THE ECONOMICS OF THE SPACE STATION

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I. Prologue

Space exploration and development are naturally conducted on the cutting edge of science and technology. Such efforts inevitably involve decisions made in the presence of extensive uncertainty. For some projects, particularly those which involve the creation and maintenance of an infrastructure, the emphasis is switching from specific engineering goals (for example, a man on the moon by 1969) to more diffuse, continuing, multiple-dimensional goals. This is especially true of the space station, which is envisioned as both a vital link in the exploration of the planets and a major facility for the advancement of commercial efforts in space. The combination of uncertainty and diffuse, long-term goals fundamentally alters the viability and validity of traditional economic and engineering approaches to the management of large public research and development projects.

It has become popular to call into question the recent management of continuing projects like the space shuttle or major new weapons systems. We must, however, recognize that cost overruns, gold plating and other forms of apparent mismanagement are usually not the result of individual venality and misbehavior but only the natural outcomes of the existing organizational rules of the game. Just as the performance of an engineering design is guided by the laws of physics, the performance of an organizational design is guided by the laws of behavior. This fact means that to improve performance we cannot simply add more or better manpower; rather, we must look for new organizational solutions. There are many ad hoc opinions about how to do this; what I propose is a more systematic, scientific approach.

This paper examines some of the economic and management issues which must be addressed if the space station is to effectively and efficiently pursue the myriad goals that have been chosen for it. I characterize and evaluate in a somewhat stylized fashion three possible policies: an "engineering" approach, an "economics" approach, and a systematic custom design approach. I will use the space station as an example to highlight some of the major economic issues facing large-scale multipurpose research and development efforts, the analytical capabilities we now have to address these issues, and the (non-engineering) research that needs to be done to advance the successful long-term development of space.

The space station is a prototype for future joint endeavors of the private and public sector. It is imperative that we learn how to organize and manage these projects optimally so that our efforts in space are truly productive. Moreover, since inefficiencies cumulate, gains in organizational performance today have multiplicative effects into the future. Inefficiencies in the design, construction and operation of the shuttle will cause higher costs of access to the space station and other low earth orbiting facilities. These higher access costs will cause the costs of operation of the space station to be higher even if it is efficiently managed. If, as is more likely, the space station is inefficiently designed, built, and operated, then the costs of design, building and operation of higher orbit space ports will be even higher than anticipated. This cumulative process will never cease, with inefficiencies compounding at each state in the process. Each step actually taken will be smaller than optimal because required budgets for the planned step will be larger than predicted. As in Zeno's Paradox when each step is a fixed fraction of the previous one, we may never get where we want to go unless we can adjust the step size using organizational solutions that eliminate inefficiencies. Exciting visions of the next fifty years in space that ignore these organizational realities are doomed to failure. The nation's organizational vision must begin to match its scientific and engineering vision.

II. Introduction

This background section first summarizes some of the economically important characteristics of the space station. Next, the language and structure of mechanism design theory and practice are introduced, since many readers may be unfamiliar with this recently developed, powerful approach to resource allocation problems.

An Introduction to the Space Station

The space station is described by NASA as a multi-use, permanent facility in low-earth orbit that will significantly enhance space utilization. It is to be a laboratory (for scientific research, technology development, and manufacturing research), an observatory, a transportation node, a servicing facility with assembly capabilities, a storage depot, and a staging base for future space missions. An economist's superficial view might be that the space station is simply a commercial development project and research complex with a special location (NASA planning seems to emphasize the research complex while some in Congress and the private sector try to emphasize the commercial aspects). An engineer's superficial view might be that the space station is simply a few modules (large cans similar to SpaceLabs and designed to fit exactly into a shuttle bay) fastened together on a frame and provided with needed services such as power. The space station is obviously more complex than either of these views would suggest, however. The station is economically different from many other projects to which one might be tempted to compare it, such as a public utility (electric power or telephone service, a major road, a dam), a major weapons system, the Apollo missions, or the shuttle and its associated facilities. The space station does share important characteristics with each of these projects but it is identical to none of them. While the station does have the large set-up costs and large common operating costs of public utilities, its technology, costs and benefits are vastly more uncertain. While the station does promise to provide large public benefits and major technology advances like Apollo, its goals, missions and performance requirements are less certain and more diverse. The space station is distinguished from the shuttle because it offers a multidimensional product to multiple, overlapping, continuous, and potentially long-term users.

Key Economic Characteristics. There are several economic characteristics of the space station that are important to keep in mind. It is a multi-use facility designed to supply a multidimensional vector of resources over time to a diverse collection of users. Moreover, user needs will change in unpredictable ways. The station is also not a single-goal project; it will need to be continuously managed after it is built.

Associated with the space station are large common costs, costs which cannot be identified as having been incurred solely for the provision of one resource (a standard example is communal computer facilities), and large public benefits, benefits simultaneously provided to many individuals at one time in a way that a single individual's consumption does not detract from any other individual's consumption (an example is the services of defense). One implication of this observation is that efficient private provision of the station is not feasible during its early operation; it should be partially publicly funded.

The benefits to be achieved by the users, both the scientific community and the commercial sector, over the life of the space station are very uncertain; the benefits may also be unknowable today but may be eventually discoverable. What is known about the extent of the benefits as well as the composition of the missions that will yield those benefits will change over time. But a deeper problem exists. Not only are the benefits uncertain, but those individuals and organizations with the most incentive to evaluate and estimate them, such as potential users, have little incentive to reveal that information correctly and inform public debate. If information can aid competitors it must be protected. If user charges for the station's resources depend on the benefit information supplied, there is a strong incentive to understate the true benefits; if the allocation of resources and not the charges for their use depends on user responses, there is an incentive to overstate the potential benefits. Since, at this time, users have no idea how the information they supply is to be used, they protect themselves by both overstating and understating the benefits. When asked what the potential for commercial development of space is, the answer is often "billions and billions of dollars"; however, when pressed for payment these same respondents indicate that the risks are huge, that it is possible that no benefits will occur, and that unless someone (usually the public sector) helps them they will be unable to participate. Thus different aspects of probability beliefs will be presented depending on the predicted use of that information.

The benefits to be achieved by the public are even more difficult to discover. Research has shown that public polls and user surveys are unreliable. We do have a preliminary, indirect measure. Congress, representing the public, has indicated a willingness to pay of at least $8 billion plus some unspecified amount for operating costs in return for the benefits that the public will receive. Assuming that public preferences are transmitted through the political system, Congressional willingness to pay supplies a lower bound on possible public benefits. Of course, as with the private sector, Congressmen and their constituents also have incentives to conceal or misrepresent information they may have, causing the political process to be an imperfect aggregator of benefit information.

The costs of building and operating the space station are very uncertain. Various cost "models" generate point estimates from scanty data sets by extending and aggregating regressions of cost upon weight to levels which raise doubts about the implicit linearity assumptions typically used in these models. An economist is immediately reminded of large scale econometric forecasting models when he sees one of these cost models. I presume that the inaccuracy of each is somewhat equivalent and that when the predictions of the model conflict with the hunches of the analyst, the model is changed.

It will not be until the new station technology is tested and operational that actual costs will be known with any certainty. Even then there is no reason to believe that these observed costs will be the minimum costs possible.[2] (A historical examination of the estimates of development and operations costs for the shuttle and a comparison of those estimates to the actual costs should be a sobering experience for anyone who wishes to make major policy decisions based on point estimates.) Since nothing like the space station exists, one cannot examine a surrogate and ask what should the station cost; one can only make educated guesses about ranges of cost. Further, as with the benefits, those who may have the better information, such as potential contractors, builders and operators of the station, have little incentive to share their knowledge. (It is possible that this is overly pessimistic for the aerospace industry. In repeated situations of long-term relationships between the contractor and the contractee, it is sometimes in the interests of each party to reveal information correctly and early.)

Even if the cost models of the space station components were accurate and information was fully shared, a larger problem exists when building a large, interactive system that involves new technologies (or old technologies at new scales). Given any design of the gross characteristics of the station, there is still uncertainty about the net resources that will be available for the users. A complicated input-output relationship with extensive feedback effects links various station resources (e.g., power, extra-vehicular activity, heat rejection, etc.), and there are uncertainties as to how much of one resource will be needed to support the provision of another. These uncertainties interact in a complicated manner to create a range of possible performance results (or a probability density over net resource availabilities). For example, power is to be both available to users and needed for the internal operation or housekeeping of the space station. As in land-based electric power generation and distribution, or in the case of the shuttle, service is interruptible. The extent and impact of these uncertain curtailments must be accommodated in any sensible policy analysis: point estimates are misleading and ignore the realities of uncertainty.

The following extended example illustrates the importance of supply reliability and the increased decision burden it places on space station operations. If a planned shuttle trip is delayed, what can happen? If astronaut survival has the highest priority, payloads may be bumped from the shuttle to make room for extra provisions for the crew (astronauts and payload specialists). Supplies already on the station may be diverted from the labs and reallocated to manpower needs. Finally, manpower effort available for both the payloads and the station may be reduced to conserve resources needed for survival. These actions will increase the probability of other supply interruptions with a chain of secondary effects on available manpower, and so on. A number of decisions will have to be made. Which payloads should be removed from the next shuttle flight? Which payloads on the station will receive reduced resources, both of supplies and manpower? The reduction in one resource supplied, transportation, causes reductions in others, supplies and manpower, in complicated proportions. Thus, uncertainty in the supply of one resource causes uncertainty in the supply of all.

For government-funded projects, if there are cost uncertainties, then supply uncertainties become even more likely unless Congress and other users are willing to cover old costs in new budgets -- no matter how high. If not, then higher than expected costs will lead to budget tightening in other areas which in turn will lead to reduced performance. Some natural reactions to unexpectedly tighter budgets are less training, less quality control, less maintenance, and fewer spare parts. All of these responses imply increased supply uncertainty. Thus, even if the technology is known with certainty, cost uncertainty will cause supply uncertainty. In large, continuing public R&D projects, this combination of unknown technology and unknown costs is inevitable and should be adequately planned for by management.

Space Station Goals. The announced goals for the space station are as varied as the users. The advancement of science, the development of new and better technologies, the advancement of the commercial development of space resources, and the improvement of international relations are just some of the desired effects of the station. Among the engineering goals are the demonstration that the station can be built and will function (feasibility) and the provision of a continuing infrastructure for users (performance). Among the economic goals are efficient operation and use (most bang for the buck) and the recovery of costs (users should pay). Other than feasibility and cost recovery, these are user-oriented goals which are not output specific; that is, they are not of the form: "put a man on Mars." Rather, three goals are primary: feasibility, efficiency and cost coverage. The other objectives can and should be accommodated within the context of these three.

As a goal, *feasibility* is certainly necessary for all others. If the station does not work, it cannot be used -- efficiently or inefficiently. On the other hand, an excessive commitment to feasibility at any cost will generally imply an inefficient design, characterized either by less performance than was possible for that expenditure, or by a competitive disadvantage in the provision of services to commercial users, or by both. Thus, although feasibility must come first, it cannot be the sole driver of design and operation. One must not just get into space; one must get there in a scientifically and commercially viable way. The number and quality of experiments, the benefits to users, and the ongoing ability of the station to advance exploration are ultimately what are important.

As a goal, *cost coverage* requires that users be charged for the costs of the project. While this may be an accountant's dream, it is bad economics for public projects. If, in the private sector, revenues do not cover costs then this is a market signal that either management is inefficient or that benefits are less than the costs. In either case, this particular line of business should be discontinued. If revenues do not cover costs on a public project, there can be no such interpretation. The issue is simply whether Congress, representing the public, is willing to cover the shortfall. If the public benefits of the project appear to be worth it, then the deficit between costs and revenues will be covered as the "price" for the public benefits. If the public benefits are viewed by Congress as not worth it, then the project will not be funded and will therefore be stopped. The question is thus not whether costs should be covered; rather, it is by whom.

As a goal, *efficiency* is necessary to all other objectives. Efficiency requires that resources be allocated such that there is no reallocation which can make anyone better off without making someone worse off; "anyone" includes users, taxpayers, contractors, designers, operators, and so forth. In many cases, efficiency is equivalent to maximizing total net benefits from the project and implies maximizing performance given expenditures. Two implications of efficiency are (a) given the (possibly random) vector of resources to be provided by the space station, efficiency requires correct (efficient) payload design and correct (efficient) payload selection, and (b) given any specification of missions, the combined life-cycle costs of the station plus the payloads needed to accomplish those missions should be minimized. If the station is designed and operated efficiently then other goals such as promoting commercialization can be more easily pursued. Efficiency does not rule out any other long-range goals; it merely augments them by providing more resources. The key to efficiency is the allocation of resources and not the allocation of costs.

We need to differentiate between two aspects of efficiency. The first concept is *short-run efficiency*, that is, efficiency given the configuration and operating levels of the space station. Short-run efficiency involves using an existing station as efficiently as possible and includes decisions about scheduling and timing, payload design, and payload selection. The other concept is *long-run efficiency*. Long-run efficiency includes station technology and size in the efficiency calculation along with use. This is the concept of efficiency normally preferred by economists and is especially appropriate when one considers alternative growth and evolution scenarios. Tradeoffs between manned and unmanned exploration naturally arise in the long-term context.

An Introduction to Organization Design

Given the goals of the space station and given the behavioral realities of information and incentives, policy analysis must determine how best to attain the goals subject to those constraints. Over the past three decades there has developed a theoretical and experimental body of knowledge aimed at exactly this type of analysis. Since this literature is the natural framework in which to evaluate various policies for the operation of the space station and other large projects, I will provide a brief introduction to what is known in the literature as "implementation theory," "mechanism design," or "organization design." The concept provides a systematic method within which to evaluate not only the impact of suggested policies but also to design new, and perhaps previously unsuspected solutions to achieve the desired goals.

Background. One purpose of engineering is to design devices that harness physical forces to serve certain specified goals, subject to the laws of nature. Similarly, the purpose of organizational design is to design devices that harness behavioral forces to serve certain specified goals, subject to the laws of nature. There are two simple analogies. The aeronautical engineer designs an airplane which will be able to fly between any two points to be specified by others at a later date; he does not choose the points, pilot the plane, or run the airline. The economist, as organizational designer, specifies the structure (the rules of the game) within which group decisions are to be made based on information provided by others at a later date; he does not provide the information, choose the actions to take, or manage the organization.

A second analogy can be found in computer design. The computer programmer designs hardware and software which will elicit inputs from others and produce a collection of desired outputs. The economist designs an organizational structure which will elicit inputs from others and produce actions that accomplish the desired ends. It is not up to the economist, who presumably does not know the scientific and engineering facts, to decide exactly which payloads should fly on a shuttle mission; it is up to the economist to design a policy that will elicit as much information as is necessary, from those who best know, to allow the informed selection of payloads that achieve the stated goals.

It is the imaginative combination of engineering design and organization design that holds the promise of success. Neither design will succeed for long without sensible integration with the other. (It must be noted that even if engineering decisions are made without systematic organizational design, an implicit design decision will still have been made. The real issue is whether what is known can be used to improve these "seat of the pants" solutions.) Aeronautical engineers, computer scientists, and economists strive to create structures so that those people with the requisite capabilities and information can more easily accomplish their goals. It is only the medium in which they work that is different.

The fundamental theoretical and empirical fact which forms the basis for organizational design is that *institutions matter predictably*. For example, we know prices affect behavior in predictable ways. The "pancake" design of the Hughes satellite engine was clearly a response to the fact that a price was charged for length, as well as weight, on the shuttle. If one really knew the demands and costs relevant to the space station, one could "choose" prices to induce the "right" outcomes. However, since no one holds all the required information, institutions must be created that "calculate" the right prices. Markets do this naturally using the power of prices to inform, coordinate and guide decisions; many times, but not always, this results in an efficient allocation. Other institutions (such as regulatory agencies, cost-benefit studies, and political processes) can also coordinate, but do not always result in efficient allocations.

Organizational design is constrained by two fundamental phenomena. The information needed to make the "optimal" decisions is either initially dispersed among a variety of participants or is more easily discoverable by some. The pharmaceutical industry probably has the best information about the benefits from production of drugs in micro-gravity, the variety of materials processing furnaces that could be used on the space station are best known to their manufacturers, contractors may have the best estimates of the costs of producing particular sub-assemblies, and I know best what the benefits of the space station will be to me. If all the information were able to be correctly transferred to a central location, optimal decisions could be made. It is one purpose of organizations to facilitate this effort. The designer of the organization must understand and accept this initial information dispersion.

The second constraint is that individual agents who are in or who interact with the organization will generally act in their own self-interest. This is especially true if there are multiple goals and difficulties in monitoring or auditing. The designer of an organization must choose the structure so that any request of an individual to provide information or to carry out a task will be self enforcing. If such a choice is not made, then it must be recognized that many actions taken and much information provided may be misleading. This outcome is not necessarily bad but it is predictable and should be anticipated.

An Extended Example. The simplest example of organizational design can be found in the following allocation problem. A seller owns an item of no value to him but which has some value to a number of potential buyers. Each buyer knows his own value, no one else can observe that value, and each buyer's value is independent of the others'. (The results below change in very interesting ways if there is correlation between the values, as there will be if there are resale possibilities, or if one buyer can benefit even though another buyer receives the item, as would occur with public goods. We do not, however, pursue these variations in this paper.) The efficient allocation gives the item to the buyer with the highest valuation. The problem is to accomplish this within the information and incentive constraints. There are many possible organizations to solve this problem; we will consider six organizations below.

Organization 1: First-Price, Sealed-Bid Auction. This organization, a pricing and allocation mechanism, asks each buyer to submit his value for the object (without knowing what any other buyer will say). The object will be awarded to the buyer with the highest "stated" value who will pay an amount to the seller equal to that stated value. If everyone is "honest" (in fact, if the buyer with the highest value is honest), the outcome will be efficient. However, the highest value buyer will be no better off than when he started since he will have to pay full value for the item. It is easy to see (theoretically and empirically) that all buyers will understate their true values for the object. Inefficient allocations may result, as naturally self-interested buyers seek to gain something from the auction; in particular, the second-highest value buyer may bid more than the highest value buyer. Experimentally, this seems to happen 10 to 20 percent of the time when values are randomly assigned according to a uniform distribution. It appears, theoretically, to be due to variations in risk attitudes among subjects.[3]

Organization 2: English (Ascending Bid) Auction. This organization asks each buyer to publicly state the value he places on the object (if he wishes to). At any time there is one such "bid" outstanding, as a commitment to buy at a price equal to the stated value. If a higher bid is made it becomes the outstanding bid. When a prespecified time elapses between improving bids, the auction stops and the item is awarded to the holder of the outstanding bid for a price equal to that bid. The predictable outcome of this auction is that the highest value buyer will make the final bid, which will be slightly more than the second highest value. The natural self-interested behavior of the buyers leads to an efficient allocation, even though the buyer with the highest value has misrepresented its true value by understating it.

Organization 3: Posted Price. A common organization for solving the allocation problem has the seller post (i.e., publicly state) a price at which he is willing to sell. If the seller chooses a price such that one and only one buyer agrees to that price, then an efficient allocation occurs. More likely, since the seller has no demand information, either no buyers or many buyers will be willing to pay this price. Thus, "posting a price" is only part of the description of the organization. How and when to adjust the price, and when and to which buyer to give the item must also be specified. For example, suppose the price is never adjusted and the item is given to the first buyer who is willing to pay the posted price (first come, first served). This is inefficient if no buyer accepts the offer; it is still usually inefficient if many buyers are willing to accept the offer since the item may well go to a buyer with a lower value. As another example, suppose the price is adjusted until just one buyer is willing to accept the latest offer (note that this requires reneging on the original offer). If the original posted price was too high (no one accepted), then lowering the price will be similar to a Dutch auction.[4] If the original posted price was too low (more than one buyer accepts) raising the price will be similar to an English auction.[5] Of course, buyers will anticipate the price changes and react in their own interest. The process of price formation will affect the behavior of buyers and, therefore, the allocation. If the analyst recognizes the incentive effects of the "price adjustment rule," the allocation can be efficient. However, if prices are posted and never adjusted in response to market information, then the allocation will be inefficient and revenue will be less than possible.

Organization 4: Second-Price, Sealed-Bid Auction. In this organization each buyer is asked to write down the value of the item to him (without seeing the others' stated values). The buyer with the highest stated value will be awarded the item and will pay a price equal to the stated value of the second highest bidder. The predictable theoretical and empirical outcome of this auction, once bidders understand the rules, is that each buyer will bid his true value, the highest value bidder will get the item, and he will pay a price equal to the second highest true value. The outcome is efficient. In fact the outcome is identical to organization 2, the English auction, even though the apparent information being provided (the bids of the buyers) is significantly different. Here there is no misrepresentation.

Organization 5: Cost-Benefit Analysis. In this case, each possible buyer is asked to tell an interviewer the value of the object to him. He is exhorted to "tell the truth." A consultant will process the information, do a cost-benefit calculation and tell the seller what the outcome should be (who should get the item and how much he should pay). The seller will presumably follow the consultant's advice. If the consultant uses "standard cost-benefit principles" he will accept the stated values as the true values and assign the item to the buyer with the highest stated value. Whether this organization is efficient depends on the "pricing policy" associated with this allocation; that is, how much the receiving buyer will pay. If the answer is nothing, then all buyers will have an incentive to overstate their benefits to the cost-benefit analyst and the allocation will generally be inefficient. If a price close to the highest stated value is charged in an attempt to maximize revenue, then this organization is identical in effect to the first-price, sealed-bid auction (organization 1) and inefficient outcomes should be expected.

If the analyst recognizes these incentive effects of the "pricing rule" on the quality of information, he should announce, before eliciting the information, that the price paid by the recipient of the item will equal the second highest stated value. This is the "market-like" solution and, as in organizations 2 and 4, will provide the appropriate, self-enforcing incentives for all potential buyers to correctly reveal their information. The allocation will be efficient. Of course, one could certainly use the second-price, sealed-bid auction (organization 4), where the commitment to the pricing rule is clearer, instead of cost-benefit analysis. From the point of view of efficiency, the allocations and the organizations are the same (ignoring, of course, the costs of the organizations themselves).

Organization 6: Sell-a-Dollar. This organization is the same as the English auction, with one crucial difference. At the end of the auction the highest bidder will receive the item, but the second highest bidder will pay an amount equal to his bid for the item. (In practice, one must constrain bidders not to bid more than the cash they have in their pockets.) The outcome of this auction will rarely be efficient.

Table 1 summarizes these six forms of organization. The table notes the extent to which each design obtains an honest revelation of preferences and efficient resource allocation. Expected levels of revenue are also compared.

Theoretical and Empirical Facts. The principles of organizational design are derived from the mathematics of the theory of games. A well-developed body of knowledge, known as mechanism theory, has been created over the last three decades. Most applications of this theory have been in the area of single object auctions, such as those above, and public goods allocation problems. Currently, the theory of regulation is being updated using the results and methods of this literature.[6] In spite of this, mechanism design is a custom process in practice. No one institution handles all possible situations even if there is a single goal such as efficiency. For example, none of the theory developed to date is directly applicable to the space station problem, although some aspects certainly suggest possible approaches.

The facts of organizational design are also developing, but at a slower pace than the theory. One reason should be obvious: unless the values of the item to each of the buyers in our auction example can be directly observed, there is no way of knowing whether a particular design leads to the theoretically predicted behavior. Market data are of no use. Fortunately there is an alternative to the economists' traditional data sources. Using experimental methods it is now possible, in a controlled environment, to test and validate organizational designs in much the same way that a wind tunnel is used to test airfoil designs. This means that organizational designs can be systematically studied before implementation. Nonetheless, just as a successful wind tunnel test does not guarantee a successful aircraft flight, a successful experimental validation of an organization does not guarantee its performance. But it is true that the economics laboratory has been shown to be

Table 1. Summary of Organization Designs

Organization	Honest Revelation	Efficient	Expected Revenue*
1. First Price Auction	no	no	higher
2. English Auction	no	yes	same
3. Posted Price			
a. first come-first served	n.a.	no	lower
b. adjust price	n.a.	yes	a little higher
4. Second Price Auction	yes	yes	same
5. Cost-Benefit			
a. pay nothing	no	no	lower
b. pay highest value	no	no	higher
c. pay second highest value	yes	yes	same
6. Sell-A-Dollar	no	no	much higher

n.a. = not applicable

*The entry in this column compares the expected revenue to the seller to the statistical expectation of the second highest actual value to buyers with some risk aversion. This comparison can be viewed as a measure of the extent of cost coverage.

useful in identifying organizational designs that are fatally flawed, and in providing an environment that is sensitive enough to measure the effects of subtle changes in organizational design and to fine-tune organizations. The availability of such "test-beds" means that theory, conjecture, opinion, or intuition need not be relied on in organizational design. A factual basis for any particular structure can be created.

III. Mechanism Design for Space Station Operation and Evolution

Having noted the goals and constraints of the space station and established mechanism design as the framework of analysis, we can now address some of the basic policy issues in the management of the station. Although this type of analysis could also be provided for the design and acquisition phases of the station, this paper focuses on its management after it has become operational, since many of the major policy issues can be highlighted in this context. Length considerations prevent analysis of both phases.

Given the initial operating configuration (IOC) of the space station, the supply of resources which will be able to be allocated to users is determined but not necessarily known with certainty. The resource allocation decisions to be made once the station is operational involve payload design (whether to automate or to use manpower), payload selection (should a science project displace a commercial R&D project), the allocation of station resources to each payload (does that project deserve 1 or 1.2 kilowatts of power), the allocation of resurces to station operation (should manpower be shifted from ground operations to the design and development of a space port), and, eventually, when and how to expand the station to provide more resources (when is another module added). The section first considers the broad outlines of three possible organizations or allocation mechanisms designed to guide the operation and evolution of the IOC. Analyzed next is the ability of each organization to provide the appropriate framework within which to pursue the goals of cost recovery, short-run efficiency, and long-run efficiency. Each design is described only in gross terms and should in fact be considered a class of designs. A summary comparison table is presented at the end of this section; more specific analysis is available in the appendix.

Team Management and Cost Recovery: The Engineers' Approach

This organizational structure assumes that the project is a team effort. It is the natural extension of the principles of small project management to the control of large organizations. The team, for the space station, includes designers, builders, users, and operators. In its purest form, every team member is assumed to share the same goal and be willing to provide any information requested. I refer to this as the "engineers' approach" since this seems to be the first structure of choice in a group design process. It is a "hands on" form of management with direct (generally hierarchical) control of as many decisions as possible. While there are many reasonable variations, I will look at only one potential allocation mechanism which I hope stimulates discussion of the issues.

In this organizational structure, the pricing policy is oriented to cost recovery (usually based on past operations) and not to resource allocation. One natural candidate is "pricing at the price of a shuttle flight plus a percentage surcharge to cover station costs." Discounts can be readily given to "encourage use." Scheduling and allocating station resources are accomplished by a committee (or a project manager) which uses various devices to establish priorities among competing ends. A prominent priority system often proposed is "first-come, first-served." This committee also directs design and growth, determining what is needed through a variety of studies similar to cost-benefit analyses. This description is essentially a continuation of current shuttle pricing policy, which uses a slightly different priority system.[7] The policy is "builder-operator oriented" as opposed to a "user oriented" policy since the designers and builders (unintentionally) determine user allocations rather than the reverse.

Ideal Conditions. Under some conditions this mechanism may be successful in pursuing its goals. There must be known and shared goals such as "land people on Mars and return them." This condition is most easily met by projects which are not continuing and which do not involve extensive interactions with users whose unknown needs evolve over time. Information should be commonly known or easily discoverable and there should be minimal gains to misrepresentation. The former requires that there be little uncertainty; the latter requires low common costs and a consistent reward structure based on strong leadership. Very accurate cost and benefit information must be available; either there should be little uncertainty or benefits should so far outweigh costs that what uncertainty there is does not matter.

Performance for the Space Station. It is fairly easy to predict the effect of this type of organization on the performance of the space station and its ability to pursue efficiency and cost recovery. At first glance, cost recovery seems straightforward since the percentage surcharge can be made as large as possible. One must, however, consider the reaction of users. Even if the station is fully used, the percentage surcharge required for full cost recovery may be so high that some potential users are rationed out; their benefits are less than the amount they are asked to pay. In this case the surcharge would have to be raised (fewer users must each pay more). This increase would eliminate more users and so on, leading to a "death spiral." Eventually space station operators will try to give discounts to encourage use, or they will argue that average costs are really lower than previously thought. Congressional studies, economists' and engineers' cost estimate studies, and numerous administrative board hearings will result. All of this unproductive effort will be designed to try to discover the value of a single number (the life-cycle cost of the space station) which is inevitably undiscoverable because the future is uncertain and the present is hidden by standard accounting techniques.

This scenario is not too far-fetched: it is exactly what happened to mainframe computers at many institutions that tried to allocate their use (recover their costs) by charging users a price equal to average costs. Users switched to personal computers, except for a very small number of users who had no alternative. The combination of a pricing policy with unanticipated, undesirable implications and the availability of a specialized technology competing with the multipurpose mainframe led to an inefficient allocation of resources. In most cases, actual costs were never recovered and never known for sure. We know that the European launch vehicle, Ariane, is the U.S. shuttle's equivalent of the personal computer for satellite launches. It is not inconceivable that there will be the equivalent of Ariane for the space station (such as privately or publicly financed free-flyers).

The implications for short-run efficiency are also easily predictable. Even if the committee that allocates resources and schedules payloads is able to identify all high benefit missions and their relative benefits (which is unlikely), there will still be inefficiencies in the use of the station. Payload designers (certainly those in the commercial sector), in response to the pricing policy of "shuttle price plus a percentage," will build payloads which conserve on the use of the shuttle (i.e., are light and short) but which do not conserve on potentially critical station resources such as electricity and manpower. Thus, for example, we will not see robotics incorporated into payloads, but instead will see heavy demands for astronaut time to monitor and operate payloads.

Another predictable implication of this allocation mechanism is that, unless the percentage surcharge is adjusted for time on the station, short-term projects will be passed up in favor of very long-term projects. Such long-term projects will not only use a lot of station resources but will use them over a long time period. If the surcharge is adjusted for time on the station, long-term projects will be eliminated in favor of short-term projects, and resources will be used more intensively.

Finally, because the supply of station resources will be uncertain (perfect reliability is infinitely costly), users will adjust their designs to adapt to the probabilities that they will be "bumped" during resource flow interruptions. If a priority scheme similar to that for the shuttle system is used, both commercial and scientific R&D payloads, which fly at a discount and with low priority, will tend to be smaller than is efficient to "fit in" as easily as possible and be easy to reallocate. The excess demand for mid-deck lockers on the shuttle[8] is traceable in large part to this reasonable response by users to the risks of delays and supply uncertainties, i.e., the price of "not fitting."

The loss due to the inability of this form of organization to deal with the uncertainty of reliability can be most easily understood by considering materials processing payloads. Virtually no graduate dissertations have been written in the area of materials processing in micro-gravity because of shuttle unreliability, which, prior to the accident involving Challenger, tended to bring a three- to four-year wait. No one was willing to chance having to wait that long even when provisionally scheduled earlier. The loss of this science research means we now have little information for evaluating the role of materials processing on the space station.

The effect of a team-managed structure on long-run efficiency is also clear. Given the extensive technical and market uncertainty, the multidimensionality of the resources supplied by the station, and the variety and large number of potential users, the information for making efficient long-run decisions will be unavailable. Cost-benefit studies will be able to provide little guidance under these conditions. Any claims about costs and benefits should be viewed with healthy scepticism. As we have seen, payload designs and resource demands will be skewed by the pricing policy and will not be representative of efficient use. Thus, we will not be able to use demand information to plan efficient expansion or contraction. We will then only be able to ask users what they want and contractors what it will cost, with all the revelation problems that will entail.

If expansion is not efficient in the long-run, there will be two effects worth noting. First, other designers and builders will be able to discover a more efficient design that would be able to effectively put the station out of business for any use that is not heavily subsidized. Second, even if subsidies are granted to prevent the defection of users to these more efficient designs, there will be a significant waste of the resources available for space exploration and development. More science missions and more commercial ventures would have been possible, but their benefits will be foregone because of the inevitable and permanent long-run inefficiencies.

Other Comments. It is obvious that the team form of management is remarkably similar to that of "centrally planned economies." The advantages and drawbacks of such systems are well-known. When resources are allocated centrally by bureaucratic quotas, managers have little knowledge about or interest in controlling costs. Such a system can be compatible with the achievement of crude quantitative goals but lacks a mechanism to improve quality or efficiency.

One might be tempted to ask why this form of organization would survive if the inefficiencies are so bad. The answer is in the combination of political and engineering realities. The important political fact is that the political process and those involved in it, such as Congress, are generally myopic. Elections occur in the next one to six years; ten years is too far ahead to be of much importance. The salient engineering fact is that these projects must be designed and built before they are operated. This means that design decisions are more imminent and operations decisions appear deferrable. In this environment, the team structure aimed at the completion of a feasible design can survive. Efficiency in operation and use can always be postponed.

To emphasize this point, let me make a small digression. I believe these two facts about political and engineering processes helped shape the organizational structure within which the Challenger accident occurred. Although no individual intentionally caused the events leading to that disaster, behavior was most certainly shaped by organizational forces. The accident was, therefore, as much an organizational design failure as it was an engineering design failure. Without repairing both flaws, the space station and other ongoing, long-term operating projects will be subject to similar risks.

While it may be argued that the inefficiencies from the mismanagement of any one project may not be big enough to cause NASA to consider a significant alteration in the method of doing business, it must be remembered that these effects cumulate. Imperfect allocation in a current project means imperfect information for future projects which might live off of this project. Inefficiencies in the design and operation of a major R&D project mean fewer science and research missions for that project. If the next project depends on the results of these experiments, then the next project is either delayed or inefficiently designed. A continual loss in the rate of possible R&D occurs at an increasing rate relative to what might have been accomplished if efficient design and operation were achieved. The fact that the shuttle is expensive (and probably inefficient) makes access to the space station more difficult. If a cheaper delivery system were developed, more science and technology would be able to be pursued with the desirable result that our long-run goals in space, whatever they are, would be more rapidly attained. Postponing consideration of possible alternative organizational designs merely further delays long-term scientific success.

Cost-Based Allocation and Long-Run Efficiency: The Economists' Approach

This organizational structure is oriented towards the goal of long-run efficiency and begins to address the information and incentive issues that arise in all large organizational structures. It is the natural extension of markets to the control of large organizations. I refer to this as the "economists' approach" since this seems to be the first structure of choice for any regulatory or public enterprise pricing problem.[9] It is an organizational structure which does not require direct "hands on" management but, instead, indirectly controls decisions. While there are many variations, I will only consider an idealized version.

Description. Pricing policy is oriented to long-run resource allocation and designed to provide information to users about the relative scarcity of station resources. Prices are also intended to provide incentives to payload designers and users to conserve on critical resources. Formal analysis under certainty leads inevitably to the conclusion that to achieve long-run efficiency when users are net benefit maximizers or team players, the price of a resource should equal the "long-run marginal cost" (LRMC) of that resource. If costs are uncertain, it is usually suggested that expected values be used. Capacity of the project is to be adjusted in response to demands at those LRMC prices. That is, if demand is larger than current supplies, then capacity should be expanded; if demand is less than current supplies, then capacity should be contracted. Lump-sum discounts or entry fees can be added to pursue the additional goal of cost recovery or to encourage use. It is not clear what is recommended in the short-run (before supplies are fully adjusted to demands) for scheduling and station resource allocation, especially if supplies adjust slowly and current supplies are uncertain. Presumably a committee, similar to that in the team structure, would make the decisions or there would be some type of ad hoc rationing scheme, such as "first-come, first-served." This allocation mechanism is a long-run, user-oriented pricing policy based on both cost and demand information and is often touted as the natural solution to the "efficiency failures" of average cost pricing.

Ideal Conditions. Under some conditions this mechanism may be successful in the pursuit of its goals. Very accurate information is required, including an accurate model of the incremental effects on costs and design requirements needed to supply more of each resource to payloads. Further, this model and the actual designs must minimize the life-cycle costs of supplying the additional resources. It is not necessary for station management to have any information on benefits to implement this policy successfully. It is also not necessary for users to be certain of benefits, although they must be able to assess the uncertainties and evaluate their own willingness to bear risk. There should be a technology which provides a fairly stable supply of resources to the users.

The uncertainty surrounding shuttle flight schedules is an example which may violate this condition. A predictable and constant flow of electric power from a utility is an example which may satisfy this condition. Design and construction technology must allow capacity to be easily and rapidly expandable to adjust readily to demands. This is not as necessary if demands are stable and predictable.

Performance for the Space Station. This allocation mechanism has vastly different but still predictable results for the performance of the space station. For projects with large common costs, such as the station, it is inevitable that a policy of charging prices equal to (expected) long-run marginal cost prices will not yield enough revenue to cover costs. There are two possibilities for making up the deficit. First, the common costs can be considered as expenditures towards the public benefit, in which case Congress should pay for them; of course, if Congress refuses then the project would have to be scrapped. The other alternative is to charge a "hook-up fee" which cannot depend on the resource use by the payload. The drawback here is that this leads immediately to problems similar to those for average cost pricing: attempts to recover too much of the deficit may lead to some payloads being eliminated that, on efficiency criteria, should fly.

When cost recovery is as important as efficiency, economists sometimes offer a hybrid approach that combines features of the team approach and the LRMC approach. Typically referred to as Ramsey pricing, it seeks to maximize net benefits subject to covering costs. In the case of the space station, if the shuttle were the only way to arrive and depart from the station (shuttle services would be relatively inelastically demanded), Ramsey pricing would involve charging (expected) long-run marginal cost prices for all resources on the station and charging a shuttle price high enough to recover the costs of both the shuttle and the station. Supply is then adjusted, as before, to satisfy demand at these prices. If the shuttle is not the sole access to the station, then the pricing rules are not straightforward. Forming such rules would require extensive demand information which is not and will not be available.

This cost-based pricing organization is not much better than the team structure in pursuing short-run efficiency. First, long-run marginal cost prices will not inform payload designers and operators about current relative scarcities. Moreover, since capacity cannot be adjusted in the short-run (by definition), the cost approach cannot lead payloads to be efficiently designed for short-run operation. Second, since LRMC prices cannot be responsive to supply uncertainties and short-run variations, they cannot provide guidance for mission selection and scheduling or short-term rationing of temporarily unavailable resources.

It is even possible, with multiple outputs, that LRMC prices will perversely affect short-run efficiency. If a resource with a low LRMC has a high variance of supply while another resource with a high LRMC has a low variance of supply, then payload designers are in fact misled by LRMC prices and efficiency may be better served, in the short-run, by ignoring them. Of course, in this case short-run use data should not be used to adjust long-run capacities.

In summary, long-run marginal cost pricing provides no help towards the goal of short-run efficiency. It is no wonder that managers, engineers, and operators of speculative R&D projects with demand variability and supply uncertainty look with some suspicion upon economists' suggestions that prices be set at (expected) LRMC and that supply be produced to fulfill demand at those prices. It is true that, at those rare times when a decision to expand facilities is made, a LRMC pricing policy would have generated valuable information. Nevertheless, decisions must be made each day about scheduling, rationing during operations, payload design and use. These decisions are made in the short-run environment and are the focus of most manpower and management effort. LMRC pricing provides no organizational help in this area and, worse, may actually impede efforts.

This organization and allocation mechanism does accomplish long-run efficiency, however, but only under these conditions: if the required cost information is available, if prices are always "updated" with the correct information, if supply and demand uncertainty become small, if all users take LRMC prices as given and are motivated to produce cost-effective payloads, and if the size of the station is adjusted to demand at these prices. Without a significant change in culture, neither the first nor the last two of these requirements will be true for the space station. The first condition will not be true unless design and acquisition procedures are changed. As noted in section II, current cost estimation procedures are primitive at best and misleading at worst. It is predictable that, as in public utility regulation, the process by which the actual value of marginal costs are chosen will be controversial and soon entangled in administrative law. The definition of marginal cost, as well as its measurement, will be questioned. These problems will be made more severe by the multiplicity of resources to be supplied to users.

The second-to-last condition will not be true unless both commercial and NASA science and technology missions are charged for resource use on the station and provided incentives to be cost effective in payload designs. Neither is true on the shuttle. NASA payload designers (the scientists and engineers) are not charged for resource use and are provided little incentive to be cost effective beyond that required to fit payloads on the shuttle. Commercial payload designers do have incentives to be cost effective if charged, but they are usually granted subsidies on the shuttle.

Other Comments. It is only recently that economists have begun to understand the serious effects of uncertainty on the usual implications of the standard models of public enterprises and regulated firms. It would have been simple to have analyzed the uncertainty case following the traditional procedure -- by taking expected values and then repeating the complete information analysis. Unfortunately this is not a legitimate procedure, because the implications of a careful analysis under uncertainty and the ad hoc analysis based on expected values are significantly different whenever the uncertainties are large and the speed of reaction to unexpected events is slow. One needs to develop new techniques to deal with uncertainty.

Benefit-Based Allocation and Short-Run Efficiency: A Custom-Design Approach

This organizational structure and allocation mechanism accepts as inevitable the uncertainties about costs, benefits, demands, and supplies. It also accepts as inevitable the incentives each participant faces. The philosophy is to custom-design the organization to achieve short-run efficiency and then, if possible, long-run efficiency subject to the information and incentive constraints. This is not done by adding more monitoring, more managers, or more accountants. Instead, it is done through harnessing natural behavioral forces to minimize organizational costs. As with the previous two structures, there are many possible variations but I will describe the general outlines as stylized facts to stimulate discussion.

Description. The pricing policy associated with this mechanism is oriented towards the efficient use of the initial operating configuration (IOC) of the space station. It is accepted that, because of uncertainties in the housekeeping technologies, supply will be uncertain, service interruptions may occur, and significant uncertainties will underlie both the operating costs and the benefits to be derived from any particular mission. There is an "optimal" allocation mechanism for environments similar to this: the priority auction, in which users bid for priority in the use of randomly provided resources.[10] There are a number of variations which could be explored. Two promising designs, based on the principles of demand revelation, have been subjected to theoretical and laboratory evaluation.[11] I will describe one for which the process is simple and could be managed as a "public auction" through an online, real-time computer bulletin board. In this mechanism, each user states a resource demand vector, a priority classification, and a bid. As in the English auction described earlier, a user displaces one or more current holders of positions in that priority class if the amount of his bid is higher than those he must displace to make room for him. All bids are considered binding once made and, at the end of the auction (when there are no improving bids after a pre-specified period of time), the final position holders determine the allocation. Each pays the price he bid and receives the priority allocation he requested. Those who are in the higher priority class are scheduled first and are the last to be "bumped" if resources become temporarily unavailable. The mechanism produces a full set of contingent plans consistent with users' risk preferences, and short-term reallocations are reasonably efficiently planned. To increase efficiency somewhat, a lower bound equal to short-run marginal cost could be placed on the bids if such a number is discoverable (which it may not be unless it is zero).

In this mechanism, the auction has replaced both the committee and marginal costs as allocator of resources and price setter. Growth and evolution decisions, however, must still be made to determine changes in capacity. While there remains some theoretical and experimental work to do, it appears that the natural mechanism, which complements the priority auction, is to use the information in the bids of the short-term priority auctions to infer the marginal benefit of an increase in any resource. This observation is especially true for a priority auction variation which requires separate bids on each resource. For example, comparing the bids for high-priority manpower to bids for high-priority use of unmanned platform space, and a comparison of both of these bids to the proposed costs of providing more manpower or more platform space, could provide invaluable information for manned versus unmanned decisions. The mangers of the space station could announce (given Congressional approval) a willingness to pay any contractor an amount equal to that marginal benefit for additional units. If a contractor agreed to supply at that price, then expansion would occur in an efficient direction. If several contractors were to agree, one could select according to other desirable criteria. There would be no need to measure either the costs or the profits of contractors; however, one would need to measure performance. There would be no need to request benefit information from users.

Ideal Conditions. Under some conditions the priority auction mechanism may be successful in the pursuit of its goals. The mechanism will perform best if there are supply uncertainties. If supply and demand are certain, however, there is nothing to bid for except the scarce resources and bids will be lower. With uncertainty, some users are willing to pay a premium for priority service. In fact, high benefit missions will be willing to bid more than low benefit missions. Therefore, if supply is uncertain, the priority auction does elicit valid information about the relative benefits of various potential missions and does allocate resources efficiently to the highest benefit missions.

The process requires that users not collude in a way that prevents bids which otherwise might be made. As with any auction, such as the English auction discussed in section II, if the users with the highest and second highest values collude, the highest value bidder can obtain the item for a price equal to the third highest value plus a small payment to the second highest bidder, who simply never bids. Of course, the two highest bidders must be able to identify themselves to each other before the auction and to enforce their agreement. This is easier in oral auctions than in sealed bid auctions.[12] Note that although the revenue received by the seller is less when these buyers collude, the item is still allocated efficiently. Thus short-run efficiency is not affected. However, the information needed for long-run efficiency is degraded and capacity will expand less than is desirable. (It should be recognized that not only auctions, but committees and other mechanisms are also potentially manipulable by these types of coalitions.)

Performance for the Space Station. Let us look at the effect of this organization on the pursuit of the goals of cost recovery and efficiency. Total cost recovery will not necessarily be achieved since the pricing mechanism is insensitive to cost information (hence the shortfalls must be covered by way of some other device). Nevertheless, one of the theoretical properties of this mechanism is that it does raise most of the revenue possible given the incomplete information about benefits and the desire to allocate efficiently. This theoretical possibility has been shown also to be true in the laboratory.[13] While we do not know whether this process extracts the maximum revenue consistent with short-run efficiency, we do know that a significant contribution will be made towards the cost of the project.

This organization and allocation mechanism does accomplish much of what it is designed to do in assuring a short-run efficient allocation of station resources. As indicated earlier, the process elicits information (bids, proposed allocations, and priorities) in such a way that higher benefit missions tend to bid higher and therefore are assigned a higher priority use of resources. The difference between this mechanism and a committee process is that the users determine the bids and priorities and have an incentive to correctly reveal their beliefs about the benefits. Since most of the operation of the space station will occur in the short-run context, the ability of any mechanism to accomplish a major portion of short-run efficiency means that more missions will fly and that these will be high benefit missions: for example, more science and more commerce will occur.

It is theoretically possible that 100 percent short-run efficiency can be achieved. For the limited experimental situations we have analyzed, at least 80-90 percent efficiency is achieved when this mechanism is used. This is a significant improvement over the 55-65 percent efficiency achieved through a posted-price policy with a first-come, first-served priority scheme. Interestingly, the key advantage of the priority auction as exhibited in the laboratory is not that this auction selects "better missions" but that it leads to a choice of payload designs that "fit better" and that, as a result, leave room for missions that otherwise would not fly. More missions and more benefits are thus achieved at the same cost. Work is currently underway at Caltech to improve the performance of the auction and to test its capabilities in wider experimental environments.[14] In addition, there exists supporting evidence of the increase in efficiency based on another set of space station experiments.[15] Based on existing data, we feel that the priority auction represents a significant potential breakthrough in the short-term management, scheduling, and planning of interruptible services such as those planned for the space station.

The theoretical and experimental performance of this mechanism with respect to long-run efficiency is still not completely understood. The research is straightforward and feasible (some directions are given in the appendix), but we have postponed it. We believe that the short-term properties are more important since they address the major sources of extensive inefficiency; moreover, this is the area in which imaginative and systematically designed mechanisms can offer the most improvement over current operating and management methods. The research question for long-term efficiency involves the following issues: whether accurate long-term marginal benefit information can be extracted from the bids made in the short-run priority auction; whether the use of this information has a deleterious effect on its quality; and whether the information improves the design and acquisition process. Preliminary work leaves us optimistic that such user-driven growth and expansion is not only desirable but possible.[16]

Table 2 summarizes this discussion of user-driven pricing and alternative organization forms.

Other Comments. Why would any large organization adopt new ways of operating that were designed by outsiders who may "really not know the business"? Reeducating individuals in the organization may be costly, and one always knows how to use the existing system to pursue one's ends. Why take a risk on an untried system especially if the transition costs are high?

Traditionally the burden of proof has been on the challenger of the old system. It is my opinion that this tradition is slowly yielding to new possibilities. The availability of increasingly sophisticated and realistic experimental "test beds" can provide the decisionmaker with convincing data about the comparative performance of the existing mechanism and its challenger. The analytically tractable, theoretically desirable, weird-sounding organization (dredged from the imagination of some ivory-tower designer) can be tested, adjusted, revised, and retested to be made compatible with the actual circumstance of the environment. Potential difficulties, such as large uncertainties,

Table 2. Summary Comparison of Three Organizations

	Allocated Cost Recovery	Marginal Cost Based Pricing	User-Driven Pricing
INTRODUCTION			
Philosophy	team effort engineer's choice hands on	mimic market economist's choice indirect control	mechanism design my choice user control
Primary goal	feasibility	long-run efficiency	short-run/long-run efficiency
Orientation	builder	user	user
Information Used	technology-based	cost-based	benefit-based
DESCRIPTION			
Pricing Policy	Shuttle + % deep discounts	post ExLRMC	negotiated priority contracts
Resource Allocation	committee	?	contracts
Evolution	cost/benefit studies	fulfill demand	impute benefits
IDEAL CONDITIONS	team players	team players or net-benefit maximizers	team player or net-benefit maximizers
	known and shared goals	accurate cost info.	random supply
	common info.	stable resource supply	modular design
	no information-processing constraints	linear cost structure easy to expand	accurate reliability of information
PERFORMANCE			
Source of Problems	ignores benefit data and operations	ignores reliability and maintainability	
Cost Recovery	?	no	some
Short-run Efficiency	no	no	yes
	payloads too small payloads do not conserve on critical resources contingencies are unplanned		
Long-run Efficiency	no	yes if all pay and minimize costs	yes

which have generally been casually assumed away by both economic theorists and practitioners, can now be confronted in a more systematic fashion.

IV. Conclusions

The design of organizations to pursue goals such as efficiency must be sensitive to three aspects of the environment: technical and engineering circumstances, information dispersion, and the motivations of the members of the organization. The space station, as a public pioneer project on the cutting edge of new technology and outside of the discipline of the marketplace, illustrates many of the difficulties involved. As we have seen, neither the team structure favored by engineers nor the cost-based pricing policy favored by economists is adequate for the task of efficient management of the station. The former ignores motivations, incentives, and information-processing constraints; the latter ignores limitations and uncertainties inherent in information and technical engineering aspects of the station. Because of these inadequacies, I have described a third alternative, based on priority contracts, which promises to perform significantly better than the other alternatives in the uncertain environment of the station. It is possible that even better alternatives could be found through a systematic, coherent research program.

Let me conclude with two opinions which I strongly hold as a result of my analysis of the economics and management of the space station.

A. It is time for a cultural change in the management of large public R&D projects, such as those undertaken by NASA. The "seat of the pants" operations based on historical accident must be replaced with a systematic approach to the pursuit of goals. Forcing new projects into old management structures, such as organizing the space station along the lines of the organization created for Apollo, will be inefficient and will retard scientific and technical advancement. Similarly, the continued addition of more manpower (auditors, monitors, and other layers of managers) will not overcome the handicap of an inappropriate organization. Just as the attempt to use 500,000 men to make an automobile fly is doomed to failure because of physical laws, so the attempt to use more men to find the "true" cost and technology of the space station is doomed because of behavioral laws. *Creative and imaginative management and economics is absolutely necessary to the successful pursuit and encouragement of creative and imaginative science and engineering.*

B. We need an extensive research and training program to upgrade the analytic policy skills of both engineers and economists to enable them to cope with the requirements of managing research and development that is on the cutting edge of technology. Moreover, discoveries in economic theory and methodology during the 1970s and 1980s provide foundations for the design of appropriate organizations. Further research in areas such as information economics, implementation and incentives, and experimental economics is vital. Funding the development of new technology without the simultaneous development of appropriate management tools is foolhardy and short-sighted. The benefits to society of advances in our ability to manage large public projects such as the space station are as extensive and far-reaching as advances in hardware. *Research on organizational design must be expanded if our scientific and technological visions for the future are to be realized.*

APPENDIX: A PRICING PRIMER

I. Introduction

This relatively self-contained but terse appendix presents a simplified version of the basic analytics which underlie the discussions in the main text. For many economists this presentation will be familiar (except perhaps for environments F,G,H, and I, below) since it is designed to summarize and emphasize, for non-specialists, basic principles and implications. I have tried to minimize the abstraction and have provided references to papers where detailed versions can be found. Readers wishing to find out more about models of public enterprises in general, especially in situations under certainty, should read the excellent, relatively non-technical analysis by Reese (1984).

II. Basics

The following list identifies the variables and other components of the basic model we will analyze. Addditional detail related to the space station is available in Ledyard (1984). Capital letters denote variables and functions related to the space station itself; lower case letters represent the analogous variables and functions for payloads.

Variables (can be multidimensional vectors)

$i = 1,\ldots,m$	*payload names*
D,d	*design parameters* (Station: number of windows, single or dual keel, number of bunks for the crew, size and type of power system) (Payload: volume, weight, ac or dc)
S,s	*operations parameters* (Station: number of scheduled shuttle launches, crew size, number of quality control inspectors, short-term reconfigurations) (Payload: self-supplied power, logistics, transportation, and spare parts)
R,r	*station resources available for users* (kilowatts of power, megabytes of data, manpower, pressurized volume, station-provided transportation on the shuttle)
G	*growth design parameters* (long-term station additions and reconfigurations)

Functions (dollars are expressed in present discounted values)

F(D),f(d)	*capital costs*
F(D + G)-F(D)	*additional cost of growth*
V(D,S,R), v(d,s,r)	*operations costs*
W(D,G,R,S,T)	*additional operations costs due to growth* where T is the date of growth, $W = g(T)\{V(D + G,S,R) - V(D,S,R)\}$ and $g(T) = (1 - e^{-it})$ (i is the rate of interest)

$b(d,s,r)$	*payload benefits* (relative to the next best use of these resources -- willingness to pay)
$n(d,s,r)$	*net payload benefits* where $n = b - f - v$
$R = H(D,S) \geq 0$	*housekeeping constraint* Let $X(D,S)$ be the gross outputs of station resources produced with design D and operations parameters S. Let $h(D,S,X)$ be the housekeeping requirements, the resources needed to maintain the station. Then $H(D,S) = X(D,S) - h(D,S,X(D,S))$
$\sum_{i=1}^{m} r^i \leq R$	*resource constraint*

Timing

Decisions are implemented in a time sequence dictated by the engineering circumstances. The timing of implementation is modeled by identifying four phases of the space station lifecycle:

	I	II	III	IV
Phase Name	Design	Manifest	Operations	Growth
Decisions to Be Made	D	d	R,S,r,s	G

Information

One of the basic constraints faced by the organizational designer is the initial distribution of information. If everyone knew everything necessary to make decisions in a way that is compatible with organizational goals, then there would be no organizational problem. If everyone does not know what is necessary, then information transmission is a necessary first step towards desired organizational performance. This is illustrated for the goal of efficiency on the space station in the following table.

INFORMATION STRUCTURE

Decisions Made By	**Chooses**	**Knows**	**Needs to Learn**
Station Designer	D,G	F,H	V,n
Station Manifester	Payloads	Nothing	n,R
Station Operator	R,S,r	V	n
Payload Sponsor	Budgets	b	n,r,s,d
Payload Designer	d	f	v,b,r,s
Payload Operator	r,s	d,v	n

Motivations

The other constraint faced by organization designers is the behavior of the decisionmakers. This behavior (how they react to organizational changes) is predictable once we know their motivations.

For this paper we assume that station designers, manifesters, and operators (jointly called station management) try to make decisions which further efficient design, operation, and use of the station.[17] With respect to users, we will consider three types of motivations.

a) *Efficiency.* We will explicitly define efficiency below. For now we simply note that the characterization of user behavior as the pursuit of efficiency is meant to capture the motivations and behavior of those whose goals are identical to station management (for whatever reason). Such users would, for example, willingly implement any action proposed by and provide any information requested by station management. For these users there is no incentive problem.

b) *Net-benefit maximizers.* This model is intended to capture the behavior of most non-NASA users of the space station, particularly that of commercial (profit-oriented) users. The model of behavior is simple and widely accepted among economists. If net-benefit maximizing users are assigned an allocation of station resources, r^i, they will then choose d^i and s^i to

(1) Maximize $n^i(d^i,s^i,r^i)$.

If instead they are presented with a payment schedule $t^i(r^i)$ to be paid to NASA for an amount r^i of resources for payload i, they will want to choose d^i, s^i, and r^i to

(2) Maximize $n^i(d^i,s^i,r^i) - t^i(r^i)$.

c) *Internal users.* This model is intended to capture the behavior of NASA-sponsored payloads within the current organizational structure. It is assumed that the user is given a budget, β, for payload expenses and is also told he will be "rated" on the basis of how well he keeps total payload costs low according to a performance measure c - f - v - t, where c is a cost target.[18] It is assumed that the payload manager cares both about the scientific benefits to be obtained from the payload and about the cost performance measure but not necessarily with equal fervor. An internal user will want to choose d,s and r to

(3) Maximize $u(b(d,s,r), c - f(d) - v(d,s,r) - t(r))$
subject to $f(d) + v(d,s,r) \leq \beta$

where the (utility) function u(b,m) is intended to capture the payload manager's view of the desirability of the scientific benefits b relative to the cost performance measure m. The function u will be different for different managers.

III. Environments and Analysis

The optimal choice of an organization depends on the particular situation within which that organization is to function. The designer of the organization is presented with an information structure and with the motivations of the participants, neither of which he can easily alter. Given these facts, called the *environment*, the designer's task is to choose those rules of communication and allocation which yield desirable solutions. We illustrate this process by considering nine different examples of theoretical space station environments and a recommended organization for each. We will analyze the possibilities for the design of organizations (pricing and allocation rules) in the pursuit of aggregate efficiency in each environment. Although there are fundamental conflicts between operators, contractors, and users of the space station, for this paper we will assume that space station management, including designers, operators, and contractors, agrees with the goal of efficiency. We will therefore only consider variations in the motives of the users and leave the analysis of organizational solutions which accommodate the actual circumstances of designer, operator, and contractor motivations to additional research. We will consider the three possible user motivations described earlier in the context of four information structures which depend primarily on what is uncertain. These four are: no uncertainty, station costs uncertain, station costs and technology uncertain, and everything (station costs and technology, payload costs and payload benefits) uncertain. The key to efficient design and use is the orderly and incentive compatible[19] transfer of the information from those who know to those who need to know.

We will generally split the analysis into two parts: operations (phases II and III) and design (phases I and IV). The major distinction between these parts is that during operations (the "short-run" to economists), the design variable D has already been chosen and cannot be varied, whereas during design (the "long-run" to economists), all decision variables can be altered.

Environment A: (no uncertainty, users seek efficiency)

In this environment (1) there is *no* uncertainty about the benefits, costs, or technology associated with the space station and its payloads, and (2) all participants are in pursuit of the same goal, efficiency. We first formalize this common goal and then describe an incentive compatible organization which can accomplish it.

Operations. Given a collection of decisions, explicit values of D,R,S, and (for each i = 1,2,3,...) r^i, s^i, and d^i, the *net life-cycle benefits of the space station and its payloads* are calculated as

$$(4) \quad [\sum_{i=1}^{m} b^i(d^i,s^i,r^i) - f^i(d^i) - v^i(d^i,s^i,r^i)] - F(D) - V[D,S,R].$$

During operations, the value of D has already been determined; decisions can be made only with respect to the other variables. Short-run efficiency in operation and use of the space station is equivalent to choosing R,S,r,s, and d to

$$(5a) \quad \text{Maximize } [\sum_{i=1}^{m} n^i(d^i,s^i,r^i)] - V(D,S,R)$$

subject to

$$(5b)\ R = H(D,S) \geq 0$$

and

$$(5c) \quad \sum_{i=1}^{m} r^i \leq R.$$

Since everyone is assumed to want to solve this maximization problem, the organizational design problem is trivial. All payload managers are told to report their true net benefit function, n^i, to the station management. Station management then solves the maximization problem and reports the appropriate values of d^i,r^i and s^i to the manager of payload i who implements those choices. Under this scheme payload managers have an incentive to report the requested information correctly, station management has all the information it needs to compute the efficient allocation, and payload managers have an incentive to implement the station management's choices.

If cost recovery is important, then the station management can also assess charges t^i to each user where, for each i, $n^i - t^i > 0$ evaluated at the assigned values. Users have the information they need to make these calculations and, since users are assumed to have the station goals as their motivation, this assessment will not change behavior.

There are also simpler organizations that would demand less information transmission and still perform efficiently in this environment. One possibility is in environment B, below. This possibility is of interest since the maximization problem we have required the station management to solve in our design may be "too large and complicated" to solve; alternatively, the functions we have asked the payload managers to communicate may be too complex and difficult to describe. We do not describe these simpler organizations since the true space station environment is significantly different from that of this section.

Design and Growth. In this environment design and growth are really the same problem because of the lack of uncertainty. Consider phase I and the choice of D. Let N(D) be the value of the maximum in (1) if D is the design. It is easy to show that long-run efficiency in design and operation requires that D be chosen to

(6) maximize $N(D) - F(D)$.

Thus efficiency requires "solving backwards in time" as in dynamic programming. If the organization described under Operations is initiated *prior to design decisions* then it will yield long-run efficient decisions. If the information about N(D) is not available, then design will in general not be efficient. If our interest is in efficiency, this necessity to use information about plans for operations' phases II and III to inform decisions for design in phase I will be a recurring theme throughout the rest of this discussion.

Environment B: (no uncertainty, users seek net benefits)

In this environment (1) there is no uncertainty about the benefits, costs, or technology associated with the space station and its payloads, and (2) payload designers and operators are interested in the maximization of the net benefits to their own payload while contractors, designers and operators are in pursuit of efficiency. These assumptions differ from A only in the motivations of the users. Let us see how these motivations affect the performance of particular organizational designs.

1. *Team.* First, reconsider the team organization in A in which the payload manager reported n, the center computed the efficient allocations and the payload manager implemented the decisions. It is easy to show, for these rules, that a payload manager motivated to maximize net benefits can do better (i.e., attain higher net benefits) if he reports a function other than his true one. Suppose, for example, that the manager of payload 1 contemplates announcing the function $(1+\alpha)n(d,s,r)$ instead of $n(d,s,r)$ where the superscript i has been suppressed and α is some number with $\alpha = 0$ representing the truth. The station management will then choose $S(\alpha), R(\alpha), r^1(\alpha), s^1(\alpha), d^1(\alpha)$, etc. to maximize

$$(7) \qquad \alpha\, n^1(d^1,s^1,r^1) + \left[\sum_{i=1}^{m} n^i(d^i,s^i,r^i)\right] - V(D,S,R),$$

$$\text{subject to } R = H(D,S) \geq 0 \text{ and } \sum_{i=1}^{m} r^i \leq R.$$

It is a fairly common exercise in comparative statics to show that

$$\frac{\partial n^1[d^1(\alpha), s^1(\alpha), r^1(\alpha)]}{\partial r} > 0, \text{ if } \frac{\partial n^1(\alpha)}{\partial r^1} \neq 0.$$

That is, 1 can raise his net benefits by overstating the benefits or understating the costs of his payload for any design, as long as he is not already at his unrestricted optimum. This incentive to report other than what has been requested means the organization is not incentive compatible. When all net-benefit maximizing managers follow this strategy, total net-benefits will be grossly overstated and the final resource allocations will usually not be efficient. In addition, the information needed to make the correct station design decisions will not be available. Overstatement of benefits will lead to a decision to build too large a station. The team design, which performed efficiently in environment A when all users were motivated by efficiency, performs inefficiently if users are net-benefit maximizers (see Groves (1973) or Marshak and Radner (1972) for more details on teams).

2. *Vickrey's "Demand Revealing Mechanism"*. One can counteract the incentive incompatibility of the team design in this environment by recognizing that the net-benefit maximizing payload manager will change his decisions and provide different information if he is charged for station resources. Knowing this, through the appropriate choice of "pricing policy" we can guide his decisions and those of the station management towards efficiency in an incentive compatible fashion using an organization first discovered by Vickrey (1961). It has a particularly simple form if cost recovery is not an issue.[20]

Operations. Each user will be given an allocation r^i and then solve (1). Let $\Phi^i(r^i)$ be the value of that maximum. Each user is asked to report the entire function $\Phi^i(\,)$ to the station management. The station accepts these reports as correct and chooses the allocation r and station variables R and S to solve

$$\text{(8)} \qquad \text{Maximize } [\sum_{i=1}^{m} \Phi^i(r^i)] - L(D, \sum_{i=1}^{m} r^i), \text{ where}$$

$$\text{(9)} \qquad L(D,R) = \min_{S} V[D,S,R], \text{ subject to } R = H(D,S).$$

The station charges each user

$$t^i = L(D, \sum_{i=1}^{n} r^i) - \sum_{\substack{j=1 \\ j\neq i}}^{n} \Phi^j(r^j)$$

evaluated at the solution to (8) and (9). Under these rules, short-run efficiency (given the design D) will occur in one iteration since it is an optimal response for net-benefit maximizing users to send their true net-benefit functions *no matter what the other users do*, as the charge depends on their information only through the choice of R and r.[21]

One major drawback is the possibility that the functions Φ are too complex to describe. We are currently conducting research on an iterative version of this mechanism, requiring simpler point messages, and its applicability for deciding manifesting and operating allocations in environments even closer to that of the space station than in this section. (This experimental environment is detailed in Banks, Ledyard and Porter (1985a)). Another drawback is that there is a potential financial problem with the Vickrey rules, since each user receives an amount almost equal to the aggregate net-benefits of the project. One can avoid this without destroying incentives through the use of lump-sum transfers. Let

$$t^{*i} = t^i + \max_{r}\{[\sum_{\substack{j=1\\ j\neq i}}^{m} \Phi^j(r^j)] - L(D, \sum_{\substack{j=1\\ j\neq i}}^{m} r^j)\}$$

and note that the term added to t does not depend on i's information, Φ^i. If users are charged t^*, tax revenues will be positive and incentives will not be affected.

Design. The Vickrey mechanism can be easily adapted to the design phase by choosing D and S to solve

$$(10)\quad L^*(R) = \min_{D,S} F(D) + V(D,S,R), \text{ subject to } R = H(D,S).$$

and substituting the long-run cost function L^* for the short-run cost function L in the computation of the tax t or t^*. If the mechanism is instituted during phase I and if the users' information, Φ, is used as in (8), (9), and (10), then long-run efficient design, operation, and use will result in this environment.

3. *Posted Prices (Marginal-Cost Pricing).* If there are a large number of potential users, each of whom will not be a major consumer of station resources, then one may be able to produce an approximately efficient allocation of resources with a more traditional and familiar pricing structure. In this form of organization the station management posts a price, p, per unit for use of station resources and then states that it will charge each user $t^i(y^i) = py^i$. The payload manager then reports his desired resource use, r^i, to the station management which adds up the requests to compute $R = \sum_{i=1}^{m} r^i$, the aggregate demand at those prices. At this point, many variations are possible. We consider three possibilities under the assumption that users believe they cannot affect prices.

Operations. Remember (short-run) efficiency is equivalent to solving problem (5). Since users will choose r^i to solve (2), it must be true that

$$\frac{\partial n^i}{\partial r^i} = p.$$

Therefore, for r and R to solve (5) it must be true that

$$p = \frac{\partial L(D,R)}{\partial R}$$

when L is evaluated at the stated demands at these prices.[22] It would be a remarkable stroke of luck if prices chosen arbitrarily led to demands which satisfied this property. One must, therefore, either design the organizational structure to generate posted prices appropriate for efficiency or else be prepared to allocate resources to users in a pattern which is different than they requested.

One organization that will not ration resources efficiently is a committee. Because users have no real incentives (remember they are net-benefit maximizing users) to provide such a committee with accurate information on the relative costs and benefits of any changes in the assigned resources, the committee will be able only to use criteria such as "find the best fit" or "first-come, first-served." If users know that this is to be the method of resource allocation then their demands at the posted prices will not solve (2). For example, if payload fit is to be the criteria then users will create smaller than efficient payloads. This natural response by users has, for example, created excess demand for middeck volume on the shuttle. Although there are no known general results, efficiencies of only 50-60 percent have usually occurred in experimental "test bed" analyses of this type of organization.

It is relatively easy to reconfigure the station design and if the cost structure is linear (i.e., if $\frac{\partial^2 L}{\partial R^2} = 0$ for all R), then there is a standard solution to the organizational design problem (see, e.g., Toman and Macauley [this volume]). Given R and D, reconfigure the station by picking G to solve

$$(11) \qquad \text{Minimize } L(D + G,R) - F(D+G)$$

where L is given by (9). Under our assumptions, from section II, if $D' = D+G$ is the solution to (11) then D′ solves (10). If prices are chosen initially so $p = \frac{\partial L^*(R)}{\partial R}$ (long-run marginal costs (LRMC)), and if G is set to solve (11) then this organization will perform efficiently in both the short-run and long-run. The proof is not too difficult to follow once one recognizes that these organizational rules "create" the appropriate first-order conditions. Taking prices as given, the payload users will solve (2) and choose r^i to solve $\frac{\partial n^i}{\partial r^i} = p$. Since $p = \frac{\partial L^*(R)}{\partial R}$ it follows that the allocation r satisfies the first order conditions for (5).[23]

If it is not easy to reconfigure the station, which seems to be more likely or if costs are not linear in R, which seems to be true, then flexible prices are a necessity during operations if efficient use is desired. Given a design D and given that growth cannot be immediately implemented, we know from above that efficiency requires prices be equal to short-run marginal cost, $\frac{\partial L(D,R)}{\partial R}$, evaluated at the quantities demanded at those prices.

those prices.[24] To achieve that equality by choosing the correct allocations, iteration of information is necessary between users, who will choose r and s, and station operators, who will choose R and S. That is, station management must post prices, users return demands, management post new prices, and so on until an equilibrium is found. Without such iteration, posted pricing will result in less than efficient operation and use.

Design. If marginal costs are constant for all R then the original design choices D in phase I could have been made in the same way as G above. That is, station management posts marginal cost prices (which can be calculated independently of R because of the linearity), gets users' demands at those prices, then chooses G as in (11) with D = 0. Only one iteration is necessary and there would be no need to readjust designs later.[25]

If marginal costs are not constant then, as in the operations phases, iteration is necessary if efficiency is to be achieved. Management posts prices. Users compute r. Management calculates $R = \sum_{i=1}^{m} r^i$ and then calculates D using (10). Management then posts new prices with $p = \frac{\partial L^*(R)}{\partial R}$. This continues until no revisions in p or r are desired. In the steady state this organization, called long-run marginal cost pricing, performs efficiently if users always state their demands for r under the assumption that prices will not change and that they cannot affect the prices.[26] If stopped prior to achieving a steady state, marginal cost pricing performs less than efficiently.

***Environment* C:** (no uncertainty, users seek benefits)

In this environment (1) there is no uncertainty about the benefits, costs, or technology associated with the space station and its payloads, and (2) payload designers and operators are interested in the maximization of the benefits to their own payload, tempered somewhat by cost considerations, while all others are in pursuit of efficiency. This differs from A and B only in the incentives of the users.

One immediate implication of these motivations is that there is no organization which will perform efficiently. A manager who behaves according to (3) will choose his decisions to satisfy

$$\left(\frac{\partial u^i}{\partial b^i}\right)\left(\frac{\partial b^i}{\partial d^i}\right) + \left(\frac{\partial u^i}{\partial c^i}\right)\left[-\frac{\partial f^i}{\partial d^i} - \frac{\partial v^i}{\partial d^i}\right] - (\lambda^i)\left[\frac{\partial f^i}{\partial d^i} + \frac{\partial v^i}{\partial d^i}\right] = 0$$

$$(12) \qquad \left(\frac{\partial u^i}{\partial b^i}\right)\left(\frac{\partial b^i}{\partial s^i}\right) + \left(\frac{\partial u^i}{\partial c^i}\right)\left(\frac{\partial v^i}{\partial s^i}\right) - (\lambda^i)\left[\frac{\partial v^i}{\partial s^i}\right] = 0 \text{ and}$$

$$\left(\frac{\partial u^i}{\partial b^i}\right)\left(\frac{\partial b^i}{\partial r^i}\right) + \left(\frac{\partial u^i}{\partial c^i}\right)\left[-\frac{\partial v^i}{\partial r^i} - \frac{\partial t^i}{\partial r^i}\right] - (\lambda^i)\left(\frac{\partial v^i}{\partial r^i}\right) = 0$$

where λ^i is the Langrangian multiplier associated with his budget constraints. For efficiency it is required that

$$\frac{\partial b^i}{\partial d^i} - \frac{\partial f^i}{\partial d^i} - \frac{\partial v^i}{\partial d^i} = 0$$

$$(13) \qquad \frac{\partial b^i}{\partial s^i} - \frac{\partial v^i}{\partial s^i} = 0, \text{ and}$$

$$\frac{\partial b^i}{\partial r^i} - \frac{\partial v^i}{\partial r^i} = \frac{\partial L^*}{\partial R} \quad \text{[from (5)].}$$

Thus efficiency will obtain under (12) if and only if β^i and c^i, as well as the pricing rule t^i, are chosen for each i such that

$$(14) \qquad \frac{\partial u^i}{\partial b^i} = \frac{\partial u^i}{\partial c^i} + \lambda^i \text{ and } \frac{\partial t^i}{\partial r^i} = \left(\frac{\partial L}{\partial R}\right)\left[\left(\frac{\partial u^i}{\partial b^i}\right)/\left(\frac{\partial u^i}{\partial c^i}\right)\right].$$

Unless $\left(\frac{\partial u^i}{\partial b^i}\right)/\left(\frac{\partial u^i}{\partial c^i}\right)$ is the same for all payload managers across all possible payload designs and operations, which is highly unlikely, each user must be subjected to a different pricing rule to achieve efficient use. Further, that rule must depend explicitly on i's utility function, the value of which is known only to i and not to station management. It is my conjecture that it is impossible to design an organization that provides the appropriate incentives to payload designers, with motivations described by (3), to transfer their information to station management in such a way that efficiency results.

It is true that if we redefine efficiency to include the preferences of the payload managers then we can find organizations that do the job, but I do not think it is correct to approach the problem in that way. The motivations described by (3) were intended to capture the behavior of an internal NASA payload manager who represents Congress. It is therefore the preferences of Congress that should be used in evaluating efficiency, not the preferences of their representatives. Those preferences are net-benefit maximizing for each payload if Congress wants to maximize the benefits to science from its total expenditures. Therefore, rather than redefining efficiency, the correct approach would be to change the internal operating procedures of NASA by changing the incentives and opportunities faced by payload managers. With a change in their motivations, one would then have some hope of efficiently designing and using the space station.[27]

Since efficiency seems to be impossible to achieve if payload managers are motivated primarily by benefits and are able to ignore costs, I will not analyze environments with these motivations again in this paper. Instead let me turn to the influence of information and uncertainty on the choice of an organization.

Environment D: (costs uncertain, users seek efficiency)

In this environment (1) there is no uncertainty about payload net-benefits or station technology but there is uncertainty about the costs of station design and operations, and (2) payload designers and operators and station management are assumed to be in pursuit of efficiency. This differs from A only in the assumption of knowledge about costs.

The easiest way to model uncertainty is to assume the existence of a random variable, w. This variable represents the complete state of the world and may only be partially known by some of the agents. Variable w has a density function $\pi(w)$ which represents all participants' *common knowledge and beliefs*. Station costs are now represented by letting capital costs be F(D,w) and operating costs be V(D,R,S,w). All other functions remain the same.

One of the complications created by uncertainty is that time is now important. In particular, we must keep track of the time at which new information is learned, since actions taken before that time cannot depend on that information but actions taken later can. Decisions can be made *contingent* on information before it is known, however. This fact will be very important as we proceed. Although more generality is possible, for ease of exposition I will assume that decisions are made in two periods: today and tomorrow. Today, design parameters D and d^i will be chosen. Tomorrow w will be known to the station management, but to no one else, and R,S,r and s will be chosen. This means that the decisions made tomorrow can depend on the value of w.[28]

Because of the inclusion of uncertainty we need to revise our formalization of efficiency. Characterizations such as (5) are no longer valid. The correct approach follows from dynamic programming and solves the maximization of "expected" net benefits "backwards." To see how this works, suppose that it is tomorrow. D and d will have already been chosen, w will be known, and it is now time to choose R,S,r and s. The *realized (present discounted value) of net benefits* to be received from any such choices can be calculated as

$$(15) \quad P(D,R,S,d,r,s,w) = [\sum_{i=1}^{m} n^i(d^i,r^i,s^i)] - F(D,w) - v(D,S,R,w).$$

Efficiency requires the choices of R,S,r and s be made to maximize (15) subject to (5b) and (5c). This yields a *decision rule* for R = R(D,d,w) and similar decision rules for the other variables. Let the value of the solution to that maximization be $P^*(D,d,w)$. Now return to the decisions today. D and d must be chosen *before w is known*. This is a decision under uncertainty and, while there are many models of such decisionmaking, I will make the common assumption that all decisionmakers are risk-neutral, expected utility maximizers. This implies that efficiency is equivalent to the maximzation of *expected net-benefits*.[29] Thus, long-run efficiency requires the choices of D and d to

$$(16) \quad \text{maximize} \int P^*(D,d,w)\pi(w)dw.$$

In effect, the efficiency problem can be solved completely today through a choice of decisions D and d and of decision rules for R,S,s and r contingent on w. The implementation of that solution involves doing D and d today, observing w tomorrow, and then following the appropriate actions as specified in the decision rules.

If there are no capacity constraints on information processing, then the organizational design solution for this environment is effectively the same as that in environment A, the team. Users submit the functions n^i to station management, who then solve (15) and (16) and report the designs, d^i, to the users. After w is observed users are told $s^i(w)$ and $r^i(w)$. Since the users are motivated to pursue efficiency, they have an incentive to provide the requested information and to abide by the solution of the station management, who fully use the information provided in their choice of design, D.

If it is difficult or impossible to process the information transfers required by this team mechanism, then other, perhaps iterative, organizational designs must be considered. One possibility is described in the next section and two additional possibilities are presented in the section covering environment G below.[30] Those discussions assume that users are net-benefit maximizing. Even if they are efficiency-seeking users, the station management need merely tell them to act as if they are net-benefit maximizing (transactions can be implicit rather than explicit). If efficiency-seeking users accept the fact that following the prescribed behavior indeed creates efficient design and use, they will do so. This has the added attraction that it can deal with situations in which some users seek efficiency and some seek net-benefits.

Environment E: (cost uncertainty, users seek net-benefits)

In this environment (1) there is no uncertainty about payload net-benefits or station technology but there is uncertainty about the costs of station design and operations, and (2) payload designers and operators are interested in the maximization of the net benefits to their payload while station management is in pursuit of efficiency. These assumptions differ from environment B only in the knowledge about costs and from environment E only in motivations.

A first attempt at organizational design for this environment might be to modify marginal cost pricing. Can one, for example, post a price today for the resources to be consumed tomorrow, design according to the planned demand given that price, and end up with an efficient allocation? We will show that the answer is yes if and only if the operating cost function V(D,S,R,w) has an additional property beyond those required under certainty. Begin with the usual way to define marginal costs under uncertainty using the *minimim expected life-cyle cost of supplying R,* defined as

$$(17) \qquad E(R) = \min_{D,S} \int [F(D,w) + V(D,S,w)]\pi(w)dw, \text{ subject to } R = H[D,S].$$

Now consider the following organizational design. Station management posts expected long-run *marginal costs* as prices by letting $p = \frac{\partial E(R)}{\partial R}$. User i then chooses d^i and plans r^i and s^i to maximize $\{n^i - pr^i\}$. Station management then sets $R = \sum_{i=1}^{m} r^i$, chooses D and plans for S to solve (17), and recomputes prices p. This process continues until it converges to a steady state. (Remember, as under certainty, iteration will be necessary unless the cost function E(R) is linear in R in which case convergence occurs in one iteration.)

This organization will perform efficiently only under certain conditions. To see what these conditions are, let us again work backwards. Once w is known, efficiency requires the maximization of (15) subject to (5b) and (5c). It is easy to see that this may require R,S,s and r to have different values depending on the realization of w. However, in the calculation of the prices p, the plans for R were independent of w. Consulting (17) one can see that the value of S must then also be independent of w since D is independent. Thus the values of r and s generated by the expected LRMC pricing organization must also not depend on w. The only hope that expected marginal cost pricing is efficient, therefore, is if the efficient allocation tomorrow is independent of w; that is, if

$$(18) \qquad \frac{\partial^2 V(D,S,r,w)}{\partial R\, \partial w} = \frac{\partial^2 V(D,S,R,w)}{\partial S\, \partial w} = 0.$$ [31]

If (18) is true, then (expected) marginal cost pricing performs in this environment in the same way as marginal cost pricing in environment B. If (18) is not true, then under (expected) marginal cost pricing, after w is learned, there will usually be advantageous reallocations which users will be unable to make. One way to correct this would be to allow prices to change, or to implement some other form of rationing and allocation, tomorrow when w is known. In this case, however, one has a different organization and users will, in the process of providing information today, take these future rationings into account. We will consider some possibilities under environment G.

Environment F: (cost and technology uncertain, users seek efficiency)

In this environment (1) there is no uncertainty about payload net-benefits but there is uncertainty about the costs and the technology, and (2) all are in pursuit of efficiency. This differs from environment D only in the assumption of knowledge about technology.

We model this form of uncertainty as in the previous section, with a random variable x. Now, however, it is also the relationship between the station parameters and the supply of services to users that is uncertain. This uncertainty can be due to lack of knowledge about the actual technical relationships or to an uncertain reliability in the demands of the station itself on the resources it produces. Let $R = H(D,S,x)$ represent this uncertainty as it exists today.[32] Costs will also depend[33] on x, represented as $F(D,x)$ and $V(D,S,r,x)$. We let $\mu(x)$ be the density function on x which is assumed to be known to station management. Tomorrow, x will be known to station operators.[34]

We must redefine expected net benefit maximization to correspond with efficiency for this environment. As in the previous section, the problem is solved backwards. Tomorrow, given D and d and having observed x, the (short-run) efficient station and payload decisions, R,S,r and s solve

$$(19) \qquad \text{maximize } [\sum_{i=1}^{m} n^i(d^i,s^i,r^i)] - F(D,x) - V(D,S,R,x) \text{ subject to}$$

$$R = H[D,S,x] \text{ and } \sum_{i=1}^{m} r^i \leq R,$$

Let $Q(D,d,x)$ represent the value of the solution to (19). Using the same model for decisions under uncertainty as above, the (long-run) efficient decisions D,d, and decision rules $S(x),R(x),r(x),s(x)$ solve (18) for each x as well as

$$(20) \qquad \text{maximize } \int Q(D,d,x)\mu(X)dx.$$

Again, as in environment D, if there are no information processing capacity constraints and if there are efficiency-seeking users, we need only request that users send the entire function $n(d,s,r)$ to the station management who then can solve (19) and (20).[35] If there are capacity constraints, then one can mimic the organizations in the next section by asking efficiency seekers to act as if they are net-benefit maximizers.

Environment G: (uncertain cost and technology, users seek net benefits)

In this environment (1) there is no uncertainty about payload net-benefits but there is uncertainty about the costs and the technology, and (2) payload designers and operators are interested in the maximization of the net benefits to their payloads while all others are in pursuit of efficiency. These assumptions differ from D only in the knowledge about technology and from F only in the motivations of users.

Expected long-run marginal cost pricing, as described in the last section, will not perform efficiently in this environment -- either in the short-run or in the long-run -- since it does not allow the flexibility in planning needed to prepare for the various possibilities tomorrow. To see this most easily let us consider the special case in which there are no possible reconfigurations and operating parameters can not be varied. In particular, $S(x) = s(x) = 0$ for all x. When prices p are posted, users choose d and r where $r(x) = r$ is constant for all x. Tomorrow, x is observed, resources available are $R(x) = H(D,x)$, and demand is Σr leaving an amount of $\Sigma r - R(x)$ to ration in some way. Let $\delta(r, \Sigma r, R)$ be the probability that i gets r if the combined orders are Σr and the supply is R. i will then choose r and d to maximize $\int \delta(r, \Sigma r, R(x))[n(d,r) - pr]\mu(x)dx$. If δ is decreasing in r (i.e., larger payloads have a larger chance of being curtailed or rationed), then each i will order a smaller value of r than he would if he knew r would be delivered with certainty. (The proof easily follows from the first order conditions.) Inefficiencies result in this environment. There are, however, at least two other ways to organize to achieve higher efficiency in this environment.

1. *Full Contingent Pricing.* This organization is a natural extension of the marginal cost pricing institution described earlier and is created by introducing a broader set of contracts. One presents a menu of prices, $p(1), p(2), \ldots, p(x), \ldots$, one for each commodity in each possible state, or realization of x. Payment of the price $p_k(x)$ entitles the user to receive one unit of resource k tomorrow *if and only if* state x obtains. Economists call this a contingent contract, the classic example of which is an insurance contract.

Each expected net-benefit maximizing, risk-neutral, price-taking user will try to choose a design choice d^i, a set of contingent contracts $r^i(1), \ldots, r^i(x), \ldots$, at the prices $p(1), p(2), \ldots$, and contingent plans for $s^i(1), \ldots, s^i(x), \ldots$, to maximize

(21) $$\int n^i[d^i, s^i(x), r^i(x)]\mu(x)dx - \int p(x)r^i(x)dx.$$

The probability density is missing from the second integral since $p(x)r(x)$ is paid for each x whether x occurs or not. If there are only a finite number of possible x then that integral and all others over x are really summations[36] over x.

Operations. During operations, D and d have been chosen and cannot be altered, but x is known. Since there is no uncertainty at this point we can omit contingent contracts. We already know, from our analysis for environment A, that if users choose r and s to

(22) $$\text{maximize } n^i(d^i, s^i, r^i) - p^* r^i,$$

if they report r^i to the station management, if station management computes $R = \Sigma r^i$ and chooses S to

(23) $$\text{minimize } V[D,S,R,x] \text{ subject to } H[D,S,x] = R \geq 0$$

and if $p^* = \frac{\partial \Phi(D,x,R)}{\partial R}$ where $\Phi()$ is the solution to (23), then the allocations r and R and the operations parameters S and s will be (short-run) efficient *for each x* for a given D. As we will see below, if contingent markets are used during manifesting and operations planning and if the correct prices are posted for these contingent contracts, then the prices which will generate short-run efficiency during operations will be easy to calculate. In particular, if $p(1), p(2), \ldots, p(x), \ldots$, are the equilibrium contingency prices (defined in the next section on manifesting), and, once x is observed, if $p^* = p(x)/\mu(x)$ then allocations and operations parameters chosen according to (22) and (23) will satisfy

$$p^* = \frac{\partial \Phi(D,x,R)}{\partial R}.$$

If planning is incomplete and prices do not equal short-run marginal cost in x, evaluated at the demands at those prices, then either the demands r cannot be filled or the operations parameters are inefficient. In either case one must then resort to an ad hoc rationing procedure (such as the working groups on Spacelab), accepting lower than possible efficiencies and wasting time and effort recalculating allocations, or one must recalculate prices and iterate between payload designers and station management, again wasting time and effort, until one settles on a steady state. Both alternatives would be better avoided.

Manifesting. By careful and timely planning during manifesting, using benefit and demand information in a systematic fashion, one can significantly improve efficiency and simultaneously avoid the need for extensive reallocations or pricing iterations during operations. We now turn to a design that organizes planning during phase II, after the station design parameters D have been chosen but before x is known and before all other decisions have been made.

Contingent contracts are offered to users at prices p(1), p(2),..., p(x),... . Users choose d and plans for s(x) and r(x) to maximize (21). They report these contingent demands to station management who compute R(x). They then choose plans S(x) to solve (23) with R = R(x). If $p(x) = \left(\frac{\partial \Phi[D,x,R(x)]}{\partial R(x)}\right)(\mu(x))$ for each x then the demands of the users are consistent with the plans of the station management. If not, then price adjustments, iterations between station management and users, will be necessary if efficiency is desired.

In a steady state, the use and operation of payloads and the station *as well as the design of the payloads* will be as efficient as possible given the design of the station. This improves on the efficiency obtained above during operations by guiding the design of payloads towards use of more reliable resources and encouraging flexibility. Further, the plans r(x),s(x),S(x) and R(x), determined *prior to knowing the actual realization of x*, are exactly those decisions indicated by efficient operation in the previous section *after x is known*. Therefore, if manifesting is done with contingent contracts and if prices of these contingent contracts are allowed to adjust in response to demand information generated by those prices, then no new decisions will be necessary during operations. One simply observes x and then implements the appropriate planned actions. No unanticipated reallocations will be needed in this environment.

Design. If we want to achieve long-run efficiency and if growth is difficult or impossible, the station design must incorporate information from manifesting and operations plans. If the contingent markets described above are available prior to the choice of D, during phase I, then full efficiency is possible. As before, we can show that if station management, having been given the users' contingent requirements r(x) for each x, plans operations S(x) to solve (23) given R(x), chooses the design D to

$$\text{(24)} \qquad \text{minimize } \int \{F(D,X) + \Phi(D,R(x),x)\}\mu(x)dx,$$

and posts prices $p(x) = \left(\frac{\partial \Phi[D,x,R(x)]}{\partial R(x)}\right)(\mu(x))$; if users choose designs and operations plans to maximize (21); and if both implement tomorrow the action specified by these contingent contracts, then *in a steady state* design choices today and implemented actions tomorrow will be (long-run) efficient.[37] The availability of contingent demand information allows the station to be designed with appropriate flexibility so that operations can adjust efficiently to information to be learned tomorrow. The availability of contingent contracts allows the same planning and flexibility for users. More bang for the buck is the result.

The primary drawback of this organization is that *all* contingencies must be priced. It is usually very difficult in practice to list all possibilities[38] in sufficient detail, and if the full set of contingencies is not specified, user plans will not be efficient. Evaluating the trade-off between the costs of planning for a large number of contingencies and the efficiency losses from planning for only a small number of contingencies is an empirical question. Another drawback is the necessity that the true state of the world, x, be mutually verifiable after it occurs. Both parties to the contract must be able to agree which contingency has actually occurred.[39] If they cannot, the contracts are meaningless. Both drawbacks are reasons why full contingent pricing is rare in practice although partial contingent pricing is common. For example, one can imagine writing contracts for delivery of station resources contingent only on the availability of those resources. Such a system of contracts is considered next.

2. *Priority pricing.* If the major uncertainty is about the amounts of resources available in each state, there is an alternative to full contingency contracting which can produce efficiency with a simpler set of contracts, called priority contracts. Priorities are numbers $\alpha = 1,2,3,\ldots,$ assigned to resource allocations which are then priced differentially according to the priority with which they are to be delivered. Simplicity occurs partly because no explicit descriptions of the various states, x, are necessary. While there are many variations depending on the timing of the collection of the payments, we consider only one. For each commodity k, a price of $p_k(\alpha)$ is to be paid to order one unit of that commodity with priority α, whether the resource is delivered or not. The payment of $p_k(\alpha)$ entitles the user to receive one unit of commodity k if and only if that unit is available after all users with priority numbers less than α have first been supplied (i.e., contingent on the supply being large enough to fill demands of those who have paid for earlier priorities).

In this organization, each user will be allocated quantities $q^i(1), q^i(2),\ldots,$ where $q^i(\alpha)$ is the amount of resource to be delivered to i with priority α. We let $Q^i(\alpha) = \sum_{j=i}^{\alpha} q^i(j)$ be i's total quantity assigned a priority of α or better. To evaluate q^i, i must have

beliefs about the reliability of each priority class. Reliabilities are determined jointly by the suppliers, station management, and the demanders, payload operators and designers, as follows. Station management provides an uncertain supply of resources (because H depends on x). Let $\sigma(Q)$ be the probability that the supply available for users, after housekeeping, is greater

is greater than or equal to Q. If $Q(\alpha) = \sum_{i=1}^{m} Q^i(\alpha)$, then

$$(25) \qquad \beta(\alpha) = \sigma(Q(\alpha)) + \int_{Q(\alpha)-1}^{Q(\alpha)} \frac{y - Q(\alpha - 1)}{Q(\alpha) - Q(\alpha - 1)} d\sigma(y) \quad \text{for each } \alpha,$$

where the last term assumes random rationing if shortages occur within a priority class. We assume that users believe they cannot individually directly affect β. An expected net-benefit maximizing risk-neutral user will try to choose d^i, contract for q^i and plan for s^i to solve

$$(26) \qquad \text{maximize} \sum_{\alpha} \delta(\alpha)[n^i(d^i,s^i(\alpha),Q^i(\alpha)) - f^i(d^i) - v^i(d^i,s^i(\alpha),Q^i(\alpha))]$$

where $\delta(\alpha) = \beta(\alpha) - \beta(\alpha+1)$ is the probability that only priorities $1,\ldots,\alpha$ will be filled (α may only be partially filled) and $s^i(\alpha)$ is i's planned operations parameters only if $1,\ldots,\alpha$ are filled. In a steady state given supply uncertainty $\sigma(Q)$ and prices $P(\alpha)$, the values for β,d,s and q simultaneously satisfy (25) for each i and (24).

Operations. If priority contracts were used in planning during manifesting and prices were correctly determined, then operations are easy and can be managed by observing x, determining the available resources R(x), and then allocating R(x) to users in order of their self-selected priority. Letting $r(\alpha)$ be the amounts contracted at priority α, r(1) will be supplied first, r(2) supplied second and so on until there is no more of R(x) to allocate.

During manifesting, if prices are incorrectly set or priority contracts are not fully utilized, then operations must be managed as in contingent markets. Since x is known, efficiency requires that a price be chosen equal to short-run marginal cost at those demands.

Manifesting. Some of the advantages of priority contracts occur in this phase. Prices paid for each priority must be flexible and responsive to benefit (demand) information. Given a vector of priority prices $p(1),\ldots,p(\alpha),\ldots$, and an uncertain supply $\sigma(q)$, users choose d,q,s to maximize (26). These choices also determine reliabilities $\beta(\alpha)$. Users report their priority demands q^i to station management which computes $Q(\alpha) = \Sigma q^i(\alpha)$, minimizes the life-cycle costs of supplying Q and β, and recomputes the prices to reflect marginal costs of those demands. Formally they choose plans for S and R, contingent on x, to solve

$$\text{(27)} \qquad \text{minimize} \int V(D,S(x),R(x),x)d\mu(x)$$

subject to $R(x) = H(D,S(x),s)$ and

$$\beta(\alpha) = \mu[\{x \quad R(x) \geq Q(\alpha)\}] + \int_{\{x|Q(\alpha) \geq R(x) \geq Q(\alpha-1)\}} \frac{R(x) - Q(\alpha - 1)}{Q(\alpha) - Q(\alpha - 1)} d\mu(x).$$

This requires station management to produce the uncertain supply to satisfy (in a least cost way) the preferences for reliability revealed by users in their choices of q and β. Given these station management plans, there is a new uncertain supply with $\sigma(Q) = \mu(\{x\ \_\ R(x) \geq Q\})$. Let $C^*[D,\beta(.),Q(.)]$ be the value of the solution to (27). If station management computes new priority prices using the rule[40]

$$\text{(28)} \qquad P(\alpha) - P(\alpha + 1) = \partial C^* / \partial Q(\alpha)$$

then, in a steady state, the allocation of resources will be as efficient as possible given the fixed number or priority classes. That is, the steady-state values of payload and station plans d,s,r,S,R and reliabilities $\beta(.)$ satisfy (19) and (20).

It is possible that the number of classes required for full efficiency is relatively small. For example, if supply is modular and lumpy then a small finite number of classes is sufficient. As an example, on shuttle trips to orbit, either the entire bay goes or it doesn't. With four orbiters each able to fly a maximum of, say, four trips per year there will be at most 16 trips. Further, the capacities per trip will be a constant R times one of 0,1,2,..., 15 or 16. Therefore, one needs at most 17 priority classes (per year) to achieve efficiency. A similar calculation can be made for manpower or electricity (the latter occurring in modular units of 5 kws). If one is willing to accept less than fully efficient performance from an organization then fewer priority classes are sufficient. While it is primarily an empirical issue, on a case by case basis, it is my conjecture that a sizeable portion of the efficiency gains (over a single price policy such as expected marginal cost pricing) can be achieved with two to four classes.

Design. As with contingent contracts, long-run efficiency requires design decisions to be guided by information available in the plans for manifesting and operations. In particular, if the priority contracting process is begun during phase 1 and if, when presented with priority demands Q(.), station management also chooses the station design D to

(29) $$\text{minimize } C^*(D,Q(.),\beta(.))$$

prior to recomputing prices, where C^* is the value of (27), then designs and resource allocations will be long-run efficient (in a steady state). Further, when x is observed and R(x) becomes known, no further reallocation process is needed. Whatever resources are available need only be distributed according to the already self-selected priorities. Careful, systematic planning using incentive compatible rules can produce efficient design and utilization in this environment and minimize reallocations.

There is one class of environments, however, in which there can never be enough classes to allow priority to achieve 100 percent efficiency. We turn now to this class.

Environment H: (everything uncertain, users seek efficiency)

In this environment (1) there is uncertainty about payload net-benefits, costs and technology, and (2) all agents are in pursuit of efficiency. These assumptions differ from environment F only in the knowledge about payload net benefits.

We model this form of uncertainty as in the previous section, with a random variable x. Now, however, it is also the net benefits to be attained by payloads from the utilization of station resources that is uncertain. This includes uncertainty about the ultimate payoff from the scientific or commercial output of the payload, about the level of costs needed to operate the payload, or about the design and construction costs of the payload. It is important to realize that the timing of the resolution of the uncertainty is also crucial. If the uncertainty is resolved only after the operation of the payload, then the situation is effectively the same as in environment F with the net benefit functions replaced by their expected value. If, however, payload designers will learn anything helpful between the time they must begin to provide information, or make decisions, and the time they finish consuming resources then some new analysis is needed. Each net benefit function is now also a function of the random variable x and is written as $n^i(d,s,r,x)$. This formulation, in which x does not have a superscript, does not mean that each i will know what every other payload manager knows. For example, n^i may depend only on one of the dimensions of x.

Again, we redefine net benefit maximization to correspond with efficiency in this new environment by working backwards. Tomorrow, given D and d and having observed x, the (short-run) efficient decisions for R,r,s and S solve

(30) $$\text{maximize } [\sum_i n^i(d^i,s^i(x),r^i(x),x)] - V(D,S(x),R(x),x)$$

subject to $\sum_i r^i(x) \leq R(x)$; $R(x) = H(D,S(x),x) \geq 0$. Let J(D,d,x) be the value of the solution to this problem. The (long-run) efficient decisions for D,d,R(x),r(x),S(x) and s(x) satisfy (30) for each x as well as

(31) $$\text{maximize } \int[J(D,d,x) - F(D,x)]\mu(x)dx.$$

As in environments D and F, if there are no information processing constraints and if all users are efficiency seekers, then one organization that achieves efficiency is easy to describe. Each user is told to inform station management about the function

$$n^*(r,x) = \max_{d,s} n(d,s,r,x).$$

The major difference between this environment and previous ones is that now users must be able to describe the net-benefits they may receive *in all relevant conceivable states x*. This is clearly a more complicated task than the previous requests required. If this is too complicated then one solution is to use the organization described in the next section, and tell each efficiency seeker to act as if it is a net-benefit maximizer. Such organization requires less information transfer at a time.

Environment I: (everything uncertain, users seek net-benefit)

In this environment (1) there is uncertainty about payload benefits, costs and technology, and (2) payload designers and operators are interested in the maximization of the net benefits from their payloads while station management is in pursuit of efficiency. These assumptions differ from environment H only in the motivations of the users.

Priority pricing, as described in environment G, will not perform efficiently in this environment since it does not allow the flexibility in planning needed to prepare for the variations in information faced by users. This is because priority contracts depend only on the availability of resources on the station and not on the variations in information about costs and benefits to users. On the other hand, full contingent pricing can perform efficiently *if all the relevant information to be learned by the users is mutually verifiable by both user and station management*. The analysis is a straightforward generalization of that presented for environment G and need not be presented here. The main observation from such an exercise is that the number of contingency contracts is large and verification is difficult.

If one wants to preserve the simplicity of priority contracts but still achieve the efficiency of full-contingent pricing, there is a hybrid structure that can do the job. One can use priority markets for planning and after-markets (spot markets) to deal with the reallocations that are necessary to yield efficient allocations after users learn, if expectations are rational. This organization is identical to priority pricing as described for environment G, with one addition. After x is observed each user is allowed to trade with other users of the station (in much the same way that trades occurred on Spacelab after manifesting and during operations in orbit). Such trading can occur in an organized manner through a market or in an unorganized manner through face-to-face bilateral or multilateral trades. It can be proven that if all mutually beneficial trades are completed after x occurs and if, before x occurs, users and station management form their expectations about trades in a rational manner, then priority pricing will perform efficiently.

IV. Summary and Conclusions

We have considered a sequence of successively complicated environments to illustrate that systematic organizational design depends on the goals of the organization and the environment in which that organization is to operate. Environment I is the closest to that faced by the space station and the recommended organizational structure (assuming efficient design, operation, and use are the goals) is a combination of priority pricing with an after-market. The entire list of recommendations follows.

ENVIRONMENTS AND RECOMMENDATIONS FOR PRICING POLICIES

	What is Uncertain	Users' Motivations	Recommended Organization
A	Nothing	Efficiency	Team
B	Nothing	Net Benefits	MCPricing, Vickrey
C	Nothing	Benefits	????
D	Costs	Efficiency	Team, ExMCPricing
E	Costs	Net Benefits	ExMCPricing
F	Costs & Technology	Efficiency	Team, Priority
G	Costs & Technology	Net Benefits	Priority Pricing
H	Everything	Efficiency	Team, Priority
I	Everything	Net Benefits	Priority w/after-markets

We can now relate the remarks in the main text of the paper to the analysis in the appendix. The team structure is recommended in environments A, D, F, and H. The common threads are the mutuality of interests of users and station management (known and shared goals) and the unrestricted information processing capacity. In these environments there are neither incentive nor information problems. Marginal-cost based pricing is recommended in environments B, D, and E. The common threads are no benefit or technology uncertainty (stable resource supply) and verifiable cost data (accurate cost information). We further found that posting prices was valid only when there was a linear cost structure and the project was easy to expand. Finally, priority pricing is recommended for environments F, G, H, and I. The common threads for these are the uncertain technology (random supply) and accurate reliability information. We further saw that modular design led to the necessity of fewer priority classes.

The importance of this list for policy analysis is not just that the ideal is attainable, but that the organizational structure must be tailored to the environment and not *vice versa*. Just as one should not expect an oxygen-consuming plane to be able to service satellites or the space shuttle to shuttle passengers from New York to Washington, D.C., efficiently, one should not expect one organization to be able to perform effectively in all environments. NASA should not try to force the management of the space station to conform to the structure which was successful for the Apollo program; rather, the management structure of NASA should be altered to fit the requirements and goals of the space station program. Inappropriate management, embodied in inappropriate pricing and allocation policies, can cause performance to be significantly less than it might be. Evidence from the space shuttle program certainly supports this hypothesis.

Notes

1. Much of the research for this paper, the details of which can be found in the referenced JPL working papers, was funded by NASA through JPL. They bear absolutely no responsibility for any of my conclusions. This paper was significantly improved with the help of comments from Jeffrey Banks, Peter Gray, Hamid Habibagahi, Molly Macauley, and especially David Porter. They also bear no responsibility for its contents.

2. See Quirk and Terasawa (1984).

3. See Cox and coauthors (1982).

4. See Cox and coauthors (1982).

5. For experimental evidence on posted prices with many sellers, see Plott and Smith (1978).

6. See Baron and Myerson (1982), Chao and Wilson (1985), Cox and Isaac (1986), Hong and Plott (1982), or Baron (1987).

7. See Banks, Ledyard, and Porter (1986) for an excellent summary of shuttle policy compiled by David Porter.

8. See Egan (1985).

9. For an excellent application of this analytic framework to the shuttle, see Toman and Macauley (this volume).

10. See Harris and Raviv (1981) and Chao and Wilson (1985).

11. See Banks, Ledyard, and Porter (1985a).

12. See Milgrom (1985).

13. See Banks, Ledyard, and Porter (1985a).

14. See Banks, Ledyard, and Porter (1985a).

15. See Banks, Ledyard, and Porter (1986).

16. See Chao and Wilson (1985) for a one-dimensional solution to this problem.

17. Actual motivations are more complex and involve interactions with Congress and private contractors. A careful analysis of these motivations would require further research.

18. I have omitted the superscript i on all functions and variables.

19. "Incentive compatible" means that all participants willingly and accurately comply with the demands of the organization for information and actions. If an organization is incentive compatible, the incentives participants face are compatible with the information transfer and decisionmaking needed to pursue the organizational goals.

20. Some of the less desirable properties of this organization as applied to public goods are discussed in Groves and Ledyard (1977).

21. Organizations with this property, such as organization 4 in Section II of the text, are generally called dominant strategy mechanisms and are considered very desirable since each agent can provide his information without concern for others' responses.

22. Economists will recognize this requires that prices be equal to short-run marginal cost and may wonder why there are no capacity constraints that must be satisfied. I have, in problem (9), implicitly assumed that there is a solution, *for any R*. This requires there to be some collection of operating parameters and resources that will allow that R to be supplied, perhaps at a very expensive cost (e.g., NASA may have been able to fly 120 shuttle missions per year

in 1985, but it would have had to spend considerably more than it did on ground support, refurbishing, maintenance, transporting orbiters from coast to coast, etc.). The theory can be easily altered to allow for capacity constraints in the short-run problem without affecting the basic conclusions. I do not make that alteration here, but one can consult Banks, Ledyard, and Porter (1985a) for some analysis in this direction.

23. The careful economist will notice that I have neglected the second order conditions that would rule out the possibility that we have arrived at a minimum. I do this to simplify the presentation. For most of this paper, there is no problem as long as the net benefit functions are concave.

24. If there are capacity constraints instead of variable short-run costs then prices must be set so that the aggregate demand of the users fits the available capacity.

25. This statement may not be immediately obvious but it is based on the fact that, in this environment, if $D' = D + G$ solves (11) then the short-run marginal cost of R for the design D' equals the long-run marginal cost of R $\left(\frac{\partial L^*(R)}{\partial R} = \frac{\partial L(D',R)}{\partial R}\right)$.

26. This is why each user's demand must be an insignificant part of the total station resources. Otherwise the user can affect prices and incentive compatibility is lost.

27. This is not the place to discuss extensive reforms in the internal decision processes used by NASA to allocate resources to science and technology development; however, making (1) payload designers and operators more sensitive to the effects of their decisions on net-benefits, and (2) NASA suppliers of resources, such as the shuttle and the station, more sensitive to the needs of the payloads would be major improvements over the present decision processes. A carefully constructed system of internal transfer pricing owuld be the natural, and perhaps only, way to lead designers and operators of the space station to create a station that serves the needs of the users in a way that the shuttle has not.

28. In practice this means that the choices of R and S can depend on the full knowledge of the cost functions while the choice of D can depend only on the prior beliefs about these costs. In practice, not all uncertainty about costs may be resolved at the time decisions are made for, say, R. We ignore this in our model since there will not be time to react to the information when it occurs. In reality, one must consider a sequence of decision days beyond "tomorrow." See Banks, Ledyard, and Porter (1985b) for one such model.

29. One can read Doherty (this volume) to understand why private sector users of the space station should be thought of as risk-neutral. It follows for similar reasons that government-financed users should be risk-neutral in their decisionmaking. Since these two groups comprise most of the potential users of the space station, the assumption of risk-neutrality seems warranted.

30. See Marshak and Radner (1972) for other possibilities.

31. One way condition (18) would be true is if station operating costs are independent of the level of operations; that is, if marginal operating costs are zero. More generally, (18) will be true if $V(D,R,S,w) = V^1(D,R,S) + V^2(D,w)$, for then $\frac{\partial V}{\partial R} = \frac{\partial V^1(D,S,R)}{\partial R}$ and $\frac{\partial V}{\partial S} = \frac{\partial V^1(D,S,R)}{\partial S}$.

32. Notice that this formulation emphasizes that choices in D determine the effective probability density on R. That is, choices of design parameters affect reliability.

33. It may be confusing to think of H,F and D as depending on the same random variable. If so, x can be thought of as a multiple dimensional vector, some of whose components are w. For example, suppose $x = (w, w^*)$. Then let F and V depend only on w and let H depend only on w^*.

34. As we know from shuttle experience, choices in operations parameters, such as the number of quality control inspectors or turn-around times, can affect reliability. Such choices are captured in this model in D since S is chosen *after* x occurs and is known. An open research topic concerns the organizational design problem when some of S must be chosen before x is observed.

35. One could also send the simpler function $n^*(r) = \max_{d,s} n(d,s,r)$.

36. To be precise we use the integral sign to represent the Riemann-Stieljes integral.

37. The only difference between this and the process described under operations manifesting is the choice of D according to (23). All else remains the same.

38. One need only consider the language of an insurance policy to realize the problems.

39. Of course, if each party completely trusts the other, then only one need observe and describe the state of the world. However, economists tend to be somewhat cynical and do not expect much self-control in the reports from self-interested observers.

40. The pricing rule in (28) is equivalent to $P(\alpha) = \sum_{\gamma \geq \alpha} \partial C^* / \partial Q(\gamma)$.

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