Customer Utilization Requirements and Their Impact for Space Station Capabilities

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ABSTRACT

This is a summary of work presented to the Level B Space Station Program Office at Johnson Space Center related to customer requirements definition and their impact for Space Station design. The study was global in scope, querying the range of potential Station users for their ranked requirements for access to Station capabilities. User groups are identified based on their common set of functional requirements for Station services, and group needs were ranked according to level of utility for each unique Space Station capability. Analysis of the design drivers identified by the utility scores was conducted, resulting in a determination of which Station capabilities are in greatest demand, and where major technical commonalities and incompatibilities exist between user groups. This analysis provides a mechanism whereby NASA managers can evaluate the impact of design tradeoffs for the Station's customer community.

Major conclusions of the study include: 1) the need to base design choices on functional user group needs in order to account for currently unknown users; 2) emphasizing operational flexibility and minimizing life cycle costs in order to provide a "user-friendly" system; 3) scarring the Station to allow for potential external resource enhancements provided by international partners or commercial firms; and 4) establishing an IOC operating envelope based on the identified "core" capabilities with the greatest utility to the widest user community. In particular, this means optimizing for users who have a primary requirement for manned interaction on the Station, and providing for users whose requirements are not met within the IOC envelope through growth configurations or logistical support for their activities outside the core manned facility.

I. INTRODUCTION: STUDY TASK AND GOALS

A solid understanding of user requirements is critical for making the engineering decisions which will define the Space Station's capabilities. The main study task was to identify the primary factors which shape Station design philosophies, and evaluate design options. The major objective of CSP's study effort was to develop a methodological approach to support the Space Station engineering decision makers, including a means to evaluate the impact of user requirements on the design for the Space Station. NASA will be able to use this approach as a tool in further refining design decisions as the Space Station program progresses.

The overall goal of this study was to define user needs in terms of Space Station design options in order to maximize the utility of the Station to <u>all</u> users consistent with program constraints (e.g. political, cost, technical, etc.). The study was global in nature, analyzing the spectrum of potential users at the broad functional level. User needs are based primarily on previously developed data in NASA's Mission Requirements Data Base, supplemented by interviews with all user groups, a customer preference questionnaire developed by CSP and circulated to NASA Space Station scientists, review of previously completed NASA studies on user requirements, and CSP's internal expertise and commercial information sources.

The major tasks of the study were:

1) Define user requirements in terms of the major functional capabilities of the Space Station. That is, to determine what functional attributes (as opposed to hardware needs) users want to see offered on the Space Station, and validate the importance of these requirements (functional design drivers).

2) Analyze user requirements to determine what level of common functions can be identified which support a broad range of user needs (user commonalities).

3) Provide a tool which NASA managers can use to maximize the utility of the Space Station to all users consistent with the constraints of the program. This requires constructing a methodology which can evaluate the relative utility of Space Station functions to the identified user groups.

4) Utilizing the above methodology, help NASA managers in determining the optimal design options for the Station in order to meet overall program goals, including: designing a "user friendly" configuration with "growth" capabilities within the constraints of the budget (defining user policies).

CSP's study provided NASA with a systematic means of evaluating functional requirements across several user groups. NASA managers will then be able to use this "tool" to evaluate various design options for the Station in terms of their impact on users, and hence on the Program.

QUESTIONS TO BE ADDRESSED

In dealing with the previous issues, we felt that two basic questions had to be addressed by NASA in order to ensure the viability of the program. First, of primary interest to design engineers is the question of how NASA should allocate its resources in order to ensure that the Station will be truly "user friendly". It is imperative to understand what user preferences are, and provide some mechanism for evaluating the utility to users of differing Station capabilities. Only in this way can hardware be designed which is "user friendly" (i.e. meets the defined needs of the customer community). It is CSP's contention that only through a customer-oriented approach can this be achieved. In many respects, NASA managers face a classic market definition problem, more closely resembling those faced by commercial entities in introducing new products to market than the traditional engineering design approach used in previous NASA programs.

Secondarily, given the current fiscal pressures being placed on all government expenditures today, it is imperative that NASA be prepared for potential cuts in the Station development budget and still provide a "user friendly" system. This places an even greater emphasis on understanding the "market" for Station capabilities, being able to prioritize those capabilities based on a clear understanding of user preferences, and then providing a Station design which is optimized for the prioritized capabilities. In order to achieve this, NASA managers must understand which users are requiring what kinds and level of capabilities, and validate the stated user needs.

II. METHODOLOGY: A FRAMEWORK FOR ANALYSIS

A solid understanding of customer requirements is critical for making the engineering decisions which will define the Space Station's capabilities. A major component of this study was the development of a methodology to support Space Station engineering decision makers, including a means to evaluate the impact of user requirements on the design for the Space Station.

CSP constructed a customer oriented framework composed of two parallel branches, a **market analysis** and external **environment analysis.** In the **market analysis,** we first identified the known and potential space station users. The user's needs were then characterized by means of a variety of data sources. In the **environment analysis,** we provided a structure to account for the programmatic and technical constraints that govern the program. The two parallel analyses can then be merged to determine the design philosophies and resource allocations that will maximize the success of the program.

A NEW APPROACH

As part of this methodology, CSP chose to adopt a new approach to defining the impact of customer requirements for Station design. First, we chose to use a customer-oriented perspective, rather than a strict engineering perspective, in analyzing user needs. This meant understanding what kinds of generic capabilities, not specific hardware, customers wanted available to them as part of the Station system. This is basically adopting a marketing approach to define systems requirements, rather than a mission-oriented engineering approach.

Second, the set of decisions surrounding how design choices are made is extremely complex, incorporating such factors as technical constraints, cost, user wants vs. needs, user identification, and programmatic issues. We felt it was necessary to break-out these decision criteria into their component parts in order to analyze their impacts on the design process. Hence, we conducted specific analyses to identify user groups, define functional user needs, identify technical constraints resulting from those needs, and place the resultant design criteria within the stated program constraints (cost, "user friendliness", requirement for growth, etc.).

Third, we feel it is vital to understand the effects to the Station design of the unknown user. Designing the Station solely from the currently identified set of missions (NASA's Mission Requirements Data Base) runs the risk of failing to provide for users who currently do not realize their interest in the Station, or providing for identified users who may change their minds prior to IOC. One of the major goals of this study was to determine how NASA managers could resolve this problem.

Finally, CSP analysts undertook a thorough review of available literature on customer requirements, distributed user questionnaires to NASA principal investigators, summarized the data in statistical format, and then conducted in-depth interviews with all major user groups and industry/NASA participants to provide cross-validation to augment the statistical data. While it was impossible due to data limitations to provide "statistically significant" results for the identified user design drivers, the results are supported by extensive direct research on user functional requirements.

A NEW DESIGN PHILOSOPHY FOR THE SPACE STATION PROGRAM

In the past NASA has taken a mission-oriented design approach to its space programs. This approach has been entirely appropriate for the type of space activities carried out in previous programs which had mission-specific goals. However, the Space Station Program is unlike traditional NASA programs in several ways. First and most importantly, the Space Station is meant to be a long-term operational facility more akin to a NASA research facility on Earth than to a specific mission-oriented hardware program. The Station will have to cater to a wide variety of users, be flexible in its applications, and have the ability to grow over time. The individual experiments that will be carried out on the station will have overlapping schedules and resource requirements. The experimenters themselves will come from a variety of organizations and have very diverse backgrounds, including a significant commercial component which is a new kind of NASA client. Many new ideas and new opportunities for work on the station are currently unforeseen or in very early stages of planning. Consequently, the Space Station's "mission" is not and cannot be clearly defined.

The Space Station Program requires a new approach -- a **Customer-Oriented Approach.** In designing a station with this new approach, NASA should attempt to maximize operating flexibility and explicitly consider future needs. Modular or standard subsystems go a long way in achieving this objective as does scarring and other provisions for planned growth. In providing a "user-friendly" station, NASA should strive to minimize operating costs, especially to the user, when making design choices. The overall goal should be to provide a multi-use flexible facility at the minimum life cycle cost to all the parties concerned. A Customer-Oriented Approach more closely meets these requirements.

DATA SOURCES

A variety of data sources were used in conducting the market and environment analyses. Over 150 published documents relevant to Space Station user requirements were reviewed by CSP staff, to provide background information. These were drawn mainly from the Phase A and B Space Station studies, the Microgravity Materials Processing Facility (MMPF) and Commerce Lab work being done at Marshall by Teledyne Brown Engineering and Wyle Labs, as well as other sources. The NASA Mission Requirements Data Base was then used as the primary source of currently identified customer needs.

Although the published data provided valuable information concerning needs for specific functional capabilities, it was insufficient to develop customer utility rankings for functional capabilities given the real constraints of the program. To help determine these preferences, a questionnaire was developed by CSP and circulated to NASA-affiliated principal investigators identified in the Mission Requirements Data Base. All of these data sources were augmented by in-depth interviews and CSP's own internal expertise.

III. MARKET ANALYSIS: WHO ARE THE USERS?

The first step in the market analysis was to identify the space station customers and segregate them into logical groups. In developing the group structure we strived to make it simple and consistent with NASA's own groupings, yet indicative of the real differences among users. Our major groups--Commercial, NASA, Academic & Scientific, International and NOAA--roughly correspond to the user groups in the Mission Requirements Data Base. However, some areas of research such as Material Processing in Space (MPS) cross over several user groups.

Our Academic & Scientific User Group captures the needs of the non-commercial research community outside of the auspices of NASA's own science and application programs. Data for this group, as well as for potential commercial users not identified in the Mission Requirements Data Base is inherently sketchy and we relied extensively on our contacts in industry and academia to fill in the data.

Although our initial inclination was to adopt "demographic" user groupings such as are used in the Mission Requirements Data Base, it quickly became apparent that this was not a useful mechanism. Our early analysis made it clear that due to divergent requirements, it made more sense to divide the broad user categories into functional sub-groups determined by the nature of their activities. The rationale for this will be discussed further later. The functional sub-groupings finally chosen included: life science-LIFE, materials science-MPS, observational (astro and Earth remote sensing)-OBS/RS, technology development-TDMX, on-orbit servicing-SVCG, communications-COMM, and physical/planetary science-PHYS. Only in the case of the international users were demographic groupings kept (ESA, Japan and Canada) due to the nature of the available data.

COMMONALITY ANALYSIS

Traditionally, NASA customers have been grouped demographically, according to which sector of the space research community they belong. However, a cursory review of user requirements made it clear that in order to usefully evaluate common and divergent needs, the users should be re-grouped by functional characteristics. Hence, we chose to group the users functionally, according to what the users are trying to do on the station.

While demographic categorization facilitates the evaluation of customer needs from a political viewpoint, functional categorization results in user groups that have real resource requirements. For example, MPS researchers have significant power and microgravity requirements, but are insensitive to pointing orientation. Assembly & servicing missions may demand heavy RMS use, but be insensitive to the microgravity level. Demographic categorization does not allow for easy definition of functional requirements.

Once the common requirements are identified for each functional group, the implications of Space Station design choices can be readily understood. This is a basic step in designing a tool by which the NASA manager can evaluate the impact on design choices to users. The major functional groups determined were: MPS commercial production, materials science research, observations/remote sensing, life science research, physical/planetary science research, assembly and servicing/TDMX, and communications.

UNIDENTIFIED USERS

In our conversations with corporate America and potential researchers outside of NASA circles, it became clear that despite the comprehensive analysis done to develop the Mission Requirements Data Base, there remain a number of latent users of the Space Station which have yet to be clearly identified and have formal missions attached to their needs. Hence, the Mission Requirements Data Base is inherently lacking in the area of unknown users.

Given that IOC for the Station is a minimum of eight to ten years away, many viable customers at IOC would not consider themselves as such today. Most firms in the commercial sector have planning horizons that do not go beyond five years. Some firms which could genuinely benefit from space research find it difficult to incorporate themselves into the aerospace infrastructure.

It also became clear that many of the currently identified users have very sketchy mission requirements. This is indicated by the large number of null or arbitrary responses in the Mission Requirements Data Base, and by some missions being referred to as "place-holders" by those knowledgable in the composition of the data base.

This lack of concrete mission requirements reinforces the need for a flexible, customer-oriented approach to Space Station design, with explicit consideration of the generic functional needs of future users and researchers. The only reasonable means to provide for the unknown user is to provide for the generic requirements of functional groups of users.

WHAT ARE THE USER NEEDS?

Users will have differing requirements for the **functional capabilities** of the Space Station. CSP's methodology provided NASA with a systematic means of evaluating functional requirements across several user groups to determine the level of utility of particular requirements at IOC. This is accomplished by relating functional attributes of the Space Station to user needs. CSP designed a matrix which related the utility of specific functional capabilities of the Station system to the users (see following discussion).

In analyzing user requirements it is important to distinguish between functional capabilities and actual hardware or systems. In many respects, it is similar to adopting a classic marketing framework in soliciting user requirements for any product. What has to be determined is the customers' need, which then allows the engineer to design a product to meet that need. Hardware per se is not of interest to a customer, rather he is interested in the capability offered by the hardware or system. This perspective should be placed foremost in the minds of all Station design engineers.

SPACE STATION ATTRIBUTES

Having identified the functional user groups and defined the terms for understanding customer requirements, the next step in the analysis was to determine actual user requirements and apply our matrix tool to evaluate the importance of these requirements to Station design. This included defining what Space Station functional attributes should be.

The method used in defining the attributes is encompassed in the MECE principle: each attribute must be Mutually Exclusive of other attributes (i.e. have a single unique characteristic), yet the total set of attributes are Collectively Exhaustive (i.e. include all Station capabilities). Each attribute was carefully defined to limit overlap and redundancy. Using this mutually exclusive, collectively exhaustive, principle to select attributes ensures that preferences for each functional capability are assessed accurately without built-in biases and limits interdependencies between attributes (although such interdependencies are impossible to eliminate completely).

CORE CAPABILITIES

CSP has separated Space Station attributes into two distinct groups: core capabilities and user-specific attributes. Core capabilities of the Space Station consist of basic life support; Guidance, Navigation and Control (GN&C)/Station Keeping; System Documentation; Tracking, Telemetry and Control (TT&C); and the Orbital Parameters (Station is assumed to be in fixed orbit at LEO with a 28.5 degree inclination). As these capabilities would be required for any manned Space Station designs, they are not easily categorized as user-specific (i.e. non-divisible by user). It would be difficult for a user to specify, for example, the incremental amount of TT&C required for his work, and as a result, CSP has chosen to focus its study efforts only on the user specific attributes.

USER-SPECIFIC ATTRIBUTES

User-specific attributes of the Space Station consist of those functional attributes which can be allocated directly to a specific user (i.e. to which incremental increases in capability can be assigned based on user needs). These attributes are deliberately defined as functional criteria rather than specific design or hardware requirements. In this manner, the underlying needs of the customer are evaluated instead of the perception of which type of hardware is needed. This should provide NASA with more "room for creativity" with the intent to maximize overall design efficiency from the users' perspective. In short, the goal was not to provide engineering solutions, but rather to identify design options which must then be addressed by NASA engineers.

The user-specific functional attributes selected by CSP for this study are listed on the attached viewgraphs. They were chosen in accordance with the MECE principle discussed earlier. This set of attributes has been reviewed extensively by NASA managers, scientists, and engineers. (Growth capability was evaluated as a separate aspect of each of the attributes.) All but one group, Operations and Protocols, are specific functional capabilities which could be offered by the Station system. See the Appendix for a complete definition of terms for these attributes which were used in determining the ranked customer utility scores.

Operations and Protocols are included within the user specific attributes because of their importance to providing a "user-friendly" environment for the Station. For this study we investigated the time-related requirements of different users in two general categories: scheduled access to the station and event-driven priority requirements. For example, commercial researchers have different needs for regularly scheduled access to the station than academic or scientific researchers, and astrophysicists have a different requirement for facilities priority during certain events (such as solar flares or supernovae) than life science researchers. The scores generated in this category are a measure of how important assured access to certain Space Station facilities is to different categories of users, and in the extreme case will indicate whether a user will be uninterested in the station if assured access cannot be obtained.

In addition, Operations and Protocols also encompass user needs for dedicated personnel to work on sensitive or proprietary activities. This could conceivably include use of private personnel, or require the development of a bonded astronaut corps. The intent was to identify which users foresee proprietary needs as vital enough to justify use of dedicated personnel to carry out their activities, and hence impact Space Station personnel requirements.

ATTRIBUTE MATRIX SCORES

In developing the attribute matrix, a zero to five scale was used to specify the overall importance of each attribute to each user group. These numbers indicate the relative importance of a functional attribute of the Space Station to the user.

The following definitions have been developed for use in applying the numerical ratings (0 to 5) to Space Station functional attributes:

0 = not relevant - this attribute is not applicable or necessary to carry out proposed work

1 = minimal importance - this attribute would be convenient but is not necessary to perform the proposed work

2 = slight importance - this attribute is useful to the proposed work but work can be carried out in its absence with only minor adjustments to the experiment

3 = moderate importance - if desired amount of this attribute cannot be obtained, proposed work can be carried out but at a cost of major experiment redesign or lower performance

4 = very important - inability to obtain desired amount of this attribute will severely compromise proposed work

5 = critical - proposed work cannot be performed without this attribute.

See the attached viewgraphs for the completed matrix with scores for each attribute given by each user group based on the definitions above. By summing up the horizontal rows, we obtain total utility scores for each attribute. A high final attribute score relative to other attributes indicates that the attribute is more important in the aggregate to all users, and indicates the major design drivers. Additionally, summing the vertical rows indicates which user groups are placing the greatest demand for resources on the system.

On the following viewgraph those matrix elements which were scored a four or five have been shaded to indicate the strongest preferences (i.e. design drivers for each sub-group). In addition, the users have been re-grouped by functional category to enhance the visual identification of common and divergent user requirements. The point of major interest here is to view how differing user groups have convergent or divergent design drivers (i.e. it can be visually discerned where the greatest commonalities lie, and where significant technical conflicts exist between functional user groups). This can be used while making the required design tradeoffs to understand the direct impact to individual users of the technical choices.

ATTRIBUTE MATRIX USES

Once the attribute matrix is completed, the results can be interpreted in a variety of ways. We can use the raw scores to perform an overall ranking of the importance of each functional capability. NASA can use these scores as a **qualitative** indication of the relative desirability of providing additional capabilities in one functional area versus another, or trading off one capability for another due to programmatic constraints.

The attribute matrix can be used to identify user needs peculiar to either a demographic or a functional group. This gives NASA managers insight into the potential winners and losers when design tradeoffs have to be made. By identifying the shared needs of many users or groups, the matrix can give a rough estimate of the overall utility of the Space Station for a trial set of functional capabilities (i.e. which capabilities bring the greatest utility to the broadest number of users). Thus, the matrix can be used to reduce the identified "mission set" of proposed Station capabilities by defining which capabilities have the highest overall utility. In this manner, cost reductions can be accomplished through elimination of less useful capabilities.

In addition, the attribute matrix is an adaptable tool. As new data is received from users and Phase B/C contractors, NASA can update the model, and thus generate a new ranking reflecting a different set of relationships between attributes and users.

Finally, the matrix analysis can be used as a starting point for developing an optimal Space Station design. Additional data on the technical and cost constraints of the program ("the environment"), are necessary to perform this optimization. In particular, marginal cost estimates for each functional capability are required. Functional interaction constraints also need to be specified to understand the linkages between capabilities and correct for this. For example, substantial rendezvous/docking activity could deteriorate the uninterrupted microgravity level, and hence incremental increases in one capability can significantly impact the utility of a separate capability.

Of course, there are limits to how the attribute matrix can be used. Unless we have a good understanding of the cost of providing each capability, as well as the technical constraints (interdependencies), we cannot specify optimal **levels** of each functional capability. Also, the attribute ranking that can be obtained by using the matrix scores is inherently qualitative. We cannot at this time claim to know **how much** more important one attribute is than another, only the relative importance to the users of each attribute.

OVERALL DESIGN DRIVERS

See the attached viewgraphs for the driving and non-driving attributes that were identified via the matrix analysis. We have listed the top eleven and bottom six attributes for illustrative purposes. The listed attributes are those functional capabilities that received the highest or lowest total scores after aggregating **ALL** of the user group preferences. It is important to recognize that this ranking is relative only, and does not indicate an absolute level of utility to users of these capabilities (i.e. non-driving attributes could also be useful to many customers, but simply do not rank as the most important).

Functional attributes that are required by a large portion of the users were naturally found to be drivers, while attributes that have specific applications to a limited number of users were found to be non-drivers. The commonality of user needs for a particular functional attribute appears to be more relevant than the absolute importance as specified by one or a few user groups. For this reason, it was no surprise to find that the "core" attributes of power, communications, thermal management, data management, pressurized volume and fluid management all ranked high. It is interesting to note, however, the level of importance of crew time (IVA), on-orbit storage space, and the requirement for automation and assured/scheduled access to the Station.

It would appear reasonable then that a guiding principal for Space Station designers would be to provide functional capabilities that have general utility to a variety of users, as opposed to mission specific hardware.

Relevant individual attribute cost factors should also be kept in mind in all design tradeoffs. In addition, there may be instances when mission specific capabilities can be accommodated with relative ease. These instances should be considered on a case-by-case basis.

USERS GROUPED BY FUNCTIONAL NEEDS

Four key user functional groupings were identified based on the commonality of their needs for specific attributes from the matrix analysis. These are: Manned Microgravity Research (including both life and materials sciences); On-orbit Service and Assembly (including NASA technology development/TDMX missions); On-orbit Observations/Remote Sensing; and Commercial Materials Manufacturing (MPS). All identified Station users (except commercial communications) fall within one of these broad categories based on the level of commonality involved in their activities.

The boundaries for these four groups have been based on specific and often unique needs for functional capabilities which define major technical incompatibilities. While a number of commonalities exist between the groups (particularly in the area of core utility needs such as power, data, thermal and fluid management), in general these four major user groups are characterized by specific conflicting technical requirements. The major design drivers specified by the four user groups are :

I. Microgravity Research: power, good microgravity levels, IVA crew time, access to pressurized volume, ability to handle hazardous materials, and significant need for data, thermal, fluid and waste management systems.

II. Observational/remote sensing: requirement for high-density/ real-time communications, access to polar and co-orbiting free-flying platforms, requirement for event-driven access to Station resources, access to Earth and astronomical pointing attached payloads, and need for a high-quality vacuum environment surrounding the Station.

III. Service and Assembly/TDMX: extensive crew time requirements for both EVA/IVA, need for a remote manipulator/teleoperator system, ability to provide maintenance/assembly/servicing to free-flyers and spacecraft/vehicles of all kinds (including the OMV/OTV), real-time communications system, and access to on-orbit storage facilities.

IV. Commercial Materials Manufacturing: very high requirements for power and high-quality microgravity levels, guaranteed/assured access to facilities on a regular basis, data and hardware security, and substantial requirements for core utilities including thermal, fluid and waste management.

As can be seen from this list, observational user requirements for a high-quality vacuum environment conflict with EVA/servicing requirements, and impose use of more costly waste management systems for MPS manufacturing and research. Similarly, the requirement for high-quality microgravity specified by commercial MPS users conflicts with users specifying high manned interaction levels (servicing and research users - see the summary of the Technical Environment analysis for a further discussion of this).

Although commonalities exist between these groups, the important point is that they are typified by major incompatibilities which, if given equal precedence in the design, would result in very costly engineering requirements to satisfy all users within the core manned facility. It appears obvious that major technical tradeoffs will have to be made in order to avoid designing a facility that meets no single user group's needs well, but rather provides something for everyone not very well. If NASA is to provide a "user friendly" Station design within budgetary and technical constraints, some choices will have to be made regarding which uses of the Station will be optimized. Grouping the users by major functional categories based on technical commonalities and conflicts allows NASA managers to understand and evaluate the impact of their design choices.

IV. ENVIRONMENT ANALYSIS: PROGRAMMATIC ENVIRONMENT

While NASA's overall objective is to build a Space Station that provides the maximum utility to a diverse set of users, it must do so within programmatic constraints set forth in the Station's charter. Programmatic constraints include an $8 billion development budget ceiling, a schedule which calls for initial operating capability within a decade (by 1992-94), and a requirement for significant international participation. The program is futher complicated by the schedule and fiscal uncertainties introduced by deficit-reduction measures affecting all major government programs.

NASA's ability to construct the current reference configuration Station by IOC for $8 billion has recently been coming under significant scrutiny in Congress and elsewhere. In response, the Agency has repeatedly upheld this budget ceiling and continues to plan for a Station design within this target figure. As a result, emphasis is being placed on designing the Station to strict economic parameters with a priority placed on efficiency of design. Fiscal austerity will force NASA managers into hard choices when tradeoffs of Station capabilities occur. This emphasis on cost places even greater importance on understanding and correctly choosing design options based on the validated requirements of the customer community.

The need to achieve IOC by the mid-1990's is also a significant factor in Station design. In order for this date to be met, NASA has adopted a very tight schedule for making major design choices. Within the year, the majority of decisions on overall Station configuration and capabilities will have been made in order to proceed with Phase C hardware design and construction. Therefore, it is imperative that NASA engineers understand now how to evaluate the impact of these design choices on the customer community to avoid costly delays or redesign in the future. It is vital to the Program's viability that the IOC Station provide the most important set of identified capabilities to service the user community. Under the current schedule there is little room for delaying major design choices.

The requirement to open the Program to international participation and accommodate foreign users introduces constraints and opportunities for the design process. As identified in the matrix analysis, foreign users place some of the greatest demands on Station resources, however, they are also providing additive resources to the system. The major issue for the design process posed by foreign participation is not the level of resource demand, but rather the impact to the design of integrating foreign hardware and providing the correct interfaces for its use at IOC and scarring for its future growth. It is imperative that NASA designers understand and provide for the unique requirements of the foreign partners. These requirements include the ability to access resources supplied by others and the potential for them to supply additive capabilities to the system.

Overall, due to these constraints, NASA managers must be able to identify the key design drivers to the system based on prioritized user needs, and configure the IOC Station such that these capabilities can be protected in times of fiscal austerity. This will help to ensure that the Station retains its user-friendly character.

TECHNICAL ENVIRONMENT

The table of data presented in the attached viewgraphs indicates, for selected functional attributes, the aggregate amount of capability requested by users in NASA's Mission Requirements Data Base. The data are CSP's own estimates. They include only those missions which will be on board during the first year of operation (IOC), and which will reside on the core Station itself. Missions that have functional requirements solely for a free-flyer or platform are not included.

Also shown is the latest published information on the reference configuration estimated resources. A quick comparison of the total requirements and the reference configuration parameters shows clearly that the currently envisioned Station cannot provide all of the requested capability. Changes to the Station design are already contemplated that will augment the most requested capabilities. However, it must be kept in mind that the requirements specified in this chart do NOT include any provisions for growth (missions beyond the first year), currently unidentified user requirements, capacity margins, or station-keeping requirements.

As can be seen from the chart, a number of key Station capabilities are already oversubscribed from currently identified users. NASA managers face a choice not only of what capabilities to offer, but in what amount. In order to provide a Station that provides an adequate level of utility within realistic programmatic constraints, NASA managers and engineers will have to choose which of the attributes are most important. The market analysis found in the previous section provides guiding principles and specific recommendations to help with these choices.

TECHNICAL ENVIRONMENT -- CONCLUSIONS

NASA managers and engineers face two major problems in trying to make design choices. The first is a result of incompatible requirements stemming from the needs of functionally divergent user groups. For instance, MPS users who wish to produce marketable quantities of materials need extremely low levels of microgravity (10_{-6} at least). However, other users need to do basic research on the station which requires considerable human activity (IVA). The needs of these two groups will be conflicting. Similarly, users performing earth and space observations would like a high quality vacuum environment around the Station, which conflicts with those users who would like the station to serve as a transportation node and require considerable rendezvous and docking maneuvers.

There will be many instances where these incompatibilities can be solved by scheduling and mission manifesting. However, significant conflicts will remain, and a system for prioritization must be developed. Indeed, at some point it may be necessary to exclude some missions that will not fall within a general functional requirement envelope. In this case, the excluded missions' requirements could be met by additive resources provided by a third party, perhaps on a commercial basis.

The second major problem is the lack of adequate resources for capabilities with widespread commonality among users. These commonly requested capabilities include power, thermal rejection, crew time, and pressurized volume. Most of these "utilities" are currently oversubscribed based on the existing mission requirement and reference configuration data. Again NASA needs to develop a prioritization policy to effectively allocate these resources. Developing a Space Station pricing policy will play an important role in addressing this problem as economic costs are expected to reduce the level of resources demanded.

In the event that budgetary constraints force a cutback in the level of these basic capabilities, NASA must be sure to provide mechanisms for augmenting the IOC Station's resources. A well thought out plan for growth and accommodation of new resources is imperative.

V. CONCLUSIONS: MANNED AND UNMANNED CAPABILITIES

In reviewing the user requirements data and placing it within programmatic goals, it became clear that functionally the Station offers one central unique characteristic: a permanently manned presence in orbit. Manned interaction (IVA/EVA) is a primary requirement for a broad segment of the total user community, and without this element the Station would not represent a fundamentally new capability for U.S. space operations. NASA should emphasize the enhancement of manned capabilities as the primary design driver. Given the budgetary constraints on the Program, NASA should prioritize Station requirements based on the need for manned interaction. That is, those user groups which have a primary requirement for manned interaction should have their requirements viewed as the drivers in Station design.

This means that the IOC operating envelope for the Station should be optimized for the two major user groups, identified in the market analysis, which have a primary requirement for manned interaction: microgravity research and service and assembly/ transportation node users. Although some technical conflicts exist between these groups, they are less severe than between these and the other two major groups: commercial materials production and observational users.

DRIVING ATTRIBUTES DEFINED BY CHOICE OF USER GROUPS

As noted in the market analysis section, the design drivers for the Station will be defined largely by the choice of user groups. Those attributes which are required by a broad base of users naturally should receive priority (crew time, and core utilities such as power and pressurized volume). Given the programmatic objective of accommodating the widest number of user groups (including commercial and international users), as well as the importance of manned capabilities, the Station design should be optimized for manned microgravity research and space servicing/ operations functions. This will provide an operating envelope which will meet the requirements of the broadest base of users while minimizing the inherent technical conflicts in those requirements.

Once the Station has been optimized for these categories, NASA should then provide Station access to as broad a base of users as possible. To this end, CSP recommends that NASA establish a manifesting policy which provides assured access to all users that can fit within the operating envelope of the optimized Station design. This would serve to help alleviate the resource constraints on the system and provide a mechanism to guarantee use of the facility to all user communities. As was noted in the market analysis discussion, assured access is a primary requirement for a wide variety of users and should be a key component of an operations and protocol policy.

MANIFESTING POLICY

Such a manifesting/access policy would have three major components to its framework. First, a decision must be made to establish an operating envelope at IOC based on the design requirements of the prioritized users: microgravity research and space operations support services. Second, within the technical characteristics of this envelope, NASA should develop a protocol document which provides for assured access to the Station for all potential users. Finally NASA, through the Station's servicing support role, should be capable of providing operational support to any users who would be unable to fit within the functional envelope of the IOC Station due to the perturbing effects of manned activities.

NASA as part of the Station's services should support such users in conducting their activities away from the core manned facility via co-orbital or polar free flying platforms or other spacecraft. This requirement in turn supports the importance of developing servicing and logistic support capabilities for the Station, including development of an Orbital Maneuvering Vehicle (OMV) capability to support free flyer activities.

SCARRING FOR GROWTH

In reviewing the requirements for growth in Station operations, our analysis suggested two basic means to address the issue. First, the technical incompatibilities between major user groups suggests that in looking at growth configurations NASA designers should be thinking in terms of duplication and replication of facilities, not simply growth of the original Station. New versions could be optimized for specific users based on their technical requirements (i.e. one facility for manned lab research, one for logistics and service support, one to serve as an observational platform serviced from the support facility, etc.). Eventually, a constellation of facilities would be developed, each tailored to the specific user group it serves. However, this will take significant time and funds, and in the nearer term the core Station will face increasing resource pressures.

Given the fact that the current demand for key resources is already projected to outstrip what can be delivered at IOC within budget, NASA should scar the Station for growth of all the key generic resources. Such growth need not be supplied solely through NASA funding. Specifically, given the fiscal austerities expected to be in place during development and construction of the Station, NASA should provide an option for allowing additive resources to be supplied by external sources. Such additive resources could come either from domestic commercial companies who see an opportunity to commercialize part of the Station system, or from foreign partners who need to augment their activities at the Station. It is imperative that appropriate scarring be included in the IOC design to allow for external resource enhancements.

In light of the expected need for additional resources at or soon after IOC, CSP recommends that NASA establish an external resource enhancement policy to aid in alleviating technical and budgetary constraints on the system. Such a policy would encompass pricing of Station resources, NASA buyback/leaseback provisions, statement of and early definition of interface requirements, and identification of specific resources or systems which would be made available for external development. Additionally, steps should be taken to open lines of communication between Station design engineers and commercial firms or international entities with an interest in supplying Station resources. The first steps in this direction have already been taken with the announcement by NASA of commercial guidelines for the Space Station which encourage commercial participation in all aspects of Station activity.

COMMERCIAL ENHANCEMENT POLICY

Examples of where specific Station resources can be opened to commercial development stem from the review of user requirements in the market analysis and technical environment sections of this report. Specific capabilities identified by CSP as having significant potential for commercial augmentation include: 1) power -- additive requirements for sustained power levels could be met by commercial development of individual "power packs" for use at the Station or for free flyers; 2) pressurized volume -- specific requirements exist for dedicated research space and even proprietary lab space which could be supplied by additional modules docked to the core Station; 3) superior microgravity environment -- which could be supplied away from the Station by for-rent free flying platforms or man-tended modules; 4) a variety of on-orbit servicing activities such as satellite repair and maintenance, and on-orbit storage (warehouse) services for users requiring space for logistics support supplies; and 5) additional crew time -- supplied through the use of a bonded or proprietary astronaut corps developed commercially to service a range of research users. In addition, many of the ground support services and facilities could, in principle, be supplied by outside organizations.

In order for commercial firms to begin planning for such services, it is vital that NASA designers specify which hardware or systems will be open to external development, that these systems have standardized interfaces, and that the specifications for these interfaces be released as soon as possible. For this reason, NASA managers should begin to actively solicit direct input from the commercial sector in the design process, and establish a mechanism for direct communications with private firms at Level B.

POLICY SOLUTIONS

The major policy issues, recommendations and design implications stemming from CSP's analysis can be summarized in the following manner:

I. Due to budget constraints, the IOC Station faces resource limitations in key areas. In response, NASA should consider acquiring or allowing commercial enhancement of key Station attributes. This would require extensive scarring for specified attributes, as well as early definition and standardization of interface requirements to aid commercial planning.

II. A major design problem is providing for the unknown user. The most efficient means to solve this problem is to focus the design effort on functional user group requirements, not specified mission sets. This requires tailoring the early design configuration to the needs specified by the primary user community, and scarring for growth to provide for other user needs in later versions.

III. Major technical incompatibilities exist between user groups. Given the programmatic constraints and stated objectives of the program, NASA should optimize the IOC design for a set of users whose requirements cover as broad a range of capabilities as possible and utilize the unique manned characteristics of the Station. This means defining a functional operating envelope. Users which cannot fit within this envelope will be given operational support for facilities outside the core Station or will be accommodated in growth versions. The system must allow for the eventual provision of user group needs which cannot be serviced on the IOC Station.

DESIGN PHILOSOPHY: CONFIGURATION MUST SATISFY PROGRAMMATIC DRIVERS

Having provided an overview of the major technical and market factors which determine how design drivers should be selected, this analysis can now be placed within the context of the stated charter for the Station Program. How should the major programmatic drivers really be interpreted in the design process? Through our analysis, CSP has redefined the three principal design goals for the Program in the following manner:

"DESIGN TO COST" — The Station system should be configured such that budgetary constraints do not jeopardize key capabilities. Core prioritized attributes should be protected from cuts in the design process.

"DESIGN FOR GROWTH" — Design the Station based on functional user requirements to account for changing needs and maximize system flexibility. This means scarring for future growth to service specific users.

"USER FRIENDLY" — The IOC configuration should be optimized to support major functional user groups. The core facility will have an operating envelope determined by a broad base of user needs as well as technical and programmatic resource constraints. Users who do not fit the envelope will be serviced off the core facility.

In this manner, a customer-oriented design philosophy can be adopted which fits within the structure and goals of the Program.

APPENDIX

DICTIONARY OF TERMS

CORE CAPABILITIES

BASIC LIFE SUPPORT

Includes all Space Station functions required to maintain an environment suitable for human support, such as adequate atmospheric pressure, potable water, radiation shielding, etc.

GN&C/STATION KEEPING

Guidance, Navigation and Control / Station Keeping. Includes all systems required to keep the Space Station positioned and oriented correctly.

SYSTEM DOCUMENTATION

All documentation requirements necessary to the proper functioning of the system. These include manuals for operations, repair and maintenance, crew training and emergency procedures.

TT&C

Tracking, Telemetry and Control. Includes all systems necessary to monitor the location of the station and telemetry data on Space Station system functions.

ORBITAL PARAMETERS

The Space Station's altitude is assumed to be fixed at LEO with an inclination of 28.5°.

USER SPECIFIC ATTRIBUTES

ELECTRIC POWER

Generation Level

Kilowatt level required by the user; should include reference to both peak and average power needs. If availability of electric power directly from the station's power grid is critical, this item's score should be 5. The ability to operate independently from station power should result in a score of 0 or 1.

Storage

Facilities for power storage such as batteries, flywheels, fuel cells, etc., for applications such as high-pulse or limited duration experiments (e.g., lasers, plasma physics). Activities requiring substantial pulse/peak power levels for short periods should rank this as a 5.

Management & Conditioning

Special formats for power requirements (AC/DC, unusual voltage or current needs) as well as process needs (e.g., power spikes which need to be filtered).

EXTERNAL ENVIRONMENT

High Vacuum/Low Contamination

Level of ambient vacuum (in torr) surrounding manned Space Station. Free flying platforms are excluded, and users should note that vacuum levels will be higher (i.e., lower contamination) at the unmanned platforms. Likely sources of contamination include Space Shuttle and OMV docking and waste venting from MPS experiments. If the presence of a low contamination/hard vacuum environment is critical to a user, this item should be rated as a 5.

Radiation Shielding

Requirement for shielding from radiation contamination (thermal or electromagnetic) in the Space Station environment due to the station's thermal radiation panels or other operational activities. User applications such as IR sensors and plasma physics experiments which could be adversely affected by thermal or electromagnetic radiation should indicate a high score for this item.

GRAVITY LEVEL

Microgravity

Level of constant (ambient) gravity available to all users aboard the Space Station, whether in pressurized or unpressurized sections. For users requiring very low levels (e.g. < 10-4g) this score should be 5.

Variable Gravity

User requirements for varying gravity levels between nominal ambient level and 1g. Users who require gravity levels greater than 10-4g should rank this element 4 or 5.

INTERNAL ENVIRONMENT

Pressurized Volume (Core Station Modules)

User needs for access to manned, pressurized workspace either within the lab module, or other pressurized volume. This does not refer to user requirements for pressurized volume either in attached payloads or on free flyers, the need for which is investigated in separate questions.

Special Environments

User needs for unusual or isolated environments (e.g., pure oxygen atmosphere) within core station modules for particular applications. Excluded are standard ECLSS requirements, which are covered in Basic Life Support, above.

Hazardous Materials Handling

Physical requirements for facilities within the pressurized environment for handling of hazardous substances (corrosives, combustibles, toxic chemicals, explosives, etc.).

MANNED INTERACTION

EVA (Extravehicular Activity)

User needs for a suited astronaut to perform work outside the pressurized environment of the core modules. Extensive man-hour requirements should result in a high rank here.

IVA/Internal Activity

User need for direct human interaction with the experiment or equipment rather than reliance on automation within the station environment. Extensive man-hour requirements should result in a high rank here.

RMS (Remote Manipulator System)

Requirements for performance of external activities which can be conducted remotely using systems similar to the Shuttle arm, rather than utilizing an astronaut EVA.

Automation

User requirements for automated capabilities instead of manned interaction. Identified need for automated maintenance, observation, data collection, etc. should result in a high rank here.

CORE UTILITIES

Data Management (DMS)

Requirements for access to the station's main computer facilities for data processing and storage, as opposed to self-contained computer capability within the experiment or equipment. Implies significant needs for interface with the computer bus. Data security requirements are discussed in a separate question.

Communication

User needs for voice, video or data telecommunications links between the station and Earth. A high score for this attribute implies significant needs for interface with the communication/antenna systems on a regular basis, especially if a high transmission rate is required as opposed to intermittent (burst/batch) or low bit rate transmission requirements. Transmission encryption needs are discussed in a separate question.

Fluid Management

User requirements for facilities for transfer and storage of exotic fluids such as propellants and cryogenics. For the purposes of this questionnaire, users should assume that purified and waste water requirements will be handled in the ECLSS system. However, if a user anticipates unusually large requirements for handling pure and waste water that would have an impact on the ECLSS, such requirements come within the scope of this question.

Thermal Rejection

User requirement for special thermal rejection capabilities such as cold plates that cannot be accommodated by the Space Station's air circulation cooling system.

ACCESS TO FREE FLYERS

Co-orbital

User requirement for access to a free flying platform in the same orbital plane and altitude as the station but separated by up to several kilometers, possibly attached by a tether. Such a free flyer would supply payloads with power, thermal control, data management and communications. A high score on this attribute would signify a user whose needs can only (or best) be accommodated on a free flyer.

Polar

User requirement for access to free flying platforms in polar orbit, either at a lower or higher altitude than the station. (See above discussion of co-orbital free flyers).

ACCESS TO ATTACHED PAYLOADS

Earth Observation

User requirement for the capability to attach earth observation and sensor payloads to the structure of the station, rather than inside the pressurized modules.

Astronomical Observation

User requirement for the capability to attach astronomical and astrophysical experiments to the Space Station structure.

Experiment Facility

User requirement for access to an unpressurized experiment facility attached to the Space Station structure.

Man-Tended Pressurized Volume

User requirement for man-tended pressurized volume attached to the Space Station structure.

RESEARCH SECURITY

Data

User requirement for secure or proprietary protection on the station's computer system to prevent unauthorized access to classified or sensitive data, or a user requirement for secure communication facilities between the station and earth such as data encryption or scrambling of sensitive voice, video or data transmissions.

Hardware

User requirement for physically separate or secure facilities sealed off from the remainder of the laboratory modules in which to perform experiments or production activities.

LOGISTICS

Volume/Mass

User requirement for large quantities of supplies (measured either in volume or mass) for both spares and maintainability purposes as well as consumables and raw materials. For the purpose of this questionnaire, food, clothing and related life support logistics needs are considered to be covered under the ECLSS category.

Resupply Interval

This element queries user needs for the timing of logistics resupply. The baseline resupply interval is 90 days. If a user anticipates a critical need for a shorter resupply interval, this category should be given a high rating. The shorter the required interval and the more pressing the need, the higher the rating to be given. Periods of 90 days or longer should receive a low rating.

On-Orbit Storage

User requirement for storage of equipment or other material on-orbit rather than storing on earth and using the logistics resupply module to bring up needed materials. Can be either pressurized or unpressurized storage.

Waste Management

User requirement for special waste processing and storage facilities for effluents, solids and gases which cannot be handled by the ECLSS system, in particular MPS venting/waste requirements.

Oversized Payloads

User requirement for equipment that would require use of very large airlocks (greater than 60" in diameter) on the station and the logistics module.

ON-ORBIT SERVICING

Attached Payloads

Requirements for servicing of attached payloads (as defined above), including docking, storage, transportation, maintenance, repair. Users with attached payloads that cannot operate autonomously should provide a high score here.

Free Flyers

Requirements for servicing of free flyers (as defined above), including docking, storage, transportation, maintenance, repair. Users with free flyers that cannot operate autonomously should provide a high score here.

Spacecraft Servicing or Staging

Requirements for preparation and launch of spacecraft to other Earth orbits (such as GEO) or on escape trajectories for planetary exploration. Eventually this category will include recovery of planetary spacecraft as well.

Structure Assembly Capability

Requirements for LEO activities based at the Space Station that involve construction and assembly of large structures. It should be noted that a corresponding score can be expected in (for example) the EVA category, above.

Transportation Servicing

Includes user needs for spacecraft such as the Shuttle, OMV's, or OTV's to carry out LEO activities based at the Space Station. This category excludes use of the Shuttle at the initiation or completion of an activity (i.e., it is assumed that all activities will require one round-trip on the Shuttle), but includes Shuttle harvest and resupply missions (where applicable). All OMV/OTV missions are included.

OPERATIONS AND PROTOCOLS

ACCESS ON REGULAR SCHEDULE

Requirements for predictable scheduling of all activities related to user applications (transportation, crew time, etc.), especially with significant planning lead-time. In contrast, "payload of opportunity" applications should receive low scores in this category.

EVENT DRIVEN PRIORITY REQUIREMENTS

Requirements for unexpected high priority based on unpredictable/unexpected developments (e.g., solar flares or supernovas for astronomical applications).

PERSONNEL REQUIREMENTS

User requirement for dedicated personnel to work on sensitive or proprietary activities. Users who foresee proprietary needs as vital should rank this as a 5 if manned interaction is required.