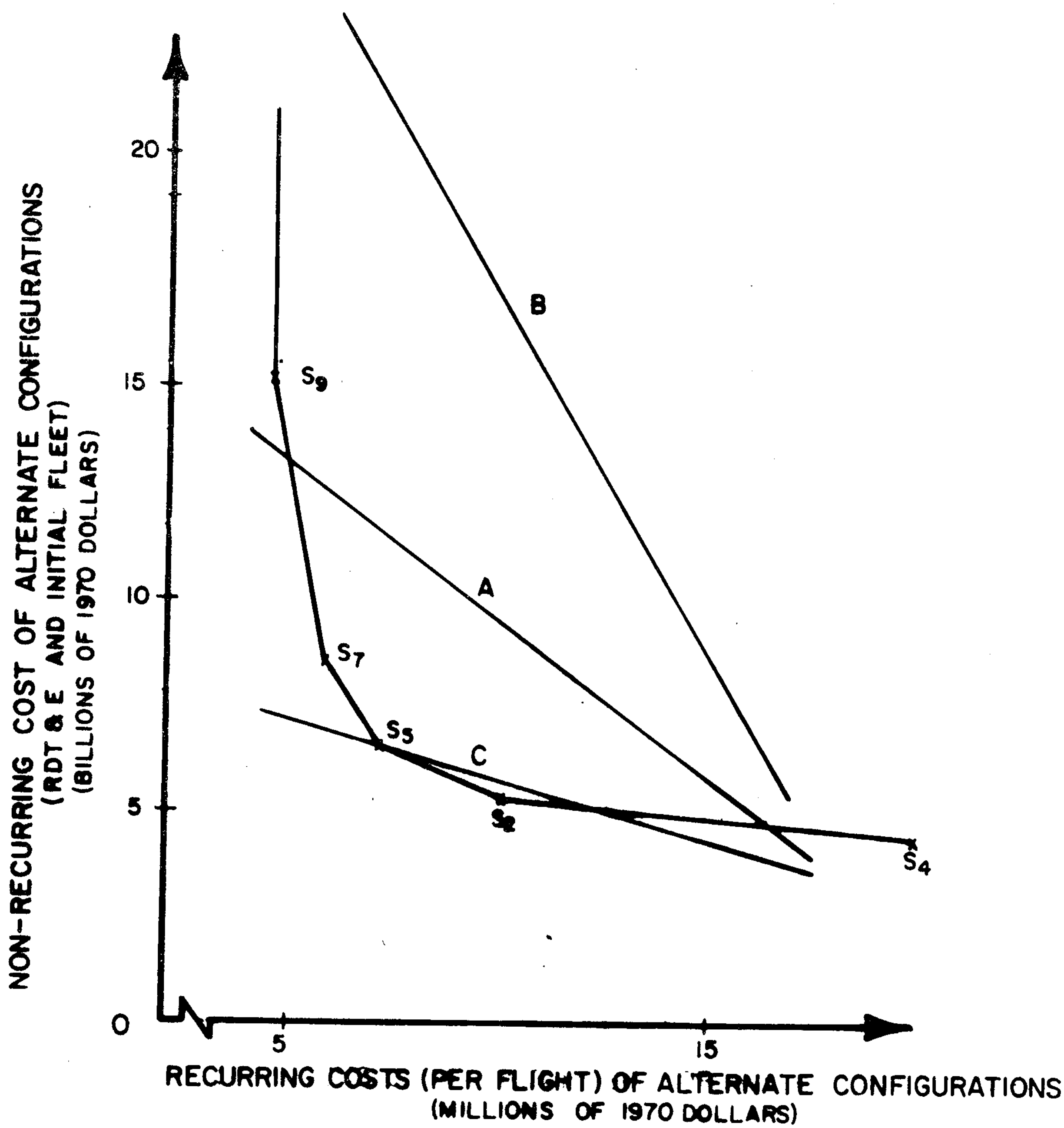
* Remember, however, that we have not accounted for any possible incremental benefits under system V. Once these benefits have been taken into account, system V might still be better than the baseline system.



Benefit tradeoff line as influenced by social rate of discount, activity level between 1978 and 1990, and payload effects. (A) At 10% social interest rate, NASA and DoD 1978-1990 baseline mission model, and payload effects (volume, mass, refurbishment and reuse), and equal capability analysis. (B) Lower discount rate, higher activity level (larger space program), larger payload effects, or equal budget analysis. (C) Larger discount rate, lower activity level, lower payload effects or less than equal capability.

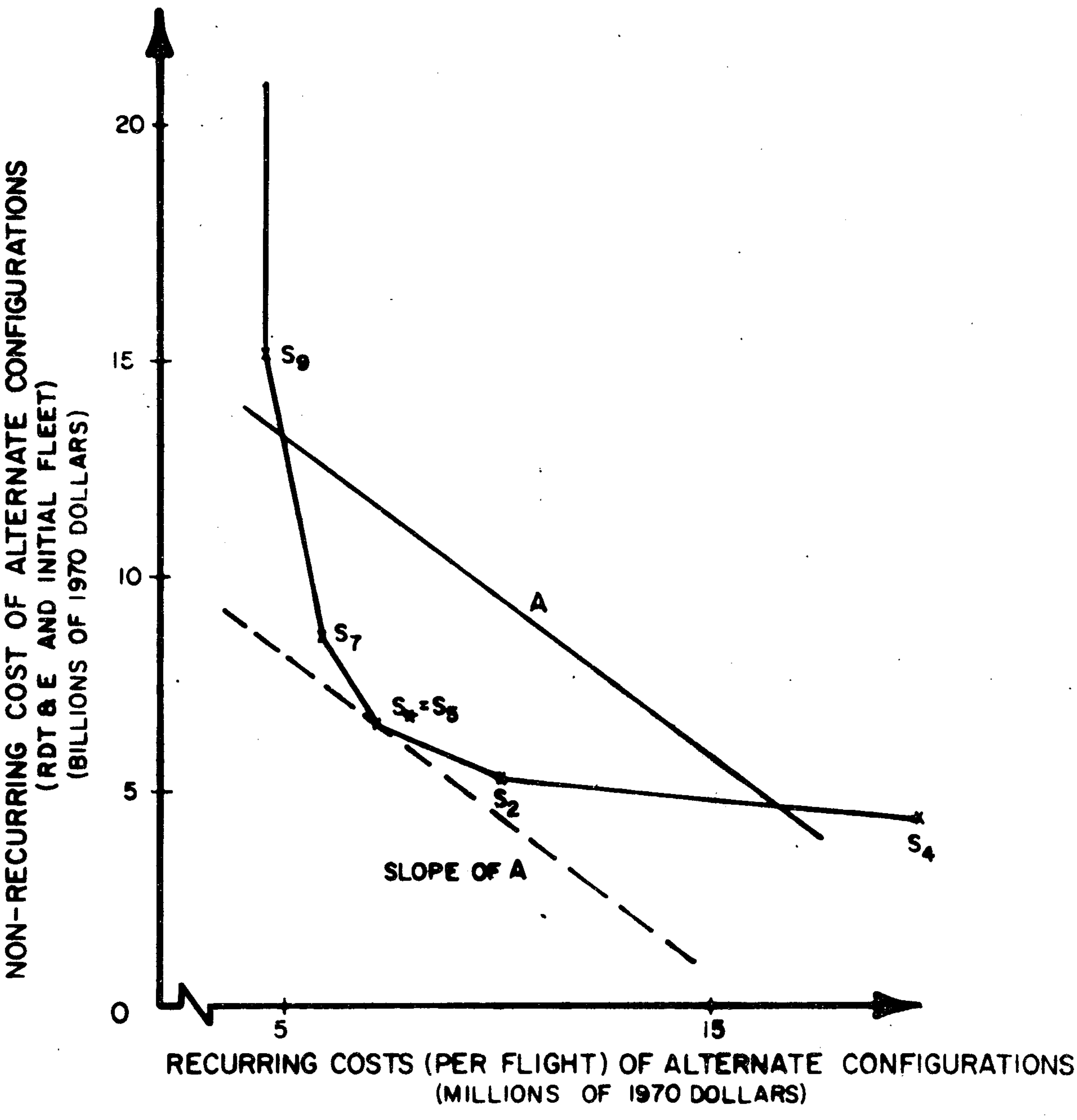
Figure 3.40

portation System along the cost-effective line developed in Figure 3.35. Tradeoff line A indicates that for the levels of activities chosen for the economic variables -- for a 10% social rate of interest, the NASA and the DoD baseline mission models for the period of 1979 to 1990, the payload effects as documented by studies used for the purposes of this analysis (due to volume, mass, refurbishment, and reuse), as well as the equal-capability-cost-effectiveness analysis described in Section 3.1 -- the expected New Expendable costs can be traded off at most against $15 billion of nonrecurring costs in the 1970's even assuming a recurring cost per launch of zero. This goes to show that given the present state of technology the most advanced system -- those of a minimal or possibly negligible recurring cost -- also have associated with them a maximum amount of economic resources that could be allocated to their development in the light of the activities that the U. S. expects to carry on in the 1980's and 1990's.

If a different set of economic parameters had been selected as representative of the economic environment in the 1970's and 1980's, then a different tradeoff would have resulted of the expected reduction of recurring costs versus the justifiable nonrecurring costs in the 1970's when compared to New Expendable Systems. Tradeoff line C as shown in Figure 3.40 reflects a substantially higher discount rate (in this case 15%) as well as lower activity levels in the 1980's, a substantial reduction of the expected payload effects, and again, an equal-capability-cost-effectiveness analysis of alternate Space Transportation Systems. It shows that under these constraints and economic conditions the most that an economic analysis could show as justified in nonrecurring costs for the 1970's would be $10 billion, even assuming inordinate reductions in the cost per flight to be expected in the 1980's and beyond.

On the other side, if some of the economic conditions prevailing in the 1970's and the activity levels expected in the 1980's were more favorable to the development of the Space Shuttle System, then Tradeoff line B reflects such conditions: a lower social rate of discount of 5%, a higher activity level in the 1980's than that represented by the NASA and the DoD 1979-1990 baseline mission model, as well as larger payload effects than those posed and given for purposes of our analysis. A similar effect on the slope of the tradeoff line could also be shown if instead of the equal-capability analysis, the equal-budget analyses were taken as the basis for the economic evaluation of alternate Space Transportation Systems. With a substantial variation in the economic parameters used for the economic analysis, alternate Space Transportation Systems will prove to be the most economic among the cost-effective systems as shown in Figure 3.35. In the case of Tradeoff line A, the most economic system is shown (S*) in Figure 3.41 -- it is the system where the distance between the Tradeoff line A and the cost-effectiveness line of alternate Space Transportation Systems is maximized, as shown by System S5. The most economic system among the cost-effective systems is selected on the basis where Tradeoff line A is tangent to the cost-efficiency line represented by Systems S7, S5, S4 and S2. The point of tangency is given at S5. With the tradeoff as represented by the slope of A between recurring and nonrecurring costs, System 5 is bounded by the technical possibilities offered by System 7 and S ystem 2 in terms of recurring versus nonrecurring costs and is closest to the tradeoff that is desirable for economic reasons, represnted by Tradeoff line A. For example, to move from System 5 to System 4 one could save an additional portion of nonrecurring costs. One would do so at an increase of recurring costs that is larger than the economi analysis shows to be desirable, i.e., the slope of Tradeoff line A. On the other side, by going from System 5 to System 7 we could further reduce the recurring costs in the 1980's; however, the increase in nonrecurring costs is larger than the one that can be justified on the basis of economic analysis, again shown by Tradeoff line A. In the absence of other technical choices between Systems 7, 5 and 2, System 5 is economically the preferred system to meet the space transportation needs of the 1980's.

If other economic conditions had held for the analysis, the tradeoff between the recurring cost and the nonrecurring cost would have been in favor of incurring higher nonrecurring costs in the 1970's with the promise of a further reduction of recurring costs in the 1970's. As discussed earlier, if the social rate of discount had been substantially lower than the one used for the economic analysis, and/or the acttvity level in the 1980's had been



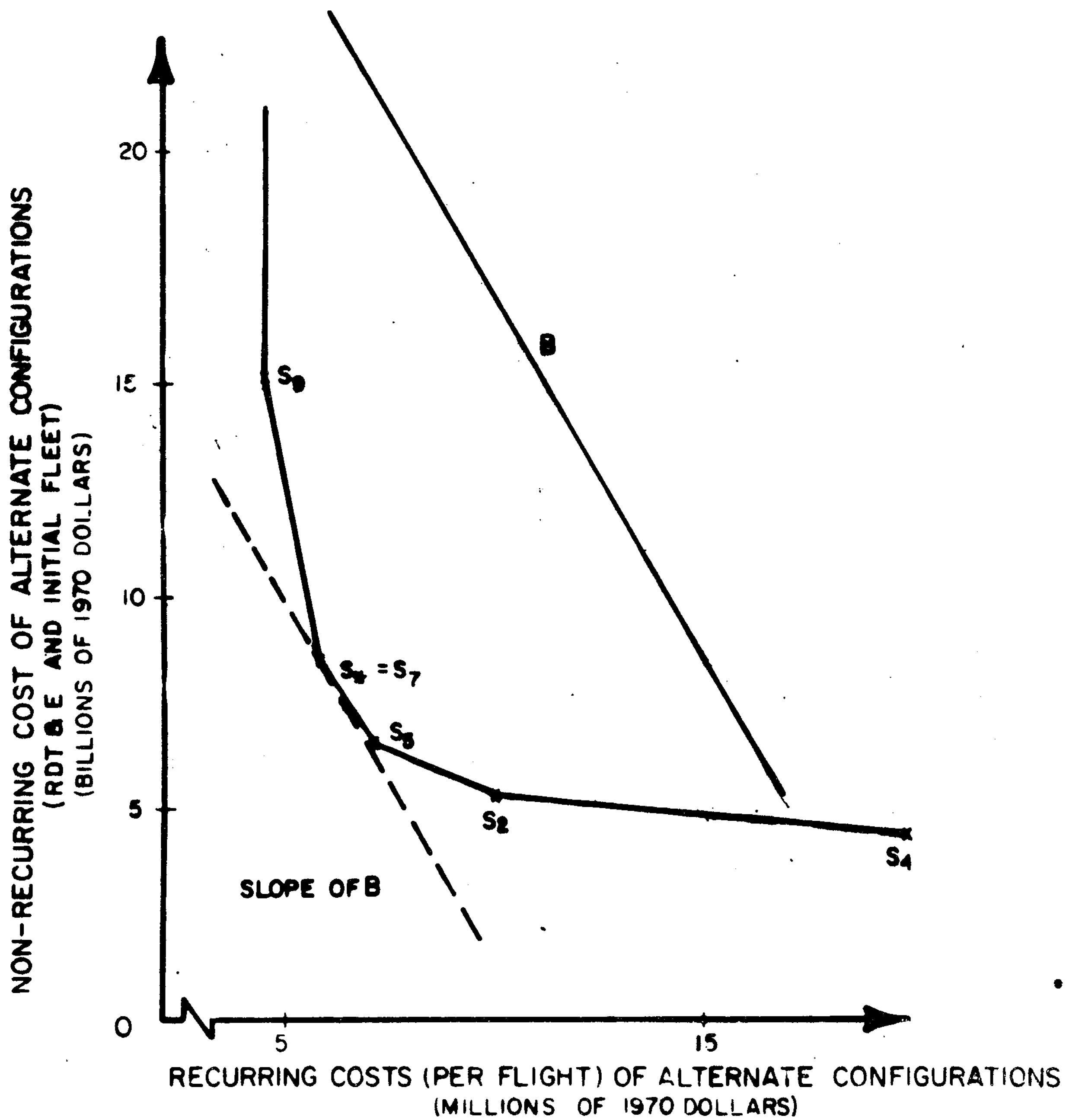
Most Economic Space Shuttle System (S_*) given Trade-Off line A: 10% rate of discount, NASA and DoD Modified Mission Model (514 flights), given Payload Effects

Figure 3.41

substantially higher than that used again in the economic analysis and/or the external effects of the Space Transportation System (mainly, the decrease or increase in the payload costs in meeting various alternate missions of space transportation in the 1980's as well as the expected reliability and operating time of the systms) and the type of cost-effectiveness analysis applied in this case by moving from an equal capability to an equal-budget analysis, then Tradeoff line B would apply. This case is represented in Figure 3.42 by the Tradeoff line B, also shown in Figure 3.40. In this case, the most economic system, that is, where the slope of line B is tangent to the cost-effectivness function, is System S7. Under these favorable economic conditions, the most advanced technological system would be developed since, when compared to the next best System, S5, the reduction in the recurring costs promised by moving from System S5 to System S7 are larger than those needed in order to justify the additional nonrecurring cost outlay as shown by the slope of line B.

Conversely, if economic conditions had been more stringent than those used by us and deemed representative of the economic environment of the 1970's and 1980's in our economic analysis, then a lower tradeoff line would have resulted for purposes of this analysis. The Tradeoff line C as shown in Figure 3.43 does reflect such an adverse combination of economic factors. Tradeoff line C reflects a higher social rate of discount at 15%, a substantially lower activity level, as well as the exclusion of significant payload effects than can be and may be achieved in the 1980's, but for purposes of a conservative economic analysis were excluded to a large extent in this case from the evaluation. Similarly, if the capabilities of this system to be developed in the 1970's would only partially meet the mission models of the 1980's, the rest having to be carried by expendable systems, then again the tradeoff line for the development of that system would be lowered to a slope as shown by Figure 3.43 and Tradeoff line C.

As a matter of fact, in the analysis of this report, Tradeoff line C is more representative with respect to at least two of the three or four key economic variables of the environment to be expected in the 1970's and 1980's, than tradeoff line A. This is reflected in the quantitative results of



Most Economic Space Shuttle given Trade-Off line B : Lower Social Rate of Discount, Higher Space Activity Level, Larger Payload Effects

Figure 3.42

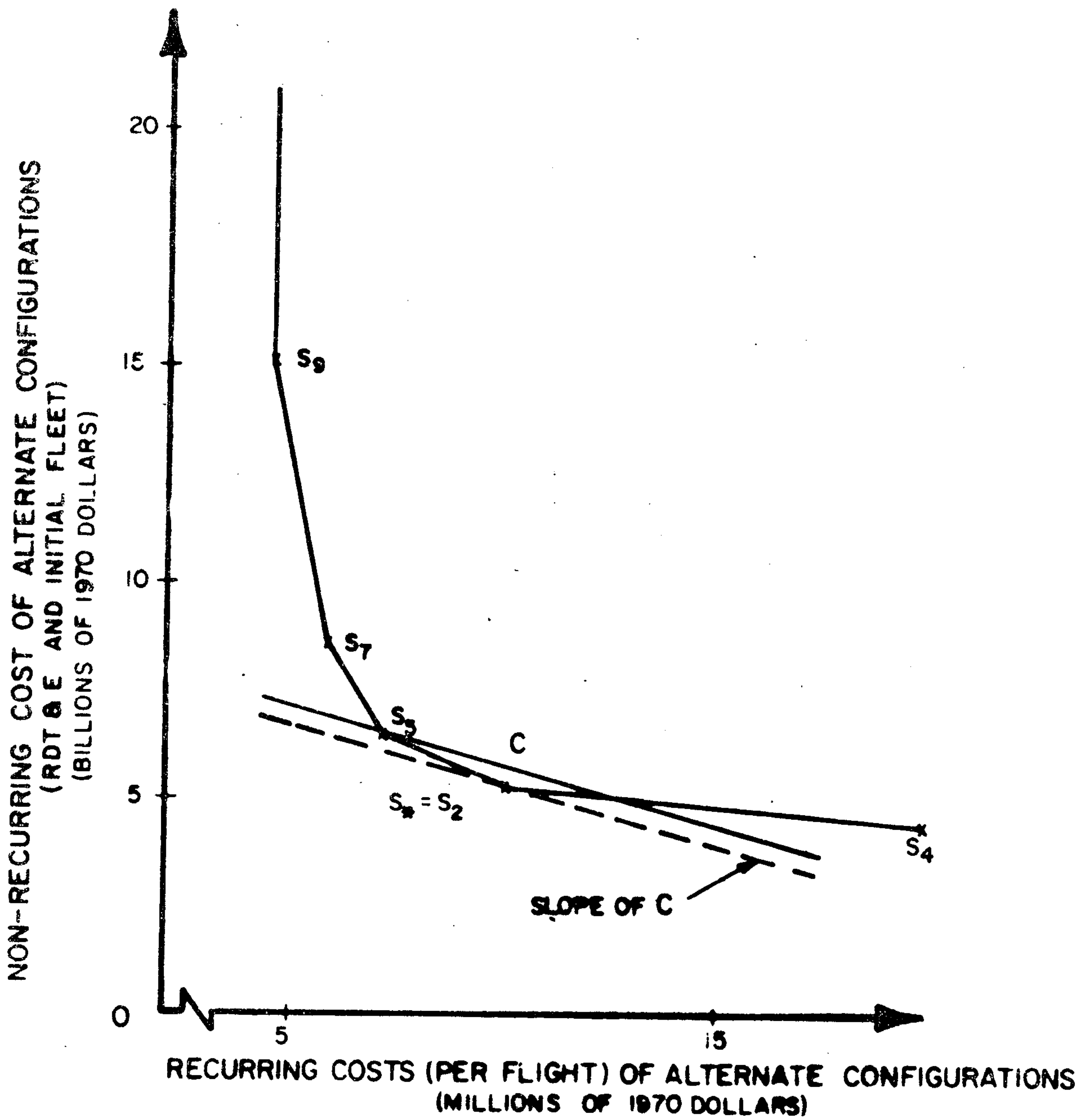


Figure 3.43

Most Economic Space Shuttle given Trade-off Line C: Higher Social Rate of Discount, Reduced Activity Level, Smaller Payload Effects our economic analysis. Using Tradeoff line C as shown in Figure 3.43 to determine the most economic Space Shuttle System among the cost-effective systems, System S2 is now preferred over any of the other systems including Systems S5 and on the other side, S4.

The actual level of the various economic variables used in our economic analysis -- mostly the discount rate, the activity level, the payload effect, as well as equal-capability and equal-budget analyses -- are discussed in the quantitative section of this report as well as in the summary of results.

In addition to these economic variables, there are other factors that also influence the economic tradeoff line and that are reflected in our calculations. Among these are the expected initial operating capability for the alternate Space Transportation Systems, the expected risk and uncertainty of the systems, as well as the availability, or unavailability, of a Fully Reusable Space Tug in the 1980's.

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FOOTNOTES IN CHAPTER 3.0

1. In our economic analysis, it is assumed that the incremental cost of the new STS (Shuttle) missions is constant. The basic arguments presented here are more general than what would be needed in subsequent economic analysis.

2. These two criteria will not usually lead to the same choice. Let B(Q) denote the benefit function, C(Q) be the cost function and B'(Q) and C'(Q) be the first derivatives, with respect to Q, of these two functions, respectively. Let Q denote capability levels. Then "net benefits" are maximized at that level Q at which B'(Q) = C'(Q), i.e., where "marginal benefits" equal "marginal costs". The cost benefit ratio, on the other hand, is maximized (subject to second order conditions) at a level Q such that

$$\frac{\partial B/C}{\partial Q} = 0, \text{ which implies}$$

$$\frac{B'(Q)}{B(Q)} = \frac{C'(Q)}{C(Q)}$$

It is clear that, in general, these two first order conditions are not satisfied at the same level of Q, i.e., the "net benefit" and "benefit/cost ratio" will not lead one to choose the same capability -- budget point.

3. Scenarios denote, roughly, different space programs for the 1980's for NASA, the Department of Defense and commercial users.

4. George Wilson, Essays on Some Unsettled Questions in the Economics of Transportation, Foundation for Economic & Business Studies, Indiana University, 1962, p. 55.

5. "The Analysis and Evaluation of Public Expenditures: The PPB System", Joint Economic Committee, the Congress of the United States, Washington, D. C., 1969.

6. Op. cit., Volume I, p. 357.

7. Op. cit., Volume I, p. 369.

8. Op. cit., Volume I, p. 357.

9. The readers may find it strange to see the output from a Space Transportation System defined as a consumable. The point is that the output from an STS becomes input into production processes which ultimately do yield consumables.

10. Klaus P. Heiss, Uwe Reinhardt, On the Principles of Public Project Evaluation, prepared for NASA, July, 1970, Chapter 5.

11. Ibid.

12. For an exposition of these conceptual differences, see Ibid., Chapter 5.

13. Ibid.

14. MATHEMATICA, Inc. [3], Section 5.2.2, pp. 88-96.

15. See, for example, K. J. Arrow and B. C. Lind [1].

16. The blueprints may become obsolete (i.e., superior knowledge may be produced in the future), but obsolescence is by no means the same as depreciation, as will be argued shortly in this section.

17. By "recovered" in this context is meant "covered by benefits" and not "covered by user charges levied by NASA".

18. This assumption means, of course, that the Shuttle would be in existence by 1985. In comparing the more advanced system to the Shuttle, one would therefore disregard the fixed RDT&E outlays for the Shuttle (they would be sunk costs), and compare the total RDT&E and operating cost of the advanced system to only the operating cost of the Shuttle.

19. Obviously we are abstracting here from a host of other managerial and technical factors which ought to be considered in such a decision. Let the reader be reminded that in this chapter, our aim is to explore basic principles, one by one. Such an analysis inevitably forces one to oversimplify and to abstract from the complexities of the real world.

20. In the context of the proposed Space Shuttle development, for example, the competing projects might consist of more scientific applications using the current expendable transportation system. The competing projects might include also programs proposed by competing federal agencies, such as the expansion of medical-school capacity or the support of basic research at institutes of higher education.

21. It may not be unfair to suggest that the arguments for the early developments of Supersonic Air Transport are predicated precisely that type of non-sequitur. That the time for an early IOC-date of the STS is not ripe may be inferred from the fact that private capital shies away from the project. Indeed, aside from the proper measurement of the social costs of the STS, a diligent search for an appropriate IOC-date is probably the single most important factor neglected by the advocates of that transportation system.

22. As a matter of fact, for such projects one could make the case of the government "risk happiness", as the low risk projects would be undertaken by the private sector.

23. "Value of expected utility of return" is used here synonymously with "expected utility return", as opposed to the "expected money return."

24. With $A = 1$, this implies "variance" neutrality, $A < 1$ implies risk (variance) aversion and $A > 1$ implies risk happiness. In Figure 3.29 we have $0 < A < 1$.

25. At present we are trying to empirically measure this rate for stock market operations.

Appendix 3A: Benefit-Cost Analysis of Space Transportation Systems Theory and Practice in Mathematical Economics

This Appendix reviews the theoretical foundation of our work on the economic analysis of new Space Transportation Systems. This Appendix is strictly intended for mathematical economists concerned with the rigor of cost-effectiveness and benefit-cost analysis. No effort is made to make it intelligible in more general, non-mathematical form. This Appendix and its implementation in our work represents in our opinion the first complete theoretic foundation of benefit-cost and cost-effectiveness analyses of alternative technologies. Some effort has been made to fill what appears to be a gap between the abstract discussion of the theory (such as recent contributions of R. W. Shephard [2] and [4]) and the concrete evaluation of the practice (such as this and earlier reports [1]).

General Framework and Specific Issues

The terms "cost-effectiveness analysis" and "cost-benefit analysis" have been distinguished explicitly by us. They are treated as one by R. W. Shephard [4]. In reality, the distinction between "benefit" and "effectiveness" is unnecessary when one is dealing exclusively with cost-benefit (effectiveness) relationships of a single technology. This technology is described by a correspondence $x \longrightarrow P(x)$, or its inverse correspondence $u \longrightarrow L(u)$, where $x \epsilon E^n_+$ and $u \epsilon E^m_+$ denote input and output vectors, respectively.[1] It is convenient to reserve the term cost-effectiveness analysis for the situation in which the cost-benefit relationships of more than one technology are involved and one technology is selected as the basis from which cost savings or additional benefits of an alternative technology are derived. In our reports, the alternative technologies of Space Transportation Systems are broadly classified into the Current Expendable System, the New Expendable System, and the New Reusable Space Shuttle System.

The cost-effectiveness analysis has been pursued in two alternative approaches, referred to as the equal-capability approach and the equal-budget approach, respectively (see Section 3.1). These two approaches correspond precisely to the two alternative cost-benefit relationships based on what Shephard called the return-afforded-input correspondence and the cost-limited-output correspondence.[2] His discussions of the analogous global cost-benefit (preference) relationships rely on the concepts of the social-preference-afforded-input correspondence and the social-preference function. They are particularly difficult to apply in practice, despite their considerable theoretical implications.[3] In fact, the equal-capability approach of our cost-benefit analysis involves merely a comparison of the cost-benefit relationships obtained for alternative Space Transportation Systems based on the return-afforded-input correspondences. Similarly, the equal-budget approach of our cost-effectiveness analysis involves merely a comparison of the cost-benefit relationships obtained for alternative Space Transportation Systems based on the cost-limited-output correspondences. More specifically, the equal-capability approach attempts to compare the minimum costs of alternative Transportation Systems for attaining any given level of revenue (which is represented by the capability or the number of space flights in our report). Similarly, the equal-budget approach attempts to compare the maximum benefit of alternative Space Transportation Systems obtainable from any given amount of cost (which is the budget for space transportation).

In what follows, we discuss how these principles were implemented in our report. It must be noted that the elegance of the theoretical framework suggested by Shephard lies largely in its flexibility to deal with the joint production of multiple outputs $u \in E^m_+$ and the externality of production $r \in R^m$, where u and r are the output vector and the associated price vector, respectively, for outputs. Note the fact that negative prices are allowed for non-desirable outputs. These aspects received very little discussion in our report. The discussion of scaling laws under the assumptions of homothetic or semi-homogeneous output and input structure is of considerable interest.[4] It has, perhaps, some important implications for practical applications of benefit-cost analysis.

Although Shephard's discussion was limited in static framework, his discussion of scaling laws offers significant insight into the problems related to the social rate of discount and the changing levels of input prices as well as output prices. Since the degree of scarcity of capital may vary for different time periods, it may not be unreasonable to apply varying social rates of discount for different time periods. In fact, one can treat the issue of the social rate of discount as a special case of changing levels of input prices where the relevant input is the service provided by the capital. Furthermore, since the levels of input prices and output prices may change at different rates, it may be argued that it is more appropriate to apply different price deflators for the evaluation of cost and benefit, respectively. Perhaps the issue of whether different price deflators should be applied to evaluating cost and benefit, respectively, does not have a significant consequence in our cost-effective analysis, since in this analysis the evaluation of benefit plays a relatively minor role compared with the evaluation of cost. In fact, the issue is somewhat relevant only in the equal-budget approach, and is not relevant at all in the equal-capability approach.

The Equal Capability Approach of Cost-Effectiveness Analysis

As pointed out in Section 3.1, the equal-capability approach involves a comparison of the minimum costs of two alternative Space Transportation Systems. Let us consider how the equal-capability approach has been employed to evaluate the cost effectiveness of the Space Shuttle System as compared with the Current Expendable System.

Following Shephard's notation, for any positive return rate, R, and a price vector $r \in R^m$ for outputs, a return correspondence $(\frac{r}{R}) \longrightarrow S(\frac{r}{R})$ for the Current Expendable System may be defined by

$$(1) \qquad S(\tfrac{r}{R}) = \left\{ x \;\middle|\; R(x, r) \geq R,\; x \in R_+^n \right\}, \quad r \in R^m,\; R > 0,$$

where

$$(2) \qquad R(x, r) = \underset{u}{\text{Max}} \left\{ r \cdot u \;\middle|\; u \in P(x) \right\}, \quad r \in R^m,\; x \in R_+^n$$

is the maximum return obtainable from an input vector x at prices r for outputs. The minimum cost of obtaining the return rate R at prices $r \epsilon R^m$ for outputs and prices $p \epsilon R^n_+$ for outputs may then be defined by

$$(3) \qquad K(\frac{r}{R}, p) = \underset{x}{\text{Inf}} \left\{ p \cdot x \,\middle|\, x \epsilon S(\frac{r}{R}) \right\}, \quad r \epsilon R^m, \; p \epsilon R^n_+, \; R > 0.$$

Similarly, for the Space Shuttle System, the corresponding relationships of (1) to (3) may be written as

$$(4) \qquad S'(\frac{r}{R}) = \left\{ x \,\middle|\, R'(x, r) \geqq R, \; x \epsilon R^n_+ \right\}, \quad r \epsilon R^m, \; R > 0,$$

where

$$(5) \qquad R'(x, r) = \underset{u}{\text{Max}} \left\{ r \cdot u \,\middle|\, u \epsilon P'(x) \right\}, \quad r \epsilon R^m, \; x \epsilon R^n_+$$

and

$$(6) \qquad K'(\frac{r}{R}, p) = \underset{x}{\text{Inf}} \left\{ p \cdot x \,\middle|\, x \epsilon S'(\frac{r}{R}) \right\}, \quad r \epsilon R^m, \; p \epsilon R^n_+, \; R > 0.$$

The primes in (4) to (6) merely indicate that these equations are defined by alternative correspondences $(\frac{r}{R}) \longrightarrow S'(\frac{r}{R})$ and $x \longrightarrow P'(x)$.

To estimate (3) and (6) directly and then to proceed to compare them is an extremely difficult task to accomplish. It appears that an assumption is in order. That assumption is that prior to the development of the new Space Transportation System, society is <u>willing to spend</u> annually, say, \$3 billion to place forty-six payloads into orbit, and that the projected joint space budget for NASA and the Department of Defense is being spent in an efficient way.[5] As a consequence of this assumption, we are, in reality, assuming (3) to be

$$(7) \qquad K(\frac{r}{R}, p) = p \cdot x = r \cdot u = (\frac{K}{u})u = R$$

where u is the output (capability) in terms of the number of space flights, and $r = (\frac{K}{u})$ is the average cost. The assumption leading to (7) is both drastic and crucial. In effect, we were forced to measure the benefit R in terms of cost K.

Once the assumption of (7) is adopted, the equal capability approach can be carried out relatively easily by constructing (6) from

(8) $$K'(\frac{r}{R}, p) = K(\frac{r}{R}, p) + p\left\{S'(\frac{r}{R}) - S(\frac{r}{R})\right\}$$

$$= R + p\left\{S'(\frac{r}{R}) - S(\frac{r}{R})\right\}$$

where $p\left\{S'(\frac{r}{R}) - S(\frac{r}{R})\right\}$ represents cost saving and $S'(\frac{r}{R})$ and $S(\frac{r}{R})$ in turn denote the input requirements of the Space Shuttle System and the Current Expendable System, respectively. While the cost-benefit relationship of the Current Expendable System (7) may be an expedience, the derivation of the cost-benefit relationship of the Space Shuttle System (8) is entirely justifiable had $K(\frac{r}{R}, p)$ been correctly estimated.

A diagram may be helpful in illustrating the nature of the equal-capability approach. In Figure 1, the straight lines labeled CE and SH represent the cost-benefit relationships of the Current Expendable System and the Space Shuttle System, respectively. At the capacity level of u_0 represented by a benefit of $R_0 = r_0 \cdot u_0$, we find $K'_0 < K_0$. Therefore, the Space Shuttle System is shown to be cost effective because selecting the Space Shuttle System in place of the Current Expendable System yields a saving of $K_0 - K_0'$. This by itself, however, cannot justify the Space Shuttle System. Suppose the true cost-benefit relationship of the Current Expendable System is the dotted-curved line CE*. The cost-benefit relationship of the Space Shuttle System cannot be justified at the capacity level of u_0 with a benefit of R_0, since even though the same savings $K_0^* - K_0'^* = K_0 - K_0'$ can be realized, the true cost of the Space Shuttle will be greater than the benefit $K_0'^* > K_0 = R_0$. In fact, assuming CE* and SH* are the correct curves, at any level of capacity beyond $\overline{R}^*$, the Space Shuttle System cannot be justified. On the other hand, the minimum capacity level which can justify favoring the Space Shuttle System over the Current Expendable System will be $\underline{R}^*$ (corresponding to the intersection of CE* and SH*).

The Equal-Budget Approach of Cost-Effectiveness Analysis

Turning now to a discussion of the equal-budget approach, we may recall that such an approach involves a comparison of the maximum benefits

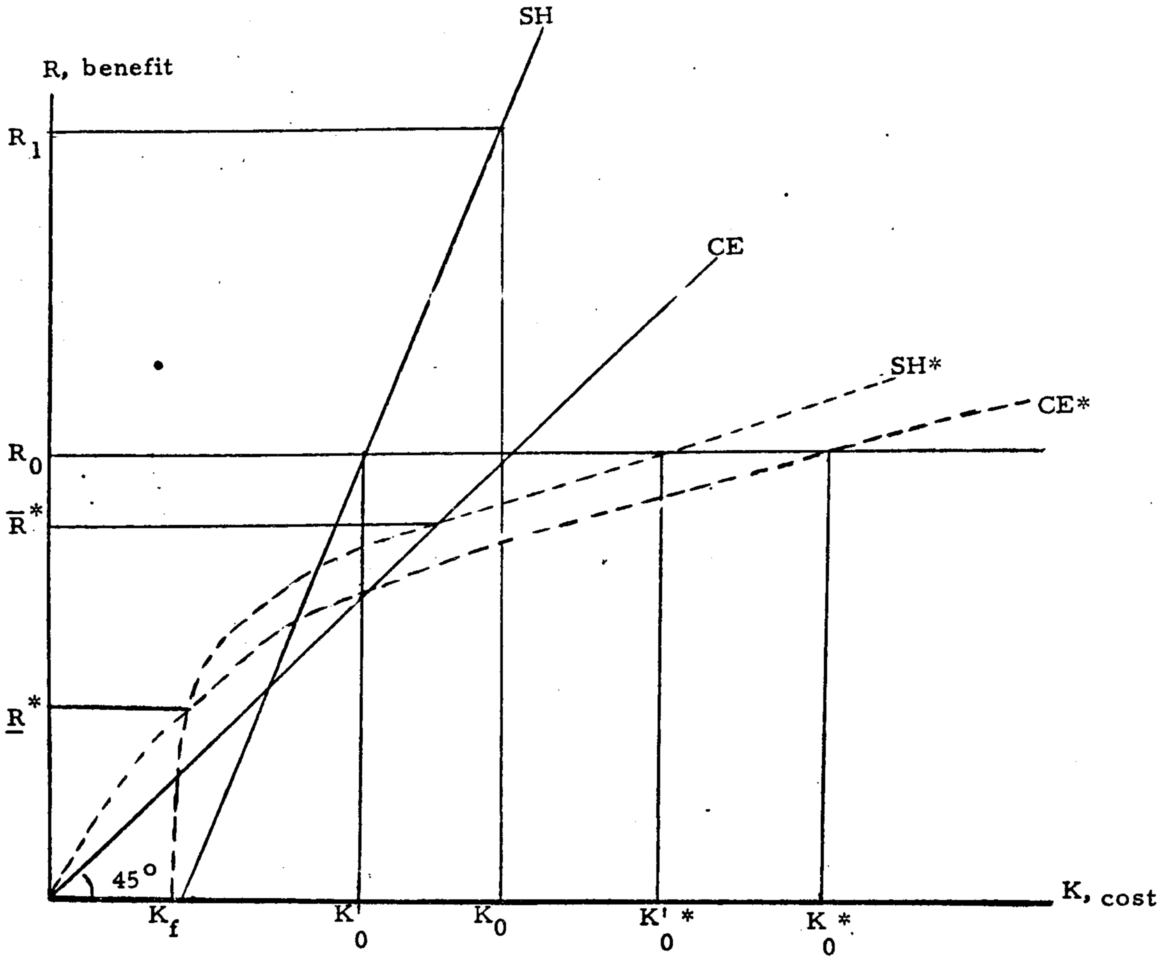

Figure 1: Equal Capability Approach

Notes:

CE: The assumed cost-benefit relationship of the current expendable system, defined by

(a) $R = K$.

SH: The assumed cost-benefit relationship of the space shuttle system, defined by

(b) $R = K' + p\left\{S'\left(\frac{r}{R}\right) - S\left(\frac{r}{R}\right)\right\}$, assuming (a)

(continued)

CE^*: An alternative cost-benefit relationship of the current expendable system, defined by

(c) $R = \alpha K^{\beta}$ with $\alpha > 0, \ \beta > 0$.

SH^*: An alternative cost-benefit relationship of the space shuttle system, defined by

(d) $R = K' + p\left\{S'\left(\frac{r}{R}\right) - S\left(\frac{r}{R}\right)\right\}$, assuming (c).

K_0 and K_0^*: Costs of the current expendable system at the benefit level of R_0, according to (a) and (c) respectively.

K_0' and $K_0'^*$ Cost of the space shuttle system at the benefit level of R_0, according to (b) and (d) respectively.

K_f: Fixed cost of the space shuttle system.

$\underline{R}^*$ and $\overline{R}^*$: The lower and upper limits of the benefit level which justifies the space shuttle system

R_0 and R_1 : The benefit levels of the space shuttle system corresponding to the cost levels of K_0' and K_0 respectively.

of alternative Space Transportation Systems obtainable for any given amount of cost.

Again, following Shephard, for any positive cost rate C, and price vector $p \epsilon R^n_+$ for inputs, a cost correspondence $(\frac{p}{C}) \longrightarrow G(\frac{p}{C})$ for the Current Expendable System may be defined by

(9) $$G(\tfrac{p}{C}) = \left\{ u \,\middle|\, Q(u, p) \leqq C \right\}, \quad C > 0, \quad p \epsilon E^n_+,$$

where

(10) $$Q(u, p) = \underset{x}{\mathrm{Min}} \left\{ p \cdot x \,\middle|\, x \epsilon L\,(u) \right\}, \quad u \epsilon E^m_+, \quad p \epsilon E^n_+$$

is the minimum cost of producing the output vector u at prices p for inputs. The maximum return of output u at prices p for inputs is defined by

(11) $$B(\tfrac{p}{C}, r) = \underset{u}{\mathrm{Sup}} \left\{ r \cdot u \,\middle|\, u \epsilon G\,(\tfrac{p}{C}) \right\}, \quad p \epsilon E^n_+, \quad r \epsilon E^m, \; C > 0.$$

Similarly, for the space shuttle system, the corresponding relationships of (9) to (11) may be written as

(12) $$G'(\tfrac{p}{C}) = \left\{ u \,\middle|\, Q'\,(u, p) \leqq C \right\}, \quad C > 0, \quad p \epsilon E^n_+,$$

where

(13) $$Q'(u, p) = \underset{x}{\mathrm{Min}} \left\{ p \cdot x \,\middle|\, x \epsilon L'(u) \right\}, \quad u \epsilon E^m_+, \quad p \epsilon E^n_+$$

and

(14) $$B'(\tfrac{p}{C}, r) = \underset{u}{\mathrm{Sup}} \left\{ r \cdot u \,\middle|\, u \epsilon G'(\tfrac{p}{C}) \right\}, \quad p \epsilon E^n_+, \quad r \epsilon E^m, \quad C > 0.$$

The primes in (12) to (14) merely indicate that these equations are defined by alternative correspondences $(\frac{p}{C}) \longrightarrow G'(\frac{p}{C})$ and $u \longrightarrow L'(u)$.

Shephard demonstrated that the two alternative cost-benefit relationships $K(\frac{r}{R}, p)$ and $B(\frac{p}{C}, r)$ are in general not the same. This is, of course, also true for $K'(\frac{r}{R}, p)$ and $B'(\frac{p}{C}, r)$. He showed that the relationships

(15) $B\left(\frac{p}{C}, \frac{r}{\beta(r)}\right) = F\left(\frac{C}{\pi(p)}\right)$

and

(16) $K\left(\frac{r}{R}, \frac{p}{\pi(p)}\right) = F^{-1}\left(\frac{R}{\beta(r)}\right)$

where $\pi(p)$ and $\beta(r)$ are homogenous functions of degree one, suitable as price indexes of input (for the cost rate C) and output (for the return rate R), respectively, hold if and only if both the input structure and the output structure are homothetic. In a special case where no price of any input or output varies, $\pi(p)$ and $\beta(r)$ can be any constant. There is no apparent reason, however, why $\pi(p) = \beta(r)$ should hold for any time period, much less for all time periods.

Earlier it was indicated that one possible approach to resolve the problem of the social rate of discount is to consider it as the price of the service of capital, which is really a special kind of input. In this context, the social rate of discount is merely a component of $\pi(p)$. There is perhaps another approach to the same problem which may be worth examining. Suppose (15) and (16) refer to all economic activities of a society. Then it appears reasonable to define the social rate of discount as $\lambda = (dB/dC) - 1 = (dR/dK) - 1$. In an extremely simplified situation where the function F is the identity function (and hence, so is F^{-1}), (15) and (16) become

(15a) $B\left(\frac{p}{C}, \frac{r}{\beta(r)}\right) = F\left(\frac{C}{\pi(p)}\right) = \frac{C}{\pi(p)}$

and

(16a) $K\left(\frac{r}{R}, \frac{p}{\pi(p)}\right) = F^{-1}\left(\frac{R}{\beta(r)}\right) = \frac{R}{\beta(r)}$

then $\lambda = \frac{1}{\pi(p)} - 1 = \beta(r) - 1 \geq 0$, where $\pi(p) \leq 1$ and $\beta(r) \geq 1$ hold. In the real world, $\pi(p)$ is reflected in the gradual decline of the interest rate, and $\beta(r)$ in the gradual increase in the consumer price index. To the extent that $\pi(p)$ and $\beta(r)$ vary at different rates in different time intervals, there appears to be some reason to favor the argument for varying discount rates for different time periods. To the extent that $\pi(p)$ and $\beta(r)$ may differ for the same time period, there also appears to be some reason to favor the argument for different discount rates for the cost stream and benefit stream, respectively. There is more on this in Sections 3.4 and 3.5.

In our reports, including the present one, the problem of the social discount rate and of inflation were treated somewhat differently. Circumvention of the problem of inflation was brought about by using 1970 constant dollars throughout. The problem of a social discount rate was then treated separately by examining the impact of alternative rates ranging from 5% to 15%. In effect, using the concept of net present value it was assumed that (15) and (16) may be written simply as

(15b) $B = C$

and

(16b) $K = R.$

The alternative cost-benefit relationship of the Current Expendable System (11) is then derived by setting $C = K$ and thus $B = R$. That is

(17) $B\left(\frac{p}{C}, r\right) = r \cdot u = p \cdot x = \left(\frac{B}{x}\right) x = C.$

The derivation of the alternative cost-benefit relationship of the Space Shuttle System (14) was based on a more complicated procedure which can be expressed as

(18) $B'\left(\frac{p}{C}, r\right) = R + p\left[S'\left(\frac{r}{R}\right) - S\left(\frac{r}{R}\right)\right] + C\left[\ln\left(R_1/R_0\right)\right] - K_f$

where $p\left[S'\left(\frac{r}{R}\right) - S\left(\frac{r}{R}\right)\right]$ is cost saving (direct benefit), $C\left[\ln(R_1/R_0)\right]$ is the induced benefit (indirect benefit) calculated on the assumption of unitary elasticity of demand, and K_f, is the nonrecurring cost.

Referring to Figure 2, we see that the straight line labeled CE is exactly the same as in Figure 1, but SH was shifted downward and to the right according to formula (18). The shift reflects the difference between total (direct and indirect) cost saving and the nonrecurring cost of the Space Shuttle System, and is measured vertically. The lines CE and SH indicate that at a budget level C_0, there will be $B'_0 - B$ $(=B'^*_0 - B^*_0)$ additional benefit attainable by selecting the Space Shuttle in place of the Current Expendable System. However, such an additional benefit, regardless of how substantial it may be, cannot justify the Space Shuttle by itself. In fact, if the true cost-benefit relationship of the Current Expendable System is not CE, but CE*, then the

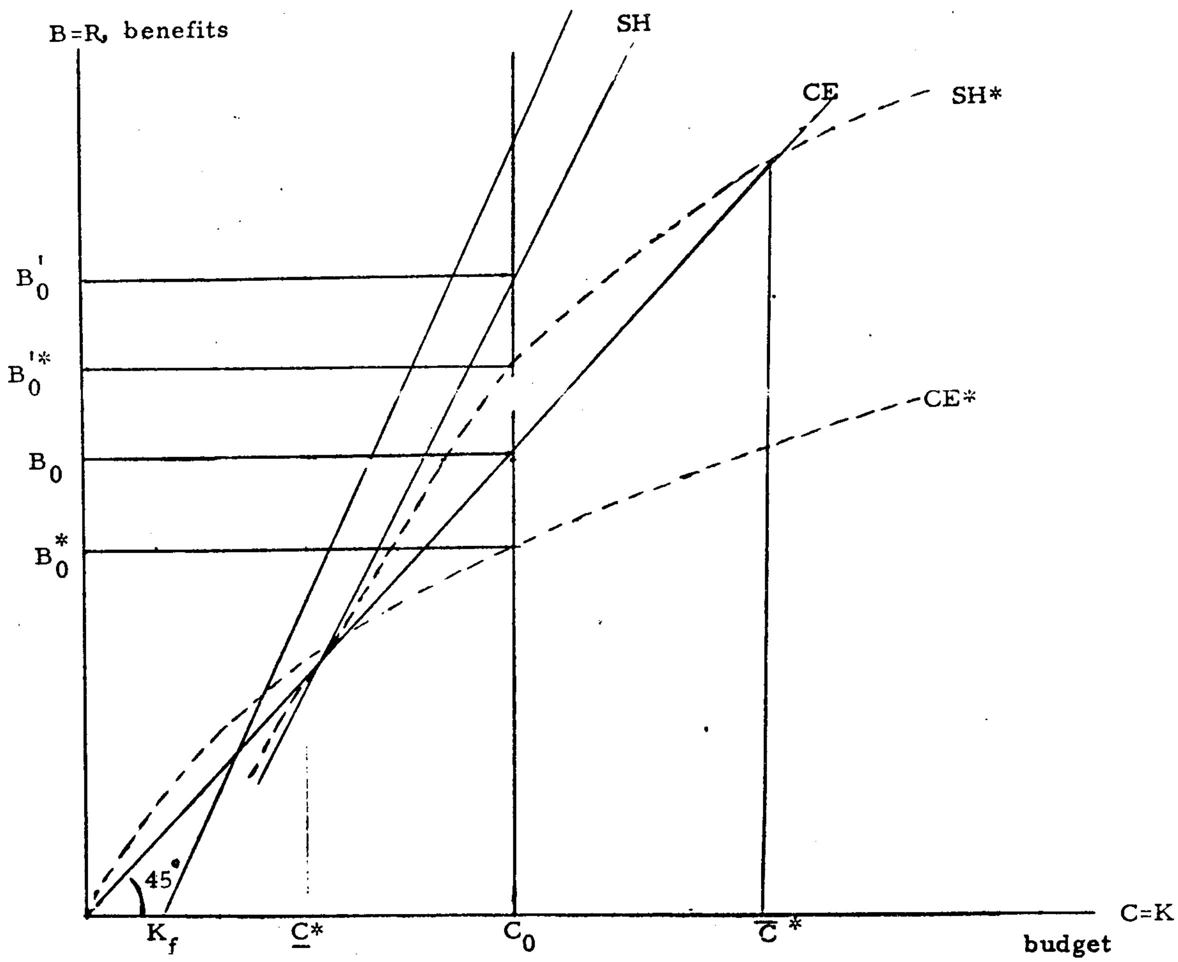

Figure 2: Equal Budget Approach

Notes:

CE: The assumed cost-benefit relationship of the current expendable system, defined by

(a) $B = C$ (or $R = K$).

SH: The assumed cost-benefit relationship of the space shuttle system, constructed according to formula (18) in the text, using (a) for R.

CE*: An alternative cost-benefit relationship of the current expendable system, defined by

(c) $B = \alpha C^{\beta}$ (or $R = \alpha K^{\beta}$), $\alpha \quad 0$, $\beta > 0$.

(continued)

SH^*_1: An alternative cost-benefit relationship of the space shuttle system, constructed according to formula (18) in the text, using (c) for R.

$\underline{C}^*$ and $\overline{C}^*$: The lower and upper limits of the budget level which justifies the space shuttle system over the current expendable system according to the alternative cost-benefit relationships CE* and SH*.

C_0: A given level of space budget.

B_0 and B_0^*: The benefits of the current expendable system attainable by the given budget C_0.

B_0' and $B_0'^*$: The benefits of the space shuttle system attainable by the given budget C_0.

Space Shuttle System is not justifiable at any budget beyond $\overline{C}^*$, despite the possibility of achieving even greater additional benefits over the Current Expendable System. The minimum budget which may justify favoring the Space Shuttle System over the Current Expendable System is $\underline{C}^*$ (break-even point).

Before concluding this section, it is perhaps worth mentioning that the cost-benefit relationship of the return-afforded-input correspondence and the equal-capability approach treats output prices r and benefit level R as exogenous and deals only with the partial equilibrium of the input market. How the output prices r and benefit level R are determined is left unanswered. It is obviously clear that the same output prices r cannot be applied for a wide range of output levels u. Similarly, the alternative cost-benefit relationship of the cost-limited-output-correspondence and the equal-budget approach regards input prices p and cost level C as exogenous and deals only with the partial equilibrium of the output market. How the input prices p and the cost level C are determined remains an open question. Obviously, the same input price p cannot be applied for a wide range of input levels x. It is therefore desirable to integrate these two analyses.

REFERENCES IN APPENDIX 3A

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[2] Ronald W. Shephard, "An Economic Theoretic Logic for Cost-Benefit (Effectiveness) Analysis", University of California, Berkeley, July 1971.

[3] ______________, "Semi-Homogeneous Technologies", (ORC 71-14), University of California, Berkeley.

[4] ______________, Cost-Benefit (Effectiveness) Analysis, University of California, Berkeley, August 1971.

[5] ______________, Theory of Cost and Production Functions, Princeton University Press, Princeton, New Jersey, 1970.

FOOTNOTES IN APPENDIX 3A

1. The subscript "+" is used to denote the non-negative domain of the Euclidean space to which it is attached.

2. See Sections 6 and 3 of [2] respectively.

3. See Sections 7, 4 and 5 of [2] .

4. See [5, sec. 9.3] for definition of homothetic output and input structure, and [3] for definition of semi-homogeneous output and input structure.

5. The consequences of this assumption do not depend on the actual dollar amount and number of payloads.

Appendix 3B: More on the Proper Rate of Discount for Government Projects

This Appendix is intended to be read in conjunction with other papers prepared by us on the same subject. It was our intention that they be coordinated, but it was not possible to do this within the time constraints.

The work by Feldstein to which Baumol refers in a separate working paper is the most recent in a sequence of papers, notably by Arrow, Marglin and Eckstein, which have considerably advanced our understanding of the special nature of discounting in public investment choices. The argument may be broadly sketched as follows: the government's objective is to obtain the "best" flow of consumption benefits possible with the instruments available to it. Under quite general assumptions, we can translate "best" into familiar financial arithmetic: one stream of benefits is better than another if it has a higher present value when discounted at the social rate of time preference. It is assumed that we can associate with an increment to capital stock in any sector (however broadly or narrowly defined) a definite stream of consumption benefits which will be induced by that increment, and we can calculate the present value of that stream using the social rate of time preference. Feldstein explicitly labels the values of unit increases in the various capital stocks "shadow prices." If we use current benefits (consumption) as a numeraire, the cost of funds to the public sector is, then the sum of current consumption reduction <u>plus</u> the present value of future consumption reduction, i.e., the sum of current consumption decrement and decrements in capital stocks multiplied by their associated shadow prices. The value of the public investment is simply the discounted value of the stream benefits, using the social rate of time preference as discount rate. Baumol expressed this principal in a form which nets out benefit losses due to withdrawal of resources from the private sectors and benefit gains from the project in each period. This net benefit stream is then discounted at the social rate of time preference.

There is one point in this procedure which is deceptively simple, and that is the step requiring us to associate with an action (be it changing a private capital stock or adding a government project) the <u>entire</u> stream of benefits. To make the points he wished to establish, Baumol assumed this information was available. But, it must be emphasized that the benefits in question may be distributed through time in complicated ways. Many investment projects, public or private, provide the wherewithal in the future for <u>further</u> investments. Those investments, in turn, provide consumption benefits and induce further investments, etc. Strictly speaking, <u>all</u> of the extra consumption, produced directly by the initial investment and indirectly via induced investment, constitutes the stream of benefits associated with the initial act. This is the so-called "throw-off" problem, and it is to this problem that we turn next.

A Simple Model of Evaluating Investment

These issues should be clarified by a close analysis of the following simple model. Let us assume that the objective of the government is simply to obtain the best time stream of consumption:

$$. . c_t, c_{t+1}, . .$$

Assume that investment in private sector capital has a marginal one-period rate of return r_t in period t. That is, \$1 invested in period t increases the total number of dollars available in period t + 1 by $\$(1 + r_t)$. Generally, r_t will be a decreasing function of the amount invested at time t.

The evaluation of time streams of consumption by the government leads quite naturally to a calculated rate of time preference, i_t, in period t. To find this we ask the question by how much must consumption be increased in period t + 1 to compensate for a \$1 reduction in period t consumption. The former amount is defined to be $1 + i_t$. The more valuable, relatively, is the earlier consumption, the higher is the social rate of time preference. Strictly speaking, the value of i_t at any point may depend upon the whole stream of consumption involved.

An increase in the private capital stock at any time* may have an impact on the entire future consumption stream, in the manner already outlined. Let s_t be the fraction of an increment in resources available to the private sector ("income") in period t which is allocated to investment. In conventional language, s_t is the marginal propensity to save in period t.

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* Since we are dealing with entirely with one-period investments, we need not here distinguish capital stock and investment. Each period the whole capital stock is up for grabs and may be consumed or invested.

Evaluating the Throw-Off

We are now in a position to calculate the stream of consumption increments following from a \$1 increase in investment at time t. To save on notation let us suppose that the investment change takes place at time 0. Then in period 1, income is larger than it would otherwise have been by an amount $(1 + r_0)$. This leads to an increment $(1 - s_1)(1 + r_0)$ in consumption in period 1, and an increase $s_1(1 + r_0)$ in period 1 investment. The period 2 income increase is thus $s_1(1 + r_0)(1 + r_1)$, of which $(1 - s_2) s_1 (1 + r_0)(1 + r_1)$ is consumed and $s_2 s_1 (1 + r_0)(1 + r_1)$ invested. In general, the increase Δy_τ in period t income resulting directly and indirectly from the \$1 investment increase at time 0 is given by

(1)
$$\Delta y_1 = 1 + r_0$$
$$\Delta y_\tau = (1 + r_0) \prod_{j=1}^{\tau-1} s_j (1 + r_j), \ \tau \geqq 2,$$

where the notation $\prod_{j=m}^{n} x_j$ represents the product of $x_m, x_{m+1}, \ldots, x_n$

The consumption increase Δc_τ generated in period τ by the \$1 time 0 investment increase is then simply $(1 - s_\tau) \Delta y_\tau$. To evaluate the throw-off at each date, taking period 0 consumption as numeraire, we need only multiply the consumption change at that date by the <u>discount factor</u> δ_τ derived from the social time preference rates in the familiar manner:

(2)
$$\delta_\tau = \prod_{j=}^{r-1} \frac{1}{(1 + i_j)}, \ \tau \geqq 1;$$
$$\delta_0 = 1$$

So, for example, a \$1 increase in period 1 consumption is worth $\delta_1 = \frac{1}{1 + i_0}$ dollars in period 0 consumption. Since $\Delta c_\tau = (1 - s_\tau) \Delta y_\tau$, the present value of the increment is

(3)
$$PV(\Delta c_\tau) = PV\left((1 - s_\tau) \Delta y_\tau\right)$$
$$= PV\left((1 - s_\tau)(1 + r_0) \prod_{k=1}^{\tau-1} s_k (1 + r_k)\right), \ \tau \geqq 2$$

$$= \frac{(1 - s_\tau)(1 + r_0)}{1 + i_0} \prod_{k=1}^{\tau - 1} s_k \frac{(1 + r_k)}{1 + i_k}$$

$$PV(\Delta c_1) = \frac{(1 - s_1)(1 + r_0)}{1 + i_0}$$

We are now in a position to write down the present value of the whole stream of consumption increments generated by a \$1 increase in period 0 investment. Let us call this quantity v_0. Then

$$v_0 = \sum_{\tau = 1}^{\infty} PV(\Delta c_\tau) \tag{4}$$

$$v_0 = (1 - s_1)\frac{(1 + r_0)}{1 + i_0} + \sum_{\tau = 2}^{\infty} (1 - s_\tau)\frac{(1 + r_0)}{(1 + i_0)} \prod_{k=1}^{\tau - 1} s_k \frac{(1 + r_k)}{1 + i_k}$$

The reader will not need to be told that to calculate v_0 in practice is likely to be a formidable task if the problem is treated in full generality. A number of reasonable simplifications will, however, bring the job within the realm of the possible.

The Case of Equal Time Preference and Rate of Return

Before we turn to this however, it should be useful to point out how things simplify when the marginal rate of return equals the social rate of time preference in every time period. As the reader will quickly verify, in this case we have

$$v_0 = (1 - s_1) + \sum_{\tau = 2}^{\infty} (1 - s_\tau) \prod_{k=1}^{\tau - 1} s_k \tag{5}$$

Writing out the first few terms,

$$v_0 = (1 - s_1) + (1 - s_2)\, s_1 + (1 - s_3)\, s_1 s_2 + (1 - s_4)\, s_1 s_2 s_3 + \cdots$$
$$= 1 - s_1 + s_1 - s_1 s_2 + s_1 s_2 - s_1 s_2 s_3 + s_1 s_2 s_2 - s_1 s_2 s_3 s_4 + \cdots$$

The n^{th} partial sum of this series is thus given by

$$1 - s_1 s_2 s_3 \ldots s_n$$

We are interested in the limit of this sequence of partial sums, which is clearly exactly 1, provided all but a finite number of the s's are strictly less than 1.

In this special case, then, the shadow price of a unit of investment at time zero is exactly 1, and this is, of course, exactly as it should be. For when the rate of time preference exactly equals the marginal rate of return in every period we should be indifferent between an extra dollar of consumption and an extra dollar of investment in every period, including period zero. Our calculations tell us that giving up $1 of consumption at time zero would generate a stream of future consumption increments just equal in value to that which is given up.

The Case of Investment Coefficient, Rate of Time Preference and Rate of Return All Constant

In order to reduce the problem to manageable dimensions, assume $s_t = s$, $i_t = i$, $r_t = r$, where s, i, and r are constants. Then we have

(6) $$v_0 = (1-s)\,\frac{(1+r)}{(1+i)} + \sum_{\tau=2}^{\infty} \frac{(1-s)(1+r)}{1+i}\left(\frac{s(1+r)}{1+i}\right)^{\tau-1}.$$

Defining ν,

(7) $$\frac{1+r}{1+i} = \gamma\ ,$$ (6) can be rewritten as

$$v_0 = (1-s)\gamma \sum_{\tau=1}^{\infty} (s\gamma)^{\tau-1}\ , \text{ or}$$

(8) $$v_0 = \frac{(1-s)\gamma}{1-s\gamma}\ , \quad \text{assuming } s\gamma < 1.$$

Since in most cases of interest, $r > i$, and hence $\gamma > 1$, we find $\gamma > 1$; an extra dollar invested at time zero generates a stream of consumption changes worth more than one dollar. Note, further, that generally $v_0 > \gamma = 1 + r/1 + i$. For the special case $i = r$, we conclude $v_0 = 1$ directly from expression (8).

We can, if we wish, come at the same problem from another angle. Let v_t be the value of an increment to investment at time t, expressed in time t consumption units. Now an increment of investment at time t generates extra consumption at t + 1 equal to $(1 + r_t)(1 - s_{t+1})$, and extra investment equal to $(1 + r_t)\,s_{t+1}$. The latter is equivalent to

$(1 + r_t)\, s_{t+1}\, v_{t+1}$, units of period t + 1 consumption, by definition of v_t. Finally, since c_{t+1} units of t +1 consumption is equivalent in social value to $c_{t+1}/(1 + i_t)$ units of time t consumption, by definition of i_t, we conclude that $1 extra invested at time t has a value

$$(9) \qquad v_t = \frac{(1 + r_t)\,(1 - s_{t+1}) + (1 + r_t)\, s_{t+1}\, v_{t+1}}{1 + i_t}$$

$$= (1 - s_{t+1} + s_{t+1}\, v_{t+1})\, \gamma_t,$$

where γ_t is defined to be $(1 + r_t)/(1 + i_t)$. If we assume $\gamma_t = \gamma$ and $s_t = s$, constants, we must have $v_t = v$, a constant. This is found by solving

$$(10) \qquad v = (1 - s + sv)\, \gamma ,$$

to yield

$$(11) \qquad v = \left(\frac{1 - s}{1 - \gamma s}\right) \gamma .$$

Illustrative Numerical Value of the Shadow Price of Capital

The simple formulation which results from assuming the various coefficients constant makes it easy to get more feel for the magnitudes which might be involved in application. A sensible number for the before tax marginal rate of return in the corporate sector is 10%, or $r = .10$; a not wild level for the social rate of time preference might be 5%, $i = .05$. Assuming all investment to be in the corporate sector, a very large value of s would be .2. In this case $v = 1.06$, a dollar of private capital is worth about $1.06.

A Complete but Simple Model of Government Investment Choice

The discussion so far has been devoted to establishing (a) that in making public investment choice it is in principle necessary to take into account both the direct and indirect effects on the consumption stream caused by changes in current capital stocks, public or private, and (b) that under simplifying assumptions it is possible to make a reasonable approximation to the correct shadow price of a unit of private capital. The model thus far used is simple in a number of respects, but we shall in this section be concerned with just one, namely the absence of a government making investment choices. Let us add, then, a government investment opportunity with rate of return ρ_t, i.e., \$1 invested in period t in the government sector makes available an increase of $(1 + \rho_t)$ dollars in period $t + 1$.

We now have three uses for income in any period: consumption, private investment and government investment. The question now is under what conditions should the incremental government investment be undertaken. To answer that question we need to consider another throw-off calculation. If we assume, however, that the private investment throw-off calculation has been taken care of, so that we are equipped with a series of shadow prices, v_t, telling us the value in period t consumption units of a \$1 increase in period t private investment, we need consider only a one-period throw-off for the government.

Specifically, let a_t be the fraction of a sum raised by the government in period t which comes out of private capital formation. For some forms of finance we would expect to find $a_t = s_t$, the marginal propensity to save out of disposable income, although clearly we shall wish to associate different a_t's with different techniques of financing government investment. Denote by α_t the amount by which private capital in period t is increased as a consequence of an increase of \$1 in the output of the government sector. For the case in which revenue is raised by direct taxation of consumer citizens and in which the implicit income from the government project is treated exactly like ordinary, after-tax income, $a_t = \alpha_t = s_t$. However, we must admit the possibility that these parameters differ.

It is now a simple matter to tote up the various effects of raising an additional dollar in period t to finance government investment. Table 1 shows the impact on consumption and capital formation in periods t and $t + 1$.

	PERIOD	
	t	t + 1
change in consumption	$-(1 - a_t)$	$(1 + \rho_t)(1 - \alpha_{t+1})$
change in private capital formation	$-a_t$	$(1 + \rho_t)\alpha_{t+1}$

Table 1 : The Effect of Undertaking an Additional \$1 of Government Investment at Time t

We know that the value in period t consumption units of \$1 of private investment is v_t. Hence the effective loss in period t consumption as a result of the government investment is $1 - a_t + a_t v_t$ dollars. Similarly, the value of the increase in consumption and private investment in period t + 1, expressed in period t + 1 consumption units, is $(1 + \rho_t)(1 - \alpha_{t+1} + \alpha_{t+1} v_{t+1})$. To compare these two sums, we must introduce the social rate of time preference, i_t. Discounting the effective t + 1 consumption increase to period t, we obtain an expression for the net gain from the whole transaction:

$$(12) \qquad -(1 - a_t + a_t v_t) + \left(\frac{1 + \rho_t}{1 + i_t}\right)(1 - \alpha_{t+1} + \alpha_{t+1} v_{t+1}).$$

By definition of i_t, we shall attain a more valued consumption stream if we undertake government investment so long as expression (12) is positive, a condition expressed by inequality (13).

$$(13) \qquad \frac{1 + \rho_t}{1 + i_t} \geq \frac{1 + a_t(v_t - 1)}{1 + \alpha_{t+1}(v_{t+1} - 1)} ,$$

which determines by how much, if at all, the rate of return, ρ, on the government investment must exceed the social time preference rate, i, in order to make the investment worthwhile.

Some Important Special Cases

It is useful to consider the implications of condition (13) as a government investment criterion in special cases corresponding to various assumptions about the coefficients a_t, α_t and v_t:

A1. $v_t = v_{t+1} = v$. This assumption says, in effect, that the degree of capital market imperfection is not changing over the period considered.

A2. $a_t = 0$. This amounts to assuming that all of the resources invested in the government project come out of current consumption.

A3. $a_t = 1$. All the resources for the project come out of current private investment.

A4. $\alpha_{t+1} = 0$. All of the output from the project is consumed.

A5. $\alpha_{t+1} = 1$. All of the output from the project goes to increase the private capital stock.

A6. $a_t = \alpha_{t+1}$. An additional dollar's worth of output from a government project causes the same increment in private capital formation as does a reduction of $1 in the amount raised through the financing instrument corresponding to which a_t is defined.

The effect of a rising or falling shadow price of private capital works in the same direction under all meaningful assumptions about the other coefficients. A glance at condition (13) will show that increasing v_{t+1}, holding v_t constant, tends to raise the denominator on the right hand side and hence to reduce the critical rate at which ρ_t becomes an acceptable rate of return on the government project. The effect of decreasing v_{t+1}, holding v_t constant, is in the opposite direction. We shall interpret this result below. For the moment we simply note that to consider the consequences of varying the other parameters it is sufficient to look at the cases for which A1 holds, i.e. $v_t = v$, a constant.

There are three extreme cases of special interest.

Case 1. $a_t = \alpha_{t+1}$. This case (which includes $a_t = \alpha_{t+1} = 0$ and $a_t = \alpha_{t+1} = 1$) is a rather remarkable one. Substituting into condition (13) we see that the acceptance condition for the public investment becomes

$$\frac{1 + \rho_t}{1 + i_t} \geq \frac{1 + a_t (v - 1)}{1 + a_t (v - 1)} = 1$$

This says that <u>government investments should be accepted as long as the marginal rate of return exceeds the time preference rate</u>. The surprising aspect of this case is that the rate of return in the private sector, sometimes called <u>the</u> opportunity cost of funds, does not enter the calculation at all. The reason is not far to seek. By our assumption that $\alpha_{t+1} = a_t$, we have assured that for every dollar of reduced investment in period t, the government project puts back $(1 + \rho_t)$ dollars of increased investment in period t + 1. The issue then is, how much must we increase investment in period t + 1 to compensate for a loss of one unit in period t. Since $v_t = v_{t+1}$, the answer is, clearly, at least $(1 + i_t)$ dollars.

This case has not received much attention before, which is somewhat puzzling, since the assumptions involved seem, upon reflection, to be rather plausible. However, the assumptions of Case 2 are much more frequently encountered.

<u>Case 2</u>. $a_t = 1$, $\alpha_{t+1} = 0$. Under these assumptions <u>all</u> of the resources for the project come from investment and the output induces no increase in private investment. Condition (13) becomes

$$\frac{1 + \rho_t}{1 + i_t} \geq v_t.$$

This case is usually interpreted to require a rate of return on the government project at least equal to the rate of return in the private sector. Note, however, that this is actually not strong enough in general. Under the conditions in which v_t, i_t and s_t (which we have called the marginal propensity to save) are all constant, we concluded that $v_t > \gamma = \frac{1 + r}{1 + i}$, indicating that the government project must have a return rate in excess of r to pass muster under the assumptions of Case 2. The reason for this is simply that the government project does not generate the favorable repercussions on future capital formation which the private investment does.

<u>Case 3</u>. $a_t = 0$, $\alpha_{t+1} = 1$. In this case all resources for the

project come from consumption and all yield is converted into private capital. Condition (13) becomes

$$\frac{1 + \alpha_t}{1 + i_t} \geq \frac{1}{v_t}$$

For obvious reasons this case would allow as desirable projects for which rate of return is actually below the time preference rate, and a fortiori below the rate of return in the private sector.

Summing Up the Analysis of the Simple Complete Model

The essential conclusions to be drawn from the simple model are obtained from an examination of condition (13) for accepting a government investment project with rate of return ρ_t. Assuming that all the parameters of (13) are constant through time, we can write it as

$$(14) \qquad \frac{1 + \rho_t}{1 + i} \geq \frac{1 + a\,(v - 1)}{1 + \alpha\,(v - 1)} \,.$$

From (14) we conclude that the required yield on the government project should exceed the rate of time preference if the dollar reduction in current private investment per dollar withdrawn to finance the government project exceeds the dollar increase in private investment per dollar of value of the project's output ($a > \alpha$). (We assume $v > 1$). The required yield on the government project falls below the time preference rate if the inequality is reversed. The extent of the divergence in each case depends upon v; the larger is v, the larger the divergence.

As we have pointed out, a tendency for v to grow with time favors government investment, ceteris paribus. The reason for this is that the government investment serves in part to shift private investment toward the future. The more rapidly v is rising, the less future private investment do we need to offset the loss of any given amount of current investment. By the same line of reasoning, a tendency for v to fall with time raises the minimum acceptable rate of return on government projects.

Generalizing to Many Private Investment Sectors

There are a number of ways in which the foregoing analysis can be generalized, and it would probably be of little use at this point to produce a catalogue of possibilities. However, in view of the previous treatment of this topic, by Baumol and others, we should consider explicitly the possibility of more than one private sector.

It is customary by now to think of private investment as being of two types, corporate and non-corporate, where decisions in the former sector are influenced by the corporation income tax. Hence, we start by considering a two-private-sector model.

Let a^1_t, then, represent the fraction of an incremental dollar raised to finance government activities which comes out of non-corporate capital formation. Let a^2_t be the corresponding value for corporate capital. Define α^1_t and α^2_t in the analogous manner, indicating the amounts of capital formation in sectors 1 and 2 induced by a \$1 increase in government output in period t. Let v^1_t and v^2_t be the appropriate shadow price of capital in the two sectors, given their respective rates of return, r^1_t and r^2_t. Table 2 shows the effect of undertaking an additional \$1 of government investment at time t in this model world.

	PERIOD	
	t	t + 1
Change in Consumption	$-(1 - a^1_t - a^2_t)$	$(1+\rho_t)(1 - \alpha^1_{t+1} - \alpha^2_{t+1})$
Change in Non-Corporate Capital Formation	$-a^1_t$	$(1+\rho_t)\,\alpha^1_{t+1}$
Change in Corporate Capital Formation	$-a^2_t$	$(1+\rho_t)\,\alpha^2_{t+1}$

Table 2 : The Effect of an Additional \$1 of Government Investment When There Are Two Private Investment Sectors

Expressed in period t consumption units, the resources taken out of the private sector in period t are valued at $(1 - a^1_t - a^2_t) + a^1_t v^1_t + a^2_t v^2_t$, while the value yield from the government project, expressed in period t + 1 consumption units, is

$$(1 + \rho_t) \left[(1 - \alpha^1_{t+1} - \alpha^2_{t+1}) + \alpha^1_{t+1} v^1_{t+1} + \alpha^2_{t+1} v^2_{t+1}\right].$$

This can be discounted to period t by social rate of time preference, so that we have all of the consequences of the decision expressed in period t consumption units. The criterion for acceptance of the government investment is, then

$$-(1 - a^1_t - a^2_t + a^1_t v^1_t + a^2_t v^2_t) + \frac{1 + \rho_t}{1 + i_t} \left[1 - \alpha^1_{t+1} - \alpha^2_{t+1} + \alpha^1_{t+1} v^1_{t+1} + \alpha^2_{t+1} v^2_{t+1}\right] \geqq 0. \tag{15}$$

A little algebraic manipulation allows us to express this condition in the equivalent form,

$$\frac{1 + \rho_t}{1 + i_t} \geqq \frac{1 + a^1_t (v^1_t - 1) + a^2_t (v^2_t - 1)}{1 + \alpha^1_{t+1} (v_{t+1} - 1) + \alpha^2_{t+1} (v^2_{t+1} - 1)} \tag{16}$$

The interpretation of condition (16) runs along the same lines as our previous interpretation of condition (14), and presents no special difficulties. Of particular interest is the case $a^1_t = \alpha^1_{t+1}$, $a^2_t = \alpha^2_{t+1}$, in which dollars taken out of the private sector by the financing methods and implicit dollars put into the private sector in the form of yield on the government investment, are divided among consumption and investment in the two sectors in the same proportions. In this case condition (16) becomes simply

$$\frac{1 + \rho_t}{1 + i_t} \geqq 1;$$

the government project's yield rate need be only as high as the social rate of time preference.

Calculating the Two Shadow Prices

If we assume constant propensities to save/invest, constant rates of return and constant social rate of time preference, we can calculate the values of the two shadow prices, v^1 and v^2 without particular difficulty. By a line of reasoning exactly analogous to that leading to equations (9) to (11), we conclude that v^1 and v^2 must satisfy simultaneous equations (17):

$$(17) \qquad v^1 = \frac{1 + r^1}{1 + i} \left[1 + s^1 (v^1 - 1) + s^2 (v^2 - 1)\right]$$

$$v^2 = \frac{1 + r^2}{1 + i} \left[1 + s^1 (v^1 - 1) + s^2 (v^2 - 1)\right].$$

Define γ^1 and γ^2, analogous to γ in the one-sector analysis, and the new variables x^1 and x^2:

$$(18) \qquad \gamma^1 = \frac{1 + r^1}{1 + i}, \quad \gamma^2 = \frac{1 + r^2}{1 + i}, \quad x^1 = v^1 - 1, \; x^2 = v^2 - 1.$$

Then (17) implies

$$x^1 = \gamma^1 \left[1 + s^1 x^1 + s^2 x^2\right] - 1$$

$$x^2 = \gamma^2 \left[1 + s^1 x^1 + s^2 x^2\right] - 1$$

or

$$(19) \qquad \begin{bmatrix} 1 - \gamma^1 s^1 & - \gamma^1 s^2 \\ - \gamma^2 s^1 & 1 - \gamma^2 s^2 \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \end{bmatrix} = \begin{bmatrix} \gamma^1 - 1 \\ \gamma^2 - 1 \end{bmatrix}.$$

Denoting the matrix of coefficients in (19) by A, we have

$$(20) \qquad \det (A) = (1 - \gamma^1 s^1)(1 - \gamma^2 s^2) - \gamma^1 \gamma^2 s^1 s^2$$

$$= 1 - \gamma^1 s^1 - \gamma^2 s^2.$$

Assuming (20) is not zero,

(21) $$A^{-1} = \frac{1}{1-\gamma^1 s^1 - \gamma^2 s^2}\begin{bmatrix} 1-\gamma^2 s^2 & \gamma^1 s^2 \\ \gamma^2 s^1 & 1-\gamma^1 s^1 \end{bmatrix}$$

and

(22) $$\begin{bmatrix} x^1 \\ x^2 \end{bmatrix} = A^{-1}\begin{bmatrix} \gamma^1 - 1 \\ \gamma^2 - 1 \end{bmatrix}$$

$$= \begin{bmatrix} -\dfrac{(1-\gamma^1 - s^2\gamma^2 + s^2\gamma^1)}{1-\gamma^1 s^1 - \gamma^2 s^2} \\ \\ -\dfrac{(1-\gamma^2 - s^1\gamma^1 + s^1\gamma^2)}{s-\gamma^1 s^1 - \gamma^2 s^2} \end{bmatrix}.$$

After a little algebraic manipulation, we can write

(23) $$\begin{bmatrix} v^1 \\ v^2 \end{bmatrix} = \left(\frac{1-s^1-s^2}{1-\gamma^1 s^1 \gamma^2 s^2}\right)\begin{bmatrix} \gamma^1 \\ \gamma^2 \end{bmatrix}.$$

Under the assumption sometimes made that the social rate of time preference is equal to the rate of time preference common to all individuals in a competitive capital market, and that this is in turn equal to the rate of return in the non-corporate sector, $r^1_t = i_t$, i. e. $\gamma^1 = 1$. Notice that, because some of the throw-off from each sector is invested in the other, even in this case generally $v^1 > 1$.

Increasing the number of private investment sectors beyond 2 is evidently a simple matter formally. The government investment test changes from (16) to

(24) $$\frac{1+\rho_t}{1+i_t} \geq \frac{1 + \sum_{j=1}^{m} a^j_t (v^j_t - 1)}{1 + \sum_{j=1}^{m} \alpha^j_{t+1} (v^j_{t+1} - 1)},$$

where m is the number of sectors. For the case in which the various coefficients, and thus the shadow prices, are constant over time we can calculate them in the manner of expression (23) from

$$(25) \qquad \begin{bmatrix} v^1 \\ v^2 \\ \cdot \\ \cdot \\ \cdot \\ v^m \end{bmatrix} = \left(\frac{1 - \sum_{j=1}^{m} s^j}{1 - \sum_{j=1}^{m} \gamma^j s^j} \right) \begin{bmatrix} \gamma^1 \\ \gamma^2 \\ \cdot \\ \cdot \\ \cdot \\ \gamma^m \end{bmatrix}$$

where $\quad \gamma^j = (1 + r^j)/(1 + i)$

Treatment of Multiperiod Returns

Thus far, the analysis has been carried on as though the government were always in a position of choosing an investment requiring inputs of \$1 in period t and producing its entire output \$1 $(1 + \rho_t)$ in period t +1. This permitted us to express the investment criterion in terms of the relationship between a well-defined rate of return (essentially, the one-period internal rate of return) and corresponding rate of time preference. However, it is a relatively simple matter to deal with more complex patterns of returns.

We capture most of the interesting aspects of this generalization in supposing that our typical government project can be described by two time sequences of numbers: b_t denoting the current dollar (consumption equivalent) value of the government service provided in period t and e_t denoting the additional resources which must be raised in period t to carry out the project. Note that in any given period either b_t or e_t or both may be negative. A negative value of b_t corresponds to costs such as environmental damage caused by the project. A negative value of e_t may result when the project yields a cash return -- for example, its output is sold on the market -- which may be applied toward a reduction in taxes in that period. Negative values for these variables may occur in another way as well. Our analysis applies equally to investment and disinvestment. Not undertaking a project is itself a project; if project A is described by $\{b_t, e_t\}$, the project "not undertaking A" is described by $\{-b_t, -e_t\}$.

Note that we are here assuming only one form of benefits and only one form of finance. More generally, we could describe a project by a sequence of vectors $(b^1_t, b^2_t, b^m_t, c^1_t, \ldots, e^R_t)$, where b^j_t = dollars worth of benefits of the j'th type (of m types in all) in period t, and e^k_t = dollars required from finance source k (of R sources, e.g., sales tax, debt issue, etc.) in period t.

Having constructed similar lines of reasoning in the previous two cases we can move fairly quickly to the appropriate criterion in this case. Things will be simplified somewhat if we define shadow prices for benefits and revenues as follows:

$$\beta_t = 1 + \sum_{j=1}^{m} \alpha^j_t \ (v^j_t - 1) \tag{26}$$

$$\epsilon_t = 1 + \sum_{j=1}^{m} a^j_t \ (v^j_t - 1);$$

where the sums in (26) are taken over all of the private sector investment possibilities distinguished by the model. Recall our definition (2) of the discount factor δ_τ, derived from the social rate of time preference, by which consumption benefits in period τ are to be multiplied in aggregating a multiperiod consumption stream to period 0 consumption equivalents.

In period t the government project produces b_t dollars in benefits, worth $b_t \beta_t$ dollars in period t consumption when the influence on private capital formation is taken into account. The project requires that e_t dollars in revenue be raised, at a cost of $e_t \epsilon_t$ dollars in period t consumption when the influence on private capital formation is taken into account. The net effect is $b_t \beta_t - e_t \epsilon_t$, which is equivalent to $\delta_t (b_t\beta_t - e_t \epsilon_t)$ units of period 0 consumption. The project is worthwhile if

$$\sum_{t=0}^{T} \delta_t (b_t\beta_t - e_t \epsilon_t) \geq 0, \tag{27}$$

where the project has its last direct payoff or resource requirement in period T.

We may check that condition (27) gives us back the criterion for one-period investments which we have already derived. For such an investment, we have $b_{t+1} = 1 + \rho_t$, $b_\tau = 0$ otherwise; $c_t = 1$, $c_\tau = 0$ otherwise. Then (27) becomes

$$(27a) \qquad \delta_{t+1}(1+\rho_t)\beta_{t+1} - \delta_t \epsilon_t \geqq 0.$$

Recall from the definition of δ_τ that $\delta_{t+1}/\delta_t = \frac{1}{1+i_t}$. Dividing (27a) by δ_t, it becomes

$$(27b) \qquad \frac{1+\rho_t}{1+i_t} \geq \frac{\epsilon_t}{\beta_{t+1}}.$$

Substituting definition (26) for ϵ_t and β_{t+1}, (27b) becomes

$$(27c) \qquad \frac{1+\rho_t}{1+i_t} \geqq \frac{1 + \sum_{j=1}^{m} a^j_t (v^j_t - 1)}{1 + \sum_{j=1}^{m} \alpha^j_{t+1}(v^j_{t+1} - 1)}$$

which is the previously derived condition (24) for one-period investments.

Condition (27) obviously bears a close family resemblence to Baumol's consition (3). The difference is largely a matter of degree of explicitness about directly versus indirectly produced consumption streams. In expression (27) a certain amount of prior discounting has gone into the construction of the shadow prices β_t and ϵ_t, since these depend on the shadow prices v^i_t of private capital, which in turn represent discounted streams of consumption. Expression (27) thereby makes explicit the distinction between nominal dollar values of benefits and expenditures and their values including imputed throw-off. Condition (27) also makes allowance for outlays by the government in periods other than the initial one.

As usual, special cases do much to reveal the character of the criterion. If an additional dollar of benefits is divided among consumption and the different sorts of private investment in the same way every year and if the shadow prices of the different sorts of private capital are constant, then $\beta_t = \beta$, a constant. If an additional dollar of financing comes out of consumption and the different sorts of investment in the same proportions every year and if the shadow prices of capital are constant, then $\epsilon_t = \epsilon$, a constant. Then (27) becomes

$$(28) \qquad \beta \sum_{t=0}^{T} \delta_t b_t - \epsilon \sum_{t=0}^{T} \delta_t e_t \geq 0,$$

which, assuming the appropriate expressions are positive, may also be written

$$(29) \qquad \frac{\sum_{t=0}^{T} \delta_t b_t}{\sum_{t=0}^{T} \delta_t e_t} \geq \frac{\epsilon}{\beta} .$$

Condition (29) says that a project is worth undertaking if the discounted stream of benefits divided by the discounted stream of costs (which are defined very precisely to refer to changes in revenue raised by a particular financing mode) exceeds a calculable critical level, ϵ / β.

Condition (29) is a form of a benefit cost ratio. It is derived here simply to show how our criterion relates to those put forth by others. It is probably usually a mistake to use ratio criteria in practice. The net present value approach is always correct, whereas ratio criteria can lead to difficulties where there are mutually exclusive or otherwise interrelated projects in question, or where capital budget constraints are involved.

A special case of case (29) may be of interest, namely that in which all the financing for the government project displaces a single kind of private capital, so that $a_t = 1$, and the yield from the project induces no private investment (usually somewhat misleadingly described as "all yield consumed"), so that $\alpha_t = 0$. As far as the consumption-investment division of resources withdrawn by and output yielded by the project are concerned, these assumptions are those least favoring government investment. Referring to definitions (26) we see that in this case $\beta = 1$ and $\epsilon = v$. Condition

(29) becomes

$$(30) \qquad \frac{\sum_{t=0}^{T} \delta_t b_t}{\sum_{t=0}^{T} \delta_t e_t} \geq v,$$

requiring the benefit cost ratio to exceed the shadow price of private capital. Interpretation of (30) is facilitated by writing it in the original form of (29),

$$(31) \qquad \sum_{t=0}^{T} \delta_t (b_t - v\, e_t) \geq 0.$$

Here it is clear that to account for these rather extreme assumptions, to the disadvantage of government investment what is required is to weigh dollar expenditures by a factor v in calculating net benefits to be discounted at the social rate of time preference. Since we have previously calculated a relatively high value of v to be 1.06 it is clear that the choices made under rule (31) are in many cases likely to be very close to those made under the simple rule, "maximize present value of the stream of net benefits $(b_t - e_t)$, discounting at the social rate of time preference."

The latter rule becomes precisely correct in the last special case, in which the investment-inducing effects of an additional dollar of benefits are exactly the same as those of a reduction of a dollar in financing and the shadow prices of the various kinds of private capital are constant through time. Then we have $\epsilon = \underline{\beta}$, and condition (27) becomes

$$(32) \qquad \sum_{t=0}^{T} \delta_t (b_t - e_t) \geq 0.$$

Although (32) does represent a special case, its preconditions are not implausible, requiring simply that extra dollars taxed away and extra dollars received (usually implicitly) in benefits are treated as about the same thing by the private sector.

General Conclusions

In a sense, condition (27) with its associated definitions, is the general solution to the public investment problem and hence the general conclusion of this analysis. The next step required is to put empirical flesh on the theoretical structure, in the form of actual estimates of the various coefficients of condition (27). However, one should not be over-optimistic about obtaining a set of coefficients which can be applied to any government investment problem to lead to a precisely correct choice. The principal reasons for this are:

A. The precise financing technique providing the source of funds for any government project is often unclear or not even well-defined, and these sources vary from project to project. Do the funds to pay for a subsidy to the merchant marine come from corporation income taxes? personal income taxes? changes in Federal debt? A strictly correct answer would not even be assured if expenditure laws specified the source of finance. For example, Federal highway programs are annually financed by gasoline taxes, and this may be the end of the story. However, it is also possible that gasoline taxes would be about what they are anyway. An increase in highway expenditures in this case forces some other program to find its financing in another revenue device, say, the personal income tax. Then the source of finance for the highway expenditure for our purposes is, in fact, the personal income tax. Furthermore, the source of finance for a project may well be funds which would otherwise have financed another government activity. In this case, then, the dollars for the project in question "cost" the foregone benefits from the alternative activity. We need not labor further the extreme difficulty of establishing the financing source.

B. Knowing the financing source, we face great difficulty in establishing how much of an incremental dollar from that source derives from consumption, how much from various forms of private capital (and, we might add, how much from unemployed resources, in effect, from nowhere). It is, of course, not sufficient to know simply the nominal payers of a tax. For example, locating the incidence of the corporation income tax is the subject of a highly arcane controversy within the economics profession, with no settlement in sight.

It is possible that identifying the precise incidence of a financing mode can be sidestepped. Since we are here concerned not with matters of distributional equity, but of intertemporal efficiency, we need only worry about the quantitative reaction of consumption and investment to increments in financing from each mode. These coefficients might be stable over time and identifiable by econometric techniques, but this writer is not sanguine about this approach.

C. On the output side, matters are not much better. Assuming, as we have been, that one can reasonably estimate dollar values of the services from the government project, determining the influence of these flows on private investment is likely to be extremely difficult. Some headway may be made by examining the character of the flow involved. Is it more like consumption or more like savings? If the government undertakes to provide medical care for the aged, presumably this reduces the incentive for citizens to accumulate a reserve against this possibility. We might expect, then, that providing an additional dollar's worth of this insurance protection will lead individuals to reduce their private savings by about a dollar and to increase consumption by a like amount. At the other extreme, benefits from public parks may be effectively pure substitutes for private consumption. A family receiving these benefits reduces its expenditures on film and baseball game attendance, and increases its savings accordingly.

Note, though, that what a service looks like may tell only part of the story. The park example illustrates this. While it is true that the recreational services are of a nature which we would usually label "consumption", there is no guarantee that these services replace other consumption They may be additive, or worse, they may induce a reduction in labor supply and a net decrease in private saving ($\alpha < 0$, a case we have implicitly ruled out for most of our analysis).

Most benefits probably are between these extremes in their influence, and many no doubt are treated exactly as any other form of income, or the benefits may actually occur as income. An irrigation project, for example, increases the incomes of landowners in the affected area, and possibly the income of cooperating factors as well.

In view of these very serious obstacles to a precise implementation of (27), we would do well to consider what rules of thumb are likely to make sense and the circumstances in which they are likely to lead us astray. The general thrust of this analysis has been supportive of the rule of thumb:

(33) In the absence of reasonably clear evidence to the contrary, treat v as constant and α^j_t and a^j_t as constant and equal. In other words, attempt to maximize present value of net dollar flows (including dollar equivalents of nonmarketed effects), discounting at the social rate of time preference.

Assuming v, α_t and a_t constants, reasonable extremes of condition (27) are given by the cases of (28) corresponding to $\beta = v$, $\epsilon = 1$ and $\beta = 1$, $\epsilon = v$. The latter case we have already discussed, as it leads to the equivalent criteria (30) and (31). In other words in the case in which all financing comes out of investment and all benefits increase consumption we should multiply financing changes by a factor v before calculating net benefits. If $\beta = 1$ and $\varepsilon = v$ and we nevertheless use our rule of thumb (33) we will, of course, undertake some socially unprofitable projects. In the case of a project just barely worthwhile, so that

$$(34) \qquad \Sigma \, \delta_t b_t = \Sigma \delta_t e_t$$

undertaking the project will lead to a net loss equal to $(v-1)\Sigma\,\delta_t e_t$. By our "reasonable" value of v, this would amount to approximately 6% of the resources involved in the project.

At the other extreme is the case in which $\beta = v$, $E = 1$, all yield from the project leads to an equivalent value increase in private investment and all finance for the project derives from private investment. Here rule of thumb (33) is too conservative. The barely worthwhile project for which (34) holds, will actually generate a net profit of $(v-1)\Sigma\,\delta_t e_t$.

Thus, while the simplification effected by rule of thumb (33) is extreme and of great practical value, ~~the~~ risk of error associated with it appears modest. If this is accepted, attention must next be devoted to establishing a truly acceptable value for the social rate of time preference, since the particular number chosen is of greatest consequence for decisions among projects of any length. Before turning to concluding remarks on this topic it is appropriate to discuss briefly the particular application of this analysis to the Space Shuttle project.

Discounting in the Space Shuttle Project

As it happens, the particular discounting problem posed by the Space Shuttle is somewhat simpler than the general problem discussed in the preceding sections. In this case, the choice is among alternative expenditure streams, corresponding to different technical methods of producing a given service stream. In the language of the model above, we have a fixed stream of gross benefits, $\bar{b}_t$, and must choose among alternative expenditures streams e_t. Here the appropriate discounting procedure is clearly to follow the rule of thumb provided it is assumed that the method of financing the alternative stream is such that the private investment loss per dollar of financing is the same in every period for every alternative considered ($\epsilon_t = \epsilon$) and the shadow prices of private capital stocks are constant. Then the problem becomes one of finding the expenditure stream to maximize

$$\sum_{t=0}^{T} \delta_t \; (\bar{b}_t \beta_t - e_t \, \epsilon) \qquad ,$$

which is the one which minimizes

$$\epsilon \sum_{t=0}^{T} \delta_t e_t \qquad ,$$

This is obviously the same choice which minimizes

$$\sum_{t=0}^{T} \delta_t e_t \qquad ,$$

the present value of the expenditure stream, discounted at the social rate of time preference.

What is the Social Rate of Time Preference?

The analysis thus far has led to the conclusion that, under plausible assumptions second-best optimal government policy calls for undertaking all projects with positive net present value discounted at "the" social rate of time preference. It will come as no surprise that this simple formula hides a large number of difficult problems. In this closing section it will not be possible to do more than sketch out some of the issues involved in settling on an actual number to use in calculation.

A. In an ideal capital market in a riskless world, we would observe all households, able to borrow and lend at the same rate, adjusting their consumption profiles to equate their rate of time preference at every period with the market interest rate. In such a world we observe unanimous agreement about the individual rates of time preference, and this uniform choice would, obviously, be a prime candidate for the job of the social rate of time preference. Even under the extreme assumptions of certainty and market perfection there is a difficulty, however. It is argued that the currently existing households take insufficient account of the welfare of future generations in making their investment decisions. The government, by this argument, should, in effect, be accumulating a trust fund on behalf of unborn citizens.

This issue is one of income distribution, pure and simple. As has been pointed out by Baumol and others, the force of the argument is greatly diminished when we recognize that as a result of current, uncorrected, investment choices there is every reason to expect future generations to be richer than the existing ones. If income is to be redistributed, a much better case can be made for favoring today's poor. Hence, the interest rate in a competitive capital market has much to recommend it as a social rate of time preference.

B. It is somewhat difficult to be precise about the meaning of capital market "perfection." We do observe capital rationing, particularly at the level of the household. Individuals cannot borrow as much as they wish, and there is generally a divergence between the rate at which they can borrow and that at which they can lend.

These phenomena are intimately connected with the presence of uncertainty. In the case of individual family borrowing and lending, the fact is that the security it buys when it lends -- say corporate bonds or savings bank liabilities -- is very different in character from the security it sells when it borrows -- a personal note. And, in fact, when a family can offer a safe asset as collateral for the loan, making the note more like the one it buys when it lends -- the obvious cases being housing mortgages and bank loans against corporation shares -- we do not observe a larger divergence between borrowing and lending rates than transactions costs would lead us to expect.

However, the fact remains that there are some families who, by borrowing at high rates, reveal that they are willing to give up more consumption tomorrow than the average citizen in order to enjoy an extra unit of consumption today. The formally correct second-best method of dealing with this problem is to identify separate time streams of consequences for every family and discount each separately at the rate appropriate for that family. As a practical matter, some sort of average appears the only recourse, but where it should lie between the 2% or so (real) rate of return or savings accounts and government bonds and the 9% to 12% (real) rate paid on consumer loans is not clear.

C. The fact that some families lend at the margin at higher expected rates of return than are obtainable on the relatively risk-free securities does not introduce the same difficulties. These lenders are choosing more risk in exchange for higher return, but generally they also hold some risk-free securities and, from the point of view of society, the government activity is risk-free. (This remark depends on simplifying assumptions which are plausible, though not entirely innocuous. Time does not permit developing this subject further).

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