United States General Accounting Office

GAO

Report to the Chairman, Committee on Armed Services, U.S. Senate

December 2000

EXPORT CONTROLS

System for Controlling Exports of High Performance Computing Is Ineffective

Accountability * Integrity * Reliability

GAO-01-10

Contents

Abbreviations

DOD	Department of Defense
ISTAC	Information Systems Technical Advisory Committee
MTOPS	millions of theoretical operations per second

United States General Accounting Office
Washington, D.C. 20548

December 18, 2000

The Honorable John Warner
Chairman, Committee on Armed Services
United States Senate

Dear Mr. Chairman:

Because high performance computing is an important enabling technology for military purposes, the U.S. government controls the export of high performance computers to sensitive destinations, such as Russia and China, based on foreign policy and national security concerns. A high performance computer[1] has both civilian and military applications,[2] operates at or above a defined performance threshold, and requires an export license to particular destinations, according to the Commerce Department, the agency responsible for licensing dual-use items. U.S. policy with respect to the export of sensitive technology, including computers, is to seek a balance between the U.S. economic interest in promoting exports and its national security interests in both maintaining a military advantage over potential adversaries and denying the spread of technologies used in developing weapons of mass destruction.

The President has periodically changed the performance thresholds above which licenses are required based on technological advances. The National Defense Authorization Act of 1998 requires the President to provide a report to Congress justifying each change for exports of high performance computers to certain sensitive countries. It requires the report, at a minimum, to (1) address the extent to which high performance computers with capabilities between the established level and the new proposed level of performance are available from other countries, (2) address all potential uses of military significance to which high performance computers at the

[1] High performance computers are regulated based on their composite theoretical performance as measured in millions of theoretical operations per second (MTOPS).

[2] An application is a program or group of programs designed for end users. Software can be divided into two general classes: systems software and applications software. Systems software consists of low-level programs that interact with the computer at a very basic level, including operating systems, compilers, and utilities for managing computer resources. In contrast, applications software (also called end-user programs) includes database programs, word processors, and spreadsheets. Figuratively speaking, applications software sits on top of systems software because it is unable to run without the operating system and system utilities.

new levels could be applied, and (3) assess the impact of such uses on U.S. national security interests. The President announced in August 2000 that the control threshold above which computers exported to countries like Russia and China would need a license would be 28,000 millions of theoretical operations per second (MTOPS) effective immediately.

Rapid technological advances in computing power have fueled concerns over the continued effectiveness of current computer export controls. You raised concerns about whether the computer export licensing process continues to protect U.S. national security interests. As agreed with your office, this report discusses (1) the effectiveness of current export controls in preventing countries of concern from obtaining high performance computing capabilities that can be used for military applications and (2) our evaluation of the President's justifications for changing the computer control thresholds. You also asked us to identify possible ways of protecting U.S. national security interests related to exports of high performance computers. We obtained the views of government and private experts on this matter, and they are presented in appendix I of this report.

Results in Brief

The current export control system for high performance computers, which focuses on controlling individual machines, is ineffective because it cannot prevent countries of concern from linking or clustering many lower performance uncontrolled computers to collectively perform at higher levels than current export controls allow. The Department of Commerce controls the export of individual high performance computers using MTOPS as its control measure. It currently requires licenses for export of computers with performance levels above 28,000 MTOPS for countries of concern, but lower performance uncontrolled computers have been clustered together from readily available components to obtain computing capabilities up to 70,000 MTOPS. However, even if control thresholds were raised to reflect this performance level, U.S. government computer experts and computer industry representatives agreed that using MTOPS to calculate computer performance and set control thresholds is an outdated and invalid means for determining whether individual high performance computers should be licensed for export. They said that the measure does not account for new designs of individual processors or for clustering computers together to achieve high performance computing levels. A Commerce Department technical advisory committee[3] has examined three alternatives to the current measure for establishing the licensing threshold, but none of the alternatives would solve the problems posed by clustering uncontrolled computer components to achieve higher computing levels. In addition, the Commerce Department has not assessed the implications of these technological advances on the effectiveness of the current licensing process to limit the access of countries of concern to high performance computing.

[3] Technical advisory committees, such as the committee on Information Systems Technical Advisory Committee, advise the Department of Commerce on the technical parameters for export controls applicable to dual-use commodities and technology and on the administration of those controls. The committees comprise representatives from industry and government who represent diverse points of view on the concerns of the exporting community. Industry representatives are selected from firms producing a broad range of goods, technologies, and software presently controlled for national security, foreign policy, nonproliferation, and short supply reasons; or that are proposed for such controls, and are balanced to the extent possible among large and small firms.

The justifications to change computer export controls in February and August 2000, which the President provided in two reports to the Congress, are inadequate for several reasons. First, the reports address the availability of individual computers to other countries, but they do not address the fact that the performance capabilities of clustered systems that can be acquired by other countries have exceeded the new control thresholds. Second, the reports address only selected computer uses of military significance to which high performance computers could be applied instead of all such uses at the new control thresholds, as required by the 1998 National Defense Authorization Act. Finally, the President's reports make no reference to how specific identified uses at the new control threshold would affect U.S. national security. Instead, the President's reports state that (1) pursuit of particular national security applications would require more than computer hardware; (2) there is little danger of most countries usefully employing high performance computers for military uses; and (3) it is important for the United States to retain a technological advantage in the design, development, and production of microprocessors and computers. The reports' sections dealing with military uses of high performance computers and how such uses could effect U.S. national security were based on information from a 1998 study[4] used by the Defense Department about military computer uses. The study's authors concluded that neither they, nor the U.S. government, had sufficient information to assess which countries could productively use high performance computers to pursue particular applications.

Appendix I discusses the three alternative measures of individual computer performance that the Department of Commerce's Technical Advisory Committee has examined. The appendix also discusses nine other ideas that have been raised at different times by various computer experts as possible alternatives to either the current MTOPS measure or the overall control system. However, neither Commerce nor others have fully assessed the feasibility of these ideas. We did not assess the feasibility of implementing any of the ideas but describe their characteristics and limitations when identified by the experts that we consulted. As technological advances in high performance computing make it more difficult to maintain the U.S. lead in military capabilities by denying

[4] Seymour E. Goodman, Peter Wolcott, and Patrick Homer, *High-performance Computing, National Security Applications, and Export Control Policy at the Close of the 20th Century* (Palo Alto, CA: Stanford University, Center for International Security and Arms Control, 1998).

advanced technology transfers to countries of concern, it may become necessary to explore other options to maintain the U.S. lead in military technology. As a step in this direction, the National Defense Authorization Act for fiscal year 2000 requires (1) an annual report on transfers of militarily sensitive technology to countries and entities of concern and (2) an assessment by the Secretary of Defense on the cumulative impact of U.S.-granted licenses for exports of technologies and technical information. The report prepared under the act must include information on countermeasures that may be necessary to overcome the use of such technologies and technical information. It is not required, however, to assess the cumulative impact of exports of nonlicensed computers, such as those that can be clustered. The report is scheduled for completion in late 2000.

We are recommending that the Secretary of Commerce, in consultation with the Secretaries of Defense, Energy, and State, convene a panel of experts to conduct a comprehensive assessment and report to the Congress on ways of addressing the shortcomings of computer export controls, including, but not limited to, the ideas noted in this report. We are also recommending that the Secretary of Defense determine what U.S. countermeasures are necessary, if any, to respond to enhancements of the military or proliferation capabilities of countries of concern derived from both licensed and nonlicensed high performance computing.

Agencies commenting on a draft of this report generally agreed with our findings and conclusions, and the Department of Energy agreed with our recommendation to convene a panel of experts to conduct a comprehensive assessment and report to the Congress on ways of addressing the shortcomings of computer export controls. The Departments of Commerce and Defense disagreed with the need to implement our recommendations because they said they are already engaged in interagency reviews of similar issues. When asked for documentation on how interagency mechanisms are pursuing the points covered in our recommendations, the agencies provided none. As a result, we believe our recommendations are still valid and necessary to protect U.S. national security interests. Since Commerce and Defense disagreed with our recommendations, we have added two Matters for Congressional Consideration. The Congress may wish to institute a requirement that the Secretary of Commerce, in consultation with the Secretaries of Defense, Energy, and State, convene a panel of experts to conduct a comprehensive assessment of and report to the Congress on possible ways of addressing the shortcomings associated with controlling individual high performance computers, including, but not limited to, the ideas noted in this report. The Congress may also wish to consider instituting a requirement that the Secretary of Defense determine and report on what U.S. countermeasures are necessary, if any, to respond to computing-related enhancements of the military or proliferation capabilities of countries of concern, as we have recommended in this report.

Background

The use of high performance computing technology is reducing the costs and time required for systems analysis, design, development, test, and deployment of military systems and is improving the integration and effectiveness of complex weapons systems, according to the Department of Defense (DOD). As DOD continues to reform and reengineer its acquisition processes, high performance computing assets are being used to reduce the number and cost of building expensive prototypes. High performance computing, a critical enabling technology, is now a key ingredient to the successful implementation of many major DOD acquisition programs, according to DOD. It is for these reasons that the United States attempts to limit the extent of high performance computing capabilities obtainable by countries of concern.

High performance computers and related components (for example, processors) are controlled under the Export Administration Act and the implementing Export Administration Regulations.[5] The act authorizes the Commerce Department to require firms to obtain licenses for the export of sensitive items that may pose a national security or foreign policy concern. The Departments of State, Energy, and Defense assist Commerce, which administers the act, by reviewing export applications and supporting Commerce in its reviews of export control policy.

Since 1993, the President has revised U.S. export control requirements for high performance computers five times, including the revisions announced in August 2000. The export control policy revision implemented in January 1996 removed license requirements for most exports of computers that could perform at or below a level of 2,000 MTOPS—an increase from 1,500 MTOPS.[6] The 1996 policy revision also organized countries into four

[5] 50 U.S.C. App. section 2401 and following and 15 C.F.R. section 730 and following.

[6] *Export Controls: Information on the Decision to Revise High Performance Computer Controls* (GAO/NSIAD-98-196, Sept. 16, 1998).

computer "tiers," with each tier after tier 1 representing a successively higher level of concern related to U.S. national security interests.

- Tier 1. The policy placed no license requirements on tier 1 countries, primarily those in Western Europe and Japan.
- Tier 2. Exports of computers above 10,000 MTOPS to tier 2 countries in Asia, Africa, Latin America, and Central and Eastern Europe continued to require licenses.
- Tier 3. A dual-control system was established for tier 3 countries.
- Tier 4. Exports of high performance computers to tier 4 countries were essentially prohibited.

In 1996 there were 50 tier 3 countries, including China, Russia, India, and Israel. Since then, the number of tier 3 countries has increased to 52. In January 1996, the threshold for exporting high performance computers without a license to tier 3 countries was set at 7,000 MTOPS for civilian end users, while exports of computers for potential military end users at and above 2,000 MTOPS required a license. Exports of high performance computers with performance capabilities above 7,000 MTOPS to civilian end users in all tier 3 countries required a license. High performance computer exports to countries in tier 4 (for example, Iran, Iraq, and Libya) were essentially prohibited because of national security and foreign policy concerns about these countries.

The Fiscal Year 1998 National Defense Authorization Act[7] requires the President to report to the Congress justifications for changes in controls for computer exports to certain sensitive countries. The act further requires exporters to notify the Commerce Department of any proposed high performance computer exports to countries that pose a concern for military or proliferation reasons to determine if these exports need a license. [8] The act also provides that if any designated agency[9] raises a written objection to the proposed export within 10 days after Commerce receives the notification of the export, the export will require a license.

[7] P.L. 105-85 sec. 1211, Nov. 1997.

[8] Advance notification to Commerce of exporter's intent to export high performance computers will rise to 28,000 MTOPS, effective in February 2001, from the current threshold of 12,500 MTOPS.

[9] Designated agencies for this purpose are the Departments of Defense, Energy, and State.

On July 27, 1999, February 15, 2000, and August 30, 2000,[10] following announced changes to the export control levels for high performance computers, the President submitted a report to the Congress, as required. According to the President's announcements, these changes were needed because of the extraordinarily rapid rate of technological change in the computer industry.

In the August 2000 announcement, the President described plans to change the controls on the exports of high performance computers by increasing the computing performance level at which export licenses would be required.[11] These changes were as follows:

- Tier 1. No changes.
- Tier 2. The licensing level was raised to 45,000 MTOPS, effective immediately.
- Tier 3. The two-level system for tier 3 countries was eliminated, and the licensing level for the tier was raised to 28,000 MTOPS, effective immediately.
- Tier 4. No changes.

Export Control System for High Performance Computers Is Not Effective

The current system of controlling the export of individual machines is ineffective in limiting countries of concern from obtaining high performance computing capabilities for military applications. In addition, information obtained from the Departments of Commerce, Defense, and Energy and computer industry representatives shows that, given advances in technology, using MTOPS to establish export control thresholds is outdated and no longer a valid means for controlling computing capabilities and that an alternative is needed to replace it. MTOPS is an outdated measure because of its limited ability to estimate the performance of new designs of processors and to account for clustering of individual computers to achieve high performance computing capability.

[10] *Summary of Findings With Respect to Criteria Set Forth in Subsection 1211 (d) of the National Defense Authorization Act for Fiscal Year 1998,* attachment to letter sent to Congress (Washington, D.C.: The White House, July 27, 1999, Feb. 15, 2000, and Aug. 30, 2000).

[11] Executive branch agencies involved with reviewing and recommending changes to computer export controls are the Departments of Commerce, Defense, State, and Energy and the National Security Council.

Computer Advances in Clustered Systems Compromise the Effectiveness of Current Controls

Over the past several years, technological advances in the ability to cluster lower performance computers have resulted in an increasing capability worldwide to achieve high performance computer levels. As a result, current U.S. export controls cannot prevent countries of concern from obtaining computing capabilities that can be used for military applications at levels much higher than those at which computers are currently controlled by the U.S. government.

Commerce's Information Systems Technology Advisory Committee, which advises and assists the Secretary of Commerce, reported in May 1999—and the Lawrence Livermore National Laboratory confirmed in February 2000—that clustered computer systems composed of readily available components have been built with a performance level up to about 70,000 MTOPS. As a result, the known performance levels of clustered systems exceed even the latest export control thresholds set by the U.S. government in August 2000. Figures 1 and 2 show examples of clustered computer systems composed of readily available components, such as personal computers and monitors, located at Clemson University and the Nehru Centre for Advanced Scientific Research, respectively.

Figure 1: A Clustered Computer System

Source: Grendel Beowulf Workstation, Clemson University.

Figure 2: A Clustered Computer System in a Tier 3 Country

Source: Jawaharlal Nehru Centre for Advanced Scientific Research, India.

According to a February 2000 analysis prepared by the Lawrence Livermore National Laboratory, "Ignoring the fact that low-performance computers can be clustered to achieve a higher level of processing leads to a false sense of security." The analysis said that it is inconsistent to control the export of individual high performance computers when the performance capabilities of clustered computers exceed the current and proposed control levels.[12] Officials of the Los Alamos National Laboratory said that expertise necessary to build clustered systems is available worldwide, including in countries such as China and India, and that laboratory officials communicate with people building these systems and solving the same types of technical computing problems as the national laboratories. While discussing the relatively lower level of expertise necessary to put a clustered computer system together, the officials stressed that it is more difficult to operate clustered systems than to build

[12] The National Security Implications of Decontrolling Export to Tier III Countries of High Performance Computers between 2,000 and 40,000 MTOPS. (February 2000)

them. For example, support for computer functions requires having an efficient schedule for running hundreds of separate problems and the input and output of data among a computer, its local disks, networks, and archival storage. Without vendor-supplied software to automate these functions on a system clustered together from readily available components, everything must be done manually, making computing a labor-intensive operation.

One computer facility in India advertises that it has developed a new computer system architecture with clusters of workstations with commercially available interconnect technologies. The facility is on the Commerce Department's "Entities List," which identifies foreign end users that have been determined to present an unacceptable risk of diversion to developing weapons of mass destruction or the missiles used to deliver those weapons. Publishing this list puts exporters on notice that any products sold to these end users may present concerns and will require a license from Commerce.

MTOPS Is No Longer Adequate as a Measure of Performance

Analyses and information from U.S. government officials[13] and computer industry representatives show that MTOPS is no longer a valid measure of individual computer performance and needs to be replaced. During the course of our review, these officials and representatives said that MTOPS is outdated and can no longer adequately account for the performance capabilities available from today's computers. As a result, the continued use of the MTOPS measure would cause systems with the same performance capabilities to be treated differently under export control regulations, according to Commerce's Information Systems Technical Advisory Committee.

The MTOPS measure is unreliable today because it is heavily, if not exclusively, dependent on the clock rate of a microprocessor, measured in megahertz, when several other factors should be considered. It does not account for certain factors, such as memory retrieval times, interconnection methods, and internal bus speeds. (A bus is a collection of wires through which data is transmitted from one part of a computer to another.) An internal bus connects all the internal computer components to the central processing unit and main memory. The size of a bus is important

[13] U.S. government officials include the Deputy Under Secretary of Defense (Science and Technology) and officials of the Commerce and Energy Departments.

because it determines how much data can be transmitted at one time. A fast bus allows data to be transferred faster, which makes applications run faster. In networking, a bus is a central cable that connects all devices on a local area network. In addition, MTOPS is inaccurate if incorrectly applied to computing elements organized in certain ways, such as computer clusters. Under DOD auspices, U.S. government officials, computer industry representatives, and academics met in December 1997 to determine whether the use of MTOPS is sufficient to rate the relative performance of current and future computer systems. The group determined that there were variances of a factor of 2 in the performance of delivered systems relative to the MTOPS-calculated performance because of the wide range of architectures in use, but it concluded that continuing rapid changes in technology might result in yet larger variances in the near future.

President's Justification for Changing Computer Export Control Thresholds Was Inadequate

The National Defense Authorization Act of 1998 requires the President to provide a report to the Congress on three factors when proposing a modification of the export control thresholds for high performance computers. First, the report is to address the availability of high performance computers from other countries. Second, it is to address all potential computer uses of military significance at the new control thresholds. Third, the report is to assess the impact of such uses on U.S. national security interests. In response to the act's requirements, the February and August 2000 reports presented information on the availability of individual computers from other countries but did not recognize such countries' capabilities to cluster computers to obtain computing performance beyond the new thresholds. Furthermore, the August report addressed only 22 of 172 known military uses of high performance computers up to the new control threshold. Finally, the report made no reference to the national security impact of specific identified uses at the new control thresholds. Instead, the report stated that (1) pursuit of particular national security applications would require more than computer hardware; (2) there was little danger of most tier 2 and 3 countries diverting high performance computers from other purposes and usefully employing them for military uses; and (3) it was important for the United States to retain a technological advantage in the design, development, and production of microprocessors and computers. The reports relied for their information about national security impacts of military computer uses on a study that stated that it could not assess which countries of concern could use computers for particular military applications because the U.S. government did not have information to make such an assessment.

Clustering Not Factored Into New Thresholds in Considering Computing Performance Availability in Other Countries

The President's reports were required to address the extent to which high performance computers with capabilities between the established level and the new proposed level of performance are available from other countries. In response to the requirement, the reports to the Congress justified the new control thresholds based on industry-provided information indicating the MTOPS performance of mass market processors that the industry expected would be produced within the next 6 months. The reports stated that such processors would be uncontrollable worldwide. While the administration discussed computer clustering as contributing to such availability, it did not factor computer clustering into its control threshold changes made during 2000, nor did it indicate that with clustered systems other countries could obtain performance capabilities that exceed the new control thresholds. If they had presented this fact in the reports, it would have revealed that the computer control system was ineffective.

Although the President's February and August 2000 reports discussed advances in clustering, they did not indicate that performance capabilities of clustered systems have exceeded the new control thresholds. The President's reports noted that advanced network technologies, particularly in parallel processing known as "distributed computing," are freely available. Cost considerations and advances in computer technology in both the United States and overseas have created a favorable environment for high performance distributed computing using readily available hardware and software, according to the reports. The reports added that relatively low-cost high performance computer systems typically consist of large clusters of commercially available workstations or personal computers that are linked by interconnection hardware and high-speed communication software. As a result, the affordability and widespread availability of these computer products permit foreign end users to configure these commercially available products into high performance computer systems. The President's reports did not state that high performance computing up to about 70,000 MTOPS is attainable.

While computer clustering was not factored into the control threshold changes made during 2000, the President's August 2000 report justified the new control thresholds based on industry information indicating the MTOPS performance of mass market processors to be produced within the next 6 months that Commerce officials believed would be uncontrollable. As of August 2000, the fastest mass-marketed microprocessor had a peak performance measure between 3,000 and 4,000 MTOPS. By the fall 2000, a new 6,100 MTOPS microprocessor was expected to be available, and a four-microprocessor computer based on this new microprocessor was expected to have a performance level of about 24,000 MTOPS. The August report further stated that the next generation of computers with eight microprocessors and a performance of 26,000 MTOPS, is expected to be widely available in early 2001. Consequently, for end users in tier 3 countries, thresholds were set at 28,000 MTOPS, slightly higher than the expected availability of the 26,000 MTOPS machine. The report stated that computer manufacturers in the United States and in foreign countries continue to produce computers that are smaller, cheaper, and easier to install and maintain but are more powerful than ever before. This trend is due in large part to rapid advances in microprocessor technology, according to the report. Computer companies projected that their chips and systems would be produced in the tens of thousands per month, depending on the specific processor.

All Potential Computer Uses Not Addressed

The National Defense Authorization Act of 1998 requires that the President's report to the Congress address all potential uses of military significance to which high performance computers at the new levels could be applied. However, the President's reports to the Congress during 2000 did not address all such computer applications, even though this information was available from the 1998 Department of Defense- and Commerce-sponsored study that was used as the basis for these sections of the reports. DOD officials from the Defense Threat Reduction Agency, which is responsible for sections of the reports on military uses of high performance computers, told us that they took their information from the 1998 study because the agency did not have the resources to initiate an independent review of this and related issues. The officials chose to report on 3 of 10 categories of applications identified by the 1998 study.

We identified a total of 22 computer applications mentioned in the President's report: 17 applications that can be operated up to a performance level of 21,000 MTOPS and 5 applications that can be operated at nonspecified levels between 1,000 and 115,000 MTOPS.[14] The 1998 Defense- and Commerce-sponsored study, however, specifically identified 172 military applications that were run on computers up to 28,000 MTOPS.[15] Of these military applications, 47 were run on computers between 20,000 and 28,000 MTOPS (the previous tier 3 computer control thresholds for civilian end users and newly announced tier 3 computer control thresholds for all end users). Appendix IV lists the applications of national security importance identified for the 1998 Defense- and Commerce-sponsored study.

Information Provided on National Security Impacts Was Inadequate

The National Defense Authorization Act of 1998 requires that the President's report to the Congress assess the impact on U.S. national security interests of potential uses of military significance to which high performance computers at the new levels could be applied. The President's reports, however, did not specifically discuss the impacts on U.S. national security interests for any of the national security applications that the report identified, as required by the 1998 National Defense Authorization Act. The reports made general statements that most countries cannot effectively use high performance computers and that there are therefore no national security impacts on the United States. This 1998 study, however, stated that the U.S. government provided insufficient information to assess this issue.

Although the President's August report identified only 22 of the 172 military applications that were run on computers up to 28,000 MTOPS, the report did not discuss the national security impacts on the United States of Russia, China, or other countries obtaining high performance computing up

[14] The President's reports do not clearly distinguish computer applications by name and performance levels. As a result, it is impossible in all cases to determine from the reports whether mentioned applications are distinct or identical.

[15] According to the 1998 Department of Defense- and Commerce-sponsored study, the absence of a particular type of problem at some performance level should not be interpreted as a statement that no version of that application can be solved at that performance level. MTOPS are only rough indicators of the performance level required for a particular kind of application. That a given problem was run on a machine with a particular MTOPS level does not mean that all systems with a greater MTOPS level can solve the problem or that all systems with a lower MTOPS level cannot.

to the new control thresholds, even for those applications identified. The President's reports also did not identify which countries of concern could gain the hardware capability to conduct militarily useful applications at the new control thresholds. For example, the reports stated that Russia and China have demonstrated that they have the expertise necessary to use high performance computers for particular national security applications, such as developing submarines, advanced aircraft, composite materials, or a variety of other devices. The reports also did not discuss other countries that can use high performance computing for military applications. India, for example, which has organizations that we identified as both using high performance computing for military purposes and being listed on the Commerce Department's "Entities List" of end users of proliferation concern, was not mentioned in the President's reports.

The reports stated that most tier 2 and 3 countries have little or no experience in a host of national security applications and there is little danger of these countries diverting high performance computers from other pressing needs and usefully employing them to develop military items. According to DOD officials responsible for the sections of the report on military uses of high performance computers, the 1998 Defense- and Commerce-sponsored study was the basis for these statements. The 1998 study, however, indicated that it did not have sufficient information to assess the impact of militarily significant applications on U.S. national security interests. The study stated that

> "A critical question, which we have been unable to pursue satisfactorily in this study, is which countries are able to productively use [high performance computing] to pursue which applications? We have requested such information from the U.S. national security community, but have received few answers. It does not appear that the U.S. government is effectively gathering such intelligence in a systematic fashion. More specifically, the U.S. government does not appear to have as good an understanding of individual end use organizations of concern as is needed by the export control regime."

The President's reports did not state which countries can use high performance computers for particular military applications or which countries cannot, and the analysis that was absent in the 1998 Defense- and Commerce-sponsored study and an earlier 1995 study has not been done. As we reported in 1998,[16] the principal author of the Defense- and Commerce-sponsored study and DOD officials told us that no assessment had been done in 1995 to determine how national security would be

---

[16] *Export Controls* (GAO/NSIAD-98-196, Sept. 16, 1998).

impacted if high performance computers were exported to particular countries of concern and what military advantages such countries could achieve. The 1998 study reiterated this position. We recommended in 1998 that the Secretary of Defense do such an evaluation, specifically addressing (1) how and at what performance levels countries of concern use high performance computers for military modernization and proliferation activities, (2) the threat of such uses to U.S. national security interests, and (3) the extent to which such high performance computers are controllable. This recommendation has not been implemented. Although DOD stated that the interagency process had considered these factors in the 1995 review of computer export controls and would consider them in any future review, it provided no evidence that this has occurred.

An annual report on transfers of militarily sensitive technology to countries and entities of concern, required under section 1402 of the National Defense Authorization Act for fiscal year 2000, might partially address the question of the national security impact of high performance computer uses of military significance. It is to include an assessment by the Secretary of Defense, in consultation with the Joint Chiefs of Staff and the Director of Central Intelligence, on the cumulative impact of U.S.-granted licenses for exports of technologies and technical information to these countries and entities. Thus, the study would be expected to include licensed high performance computers as part of the assessment. This report is also required to include information on countermeasures that may be necessary to overcome the use of such technologies and technical information. However, it is not required to include an assessment of the cumulative impact of nonlicensed computer exports, such as those that could be clustered. The report is scheduled for completion by the end of 2000.

Conclusions

The current export control system for computers, as implemented by the Department of Commerce and which focuses on controlling the export of individual computers, is not effective in limiting countries of concern from obtaining high performance computing capabilities. As a result of advances in clustering technology, countries of concern can obtain computing capabilities above current U.S. export control levels necessary for military applications. It is also now widely recognized within the Departments of Commerce, Defense, and Energy and the computer industry that the use of MTOPS as the means of determining export control thresholds is outdated, no longer a valid means for controlling computing capabilities, and needs to be replaced. In light of these now well established developments, the process needs to be reexamined, and potential alternative ways to safeguard U.S. national security interests related to high performance computer exports need to be explored.

In addition, the President's reports justifying computer control changes continue to be inadequate. It is a particularly important omission for the U.S. government to not assess the national security impacts of how countries of concern can use high performance computers at successively higher performance levels for military purposes. Although we have highlighted this issue in the past, the administration has presented no further assessment. As advances in high performance computing make it more difficult to maintain the U.S. technological lead in military capabilities by denying advanced technology transfers to countries of concern, it may become necessary to explore other options to maintain the U.S. military technology lead. For example, the National Defense Authorization Act for fiscal year 2000 required the Secretary of Defense to assess the cumulative impact of U.S. export licenses—including high performance computing licenses—and possible countermeasures that may be necessary to overcome the use of such technologies and technical information. However, it did not require an assessment of the cumulative impact of exporting nonlicensed computers that could be clustered, or of potential countermeasures to such an impact.

Recommendations for Executive Action

Since the current export control system for high performance computers cannot prevent countries of concern from obtaining high performance computing capabilities, we recommend that the Secretary of Commerce, in consultation with the Secretaries of Defense, Energy, and State, convene a panel of experts to comprehensively assess and report to the Congress on possible ways of addressing the shortcomings of computer export controls, including, but not limited to the ideas noted in this report. For example, the Commerce Department's National Institute of Standards and Technology, which researches computer systems' performance and promotes the effective evaluation and efficient use of advanced computers, might participate in the panel because it designs evaluations that economically and reliably characterize high performance computer designs. This assessment should report on the costs and benefits of each proposed idea, including its technical feasibility.

In addition, the report required by the National Defense Authorization Act of 2000 concerning countermeasures that may be necessary to overcome the use of sensitive technologies and technical information exported to countries of concern is not required to include an assessment of the cumulative impact of exports of nonlicensed computers, such as those that could be clustered. Therefore, we recommend that the Secretary of Defense determine what U.S. countermeasures are necessary, if any, to respond to computing-related enhancements of the military or proliferation capabilities of countries of concern.

Agency Comments and Our Evaluation

The Department of Commerce provided written comments (see app. IV) on a draft of this report. The Department of Energy's Acting Chief Operating Officer for the National Nuclear Security Administration and the Principal Deputy Under Secretary of Defense for Policy provided oral comments. The Department of Energy concurred with the report's findings and conclusions and our recommendation concerning the convening of a panel of experts and said that the Department looks forward to participating with the Secretaries of Commerce, Defense, and State in such a panel to conduct a comprehensive assessment of possible ways of addressing the shortcomings of computer export controls. The Departments of Commerce and Defense generally agreed with the report's findings and conclusions relating to the problems we identified with clustering technology and the continuing use of MTOPS as a measure for controlling individual high performance computers. However, they disagreed with the need to convene an expert panel or to determine what countermeasures are necessary to respond to enhancements of military capabilities of countries of concern which such countries may have gained through the use of high performance computing.

The Departments of Commerce and Defense said that they disagreed with the need to implement our recommendation that the Secretary of Commerce and other secretaries convene a panel of experts to comprehensively assess possible ways of addressing the shortcomings of computer export controls because they said the administration and experts are already studying similar issues. Commerce stated that it would be counterproductive and unnecessary to convene a panel of experts, since the administration was already examining this issue through existing interagency mechanisms involving DOD, Energy, and State. Commerce also said that the Center for Strategic and International Studies has a broad group of experts currently studying the same issues as encompassed in the recommendation. DOD said that the administration has been consulting with experts to formulate an approach for controlling computing capabilities and is assessing various alternatives—including "some" identified in our draft report. Subsequent to receiving these comments, we asked both Departments to describe in more detail and document what comprehensive study was being conducted. Neither Department provided any additional information to show that there was an interagency study being conducted as we are recommending. Although we sought information on steps being taken that would address the issues covered by our recommendations, neither the Commerce Department nor Department of Defense provided any evidence that an interagency mechanism is systematically examining alternative ways to protect U.S. national security interests related to the shortcomings of computer export controls—beyond the narrowly focused effort to seek alternatives to the MTOPS measure for controlling individual machines.

Regarding the study by the Center for Strategic and International Studies, we note that it is tasked to "develop the framework for a new effective . . . agreement that would regulate certain militarily useful goods and technologies on a multilateral basis," not to examine the costs, benefits, and technical feasibility of each possible way identified in this report of addressing the shortcomings associated with controlling individual high performance computers.

The Departments of Commerce and Defense also disagreed with the need to implement our recommendation that the Secretary of Defense determine what U.S. countermeasures are necessary to respond to enhancements of the military capabilities of countries of concern from both licensed and nonlicensed high performance computing. Commerce stated that the best countermeasure is to ensure that the U.S. military and defense industries continue to have access to the computer technology needed to maintain the U.S. military advantage. DOD stated that the Department continuously assesses the military capabilities of potential adversaries and countries of concern to identify threats to U.S. forces and described the assessment process. While we agree that maintaining the U.S. technological advantage in computing is important, we note that neither Commerce nor Defense specified how or whether DOD (1) has assessed and identified any threats posed by high performance computing to U.S. national security interests or (2) identified and implemented countermeasures to such threats. Furthermore, ongoing studies tasked to assess the need for countermeasures related to U.S. exports of sensitive technologies are not reviewing threats posed by nonlicensed clustered computer systems, a factor that we believe is critical to assess.

DOD disagreed with our conclusion that the President's February and August 2000 reports to the Congress were inadequate with regard to required national security assessments accompanying changes to computer control levels. DOD stated that the President's reports have consistently noted that most activities associated with various aspects of military capabilities benefit from some computing capabilities. It further stated that the President's reports to the Congress have provided examples of national security applications to illustrate that the range of military applications that (1) benefit from high performance computing is "almost ubiquitous" and (2) can be performed on almost any computer is extensive. Nonetheless, as this report and our prior reports have pointed out, we continue to believe that the President's reports did not adequately provide the information that the law requires. The President's reports did not address all potential uses of military significance to which high performance computers at the new levels could be applied—even though the administration possessed information on such uses in the 1998 Defense- and Commerce-sponsored study (part of which we have reprinted in app. III)—and did not assess the impact of such uses on U.S. national security interests.

Matters for Congressional Consideration

Since the Departments of Commerce and Defense disagreed with recommendations which we believe are still valid and needed, the Congress may wish to institute a requirement that the Secretary of Commerce, in consultation with the Secretaries of Defense, Energy, and State, convene a panel of experts to conduct a comprehensive assessment of and report to the Congress on possible ways of addressing the shortcomings associated with controlling individual high performance computers, including, but not limited to, the ideas noted in this report.

In addition, to address the issue of countermeasures that may be necessary to overcome the use of sensitive technologies and technical information exported to countries of concern, the Congress may also wish to consider instituting a requirement that the Secretary of Defense determine and report on what U.S. countermeasures are necessary, if any, to respond to computing-related enhancements of the military or proliferation capabilities of countries of concern, as we have recommended in this report.

Scope and Methodology

To assess the effectiveness of current export controls in preventing countries of concern from obtaining high performance computing capabilities that can be used for military applications, we reviewed studies and briefing slides by U.S. government agencies and computer industry technical specialists that described technological computing advances and assessed the MTOPS measure. Such studies included assessments by the Lawrence Livermore and Sandia National Laboratories on possible alternatives to current computer controls. We interviewed officials from the Departments of Defense, Commerce, State, and Energy; the Central Intelligence Agency; and the three major national weapons laboratories, Lawrence Livermore, Los Alamos, and Sandia. We interviewed officials from major computer manufacturers, Compaq, Hewlett Packard, IBM, and SUN Microsystems, as well as the computer scientist responsible for the Top 500 List of the most advanced high performance computers in the world. In addition, we observed meetings of Commerce Department's Information Systems Technology Advisory Committee.

To evaluate the President's justifications for changing the computer control thresholds, we reviewed the President's February 2000 and August 2000 reports to the Congress justifying changes to computer control thresholds and a White House fact sheet detailing the changes made in August 2000. We reviewed Commerce Department analyses and computer industry information regarding projected production schedules and technical performance ratings for processors scheduled to be marketed in the next 6 to 12 months. In addition, we reviewed studies and briefing slides by U.S. government agencies and computer industry technical specialists that described technological computing advances and assessed the MTOPS measure. We interviewed officials from the Departments of Defense, Commerce, State, and Energy; the Central Intelligence Agency; and the three major national weapons laboratories, Lawrence Livermore, Los Alamos, and Sandia. We interviewed officials from major computer manufacturers, Compaq, Hewlett Packard, IBM, and SUN Microsystems, as well as the computer scientist responsible for the Top 500 List of the most advanced high performance computers in the world. In addition, we observed meetings of the Commerce Department's Information Systems Technology Advisory Committee.

We conducted our review from February through November 2000 in accordance with generally accepted government auditing standards.

Unless you publicly announce the contents of this report earlier, we plan no further distribution of this report until 15 days from its issue date. At that time, we will send copies of this report to other appropriate congressional committees; the Honorable William S. Cohen, Secretary of Defense; the Honorable Madeleine K. Albright, Secretary of State; the Honorable Norman T. Mineta, Secretary of Commerce; and the Honorable William

Richardson, Secretary of Energy. Copies will also be made available to others upon request.

If you or your staff have any questions concerning this report, please call me at (202) 512-4128 or Mr. Rhodes at (202) 512-6412. Key contributors to this assignment were Claude Adrien, Jeffrey D. Phillips, F. James Shafer, and Hai Tran.

Harold J. Johnson
Director, International Affairs
and Trade

Keith A. Rhodes
Chief Technologist

Possible Ways of Safeguarding U.S. National Security Interests Related to Computer Exports

To identify possible alternative ways to safeguard U.S. national security interests related to computer exports, we reviewed analyses and other documentation prepared by the two Department of Energy national laboratories addressing this question, Lawrence Livermore and Sandia. We also interviewed officials from the Departments of Defense, Commerce, State, and Energy—including Los Alamos, Lawrence Livermore, and Sandia National Laboratories; the Central Intelligence Agency; and officials from major computer manufacturers, Compaq, Hewlett Packard, IBM, and SUN Microsystems.

We identified 12 ideas for addressing shortcomings to the current export control system. These ideas have not been comprehensively evaluated by the U.S. government. The Department of Commerce has considered the first three ideas we describe in this appendix, but none of the three addresses the export control problem created by clustering technology. We also present nine additional ideas identified through our research and discussions with experts. We did not assess the feasibility of implementing any of the ideas but rather describe their characteristics and limitations when identified by the experts. It is important to note that these ideas have not been assessed for their feasibility to replace the current export control mechanism; moreover, most of them do not address the challenge created by advances in clustering technology.

Alternatives to Using MTOPS Considered by the Commerce-Sponsored Technical Advisory Committee

The three ideas that the Commerce-sponsored Information Systems Technical Advisory Committee (ISTAC) reviewed are (1) counting processors, (2) measuring power dissipation, and (3) indexing control thresholds to a common benchmark.

Counting Processors Instead of Using MTOPS

Using this approach, computers would be controlled by counting the number of processors in each computing system. For example, a license might be required if a computer to be exported to tier 3 countries contained eight or more processors, while computers with fewer processors could be exported without a license. Presumably, the precise number of processors for each tier would be determined as the details of such a proposal were finalized.

Computer industry representatives and ISTAC members stated that counting processors would be simpler than using the MTOPS measure. Under current controls, computer chip manufacturers must calculate the MTOPS rating for each processor they manufacture, and computer companies must calculate the MTOPS rating for each of the computer systems they produce. Department of Energy and ISTAC officials also noted that by counting processors, they could better adapt to changes in computer technology because advances in processors used in a system would not result in the need to change the export controls. On the other hand, ISTAC members said that counting processors is no more accurate an indicator than MTOPS for indicating a level of computer performance. Furthermore, despite the intended simplicity of the approach, the Committee members noted that there is no consensus within the computer community on the definition of a processor. They also said that exceptions to the counting procedure would need to be determined for high performance single processors and for processors and computers with unique designs. For example, some processors today include advanced graphics or memory capabilities, but others do not and therefore have different performance capabilities.

Measuring Power Dissipation

Power dissipation is a measure of watts per MTOPS that is currently used in Japan to determine the environmental effects of computers. The measure produces a ratio of the watts per MTOPS to the size of the box housing the microprocessor. The May 2000 ISTAC paper stated that this alternative was briefly studied but rejected because of its inability to accurately measure the performance capabilities of a system. Two systems with the same performance capability might have different ratios because each is housed in a different sized box with different power supplies and different disk drives, according to the Committee paper. As a result, the system measured to have a lower ratio would be controlled less stringently than the smaller system.

Indexing Control Thresholds to a Common Benchmark

Computer export control levels could be set by using a common performance benchmark. The May 2000 ISTAC paper on alternative control measures[1] also identified one benchmark, Linpack, that it called an accepted industry standard for performance measurements. The paper

[1] Alternative Control Parameter for High Performance Computers.

noted, however, that changing the operating system on a computer would change the measure and that unless the exporter knows what operating system the end user has, the measure would be impossible to accurately gauge. Nonetheless, the paper suggested continued study of the benchmark, which might have more relevance to higher performance computers (at 100,000 MTOPS) in the future. We observed that the Commerce Department's National Institute of Standards and Technology does research in the area of computer systems performance, promotes the effective evaluation and efficient use of advanced computers, and designs coherent evaluations that economically and reliably characterize high performance computer designs.

Some computer industry representatives said that the industry would never achieve consensus on which benchmarks to use. Furthermore, they said that once any specific benchmark was established, computer designers could circumvent the intent of the benchmark.

Other Alternatives to Replace MTOPS Drawn From Studies and Discussions With Computer Experts

In addition to the three alternatives to replace MTOPS considered by the Commerce-sponsored advisory committee, the following two were identified from studies and discussions with government and industry experts.

Indexing Control Thresholds

Sandia National Laboratory, computer industry representatives, and a computer expert from academia have presented the idea of indexing the control thresholds through the use of various criteria, including (1) actual sales or market data or (2) a list of the 500 most powerful computers, which is maintained by the University of Tennessee and the University of Mannheim.[2]

Actual Sales

According to an analysis prepared by Sandia National Laboratory, one way of implementing a sales-based index would be for the Secretary of Commerce, in consultation with other agencies, to determine every 6 months or after a petition by industry, which U.S.-origin microprocessors have entered into mass production during the preceding 180 days. The Secretary would then have 30 days to make the determination. Computers incorporating such microprocessors could then be controlled by requiring export licenses based on a multiple of the performance of a single mass-produced microprocessor. Under this indexing option, U.S. computer companies would have to first establish a threshold level of sales within the United States before they are exported, according to Sandia National Laboratory. The threshold might initially be 100, 500, or more commercial sales within the United States and maybe tier 1 countries to establish that the product is indeed a broadly applicable, commercial product. Once the company demonstrates that it has reached the threshold through actual sales, it would no longer be prohibited from exporting such computers to tier 2 and tier 3 countries, although documentation of end use and controls could be maintained for tier 3 countries, according to Sandia National Laboratory.

Experts we consulted raised concerns about whether the sales or market-based data would be reliable and a U.S. government official told us that this option was flawed because it would not be based on national security interests. Finally, some computer industry representatives questioned whether this control could be effectively implemented because

[2]To provide a better basis for statistics on high performance computers, the University of Tennessee and the University of Mannheim maintain a list of sites that have the 500 most powerful computer systems installed in the world. The Top 500 List has been updated twice a year since June 1993 with the help of high performance computer experts, computational scientists, manufacturers, and the Internet community who responded to a questionnaire. The producers of the Top 500 List have also used parts of statistical lists published by others for different purposes.

of a perceived government inability to keep up with market and/or technological changes.

Top 500 List

Another proposal suggested by some experts we consulted was to apply export controls to computers based on the list of the world's top 500 most powerful computers maintained by the University of Tennessee and the University of Mannheim. For example, licenses could be required for computers whose capabilities qualified them for inclusion on the list, at least at the 500th rank. Alternatively, the threshold could be set for computers surpassing the 250th, 100th, or any other ranking on the list.

Proponents of this idea point out that the list is based on a transparent measure: a publicly available, testable benchmark. Unlike the current control system, this list would not be subject to sudden and significant changes in license thresholds due to marketplace changes in just one or two chips. The controls would therefore be tied much more closely to technological realities.

Other Ideas for Safeguarding U.S. National Security Interests

In addition to ideas to replace MTOPS discussed above, the following seven ideas were identified from studies and discussions with government and industry experts as other ways to protect U.S. national security interests relative to high performance computer exports.

Tagging and Remote Monitoring

Tagging and remote monitoring is an idea that has been discussed in export control literature for several years. It is achieved by attaching a monitoring system to the item that is to be exported. The active system would both monitor the object tagged and communicate that information to the United States. Elements of a remote monitoring system are data acquisition, communications, and a command center.

U.S. government officials[3] and computer industry representatives pointed out several limitations of tagging and remote monitoring. Both procedures require the cooperation of the end user of the computer system. In addition, the American computer industry may resist having its products

[3] These officials were from the Lawrence Livermore, Los Alamos , and Sandia National Laboratories and the Department of Energy.

tagged, given that this practice might discourage legitimate foreign customers from buying American computers because of privacy concerns, according to the officials. They also noted that a remote monitoring system for exported computers might not be feasible because of the resources that might be required to monitor computer operations and send data to the United States. Also, even remote monitoring of computer operations cannot distinguish how the computer is being used and for what applications, according to the officials. Some officials cautioned that any type of tagging or remote monitoring to which the end user has unsupervised access could be tampered with without the U.S. government's knowledge.

Assessing End-User Attainable Performance

This idea is simply a modification of the current licensing process for determining when export control thresholds apply. Under this approach, the licensing threshold would be applied according to the potential capabilities of a computer system, rather than the actual performance level at the time of sale, as under the current system. One option would be to retain the MTOPS measure and adjust the control level to account for the maximum processing capability of the system instead of setting the threshold based on the capabilities of the system as configured at the time of shipment. For example, under the current system, a computer that had four microprocessor slots but was shipped with only one microprocessor would likely be exported without a license. However, the end user could buy three additional uncontrolled microprocessors and increase the rated performance. Considering the end user's attainable performance, the system would be rated at its full four-processor potential and likely require a license to better reflect the true capabilities acquired in the purchase. This standard could be applied in any performance-based system, whether using MTOPS or another measure.

Proponents of end-user attainable performance as a measure argue that controls based on maximum capabilities prohibit the buyer from increasing the capabilities of the purchased system without the U.S. government's knowledge. One criticism of this approach is that clustering can still obviate the control because users can link computers together after delivery without detection by the U.S. government. This control could also be rendered less effective or ineffective by advancing technology that allows users to upgrade their computers with next generation chips, making the capabilities of the systems shipped difficult or impossible to track. In addition, some critics stated that this control is not replicable in a consistent fashion and raised questions about how to choose the control levels and use them. Finally, some doubted the acceptability of this option within the computer community.

Raising Export Control Thresholds to the Level Obtained by Clustering

Under this option, the government could set the control levels to match the computational power that can be effectively provided by computer clusters composed of readily available components. This approach to setting export control levels is based on the notion that effective parallel computers can today be built using readily available commercial computers and networking technology with performance between 50,000 to 70,000 MTOPS. Periodic revision of the export control levels could reflect the combined effects of advances in central processor unit technology and the increasing capabilities of adjunct technologies in communications and networking to achieve very high levels of computing power by linking together larger numbers of computers.

Using this approach, today's large inconsistency between the levels at which high performance computers are controlled and the performance levels achievable by commercially available parallel clusters would be eliminated, according to the Lawrence Livermore National Laboratory analysis.[4] The analysis stated that the true state of U.S. exposure to changing national security threats would be acknowledged and addressed. Appropriately responding to the implications of the actual availability of high performance computing would require extensive review and discussion in the national security community. Some critics of this approach stated that this control is not replicable in a consistent fashion and raised questions about how to choose the control levels and use them.

[4] The National Security Implications of Decontrolling Export to Tier III Countries of High Performance Computers between 2,000 and 40,000 MTOPS (Feb. 2000).

Controlling Software Applications

This option involves denying countries of concern key software applications used in high performance computing through the use of security classifications and/or export controls. According to the Director of DOD's High Performance Computing Modernization Program,[5] one concept under discussion is the development of approaches to ensure that software is used as intended and authorized. He said that research would be needed to develop encryption technology to restrict access for source and executable applications. The intent of this concept is to develop means that will prevent militarily relevant applications from operating on unauthorized machines. The official stated that technology advances can provide improved protections for militarily relevant applications. According to the DOD Deputy Under Secretary (Science & Technology), militarily significant software might be made more tamper-proof, that is, able to operate on only one type of machine or to self-destruct if tampered with. The official said that DOD is just beginning to examine this option.

The prevalent view among government and computer industry officials with whom we spoke is that the applications software that can be controlled is already protected by security classification, export controls, and proprietary rights and that commercial dual-use software cannot be controlled. A Lawrence Livermore National Laboratory analysis pointed out that some software used in clusters is freely available on the Internet. Operating systems such as Linux can also be downloaded free from the Web. Even operating systems like Windows NT or Windows 2000 are sold in such quantities that controls are viewed as impractical and unenforceable. Research and academic institutions whose culture is characterized by the free exchange of information and software are notable users and developers of high performance computing technology. Thus, it is difficult to find any part of the software application market that lends itself to controls because distribution is easy and applications of national interest are already tightly held by their owners, either through security classification or efforts to protect a commercial interest. In contrast, the Director of DOD's High Performance Computing Modernization Program stated that dual-use applications are being controlled to a limited extent.

[5] The DOD High Performance Computing Modernization Program provides advanced hardware, computing tools, and training to DOD researchers utilizing the latest technology to aid their mission in support of the warfighter. The program seeks to modernize the total high performance computational capability of DOD Science and Technology, Development Test and Evaluation, and Ballistic Missile Defense Organization to a level comparable to that available in the foremost civilian and other government agency research and development environments.

He noted that several commercially available applications cannot be run without receiving an annually provided key from the vendor.

Controlling Technology Used for Interconnection

The idea of controlling technology used to link computers together is based on the control of the number and capability of commercial readily available parallel clusters that can be created by controlling networking hardware such as switches, interface cards, and related equipment.

However, the hardware used in high-speed, commercial, ready-made networking is already widely available and relatively inexpensive throughout the world, according to U.S. government officials[6] and computer industry representatives. They believe that establishing controls at this point would be extremely difficult, if not impossible. To be effective, this approach would depend on networking technology originating solely in the United States or countries with binding agreements to enforce U.S. export control objectives, according to U.S. government officials and computer industry representatives. However, manufacturing capability for interconnecting technology is available worldwide, and with the growth in the cluster market, it will be considerably more difficult to restrict supply. Industry representatives consider only some of the equipment related to this technology controllable at the higher end of the market because of its proprietary nature and the continued importance of vendor support.

Controlling Computer Systems Based on Bandwidth

According to the Director of DOD's High Performance Computing Modernization Program, a concept under discussion would develop a methodology to control computer systems by some measure of processor-to-main-memory bandwidth[7] and potentially the number of processors in each system. The methodology would need to distinguish between commodity systems and the traditional class of supercomputers characterized by specialized processors. Such computer systems typically have a single processor and require a high level of bandwidth, such as those manufactured by Cray, NEC, and Fujitsu. Another official from DOD's High Performance Computing Modernization Program said that these computers still possess capabilities, capacities, and characteristics that should be

[6] Officials were from the Lawrence Livermore, Los Alamos, and Sandia National Laboratories and the Departments of Commerce, Defense, and Energy.

[7] Bandwidth is the amount of data that can be transmitted in a fixed amount of time.

denied to countries of concern. The DOD official identified as a concern those computers that can solve militarily significant problems that cannot be broken down and operated on clustered systems. Computer industry experts placed the total market for these computers in the range of 300 per year. The Department did not provide any additional information about this option because it was still under review.

Implementing Countermeasures to Military Advantages Gained by Countries of Concern From More Advanced Computer Exports

Using this option, DOD would design countermeasures to deal with the implications of wider computer availability. One purpose of export controls is to maintain the U.S. technological lead in military capabilities by denying transfers of advanced technology to countries of concern. As technological advances in high performance computing make this purpose more difficult for export controls to achieve, it may become necessary to explore other options to maintain the U.S. technology lead. As a step in this direction, section 1402 of the National Defense Authorization Act for Fiscal Year 2000 requires an annual report on transfers of militarily sensitive technology to countries and entities of concern. It is to include an assessment by the Secretary of Defense, in consultation with the Joint Chiefs of Staff and the Director of Central Intelligence, on the cumulative impact of U.S.-granted licenses for exports of technologies and technical information. This report is required to include information on countermeasures that may be necessary to overcome the use of such technologies and technical information. It is not required to include an assessment of the cumulative impact of nonlicensed computers, such as those that could be clustered. The report is scheduled for completion in late 2000.

Additional Information on Computer Clustering Technology and MTOPS

In the past few years, broadly recognized technological advances in the ability to cluster together low performance computers have resulted in an increasing capability worldwide to achieve high performance computer levels. As a result, the known performance levels of clustered systems exceed the export control thresholds set by the U.S. government. In addition, U.S. government officials[1] and computer industry representatives have discussed the shortcomings of the MTOPS measure for export control purposes and now agree that MTOPS is no longer a valid measure of computer performance and needs to be replaced.

Computer Advances in Clustered Systems

Technological advances in computing that would threaten the effectiveness of export controls have been expected for several years. For example, a 1994 U.S. government study[2] warned that technological computing advances would seriously impair the ability of U.S. export controls to protect computer technology by the turn of the century. A Defense- and Commerce-commissioned team in 1995[3] reviewed the computer industry's technological advances in parallel processing and concluded that advances in clustering contribute to the uncontrollability of high performance computing worldwide and inevitably reduce the effectiveness of U.S. export controls. One of the technology trends of concern at that time included other countries' ability to link individual computers to achieve higher performance levels. We reported 2 years ago that trends in high performance computing technology development might pose security and export control challenges and recommended further study to determine their implications for national security and export controls.[4]

According to a Lawrence Livermore National Laboratory analysis dated February 2000, in determining the usefulness of clusters made with readily available commercial components, the following four aspects of computing must be considered:

[1] U.S. government officials include the Deputy Under Secretary of Defense (Science and Technology) and officials of the Commerce and Energy Departments.

[2] The unclassified title of this classified report is *High Performance Computing Technology: Implications for Development of Weapons of Mass Destruction.*

[3] *High-Performance Computing Export Control Policy in the 1990s* (Palo Alto, CA: Stanford University, Center for International Security and Arms Control, 1995).

[4] *Export Controls* (GAO/NSIAD-98-196, Sept. 16, 1998).

- Performance, flexibility, low cost, and the ease of integration, taken together, make the development of effective parallel computers using commercial readily available networking hardware dramatically easier than it was just 3 years ago, according to Lawrence Livermore National Laboratory officials. Commercial clusters of readily available components perform up to about a third as well as today's best distributed memory parallel computers (stand-alone high performance computers), while the cost of clustering adds only 10 to 30 percent to the cost of the computers that are clustered.
- The system software necessary to integrate a cluster of computers into an effective computing system with a correspondingly higher capability than its individual constituent processors is now widely available.
- Programming a commercial cluster of readily available components is no different from programming most other commercial parallel processing computers because the system software is the same on both. Computer science departments in universities worldwide teach concepts to support the development of parallel applications for commercial, readily available clusters. Other U.S. government and computer industry specialists, however, stated that there might be some number of computer applications that cannot be adapted for clustered parallel processing. To the extent that such applications are militarily significant and must be operated on individual computers, maintaining threshold controls on these machines could still be effective.
- Support for computer functions means having an efficient schedule for running hundreds of separate problems and the input and output of data among a computer, its local disks, networks, and archival storage. Without vendor-supplied software to automate these functions, everything must be done manually, making production computing a labor-intensive operation. While U.S. practice is to pay computer vendors to supply this support, foreign countries such as India and China, where skilled labor is plentiful and low cost, may find providing this support much less of a problem.

Other U.S. government and computer industry specialists also stated that there might be some computer applications that cannot be adapted for clustered parallel processing. The President's August 30, 2000, report indicated that some small number of computer applications still requires traditional computer systems and that the lack of hardware may be a barrier to solving certain kinds of problems. The President's report did not identify these applications. However, computer applications that have problems which cannot be broken up to be solved in parallel and applications associated with battlefield operations that rely on rapid solutions might not practically be run on clustered computer systems, according to ISTAC members and a DOD official.

Shortcomings of MTOPS as a Measure of Performance

U.S. government officials[5] and computer industry representatives agreed that MTOPS is no longer a valid measure of computer performance and needs to be replaced. In 1991, the Commerce Department began using MTOPS as a measure to decide when an export license would be required for high performance computers. But because of the diverse computer designs that have evolved since then, the increasing performance level of commercial microprocessors, and the capability to connect local and wide area networks, it became prudent to reexamine the suitability of MTOPS as a measure, according to the Institute for Defense Analyses. As a result, under DOD auspices, U.S. government officials, computer industry representatives, and academics met in December 1997 to determine whether the use of MTOPS is sufficient to rate the relative performance of current and future computer systems. They determined the following:

- The use of MTOPS was still an effective means at that time for determining export controls for a single computing element. The attendees stated that modest refinements could be made to the MTOPS measure for systems comprising aggregate computing elements.
- There could be variances up to a factor of 2 in the actual performance of delivered systems relative to the MTOPS-calculated performance because of the wide range of designs in use. Continuing rapid changes in technology might result in yet larger variances in the near future.
- Any export control measure should be reevaluated every 2 years because of the rapid changes in computer designs.

By 2000, however, it had become clear to both government and industry computer experts that MTOPS does not account for new processor designs, particularly those dependent on the capability to exchange information internally at high speeds. Representatives of three computer companies said that MTOPS was an archaic measure not designed with new chip designs in mind and should be replaced. The MTOPS measure today is unreliable because it does not account for certain factors, such as memory access times, interconnection methods, and internal bus speeds. As a result, two microprocessors with the same megahertz could have

[5] U.S. government officials include the Deputy Under Secretary of Defense (Science and Technology) and officials of the Commerce and Energy Departments.

different MTOPS ratings if the additional factors were considered. The MTOPS indicator also would be inaccurate if it were applied incorrectly for computing elements organized in certain ways, such as in clusters of individual computers. It is not accurate to take the MTOPS measure of one clustered machine and multiply it by the total number of computing processors of the cluster because key characteristics, such as the time taken to distribute tasks and exchange intermediate results, have not been taken into account.

Identified Applications of National Security Importance

This appendix lists the applications of national security importance identified for the 1998 Defense- and Commerce-sponsored study, which was the basis for information on computer applications in the President's reports in February and August 2000. The list is reprinted in its entirety as it appeared in the 1998 study.

Appendix A: Applications of National Security Importance

The following table provides a summary of national security applications reviewed in this study. It indicates the kind of problem solved, the HPC configuration on which it was solved, and the time required for the solution.

This selection, compiled through a combination of direct communications with practitioners and a review of published literature, is not an exhaustive listing. However, it does include many of the more important national security applications, and gives policy makers a rough idea of the kinds of applications being solved at various performance levels.

Two points in particular should be kept in mind when reading the table. First, the applications shown here constitute data points that often, in practice, lie along a continuum. The specific size of the application is often a function of the computational resources available in a given configuration and the "threshold of patience" of the practitioner. If the configuration available were slightly larger, or smaller, the practitioners in most cases would solve the same kinds of problem, but perhaps with a different grid size, or time-step, etc. In short, the absence of a particular type of application at some performance level should not be interpreted as a statement that no version of that application can be solved at that performance level.

Second, the CTP value shown is the composite theoretical performance of the configuration used to solve the problem. It is well known that any metric, including the CTP, does not perfectly predict the performance of all systems on all applications. Consequently, the CTP measures given here should be used only as rough indicators of the performance level required for a particular kind of application. The fact that a given problem was run on a machine with a CTP of *n* Mtops does not mean that all systems with CTP > *n* Mtops can solve the problem, or that all systems with CTP < *n* Mtops can not. The CTP simply does not have this kind of precision.

The following acronyms are used for applications categories:

CCM	Computational Chemistry and Materials Science	CWO	Climate/Weather/Ocean Modeling and Simulation
CEA	Computational Electromagnetics and Acoustics	FMS	Forces Modeling and Simulation/C4I
CFD	Computational Fluid Dynamics	Nuclear	Nuclear weapons development and stockpile maintenance
CSM	Computational Structural Mechanics	SIP	Signal/Image Processing

Machine	Year	CTP	Category	Time	Problem	Problem size
VAX 6210		1	SIP	35 min	Focus an image [1]	5040 x 1260 samples (18km x 8km)
Cray-1	1984	195	CFD	1.4 CPU hours	SCRAMJET wing-fuselage aerodynamic interaction simulation [2]	56,730 grid points, Mach 6
Cray-1S	1984	195	CFD	20 CPU hr	Simulation of after-body drag for a fuselage with propulsive jet. Reynolds averaged Navier-Stokes [3]	
Cray-1S	early 1980s	195	nuclear	1127.5 CPU sec	LANL Hydrodynamics code 3 [4]	
Cray-1S	early 1980s	195	nuclear	117.2 CPU sec	LANL Hydrodynamics code 1 [4]	
Cray-1S	early 1980s	195	nuclear	4547.1 CPU sec	LANL Hydrodynamics code 2 [4]	
Cray-1		195	[illegible]	24 hours	Crash simulation [5]	5,500 elements
Cray-1S		195	CFD		Nonlinear Inviscid (STAGE II): Above, plus transonic pressure loads; wave drag [3,6]	100,000 grid points
Cosmic Cube (6)	1991	293	SIP	1.81 millisec	Discrete Fourier transform algorithm [7]	5040 complex data sample
Cray X-MP/1	mid 1980s	316	nuclear		Two-dimensional, reduced physics simulation	
Cray XMP/48 (1proc)	1988	353	CFD	20-50 hr	Flow simulation around complete F-16A aircraft (wings, fuselage, inlet, vertical and horizontal tails, nozzle) at 6 deg angle of attack, Mach 0.9. Reynolds Averaged Navier-Stokes. Reynolds number = 4.5 million. [8]	1 million grid points, 8 Mwords (one 2 Mword zone in memory at a time), 2000-5000 iterations
Cray XMP/1	1990	353	CCM	1000 CPU hours	Molecular dynamics of bead-spring model of a polymer chain [9]	Chain length=400
Cray J916/1	1996	450	CFD	300 CPU hr	Modeling of transonic flow around AS28G wing/body/pylon/nacelle configuration. 3–D Reynolds averaged full Navier-Stokes solution. [10]	3.5 million nodes, 195 Mwords memory
Origin2000/1	1997	459	SIP	5.650 s	RT_STAP benchmark (hard) [11]	2.7 million samples per .161 sec
Cray Y-MP/1	1987	500	CSM	200 hours	3–D shock physics simulation [12]	200,000 cells
Cray YMP/1	1990	500	CSM	39 CPU sec	Static analysis of aerodynamic loading on solid rocket booster [13]	10,453 elements,9206 nodes,54,870 DOF 256 Mword memory
Cray YMP	1991	500	CCM	1000 CPU hours	Molecular dynamics modeling of hydrodynamic interactions in "semi-dilute" and concentrated polymer solutions [9]	single chain, 60 monomers
Cray YMP	1991	500	CCM	1000 CPU hours	Modeling of thermodynamics of polymer mixtures [9]	lattice size - 112EXP(3); chain size = 256
Cray YMP/1	1991	500	CFD	40 CPU h	Simulation of viscous flow about the Harrier Jet (operating in-ground effect modeled) [14]	2.8 million points, 20 Mwords memory.
Cray YMP/1	1993	500	CCM	1.47 CPUs/ timestep	MD simulation using short-range forces model applied to 3–D configuration of liquid near solid-state point [15]	100,000 atoms
Cray YMP/1	1996	500	CFD	170 CPU hr (est)	Modeling of transonic flow around AS28G wing/body/pylon/nacelle configuration. 3D Reynolds Averaged full Navier-Stokes solution [10]	3.5 million nodes, 195 Mwords memory
Cray YMP/1	1996	500	CFD	6 CPU hr	Modeling of transonic flow around F5 wing (Aerospatiale). 3D Reynolds Averaged full Navier-Stokes solution [10]	442368 cells (192x48x48).
Cray YMP	1996	500	CFD	8 CPU hr, 3000 timesteps	Large-Eddy simulation at high Reynolds number [16]	2.1 million grid points, 44 Mwords

Machine	Year	CTP	Category	Time	Problem	Problem size
workstation	1997	500	CSM		2–D modeling of simple projectile striking simple target. [17]	10,000s of grid points
Cray Y-MP/1	late 1980s	500	nuclear	1000s hours	two-dimensional, almost full physics (e.g. Monte Carlo neutron transport)	
Cray Y-MP/1	late 1980s	500	nuclear	seconds	one-dimensional, full physics simulation	
Cray YMP/1		500	CEA	5 CPU hr per timestep	Signature of modern fighter at fixed incident angle at 1 GHz [18]	50 million grid points @ 18 words/grid point
Cray Y-MP/1		500	nuclear		two-dimensional, reduced physics simulations	100-500 Mbytes
Mercury Race (5 x 4 i860 processors, Ruggedized)	1997	866	SIP		SAR system aboard P3-C Orion maritime patrol aircraft [19]	
Cray YMP/2 256 MW	1990	958	CSM	19.79 CPU s	Static analysis of aerodynamic loading on solid rocket booster [13]	10,453 elements, 9206 nodes, 54,870 DOF
Cray Y-MP/2	late 1980s	958	CFD		Design of F-22 fighter [20]	
CM-5/32	1993	970	CCM	449 CPU sec	Determination of structure of Eglin-C molecular system [21]	530 atoms, with 1689 distance and 87 dihedral constraints
Cray-2/1	1987	1,098	CSM	400 hours	3D modeling of projectile striking target. Hundreds of microsecond time scales. [17]	.5-1.5 million grid points256 Mword memory
Cray-2	1992	1,098	CSM	5 CPU hours	Modeling aeroelastic response of a detailed wing-body configuration using a potential flow theory [13]	
Cray-2	1992	1,098	CSM	6 CPU days	Establish transonic flutter boundary for a given set of aeroelastic parameters [13]	
Cray-2	1992	1,098	CSM	600 CPU days	Full Navier-Stokes equations [13]	
Cray-2		1,098	CSM	2 hours	3–D modeling of symmetric, transonic, low angle of attack impact of warhead and defensive structure [20]	
Cray-2		1,098	CSM	200 hours	Penetration model against advanced armor [20]	
Cray-2		1,098	CSM	2000 hours	Modeling full kinetic kill effects against hybrid armors [20]	
Cray-2		1,098	CSM	40 hours	3–D modeling of asymmetric, transonic, low angle of attack impact of warhead and defensive structure [20]	
Cray-2	1984	1,098	CFD	15 CPU m	Simulation of 2–D viscous flow field about an airfoil [3]	
Cray-2	1988	1,098	CFD	20 hr	Simulation of flow about the space shuttle (Orbiter, External Tank, Solid Rocket Boosters), Mach 1.05, Reynolds Averaged Navier-Stokes, Reynolds number = 4 million (3% model) [8]	750,000 grid points, 6 Mwords.
Cray-2	1980s	1,098	CFD	100 CPU h	Simulation of external flow about an aircraft at cruise. Steady flow. Steady Navier-Stokes simulation. [14]	1.0 million grid points.
	1995	1,400	nuclear		Credible one- and two-dimensional simulations [22]	
Cray C90/1	1993	1,437	CCM	.592 sec/ timestep	MD simulation using short-range forces model applied to 3–D configuration of liquid near solid state point [15]	100,000 atoms
Cray C90/1	1994	1,437	CEA	161 CPU hour	Compute magnitude of scattered wave-pattern on X24C re-entry aerospace vehicle [23]	181x59x162 grid (1.7 million)
Cray C90/1	1994	1,437	CFD	overnight	Modeling of flow over a submarine hull with no propulsion unit included [24]	1-2 million grid points.

Machine	Year	CTP	Category	Time	Problem	Problem size
Cray C916	1994	1,437	CEA		Radar cross section on perfectly conducting sphere [25]	48x48x96 ((221 thousand)
Cray C90/1	1995	1,437	CEA	1 hour	Submarine acoustic signature for single frequency	
Cray C90/1	1995	1,437	CEA	1 hour	Submarine acoustic signature for single frequency [26]	
Cray C90/1	1995	1,437	CEA	12,475 sec	Radar cross section of perfectly conducting sphere, wave number 20 [27]	97x96x192 (1.7 million grid points), 16.1 points per wavelength
Cray C90/1	1995	1,437	CEA	200 hour	Submarine acoustic signature for full spectrum of frequencies [26]	
Cray C90/1	1995	1,437	CWO		CCM2, Community Climate Model, T42 [28]	128 x 64 transform grid, 4.2 Gflops
Cray C90/1	1996	1,437	CFD	19 CPU hr	Simulation of turbulent flow around the F/A-18 aircraft at 60 degree angle of attack. Mach 0.3. Reynolds number = 8.88 million [29]	1.25 million grid points, 100 Mwords of memory.
Cray C90/1	1996	1,437	CFD	200 CPU hr	Simulation of unsteady flow about an F-18 High Alpha Research Vehicle at 30, 45, 60 deg angle of attack [30]	2.5 million grid points for half-body modeling. 40 Mwords memory
Cray C90/1	1996	1,437	CFD	3 CPU hr	Modeling of flow over a blended wing/body aircraft at cruise. [31]	45 Mwords of memory
Origin2000/4	1997	1,517	SIP	1.475 s	RT_STAP benchmark (hard) [11]	2.7 million samples per .161 sec
SGI PowerChallenge4 nodes	1997	1,686	CCM	overnight	Explosion simulation [32]	30 thousand diatomic molecules
SGI Onyx	1990	1,700	SIP		Attack and Launch Early Reporting to Theater (ALERT) [20].	
Mercury Race (52 processor, i860)	1996	1,773	SIP		Sonar system for Los Angeles Class submarines [33]	
Cray YMP/4 256 MW	1990	1,875	CSM	10 CPU s	Static analysis of aerodynamic loading on solid rocket booster [13]	10,453 elements, 9206 nodes, 54,870 DOF
Intel iPSC/860/64	1993	2,097	CCM	.418 CPUs/time step	MD simulation using short-range forces model applied to 3D configuration of liquid near solid state point [15]	100,000 atoms
Intel iPSC/860/64	1993	2,097	CCM	3.68 CPUs/ timestep	MD simulation using short-range forces model applied to 3D configuration of liquid near solid state point [15]	1 million atoms
Cray 2, 4 proc	1990	2,100	CSM	400 hours	armor/anti-armor, 3-D	
Cray T3D/16	1996	2,142	CFD	20,000 CPU sec. 50 CPU sec x 400 steps	Aerodynamics of missile at Mach 3.5. Reynolds number = 6.4 million [34]	500x150 (75,000) elements in mesh. 381,600 equations solved every timestep.
CM-2		2,471	SIP	10 minutes	Creation of synthetic aperture radar image [20]	
Cray C90/2	1993	2,750	CCM	117 CPU sec	Determination of structure of Eglin-C molecular system [21]	530 atoms, with 1689 distance and 87 dihedral constraints
Cray C90/2	1993	2,750	CCM	12269 sec	Determination of structure of E. coli trp repressor molecular system [21]	1504 atoms6014 constraints
iPSC860/128	1997	3,485	CFD	120 hr	small unmanned vehicle, fully turbulent	
iPSC/860 128 nodes	1997	3,485	CFD	5 days	Full ship flow model [35]	
iPSC860/128	1997	3,485	CFD	5 days	Small unmanned undersea vehicle. Fully turbulent model with Reynolds numbers. [35]	2.5 million grid points
Cray YMP/8	1989	3,708	CFD		Model of flow around a fully appended submarine. Steady state, non-viscous flow model. [35]	250,000 grid points
Cray Y-MP/8	early 1990s	3,708	CSM	200 hours	3D shock physics simulation [12]	6 million cells

Machine	*Year*	*CTP*	*Category*	*Time*	*Problem*	*Problem size*
Cray Y-MP/8	mid 1990s	3,708	CSM	10-40 hrs	3–D shock physics simulation [12]	100K-1 million cells
IBM SP1/64	1993	4,074	CCM	1.11 sec timestep	Molecular dynamics of SiO2 system [36]	0.53 million atoms
Intel Paragon		4,600	CEA		Non-acoustic anti-submarine warfare sensor development [20]	
IBM SP-2/32	1996	4,745	CFD	80 minutes	3–D unsteady incompressible time-averaged Navier-Stokes. Multiblock transformed coordinates [37]	3.3 million points
IBM SP-2/32	1997	4,745	CFD		Helicopter rotor motion coupled with rotor CFD, predict 3–D tip-relief flow effect, parallel approximate factorization method [38]	
Origin2000/12	1997	4,835	CFD	4329 sec	CFL3D applied to a wing-body configuration: time-dependent thin-layer Navier-Stokes equation in 3–D, finite-volume, 3 multigrid levels [39]	3.5 million points
Intel Paragon/150	early 1990s	4,864	CFD		JAST aircraft design [20]	
Cray C90/4	1993	5,375	CFD	1 week	Modeling of flow around a smooth ellipsoid submarine. Turbulent flow, fixed angle of attack, [35]	2.5 million grid points
CM-5/128	1993	5,657	CCM	436 CPU sec	Determination of structure of Eglin-C molecular system [21]	530 atoms, with 1689 distance and 87 dihedral constraints
CM-5/128	1993	5,657	CCM	6799 CPU sec	Determination of structure of E. coli trp repressor molecular system [21]	1504 atoms, with 6014 constraints
Origin2000/16	1997	5,908	SIP	.39 s	RT_STAP benchmark (hard) [11]	2.7 million samples per .161 sec
IBM SP-2/45	1997	6,300	CFD	2 to 4 hours	Helicopter blade structural optimization code, gradient-based optimization technique to measure performance changes as each design variable is varied [38]	up to 90 design variables, one run per variable
Cray T3D/64	1995	6,332	CWO		CCM2, Community Climate Model, T42 [28]	128 x 64 transform grid, 608 Mflops
IBM SP-2/64	1997	7,100	CFD	2 to 4 hours	Helicopter rotor free-wake model, high-order vortex element and wake relaxation [38]	
Paragon 256	1995	7,315	CCM	82 sec/ timestep	Particle simulation interacting through the standard pair-wise 6-12 Lennard-Jones potential [40]	50 million particles
		8,000	CEA		Bottom contour modeling of shallow water in submarine design [20]	
		8,000	SIP		Topological Synthetic Aperture Radar data processing [20]	
Paragon /321	1995	8,263	SIP		2–D FFT [41].	200 x 1024 x 1024 (200 Mpixels) images/sec
Intel Paragon/321		8,980	SIP		Development of algorithms for Shipboard Infrared search & tracking (SIRST) [20]	
SGI PowerChallenge (R8000/150)/16	1996	9,510	CFD	3.6 hr, 3000 timesteps	Large-Eddy simulation at high Reynolds number [16]	2.1 million grid points, 44 Mwords
ORNL Paragon/360		9,626	FMS		Synthetic forces experiments [42]	5713 vehicles, 6,697 entities
		10,000	SIP		Long-range unmanned aerial vehicles (UAV) on-board data processing [20]	
Cray T3D/128	1995	10,056	CEA	12,475 sec	Radar cross section of perfectly conducting sphere, wave number 20 [27]	97x96x192 (1.7 million grid points), 16.1 points per wavelength
Cray T3D/128	1995	10,056	CEA	2,874 s	Radar cross section of perfectly conducting sphere [27]	128x96x92 cells (2.4 million cells), 600 time steps

Machine	Year	CTP	Category	Time	Problem	Problem size
CM-5/256	1993	10,457	CCM	492 CPU sec	Determination of structure of Eglin-C molecular system [21]	530 atoms, with 1689 distance and 87 dihedral constraints
CM-5/256	1993	10,457	CCM	7098 CPU sec	Determination of structure of E. coli trp repressor molecular system [21	1504 atoms, with 6014 constraints
Cray C98	1994	10,625	CWO	~5 hrs	Global atmospheric forecast, Fleet Numerical operational run [43]	480 x 240 grid; 18 vertical layers
Origin2000/32	1997	11,768	SIP	.205 s	RT_STAP benchmark (hard) [11]	2.7 million samples per .161 sec
Origin2000/32	1997	11,768	CWO		SC-MICOM, global ocean forecast, two-tier communication pattern [44]	
Intel Paragon/512	1995	12,680	CCM	84 CPU s/timestep	MD simulation of 102.4 million particles using pair-wise 6-12 Lennard Jones potential [40]	102.4 million atoms
IBM SP2/128	1995	13,147	CEA	3,304.2 s	Radar cross section of perfectly conducting sphere [27]	128x96x92 cells (2.4 million cells), 600 time steps
Maui SP-2/128		13,147	FMS	2 hours	Synthetic forces experiments [42	5086 vehicles
Intel Touchstone Delta/512	1993	13,236	CCM	4.84 sec/time step	Molecular dynamics of SiO2 system [36]	4.2 million atoms
Intel Paragon	1995	13,236	SIP	55 sec	Correlation processing of 20 seconds worth of SIR-C/S-SAR data from Space Shuttle [45]	
NASA Ames SP-2/139		14,057	FMS	2 hours	Synthetic forces experiments [42]	5464 vehicles
IBM SP-2/128	1995	14,200	CWO		PCCM2, Parallel CCM2, T42 [46]	128 x 64 transform grid, 2.2 Gflops
Origin2000/40	1997	14,698	CSM		Crash code, PAM	
IBM SP-2/160	1995	15,796	CWO		AGCM, Atmospheric General Circulation Model [47]	144 x 88 grid points, 9 vertical levels, 2.2 Gflops
Cray C912	1996	15,875	CSM	23 CPU hours	Water over C4 explosive in container above wet sand, alternate scenario: container next to building, finite element [48]	38,000 elements, 230 msec simulated time,16 Mwords memory
Cray C912	1996	15,875	CSM	36 hours	water over C4 over sand	
Cray C912	1996	15,875	CSM	435 CPU hours	Water over C4 explosive in container above wet sand, building at a distance [48]	13 million cells,12.5 msec simulated time
Cray C912	1997	15,875	CWO	~ 5 hrs	Global atmospheric forecast, Fleet Numerical operational run [43]	480 x 240 grid; 24 vertical layers
Cray C912	1997	15,875	CWO	1 hr	Global ocean forecast, Fleet Numerical operational run [49]	1/4 degree, 25 km resolution
ORNL Paragon/680		16,737	FMS		Synthetic forces experiments [42]	10913 vehicles, 13,222 entities
Cray T3D/256	1993	17,503	CCM	.0509 CPUs/time step	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	100,000 atoms
Cray T3D/256	1993	17,503	CCM	.405 CPUs/time step	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	1 million atoms
Cray T3D/256	1993	17,503	CCM	1.86 CPUs/time step	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	5 million atoms
Cray T3D/256	1995	17,503	CWO		Global weather forecasting model, National Meteorological Center, T170 [50]	32 vertical levels, 190 x 380 grid points, 6.1 Gflops
Cray T3D/256	1995	17,503	CWO		AGCM, Atmospheric General Circulation Model [47]	144 x 88 grid points, 9 vertical levels, 2.5 Gflops

Machine	Year	CTP	Category	Time	Problem	Problem size
Cray T3D/256	1996	17,503	CWO	105 min	ARPS, Advanced Regional Prediction System, v 4.0, fine scale forecast [51]	96 x 96 cells, 288 x 288 km, 7 hr forecast
Cray T3D/256	1996	17,503	CFD	2 hr, 3000 timesteps	Large-Eddy simulation at high Reynolds number [16]	2.1 million grid points, 44 Mwords
Cray T3D/256	1996	17,503	CFD	52,000 CPU sec.130 CPU sec x 400 timesteps	Aerodynamics of missile at Mach 2.5, 14-degrees angle of attack for laminar and turbulent viscous effects [34]	944,366 nodes and 918,000 elements. 4,610,378 coupled nonlinear equations solved every timestep.
CM-5/512	1993	20,057	CCM	8106 CPU sec	Determination of structure of E. coli trp repressor molecular system [21]	1504 atoms, with 6014 constraints
CM-5/512	1995	20,057	CFD	15,000 CPU sec, 30 CPU sec per each of 500 timesteps.	Flare maneuver of a large ram-air parachute. Reynolds number = 10 million. Algebraic turbulence model [52,53]	469,493 nodes, 455,520 hexahedral elements. 3,666,432 equations solved per timestep.
CM-5/512	1995	20,057	CFD	500 timesteps	Parafoil with flaps flow simulation. [52]	2,363,887 equations solved at each timestep
CM-5/512	1995	20,057	CFD		Parafoil with flaps flow simulation [52].	2,363,887 equations solved at each of 500 timesteps
CM-5/512	1995	20,057	CFD		Fighter aircraft at Mach 2.0 [52]	3-D mesh of 367,867 nodes, 2,143,160 tetrahedral elements, and 1.7 million coupled nonlinear equations solved per timestep.
CM-5/512	1996	20,057	CFD	500 timesteps	Steady-state parafoil simulation, 10 deg angle of attack, Reynolds number = 10 million [54]	2.3 million equations every timestep
CM-5/512	1996	20,057	CFD	500 timesteps	Inflation simulation of large ram-air parachute, Box initially at 10 deg angle of attack and velocity at 112 ft/sec, 2 simulated seconds [55]	1,304,606 coupled nonlinear equations solved every timestep.
CM-5/512	1996	20,057	CFD	7500 CPU sec = 50 CPU sec x 150 timesteps	Aerodynamics of missile at Mach 2.5, 14 deg angle of attack for laminar and turbulent viscous effects [34]	763,323 nodes and 729,600 elements. 3,610,964 coupled nonlinear equations solved in each of 150 pseudo-time steps.
CM-5/512	1996	20,057	CFD		steady-state parafoil simulation. 10 degree angle of attack [54]	2.3 million equations x 500 timesteps; Reynolds number 10 million
CM-5/512	1996	20,057	CFD		Inflation simulation of large ram-air parachute. Box initially at 10 degree angle of attack and velocity of 112 ft/sec. 2 seconds simulated [55]	1,304,606 coupled, nonlinear equations solved per each of 500 timesteps.
CM-5/512	1996	20,057	CFD		Flare simulation of large ram-air parachute [55]	3,666,432 coupled nonlinear equations solved every timestep.
CM-5/512	1996	20,057	CFD		3-D simulation of round parachute, Reynolds number = 1 million [56]	
CM-5/512	1996	20,057	CFD		3-D study of missile aerodynamics, Mach 3.5, 14 deg angle of attack, Reynolds number = 14.8 million [57]	340,000 element mesh, nonlinear system of 1,750,000+ equations solved every timestep.
CM-5/512	1997	20,057	CFD	30 hours	Parafoil simulation [54]	1 million equations solved 500 times per run
CM-5/512		20,057	CCM	8106 sec		

Machine	Year	CTP	Category	Time	Problem	Problem size
C916	1995	21,125	CSM	900 CPU hours	Hardened structure with internal explosion, portion of the overall structure and surrounding soil. DYNA3D, nonlinear, explicit, FE code. Nonlinear constitutive models to simulate concrete & steel [58]	144,257 solid & 168,438 trust elements for concrete & steel bars,17,858 loaded surfaces,500,000 DOF,60 msec simulated time
Cray C916	1995	21,125	CWO		CCM2, Community Climate Model, T170 [28]	512 x 256 transform grid, 2.4 Gbytes memory, 53. Gflops
Cray C916	1995	21,125	CWO		IFS, Integrated Forecasting System, T213 [59]	640 grid points/latitude, 134,028 points/horizontal layer, 31 vertical layers
Cray C916	1995	21,125	CWO		ARPS, Advanced Regional prediction System, v 3.1 [60]	64 x 64 x 32, 6Gflops
Cray C916	1996	21,125	CSM	325 CPU hours3 day continuous run	Explosion engulfing a set of buildings, DYNA3D analysis to study effects on window glass & doors done off-line after the blast simulation completed [61]	825 Mwords memory
Cray C916	1996	21,125	CWO	45 min	ARPS, Advanced Regional Prediction System, v 4.0, coarse scale forecast [51]	96 x 96 cells, 864 x 864 km, 7 hr forecast .
Cray C916	1996	21,125	CSM	72 hours	explosion engulfing bldgs	
Cray C916	1996	21,125	CFD		3–D simulation of flow past a tuna w/ oscillating caudal fin. Adaptive remeshing. Integrated with rigid body motio [62]	
Cray C90/16	1997	21,125	CFD	9 months	3–D simulation of submarine with unsteady separating flow, fixed angle of attack, fixed geometry [35]	
Cray C916	1998	21,125	CWO	~5 hrs	Global atmospheric forecast, Fleet Numerical operational run [43]	480 x 240 grid; 30 vertical layers
Cray C916		21,125	CSM	200 hours	2–D model of effects of nuclear blast on structure [20]	
Cray C916		21,125	CSM	600 hours	3–D model of effects of nuclear blast on structure [20]	
Cray C916		21,125	CSM	several hundred hrs	Modeling effects of complex defensive structure [20]	
Cray C916		21,125	CFD		Modeling of turbulent flow about a submarine [20]	
CEWES SP-2/229		21,506	FMS	2 hours	Synthetic forces experiments [42]	9739 vehicles
Origin2000/64	1997	23,488	CFD		ARC3D: simple 3–D transient Euler variant on a rectilinear grid [63]	
Paragon 1024	1995	24,520	CWO		PCCM2, Parallel CCM2, T42 [46]	128 x 64 transform grid, 2.2 Gflops
Intel Paragon/1024		24,520	CCM	.914 sec/ timestep		5 million atoms
Intel Paragon/1024		24,520	CCM	.961 sec/ timestep		10 million atoms
ORNL Paragon/1024		24,520	FMS	2 hours	Synthetic forces experiments [42]	16995 vehicles
Intel Paragon/1024		24,520	CCM	8.54 sec/ timestep		50 million atoms
Paragon 1024		24,520	CCM	82 sec/ timestep		200 million particles
Paragon 1024		24,520	CCM	82 sec/ timestep		400 million particles
ORNL Paragon/1024		24,520	FMS		Synthetic forces experiments [42]	16606 vehicles, 20,290 entities

Machine	Year	CTP	Category	Time	Problem	Problem size
Intel Paragon/1024	1993	24,520	CCM	.0282 CPUs/ timestep	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	100,000 atoms
Intel Paragon/1024	1993	24,520	CCM	.199 CPUs/ timestep	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	1 million atoms
Intel Paragon/1024	1993	24,520	CCM	.914 CPUs/ timestep	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	5 million atoms
Intel Paragon/1024	1993	24,520	CCM	.961 CPUs/ timestep	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	10 million atoms
Intel Paragon/1024	1993	24,520	CCM	8.54 CPUs/ timestep	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	50 million atoms
Intel Paragon/1024	1995	24,520	CCM	160 CPUs/ timestep	MD simulation of 400 million particles using pair-wise 6-12 Lennard Jones potential [40]	400 million atoms,
Cray T3D/400	1995	25,881	CWO		IFS, Integrated Forecasting System, T213 [59]	640 grid points/latitude, 134,028 points/horizontal layer, 31 vertical layers
Mercury Race (140 PowerPC 603e processors)	1997	27,113	SIP		Large Mercury System shipped in 1997 [64]	
Cray T3D/512	1993	32,398	CCM	.0293 CPUs/ timestep	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	100,000 atoms
Cray T3D/512	1993	32,398	CCM	.205 CPUs/t timestep	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15	1 million atoms
Cray T3D/512	1993	32,398	CCM	.994 CPUs/ timestep	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	5 million atoms
Cray T3D/512	1993	32,398	CCM	1.85 CPUs/ timestep	MD simulation using short-range forces model applied to 3-D configuration of liquid near solid state point [15]	10 million atoms
Cray T3D/512	1995	32,398	CFD	500 timesteps	Steady-state parafoil simulation. 2 deg angle of attack. Reynolds number = 10 million [52]	38 million coupled nonlinear equations at every pseudo-timestep.
Cray T3D/512	1995	32,398	CFD		Modeling paratroopers dropping from aircraft. Moving grid. Cargo aircraft traveling at 130 Knots. High Reynolds number. Smagorinsky turbulence model [52]	880,000 tetrahedral elements for half of the domain.
Cray T3D/512	1995	32,398	CFD		Fighter aircraft at Mach 2.0. [52]	3-D mesh of 185,483 nodes and 1,071,580 tetrahedral elements
Intel Paragon	mid 1990s	44,000	CSM	<24 hours	3-D shock physics simulation [12]	6 million cells
Intel Paragon	mid 1990s	44,000	CSM	several restarts	3-D shock physics simulation [12]	20 million cells
Intel Paragon	1994	46,000	nuclear		3-D reduced physics simulation of transient dynamics of nuclear weapon [12,65]	
ASCI Red	1997	46,000	CSM	few hundred hours	3-D modeling of explosive material impact on copper plate [12]	1.29 billion cells
Origin2000 /128	1997	46,928	CEA		Radar cross section of VFY218 aircraft under 2 GHz radar wave [66]	1.9 million unknowns
Origin2000 /192	1998	70,368	CSM	400 hours	armor/anti-armor, 3-D	

Machine	Year	CTP	Category	Time	Problem	Problem size
Origin2000 /192	1998	70,368	CFD	months	3–D simulation of submarine with unsteady flow, fixed angle of attack, and moving body appendages and complex repulsors [35]	
ASCI Red/1024	1997	76,000	CSM	<25 hours	3–D shock physics simulation [12]	100 million cells
ASCI Red/1024	1997	76,000	CSM	<50 hours	3–D shock physics simulation [12]	250 million cells
ASCI Red/1024	1997	76,000	CSM	few hours	3–D shock physics simulation [12]	2-4 million cells
		80,000	SIP		Tier 2 UAV on-board data processing [20]	
Cray T3E-900/256	1997	91,035	CFD	500 timesteps	Steady-state parafoil simulation, 10 deg angle of attack, Reynolds number = 10 million [54]	2.3 million equations every timestep
Cray T3E-900/256	1997	91,035	CWO	590 hrs	Global ocean model "hindcast" [49]	1/16 degree, 7 km resolution
Cray T3E-900256 nodes	1998	91,035	CSM	450,000 node hours	Grizzly breaching vehicle plow simulation, parametric studies, different soil conditions & blade speeds [67]	2 to 4 million particles (soil, rock, mines, obstacles, etc.)
ASCI ++	??	50,000,000+	nuclear		First principles 3–D modeling [68]	

Source: *High-Performance Computing, National Security Applications, and Export Control Policy at the Close of the 20th Century,* Seymour E. Goodman, Peter Wolcott, and Patrick Homer, (Palo Alto, CA: Stanford University, Center for International Security and Arms Control, 1998).

Comments From the Department of Commerce

Note: GAO comments supplementing those in the report text appear at the end of this appendix.

THE SECRETARY OF COMMERCE
Washington, D.C. 20230

NOV 16 2000

Mr. Harold J. Johnson
Director, International Affairs and Trade
U.S. General Accounting Office
Washington, D.C. 20548

Dear Mr. Johnson:

Thank you for the opportunity to review your draft report, *Export Controls: System for Controlling Export of High Performance Computing is Ineffective* (GAO code 711480). We studied the draft report and our comments and clarifications are outlined below.

See comment 1.

In the background section, the GAO refers to the new control threshold of 28,000 Million Theoretical Operations Per Second (MTOPS) announced by the Administration in August 2000. Due to the FY 1998 National Defense Authorization Act (NDAA) provisions, this control threshold will not take effect until February of 2001. The current licensing threshold is 12,500 MTOPS. Your report should be revised accordingly. Additionally, in the section entitled 'President's Justification for Changing Computer Export Control Thresholds Was Inadequate,' GAO makes several references to a 1998 study entitled *High Performance Computing, National Security Applications, and Export Control Policy at the Close of the 20th Century* sponsored by Defense and Commerce. GAO states that we relied on the 1998 study to make our conclusions in the past few Presidential Reports to Congress justifying control level changes. While Defense may have cited this study in their portions of the past two reports, Commerce did not base its most recent conclusions on this study. We use current assessments of technology, foreign availability, and national security in determining appropriate control thresholds.

See comment 2.

Your report concludes that foreign countries are now able to obtain high performance computing (HPC) capabilities due to advances in, and widespread availability of, clustering technology. We cannot disagree with GAO on this conclusion as it is a point we have made repeatedly to Congress and GAO in the past as a major factor affecting export control policy. We are pleased that GAO has taken note of the information we provided on clustering and the concerns it raises. We also note, as we have in the past, that some countries of concern have indigenous high performance computing development initiatives, and this factor needs to be taken into account when determining the future course of HPC export controls.

We agree with the report's conclusion that the control parameter for high performance computers - - composite theoretical performance (CTP) as measured in MTOPS - - is becoming increasingly inadequate as a means to control high performance computing capabilities. We are pleased that GAO has noted our efforts on this front; however, the tone of your report implies that GAO recently "discovered" the fact that CTP is a poor metric. In reality, for over a year now, the Administration has been actively exploring alternatives to CTP that will allow us to better focus our controls on those computers with the greatest potential military application without over regulating our domestic computer industry or overburdening our export control system. Under Secretary for Export Administration William Reinsch testified before Congress on this subject in the Fall of 1999.

- 2 -

We do not have any specific comments on the part of your report concerned with national security applications for high performance computing, since this topic is more appropriately addressed by the Department of Defense. However, the President's report to Congress clearly states that military applications exist both well below and well above current control levels. Current control levels are largely based on performance levels we believe are controllable in light of widespread availability of computers and microprocessors.

With respect to the report's recommendations, we believe it would be counterproductive and unnecessary to convene a panel of experts to prepare a report addressing the shortfalls of computer export controls. We are already examining this issue through existing interagency mechanisms involving the Departments of Defense, Energy and State. Additionally, we would also note that the Center for Strategic and International Studies (CSIS) is currently undertaking a very similar exercise that involves a broad group of experts studying the same issues that are encompassed in your recommendation. Creating yet another group of experts to do the same thing would be redundant and an unnecessary expenditure of taxpayer funds.

The second recommendation in the report calls for the Administration to determine what countermeasures, if any, are necessary to respond to computing-related enhancements of the military or proliferation capabilities of countries of concern. The premise of our export controls on computers is based on the fact that computers at all levels, including PCs, have potential military applications. Our conclusion is that the amount of computing power needed to design and manufacture modern weapons, once a level of a few hundred MTOPS is exceeded, is not a critical variable. Other factors - - software design, access to sophisticated manufacturing techniques, experience and test data - - are more important. For this reason, our policy reviews focus less on potential military applications and more on the issues of controllability and technological leadership. The national security interests of the United States are best served by ensuring that the United States retains its technological advantage in the design, development, and production of microprocessors and computers. As some 50 to 60 percent of revenues for these sectors are generated through exports, the ability to compete internationally is an essential ingredient to the continued viability of these industries. Today, no nation can remain at the leading edge of technology unless it participates in the global market. The continued generation of revenues from exports provides the needed capital for research and development which keeps these industries at the cutting edge of technology. This, in turn, ensures that the U.S. military and U.S. defense-related industries will continue to have access to the computer technology which they need to maintain our military advantage -- which we believe is the best countermeasure.

Sincerely yours,

Norman Y. Mineta

The following are GAO's comments on the Department of Commerce's letter dated November 16, 2000.

GAO Comments

1. Our report stated that the computer licensing level for tier 3 countries was raised to 28,000 MTOPS, effective immediately. Commerce's letter refers to the 28,000 MTOPS threshold at which advanced notifications to Commerce of computer exports would be required. According to the President's August 30, 2000, letter transmitting his report justifying changes to computer export control thresholds, "the new level above which an individual license will be required for exports to tier 3 countries is 28,000 MTOPS. The aforementioned licensing adjustments will take place immediately." Furthermore, an October 13, 2000, rule amending the Export Administration Regulations stated that the upper licensing level for computer tier 3 countries was raised from 20,000 to 28,000 MTOPS. In comparison, the President reported in the same August 30, 2000, letter transmitting his report that he was establishing a new notification level of 28,000 MTOPS which cannot take effect until 180 days after the Congress receives the President's Report, that is, February 2001. Section 1211 (a) of the National Defense Authorization Act for Fiscal Year 1998 (P. L. 105-85) requires exporters to notify the Commerce Department of any proposed high performance computer exports to countries that pose a concern for military or proliferation reasons to determine if these exports need a license. Also, the October 13, 2000, rule amending the Export Administration Regulations stated that the level for advance notification of high performance computer exports to tier 3 countries was raised from 12,500 MTOPS to 28,000 MTOPS, effective on February 26, 2001.

2. We have clarified the sentences related to the 1998 Defense- and Commerce-sponsored study in response to Commerce's suggestions by adding language to stress that "DOD officials responsible for the sections of the report on military uses of high performance computers told us that they relied on the 1998 Department of Defense- and Commerce-sponsored study for support in the President's reports."

Ordering Information

The first copy of each GAO report is free. Additional copies of reports are $2 each. A check or money order should be made out to the Superintendent of Documents. VISA and MasterCard credit cards are accepted, also.

Orders for 100 or more copies to be mailed to a single address are discounted 25 percent.

Orders by mail:
U.S. General Accounting Office
P.O. Box 37050
Washington, DC 20013

Orders by visiting:
Room 1100
700 4th St. NW (corner of 4th and G Sts. NW)
U.S. General Accounting Office
Washington, DC

Orders by phone:
(202) 512-6000
fax: (202) 512-6061
TDD (202) 512-2537

Each day, GAO issues a list of newly available reports and testimony. To receive facsimile copies of the daily list or any list from the past 30 days, please call (202) 512-6000 using a touchtone phone. A recorded menu will provide information on how to obtain these lists.

Orders by Internet:
For information on how to access GAO reports on the Internet, send an e-mail message with "info" in the body to:

info@www.gao.gov

or visit GAO's World Wide Web home page at:

http://www.gao.gov

To Report Fraud, Waste, or Abuse in Federal Programs

Contact one:

- Web site: http://www.gao.gov/fraudnet/fraudnet.htm
- e-mail: fraudnet@gao.gov
- 1-800-424-5454 (automated answering system)

PRINTED ON RECYCLED PAPER

United States
General Accounting Office
Washington, D.C. 20548-0001

Official Business
Penalty for Private Use $300

Address Correction Requested

Bulk Rate
Postage & Fees Paid
GAO
Permit No. GI00

[redacted]