

SCALING OF DATA COMMUNICATIONS FOR AN ADVANCED SUPERCOMPUTER NETWORK

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The goal of NASA's Numerical Aerodynamic Simulation (NAS) Program is to provide a powerful computational environment for advanced research and development in aeronautics and related disciplines. The present NAS system consists of a Cray 2 supercomputer connected by a data network to a large mass storage system, to sophisticated local graphics workstations and by remote communications to researchers throughout the United States. The program plan is to continue acquiring the most powerful supercomputers as they become available. This paper describes the implications of a projected 20-fold increase in processing power on the data communications requirements.

1. INTRODUCTION

The Numerical Aerodynamic Simulation (NAS) Program was initiated by NASA to establish a national resource for advanced research and development in aeronautics and related disciplines. To achieve this goal the NAS Program is to, "act as the pathfinder in advanced, large-scale computer system capability..." [1,2,3,4]. The first major milestone has been achieved and the initial configuration (Figure 1) is now operational at the NASA Ames Research Center. The centerpiece is a Cray 2 supercomputer with 256 million (64-bit) words of memory and a *sustained* performance rated at 250 MFLOPS (250 Million FLoating-point OPerations per Second) as measured on benchmark tests for optimized large-scale computational aerodynamic codes.

The need for much more powerful processors can be seen from Figure 2 [1, 2, 3] which depicts the estimated speed and memory requirements for various approximations to the governing equations and three levels of geometric complexity; an airfoil, a wing and a complete aircraft. Note, for example, that if viscosity effects are included by using the Reynolds-averaged Navier-Stokes equations, a three dimensional solution for a wing requires about 100 times the computing speed of a comparable inviscid solution and only now has it become feasible to perform highly repetitive design optimization studies for such cases. Furthermore, if still more realistic large eddy effects are considered, a further factor of about 1000 is required for runs of the same duration. Finally, Figure 2 indicates that (with 1985 algorithms), a single 15 minute run including large eddy effects for a complete aircraft would require computer speed in excess of 10^{12} floating point operations per second and a random access memory of about 10^{11} bytes!

* Work supported in part by Cooperative Agreement NCC 2-387 from National Aeronautics and Space Administration to Universities Space Research Association.

N87-26580

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CSCCL 09B

(NASA-CR-180979) SCALING OF DATA COMMUNICATIONS FOR AN ADVANCED SUPERCOMPUTER NETWORK (NASA) 16 p Avail: NIS HC A02/MF A01

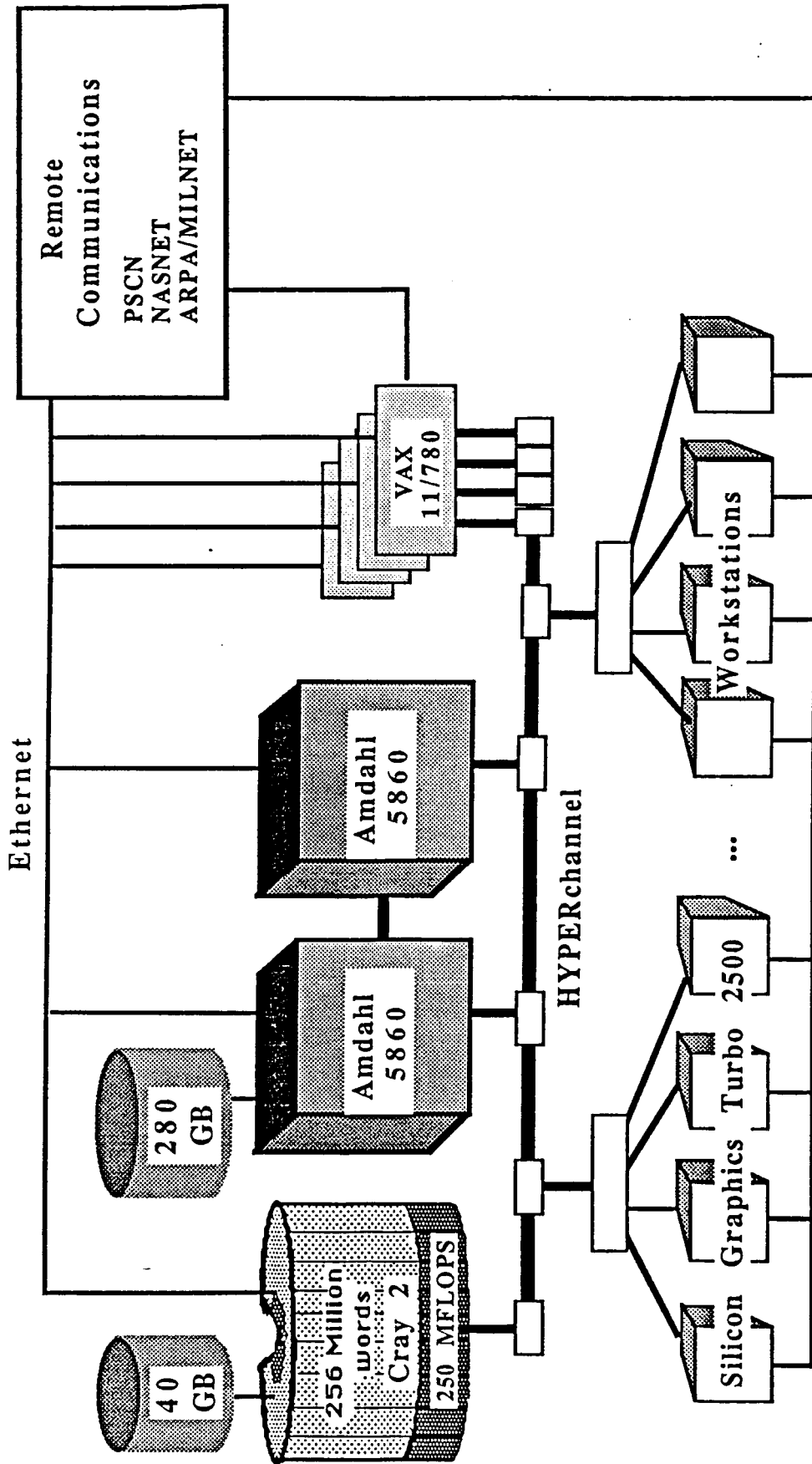


Figure 1. Initial Operating Configuration

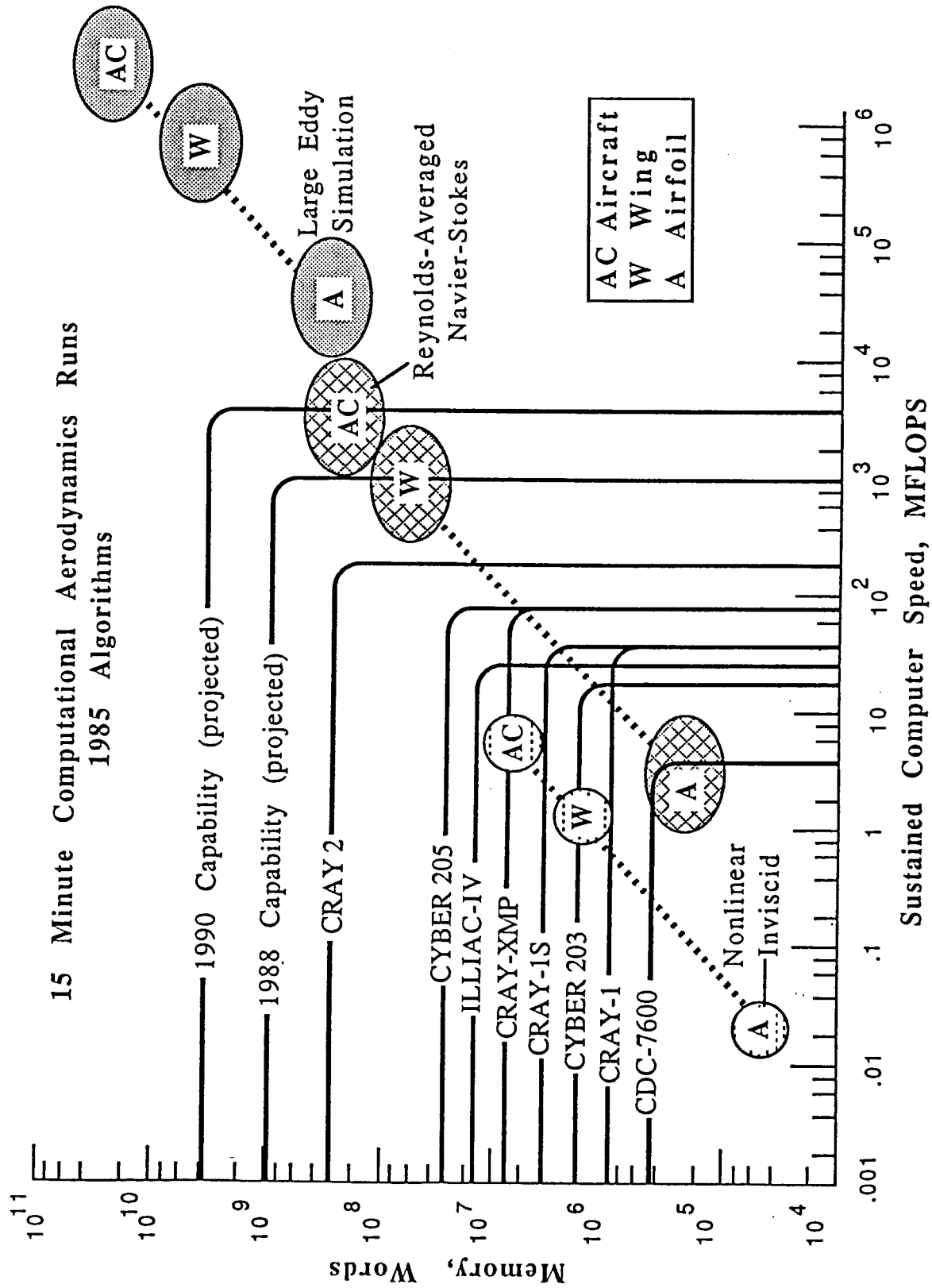


Figure 2. CPU Speed and Memory Requirements

In consideration of these computational needs, the NAS Program plan is to continue to acquire the most powerful supercomputers as they become available. By 1988 it is anticipated that a "one GigaFLOPS" computer with 4 times the *sustained* speed of a Cray 2 will be obtained and by 1990 an additional supercomputer with 16 times the sustained Cray 2 speed (4 GigaFLOPS, i.e., 4000 MFLOPS) will be added. To assure that this increased power can be fully utilized, it is essential to examine the total supporting system-level infrastructure. In particular, it is critical to provide sufficient capacity for the very large data files characteristic of fluid dynamics computations and to scale the bandwidth of the communication systems to handle the increased traffic.

2. RELATED WORK

Several authors have recently considered the "balances" needed between computer speed, storage requirements and data communications. Kung [5] presents a model of balanced computer architectures for particular classes of computation; however his work is primarily concerned with the characteristics of the processor itself and not the total environment. The same limitation is true of "Amdahl's rules of thumb" (see [13]) which Worlton [6] states in the form, "One byte of main memory is required to support each instruction per second," and, "One bit of I/O is required to support each instruction per second."

Thorndyke [7] does consider the support environment for the ETA-10 supercomputer and views the mass storage subsystem as part of a memory hierarchy consisting of central processor memory, shared memory, local disks, and mass storage. He concludes that the capacity ratios between each level of this hierarchy should increase by a factor of 16:1. He also proposes that data communication rates be matched to disk transfer rates of 10 Megabytes/sec. Ewald and Worlton [8] note that the Cray XMP/48 also exhibits a 16:1 ratio between local "disk" storage (Solid State Disk, in this case) and main memory. Furthermore, they note that historically the requirements at all levels of the storage hierarchy have been roughly proportional to the speed of the computer. For future scaling, they propose that on-line disk capacity requirements should grow at about 2/3 of the performance growth of the supercomputer and that transfer rates be increased to achieve a balanced system.

The 1986 work of Wallgren [9] uses similar theoretical scaling laws based on past and current experience to project the supporting environment needed for future supercomputers. His primary focus is on storage and not on data communications requirements. He correctly notes that the results are dependent on the assumed system architecture and on the usage profile. Wallgren's extrapolations extend over more than a decade in time and a factor of as much as 10^4 increase in supercomputer speed.

3. SCOPE

The present study examines the impact on the data communications of a 20-fold increase in computer speed over a 3-4 year time period and specifically assumes an architecture (Figure 3) which is structurally the same as the existing initial operating configuration of Figure 1. Furthermore, the user population is well defined since the NAS Program is not a general purpose scientific computing center but is devoted specifically to aeronautics studies and applications; the program plan calls for some 90% of the total time to be used for computational fluid dynamics and aerodynamics. This permitted a detailed workload model to be developed.

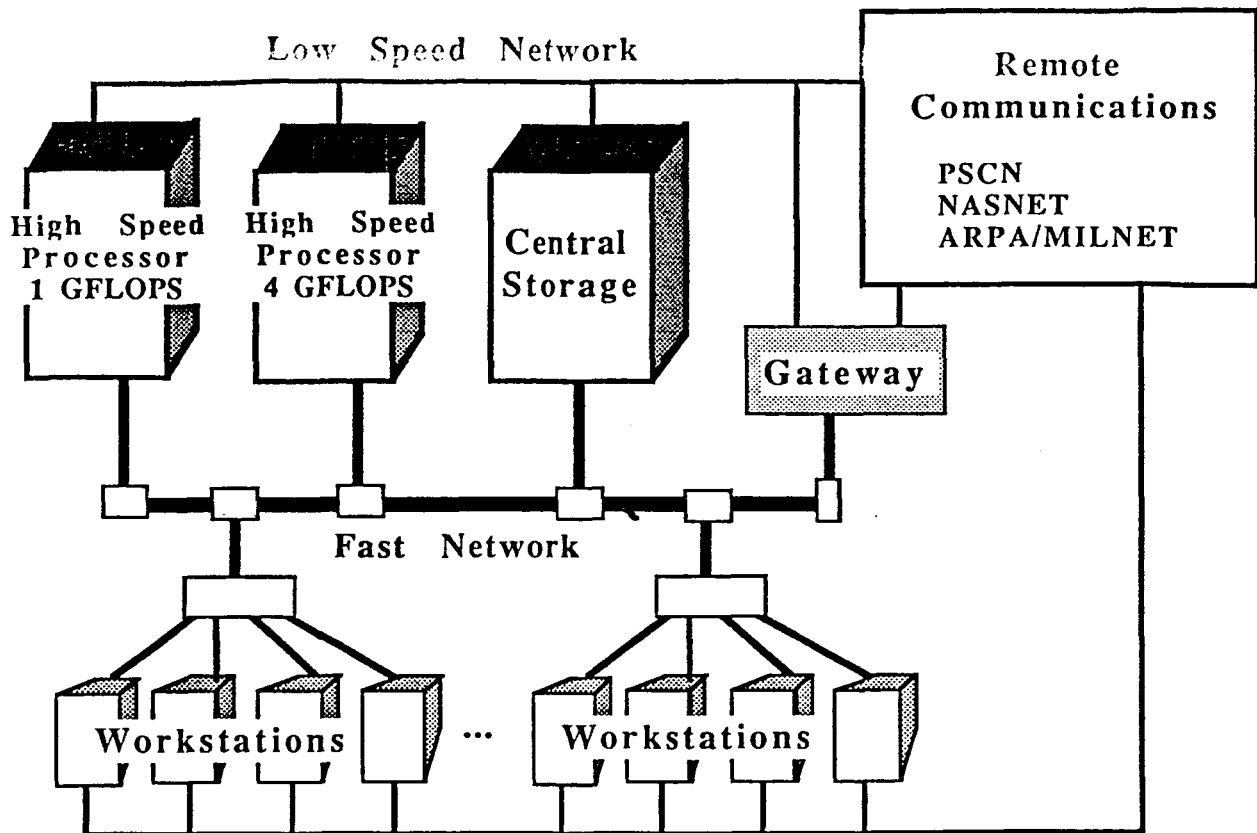


Figure 3. 1990 Model Configuration

4. ANALYSIS OF DATA COMMUNICATIONS

The 1990 system architecture shown in Figure 3 consists of a primary high speed data network between two supercomputers and a central mass storage system; a secondary network for communication between local workstations and the remaining subsystems; and a remote communication subsystem. The primary focus of the study was to determine the requirements for the "backbone" high speed data network for the movement of large files (typically from 5-80 million words) to and from the high speed processors. The remote communication subsystem and the local area network serving the workstations are also scheduled for upgrade, however their sizing was determined by factors *other* than the speed of the supercomputer(s).

4.1. REMOTE COMMUNICATIONS

The NAS remote communications system currently supports Arpanet/Milnet, NFSnet, NASnet, and the NASA-wide Program Support Communication Network (PSCN). Access to the NAS network from remote sites is shown in Figure 4. Vitalink bridges manage the inter-network connection and monitor all traffic on the ethernet local area network passing only those messages that have remote destination addresses to the appropriate Vitalink unit.

Both terrestrial links (at 56 and 244 Kilobits/sec) as well as satellite T1 links (at 1.544 megabits/sec to the NASA centers) are provided. At present, over 20 remote sites (with approximately 100 users) have been activated and additional sites will be added to expand the user community.

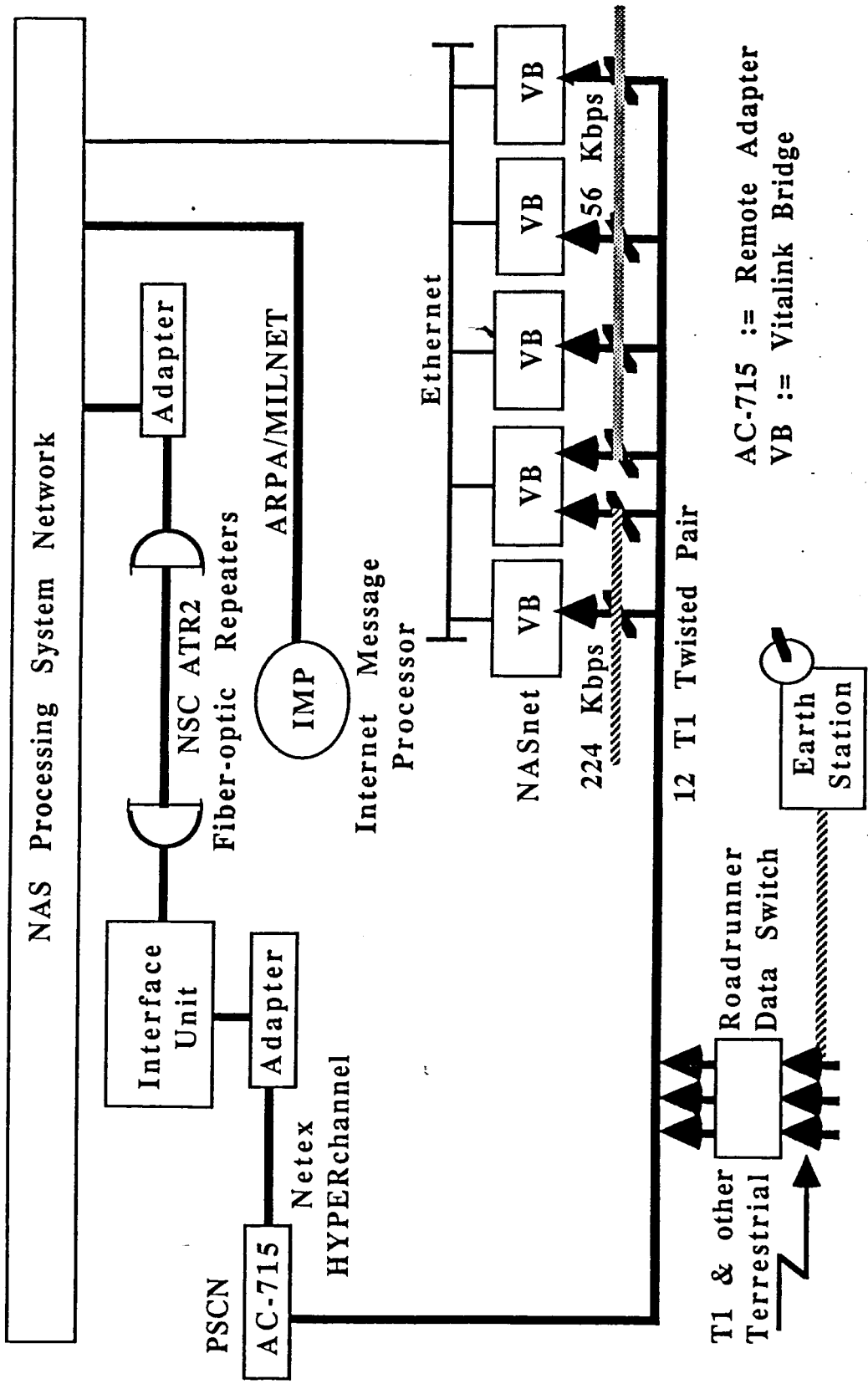


Figure 4. NAS Remote Communications

The long term goal is to provide equivalent services to both local and remote NAS users. This objective is constrained by technology and funding limitations. Upgrade to T2 rates (6.2 megabits/sec) for selected NASA centers is planned during the 1988/1989 time period. Additional improvements under investigation include implementing class of service protocols (such as distinguishing bulk file transfers from interactive traffic) and techniques for reducing the volume of remote data communications (such as remote block editors and distributed graphics services).

4.2 LOCAL WORKSTATION COMMUNICATIONS

The principal local users access the NAS system through powerful graphics workstations (Silicon Graphics 2500 Turbos). The workstation is an essential element of the system to permit graphical analysis and interpretation of the extremely large output files generated by computational fluid dynamics batch programs. It also enables the user to work interactively with the supercomputer. For example, a user may designate locations in the vicinity of an aerodynamic surface on his display, the flow patterns representing particle traces from those locations are computed on the supercomputer and the results returned to the user's display. The data communications services to the workstation must be sufficient to enable the user to make maximum use of both the batch and interactive workstation/supercomputer capabilities.

There are three modes in which graphics can be displayed at the workstation. It is possible to send down the solution files (or large subsets of these files) for computation and display at the local workstation. Although the workstation has the processing power comparable to a Vax 11/780 and the special purpose graphics hardware expedites the generation and transformation of vectors and polygons, there are many limitations to this mode of operation including the I/O bandwidth of the workstation and limitations of main memory and disk space. The preferred modes use the supercomputer for the computationally intensive tasks and send down either display lists or pixel data to the workstation. Both modes may be used, however with the current workstations it is difficult to use the pixel mode of interaction effectively. Future workstation upgrades will alleviate this limitation and the 1990 model assumes that both the display list mode and the pixel mode of interaction will be used extensively.

Based on the above description of operational use, the data communications requirements to the workstation are primarily sized according to the graphics needs of the user and the projected capabilities of future workstations. The present effective rate of approximately 2 Megabits per second is appropriate for the current workstation receiving display lists (typically 2.6 Megabits in size) from the supercomputer since the transmission time (1.3 seconds at 2 Megabits per second) is only a fraction of the time needed for the workstation to generate the display (approximately 5 seconds). Some representative display capabilities at 8 Megabits per second (the minimum planned for 1990) are shown in Table 1. For example, a minimal pixel file of 8 Megabits (display resolution of 1,000 x 1,000 with 8 bits/pixel for simple color and shading) can be transmitted in 1 second and the time for the workstation to generate a display from such a file is negligible. A very high quality pixel file of 96 Megabits would require 12 seconds of transmission time but this would typically be used for presentation quality graphics only. (For comparison, the data rate needed to support real time, interactive, color graphics with animation at 30 frames/sec. would be about 800 megabits/sec. The NAS Program is funding a prototype of such a bus and considering prototyping an advanced graphics workstation with a massive frame buffer and very high resolution, however this is not included in the 1990 system model.)

Table 1. Display of Color Images

Type of Output from Supercomputer to Workstation	Typical File Size	Channel Time @ 8 Mbps	Time for Workstation to Generate Display
Current Workstation (8000 Polygons, includes Hidden Surface Removal, Flat Shading)			
Solution File	400 Megabits (near storage limit)	30 seconds	≈ 25 seconds
Display List	2.6 Megabits	0.3 seconds	≈ 5 seconds (≈ 1 second if no hidden surface removal)
Future Workstation			
Minimal Pixel File	8 Megabits (1k x 1k x 8 bits)	1 second	<< 1 second
Fully Rendered, Very High Quality, Pixel File	96 Megabits (2k x 2k pixels 24 bits/pixel)	12 seconds	<< 1 second

4.3. HIGH SPEED "BACKBONE" COMMUNICATIONS

The high speed data communication requirements were derived by analysis of a model of the expected workload and checked using a discrete simulation program. The workload model assumed that the processing power of 5 Gigafllops available from the two 1990 high speed supercomputers (Figure 3) was fully utilized. A detailed profile (for computational fluid dynamics) of types of user tasks and expected frequencies had been developed over a six year time period and was updated in 1986 to reflect current algorithms, projected increased interactive usage and substantially increased use of graphics [10, 11, 12].

The model contained over two hundred parameters including: numbers and types of local and remote users, number of host processors, protocol delays, amount of disk storage attached to the supercomputers, distribution of batch and interactive work, frequency of task execution, probability of abortive runs, etc. Scripts were developed to represent characteristic delays associated with "think time" to separate user-initiated sequential processes. These asynchronous processes compete for system resources. The high speed data communications capability was initially taken as unbounded and the workload was progressively increased until the full capability of the supercomputers was saturated.

A simplified listing of the classes of work initiated by the users is summarized in Table 2. The principal execution runs represent various types of numerical aerodynamic simulations used to solve fluid flow problems. These generally involved repeated iterations of

difference equations over a three-dimensional grid which was assumed to consist of one million grid points. The simple steady state design simulations used an inviscid potential and required approximately 20,000 calculations per grid point of result file. The more complex steady state design simulations used the Reynolds-Averaged form of the Navier-Stokes equations and required approximately 600,000 calculations per grid point. The comparable unsteady solutions typically required over 4 million computations per grid point. The "model day" included 73 hour-long runs of this computation, each requiring 1.0 GigaFLOPS of sustained processing power. From Table 2 it is evident that this represented the dominant load on the supercomputers.

Table 2. Estimated Processor Load of User Initiated Runs

<u>TASK</u>	<u>GFLOP/DAY</u>
CODE & PARAMETER PREPARATION	66
PATCH GENERATION	43
GRID GENERATION	96
METHOD AND CODE DEVELOPMENT	13,003
SIMPLE STEADY STATE DESIGN SIMULATIONS	5,732
COMPLEX STEADY STATE DESIGN SIMULATIONS	31,834
COMPLEX UNSTEADY STATE DESIGN SIMULATIONS	250,978
FLUID RESEARCH LARGE EDDY SIMULATIONS	53,472
RESULT EDITING & VIEWING	17,465
DOCUMENT PREPARATION & USER COMMUNICATIONS	31
<u>TOTAL</u>	<u>372,719</u>

In order to relate the computational loads to network traffic, a Workload Data Base was constructed which contained detailed estimates of the sizes of the various input/output files for each task and a model of how they would be utilized. This provided a means for determining the specific files generated and their movement across the network. For example, Table 3 shows the network traffic load for the dominant Unsteady Design Simulation task.

Table 3. Network Load for Unsteady Design Simulations
MB/day

Sources Destinations	MASS STORAGE	HIGH SPEED PROCESSORS	TOTAL
MASS STORAGE	-	4,428	4,428
LONG-HAUL COMMUNICATIONS	0.2	2,048	2,048
WORK-STATIONS	0.1	1,810	1,810
HIGH SPEED PROCESSORS	1,555	-	1,555
TOTAL	1,555	8,286	9,841

The source of most of the data communications load comes from the output of large files from the the high speed processors to their local disks and the subsequent movement of these files between the supercomputers and the central mass storage system. Figure 5 shows the results of the model study for this traffic. There is a predicted net accumulation on the local disks of 42 Gigabytes per day which must be moved (by system-managed file migration) to the central mass storage system so that the supercomputers' disk space will be available for current work. The two supercomputers of the 1990 system were modelled with a total of 400 Gigabytes of local storage. Since more than half the available 400 Gigabytes is needed for current working space each day, the average age of files before automatic migration to central storage was found to be about 3.5 days. This additional load (of automatic migration) on the data communications can, however, be distributed over the periods of lightest user activity. Typically the nighttime workload consists of large batch jobs with little interactive traffic. Under these conditions the supercomputers are fully saturated but the network is only lightly loaded.

**Note: Supercomputer Disks
Daily Net Accumulation = 42 GB**

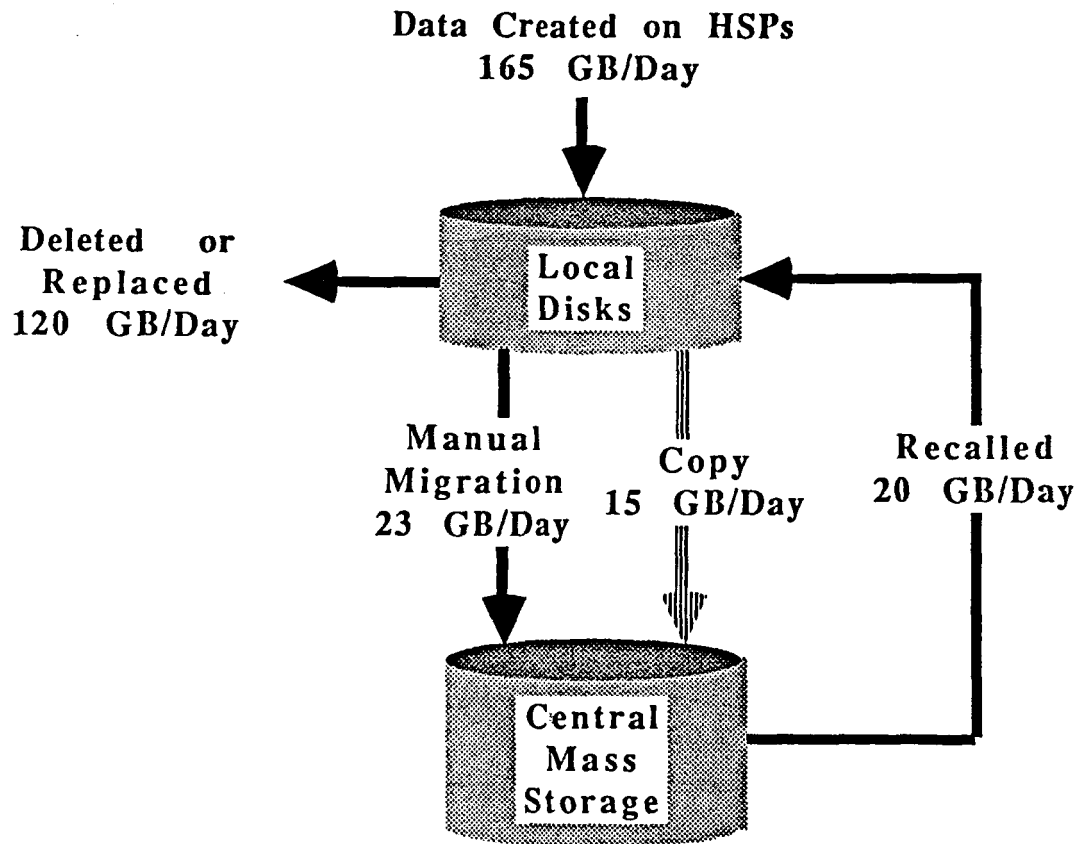


Figure 5. Daily File Activity

Figure 6 summarizes the major result of the study and illustrates both the hourly distribution of traffic as well as the average daily traffic including migration. To avoid significant queuing delays during times of peak activity, and to handle periodic bursts within an hour efficiently, the bandwidth for the 1990 system should be sized well in excess of the peak rates shown on Figure 6. The design value recommended was 100 megabits per second [14]. This was regarded as a reasonable requirement in view of projected technological advances.

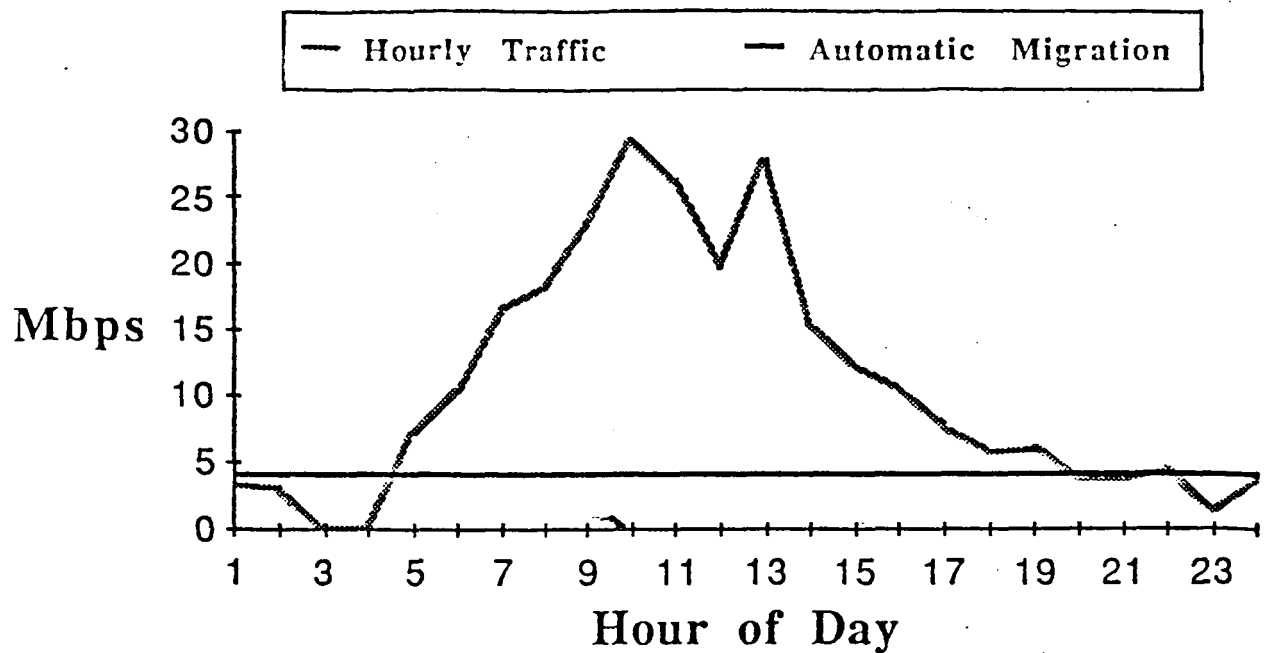


Figure 6. Data Transfer Rates

5. CRITIQUE OF RESULTS

An essential (but often neglected) step in studies of this type is to estimate the sensitivity of the results to the assumptions inherent in the model. The succeeding sections provide estimates of the effects of some of the major assumptions on the projected data communications requirement.

5.1. USE OF GRAPHICS

The need for sophisticated graphics to analyze the very large data files typical of computational fluid dynamics is unquestioned and a significant allowance for this type of processing was included in the model. However, this was a projection and might not correspond to the actual future usage. Among other factors it is dependent on the capabilities of future workstations.

The model provided a breakdown into various types of output. The three principal classes created were raw solution results, graphics display lists and pixel files. It was found that a very useful measure for scaling data communications with processing power was the ratio of bytes of output to MFLOPs (millions of floating point operations) required to generate that output. This *characteristic output ratio* will be designated β_M with units of Bytes/MFLOP. The importance of this parameter is that if the *only* deviation from the assumed model is processing power, the results can (within reasonable limits) be scaled directly. Furthermore, if the mix of classes of output varies, it is possible to estimate the effect on this critical parameter and hence (within modest bounds) on the final results.

Over the distribution and frequency of tasks initiated by users, the model showed that raw result files (including debug runs) were found to generate $\beta_M = 130$ B/M (Bytes per MFLOP). In contrast, the generation of graphics display lists generate $\beta_M \approx 8,000$ B/M and pixel files generate $\beta_M \approx 5,000$ B/M. In the model, 5% of the total available processing power (FLOPs) was devoted to graphics. Approximately 75% of the graphics

FLOPs were utilized for pixel files, however much more processing is required for pixel files. Hence, this distribution corresponded to approximately three graphics display lists for each pixel file produced. Since the supercomputer power of the 1990 model system was sized at 5 GFLOPS, the 5% utilized for graphics corresponds to 250 MFLOPS, equivalent to the total sustained processing capability of the 4 CPU's of a CRAY 2!

For the assumed usage distribution, the overall value of the characteristic output ratio for the 1990 model was found to be $\beta_M \approx 400$ Bytes/Mflop. Figure 7 shows the variation in this parameter with changes in the relative amount and type of graphics usage. The abscissa represents the proportion of processing power used for graphics processing (both display list and pixel data) and the one-parameter family of lines represents various mixes of pixel output and display list output. The reference point corresponding to the model is marked. As an example, the calculation of the design point (using the data values of the paragraph above) is shown below:

$$0.95(130) + 0.05[0.75(5000) + 0.25(8000)] = 411 \text{ Bytes/Mflop.}$$

It may be noted that increased use of pixel data relative to display list output has a significant effect in reducing β_M . Display list output with a β_M of 8,000 B/M (compared with pixel file output with a β_M of 5000) utilizes less supercomputer processing power but places a greater load on the data communications (and on the workstations).

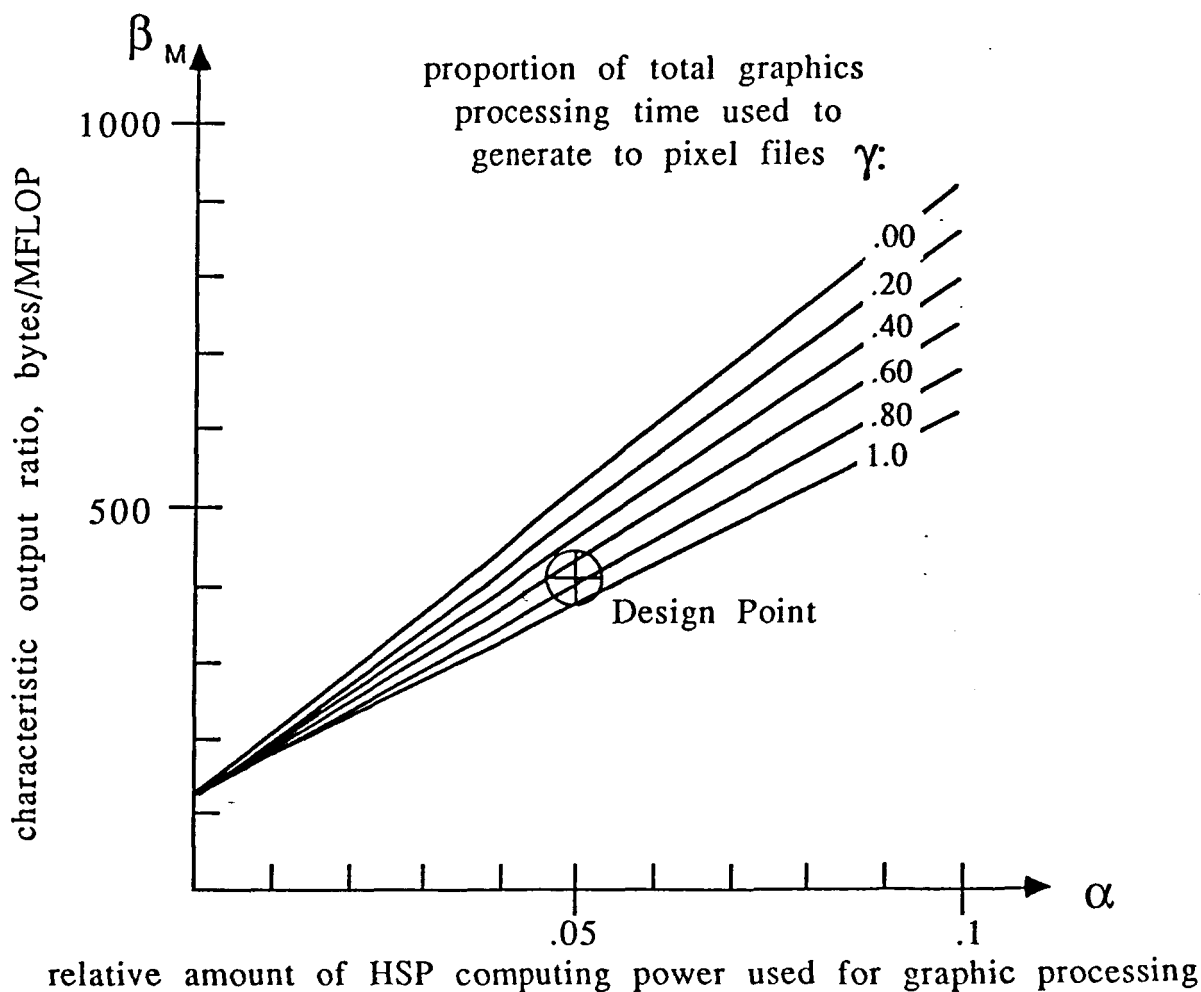


Figure 7. Influence of graphics processing

5.2. THE USER PROFILE

The workload model was specifically designed for solving problems in computational fluid dynamics. Table 4 summarizes a 1986 study of major users of supercomputers at the NASA Ames Research Center. The first two columns represent supercomputers of the Ames Central Computing Facility and only the Cray 2 is a NAS supercomputer. Furthermore, the sampling period shown in Table 4 occurred shortly after the Cray 2 was initially installed, in a pre-operational time period, and does not represent the *intended* operational distribution of users. Nevertheless, it appeared that computational chemistry utilized large amounts of supercomputer time and might represent a future NAS system user that was not reflected in the workload model.

Table 4: Ames Vector Processor Utilization
Percentage of User Time by Organization

USERS	CYBER 205 FY 85	CRAY X-MP 48 3/86-10/86	CRAY 2 3/86-10/86
Remote	-----	-----	36.8 %
Advanced Aerodynamics Concepts	-----	7.1 %	-----
Applied Computational Fluids	0.1 %	24.1 %	7.0 %
Experimental Fluid Dynamics	0.7 %	6.1 %	-----
Computational Fluid Dynamics	25.0 %	24.1 %	13.8 %
Computational Chemistry	67.9 %	16.0 %	19.2 %
TOTAL	93.7 %	77.4 %	76.8 %

Much of the current work in computational chemistry at NASA Ames Research Center is devoted to determining the electron density distribution of molecular structures by solving the Schrodinger equation. The methods used involve evaluation of many multi-dimensional integrals and manipulation of very large matrices to find eigenvectors and eigenvalues. These methods are quite different than those used in computational aerodynamics studies. Hence the output of such runs might produce larger or smaller files than those used in the model.

Consequently, a study was made of the character of the output files generated by these supercomputer users. The results are shown in Figure 8 in terms of the parameter β_M . The prediction of the 1990 model study is shown for comparison. The characteristic output of computational chemistry was found to be comparable to the major computational aerodynamics users. Hence, even if computational chemistry were in the future to become a significant component in the mix of NAS users, it was concluded that this would not invalidate the results.

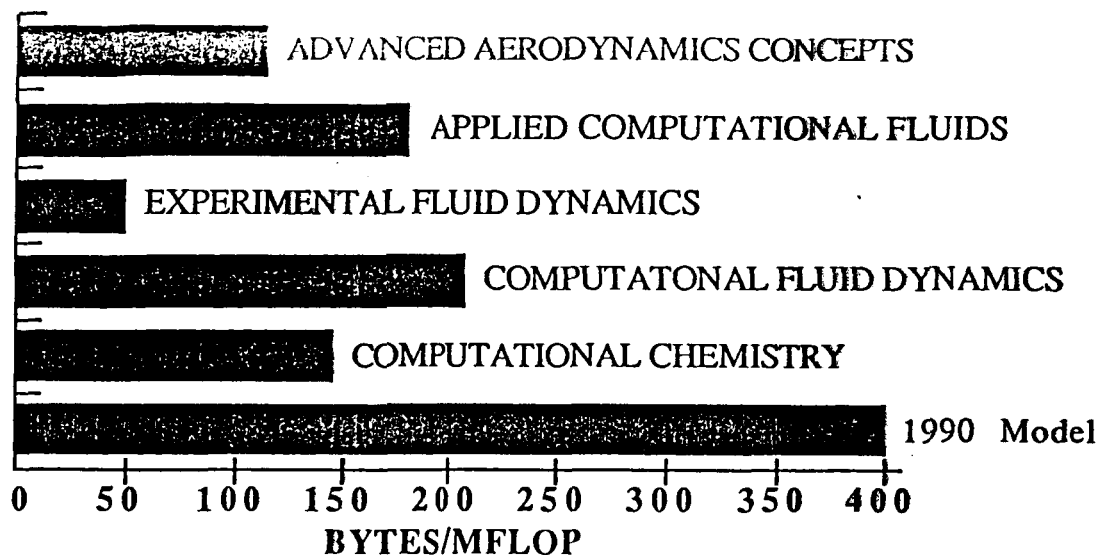


Figure 8. Comparison of Current Usage and 1990 Model

It is also of considerable interest to note the relationship of the predicted 1990 usage compared to actual 1986 usage. It is not surprising that the predicted value of β_M (≈ 400 Bytes/MFLOP) is almost twice the 1986 measured values in Figure 8 since extensive use of graphics was just beginning. Figure 7 confirms that increased graphics use results in an increase in β_M .

5.3. AMOUNT OF LOCAL DISK STORAGE

Locality of files increases the hit rate and reduces the volume of data traffic (see [15]). If local storage were unlimited, there would be no need to move files to a central storage facility. If files could be maintained local to the supercomputers for about 10 days (two working weeks) instead of 3.5 days, it was estimated that the recall load would be reduced from 20 Gigabytes per day to less than 10 Gigabytes per day. Aging would also increase the number of files deleted and decrease the amount of manual migration shown in Figure 5. All of these effects decrease the traffic on the network. It was estimated that increasing the local disk storage by an additional 250 Gigabytes could reduce the traffic between the supercomputers and central storage by 30-50%.

5.4. OTHER CONSIDERATIONS

The model assumed a typical grid size of 10^6 points. Increasing the geometrical refinement by using more grid points does not have any affect on β_M provided the computations needed per grid point remain constant. However, in many cases not all the final data needs to be saved. The finer grid not only yields results at more spatial locations but also permits a more accurate approximation to the differential equation. It is often only necessary to save the results on a much coarser grid (except for critical regions of interest) and recompute the interior points if needed. For example, saving every fourth grid point in each dimension would reduce the output by a factor of 64. Similarly, it may not always be necessary to save 64-bits of precision in the output data.

The realism of the physics was discussed briefly in connection with Figure 2 where it was noted that solving the more complex equations such as large eddy simulation involved an enormous increase in the number of computations. There would certainly not be a proportionate increase in the output, hence the trend towards removing the approximations would result in a sharp decrease in the ratio β_M and alleviate the data communications load. This was a factor in the 1990 model and will become increasingly significant as more powerful supercomputers become available.

It was assumed that the algorithms used in the 1990 time frame would be the same as those presently known or in use. This is quite unlikely since algorithm development is a fertile, on-going activity. Prior trends have been in the direction of progressively decreasing β_M , but it is impossible to predict the implications of undiscovered algorithms. If there is a *radical* change from deterministic approaches to statistical techniques (for example, gas lattice automata methods, [16]) this would clearly require much more computational effort without a corresponding increase in output, resulting in a sharp decrease in β_M .

6. SUMMARY

The results of an analysis of the 1990 "backbone" data communications requirements for the advanced Numerical Aerodynamic Simulation Program showed that the expected workload required an *effective* bandwidth of 100 megabits per second.

A critical examination of the various assumptions inherent in the model indicated that 100 Mbps was a safe, conservative result.

Among the most sensitive assumptions was the projected amount and type of interactive graphics expected to be used.

Increasing the amount of disk storage local to the supercomputers would result in a significant decrease in the data communications requirements.

The characteristic output ratio β_M (representing a measure of bytes of output relative to megaFLOPs of processing) made it possible to estimate the effects of (modest) variations in the model assumptions on the data communications requirements.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Mr. Frank Preston of the NAS Systems Division, NASA Ames Research Center and Mr. Ari Ollikainen of General Electric Western Systems for useful data and valuable suggestions during the preparation of this paper.

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