This paper was cleared by ASC98-1789 dated 24 August 1998

Performance specification methodology: introduction and application to displays *

Darrel G. Hopper

Air Force Research Laboratory
Mailing Address: 2255 H Street, Bldg. 248 Rm 300, Wright Patterson AFB OH 45433-7022 USA
Telephone: (937) 255-8822, *Fax:* (937) 255-8366, *E-mail:* darrel.hopper@wpafb.af.mil

ABSTRACT

Acquisition reform is based on the notion that DoD must rely on the commercial marketplace insofar as possible rather than solely looking inward to a military marketplace to meet its needs. This reform forces a fundamental change in the way DoD conducts business, including a heavy reliance on private sector models of change. The key to more reliance on the commercial marketplace is the performance specification (PS). This paper introduces some PS concepts and a PS classification principal to help bring some structure to the analysis of risk (cost, schedule, capability) in weapons system development and the management of opportunities for affordable ownership (maintain/increase capability via technology insertion, reduce cost) in this new paradigm. The DoD shift toward commercial components is nowhere better exemplified than in displays. Displays are the quintessential dual-use technology and are used herein to exemplify these PS concepts and principal. The advent of flat panel displays as a successful technology is setting off an epochal shift in cockpits and other military applications. Displays are installed in every DoD weapon system, and are, thus, representative of a range of technologies where issues and concerns throughout industry and government have been raised regarding the increased DoD reliance on the commercial marketplace. Performance specifications require metrics: the overall metrics of "information-thrust" with units of Mb/s and "specific info-thrust" with units of Mb/s/kg are introduced to analyze value of a display to the warfighter and affordability to the taxpayer.

Keywords: performance specification, displays, flat panel displays, electronics, cycle time, testing, situational awareness

1. INTRODUCTION

The present discussion of performance specifications is introduced by citing its origins in national technology policy and by suggesting a working definition. Much of the implementation of acquisition reform the past five years may have missed the mark of the intent of federal policy, and industry has voiced confusion with how the new process operates in defense programs.

A new federal technology policy emphasizing economic security was unveiled by President Clinton on February 22, 1993. [1] To implement this new policy in DoD the Deputy Secretary, William Perry, called for sweeping reforms to defense procurement policy to enable companies to adapt their products for the commercial market and to reduce costs associated with selling to the federal government. These defense acquisition reforms had been long called for by many in industry [2] and included (a) reduced overhead for contractors by elimination of the requirement that separate accounting systems and manufacturing lines be used for DoD work, (b) greater use of commercial products and specifications (especially for things like peanut butter), and (c) more opportunities for companies to sell defense-derived products in the commercial marketplace by permitting contractors to have greater rights to the intellectual property developed by them while under contract to DoD. [3]

* Publication Citation: D.G. Hopper, "Performance specification methodology: introduction and application to displays," in ***Cockpit Displays V: Displays for Defense Applications,*** Darrel G. Hopper, Editor, Proc. SPIE 3363, 33-46 (1998).

This policy change emphasized "dual-use" technology investments and affected products ranging from food (e.g. peanut butter), clothing (e.g. undergarments), software (e.g. accounting) to electronics (e.g. displays). Over-reaction to this new policy has become evident over the past five years. DoD policy makers repeatedly noted that some things were inherently defense-only concerns, like fighter aircraft, main battle tanks, nuclear aircraft carriers, ballistic missiles, nuclear warheads, and attack submarines. Some in the DoD bureaucracy, however, sought to kill the new policy by branding it "commercial-off-the-shelf (COTS)," although Sec. Perry did not use the term (see paragraph above for wording he did use); even in his speech to the International Optical Engineering Society in 1997 former SECDEF Perry continued to studiously avoid the terms "COTS." [4] The term "COTS" is a political term that has no meaningful use in any serious discussion of acquisition reform.

Prior to 1993 DoD regulations required military products to meet special standards that may not have been necessary. The military specification for peanut butter was a favorite example at the time. After the 1996 revision to acquisition regulations, DoD Instruction (DoDI) 5000.2, as revised in 1996, contains the following statement regarding the use of military standards versus commercial standards: DoDI 5000.2, Section 4.4.3 Standardization Documentation. "Preference shall be given to specifications and standards developed under the DoD Standardization Program." [5]

The President's policy for the entire federal government states that federal agencies are to "use commercial specifications and products." However, if commercial specifications and products do not exist, military specifications and products will be produced and maintained. Where possible private standards bodies are to be used to turn current and future DoD standards into private-sector standards. If non-government bodies will not establish a standard that DoD needs, an exception may be sought and granted for its maintenance by DoD (e.g. night vision goggles, weapon attachment/release mechanisms). The policy also stated that when military technology and products must be developed (due to the absence of commercial technology and products) that the government should obtain intellectual property (patents, trademark, copyright, technical data rights) ***only*** to the extent necessary to meet the agencies' needs, in order to leave the contractors with the rights necessary to attract private-sector investment and develop commercial products. In this way a display developed for the F-22 Raptor air-superiority fighter aircraft can become a "catalog" item and sold to additional (DoD and commercial aviation) customers as a non-developmental-item (NDI). That is, the initially militarily unique display becomes a commercial item that can be ordered by several other DoD and commercial programs. Subsequent clarifications stated that the federal government should stop issuing detailed design specifications and instead rely on performance specifications with tough performance parameters. [6]

The President's policy stated that government should evaluate bids based on their ability to minimize life-cycle-cost (LCC), rather than acquisition cost. The LCC comprises acquisition cost plus operational and sustainment (O&S) costs for the planned life (PL) of 20 years for DoD systems. The performance specification can, in general, be achieved via several routes: (a) development of military-unique technology (e.g. avionics displays); (b) purchase a high-quality display designed for a civil commercial product (automotive) and add value via re-manufacturing to achieve the necessary performance; (c) variations which save acquisition time or costs but cheat the warfighter out of affordable capability. The LCC for the custom-military approach must be compared to the LCC for the consumer-civil approach, not just the cost of the consumer-civil display. Additional cost factors in the consumer-civil approach are remanufacturing and the rapid 18-month product cycle configuration control. Both the custom-military and the consumer-civil approach will suffer from the vanishing vendor syndrome (VVS) as companies exit sunset technologies. In the custom-military approach a redesign is expected. In the consumer-civil approach the remanufacturing may not be able to achieve the desired performance some 10 years into the life cycle except by a re-engineering of the product. Reason: after 10 years the consumer–civil technology will have gone through seven generations and the seventh may not resemble the first nor work in the desired next-higher-level assembly without redesign of that assembly. Agile flexible engineering is needed during the life cycle for both the unique-military and the commercial-civil approaches.

Display technology is the quintessential dual use technology and is at the heart of the information revolution. Thus, the rise of a world industry in flat panel and other advanced displays has profound ramifications for advanced economies (laptops, personal digital assistants, digital television) and for advanced DoD strategy (combat capability advantage through information dominance). These implications have been recognized by Congresses since 1988 and led to the five-year congressionally-directed High Definition Display Technology (HDDT) initiative in 1989, which was renamed the High Definition Systems (HDS) Program in 1991. In 1993 the Clinton administration picked displays as representative of dual-use technologies in general. The administration sought to establish mechanisms by which to pursue a national strategy to balance the trade imbalance with Japan. Also, the Japanese lead in the manufacture of flat panel displays, active matrix liquid crystal displays (AMLCD), in particular, was identified as an area where the Japanese could give something of value back. In October 1993 a "U.S.-Japan Meeting on Flat Panel Display Technology (FPDT)" was hosted in Tokyo by the Defense Research Center with attendance on the U.S. part by technology representatives from the U.S. Air Force, Army, Navy, and ARPA. [7] Failure of the Japanese to be sufficiently responsive to U.S. concerns let to the establishment of the National Flat Panel Display Initiative (NFPDI), published by the administration in late 1994, which covered efforts in federal S&T programs in the DoD (DARPA and service labs), DoE (LLNL, LASL, SNL), and DoC (NIST). [8] Renewed emphasis resulted from a FY1998 congressionally-mandated report to address concerns of many in industry that procurement officials in programs throughout DoD service logistic and systems centers did not understand, did not apply, or did not communicate the ways in which acquisition reform initiatives were being reflected in display acquisition award decisions. The March 1998 report to the Senate Armed Services Committee, "The Acquisition of Flat Panel Displays for Military Applications", identified needed improvements in how the Department acquires and inserts flat panel displays (FPD) into weapon systems. [9,10] The report concluded that DoD needed better cross Service and cross program coordination of FPD activities; promotion of life-cycle affordability in FPD decision-making; improved long-term supply assurances; and FPD guidance. The Under Secretary of Defense (Acquisition & Technology), Jacques S. Gansler, may request that the service acquisition executives joint with him in improving the FPD technology insertion process by forming a DoD-wide action team to bring together Service initiatives currently addressing these issues. Ultimately, the action team's results should provide guidance to Service program managers. [*]

2. PERFORMANCE SPECIFICATION: DEFINITION

2.1 Basic definition of performance specification

A performance specification (PS) is herein defined to be a vector, **V**, of N performance variables, X_i. Each variable is time dependent and has weighting of importance W_i . Thus, for a given time, state-of-the-art (SoA) level, and application group (phylum), a PS may be represented symbolically as

$$\text{Performance Specification} \equiv \mathbf{V}_{PS} \equiv V(X_i, W_i, \ i=1 \text{ to } N),$$

where the weighting factors sum to unity,

$$\sum W_i = 1 \ .$$

Weighting factors may be established by use of a technique such as quality function deployment (QFD) and may vary with time, by SoA (knowledge level) and application (phylum). For fighter aircraft cockpit displays the most heavily weighted variables would include sunlight readability (ultrahigh day luminance with good contrast) and night vision goggle compatibility (hyperlow night luminance and virtually no energy beyond red cutoff wavelength). For low ambient lighting environments like C4I crewstations, FLIR or LLTV generated synthetic vision systems, and computed generated synthetic vision systems, the most heavily weighted variables would include high resolution and a large range of colors and grayshades per color.

Including the sub-variables of time, level, and phylum,

$$\mathbf{V}_{PS}(t, \text{level}, \text{phylum}) \equiv V(X_i(t), W_i(t, \text{level}, \text{phylum}), \ i=1\text{-}N) \ .$$

Each variable is quantitative but independent of a particular variant of or design approach to the technology. The variables are just sufficient in number that when used in concert they describe to *Homo sapiens* usage by *Homo sapiens* in an environment selected by *Homo sapiens*. The particular technologies will have representation at one or more levels of knowledge (laboratory, production, fielded) and will, ***ipso facto***, define the state-of-the-art at each of these levels. The job of the government S&T community is to make the impossible possible and to create options by investing to bring particular technology variants into being and then improving them. Industry picks the winners. That is, it is the job of industry, in responding with proposals to the government acquisition community, to draw from the technology base in designing affordable solutions at the time of the solicitation. For example, a PS for a cockpit display does not specify the particular display technology variant. However, only variants that exist can be considered in writing any but the ideal PS.

Variables may be grouped into subsets such as cost, environment, technology, human.

[*] Throughout this paper the term "FPD" will often be used to include other new display technologies that reduce cost, weight, power, and space while increasing availability, performance, and resolution. Examples include laser, quantum cavity phosphor layer, and optical waveguide displays, and projection displays based on FPD imaging devices. That is "FPD" is often used generically like "Kleenex" for tissues as compared to sleeves, or "Frigidaire" for refrigerators as compared to iceboxes.

Cost may be a represented as a single variable, life-cycle cost (LCC), or broken down into several variables which taken together define LCC: vendor viability relative to planned life (PL), vendor replacement, probability vendor will need to be replaced (at 50, 100, 200% of PL), non-recurring engineering costs (NRE), acquisition cost, mean-time-between failure (MTBF), repair cost, mean-time-between maintenance (MTBM), replacement cost when initial vendor is not available, maintenance cost, et cetera. In acquisition reform all costs may be passed on to the vendor to manage by negotiation and payment of a warranty fee. Unfortunately, warranties are no good when the company goes out of business. Also, company legal staff is adept at passing the bill back to the government. Thus, it is here recommended that all PS include several cost variables, including, in decreasing importance, MTBF and probability vendor will need to be replaced at/by 100% PL.

Environment may be represented as a single variable (works in any situation ever encountered in combat on or near earth), or broken down into several variables, such as temperature range (storage, operational), resistance to direct exposure (to weather, lightning strikes, electromagnetic interference, sand, salt spray, mud, boot kicks, shock, vibration, solar storms, battle damage).

Technology may be represented as a single variable (works as and when needed in the system in which it resides), or broken down into several variables whose identity is based on the general technology. For the general technology of displays, for example, potential variables include the following: luminance (day, night), resolution (pixels per frame), grayscale and color (bits per pixel), frame rate (Hz), luminance contrast, chromaticity, chromaticity contrast, rolloff, weight, power (which may be represented as weight), drive voltage (indicates damage/fatigue potential of materials), angle of view, efficacy, efficiency, night vision goggle compatibility. The display technology variants include electromechanical (EM), cathode ray tube (CRT), active matrix liquid crystal display (AMLCD), passive matrix twisted nematic liquid crystal display (TN-LCD), plasma-addressed active matrix liquid crystal display (PALCD), thin film electroluminescent (TFEL), active matrix electroluminescent (AMEL), AC gas plasma discharge display (PDP), digital micromirror device (DMD), gas dye laser projector (GDLP), solid state laser projector (SSLP), reflective cholesteric liquid crystal display (RCh-LCD), reflective holographic liquid crystal display (RH-LCD), ferroelectric liquid crystal display (FE-LCD), field emission display (FED), organic light emitting diode (OLED), active matrix organic light emitting diode display (AMOLED). Similarly, the PS is independent of the design approach: direct-view, projection, or helmet-mounted display.

2.2 Examples of performance specifications: displays

The flat panel challenge is before us and represents an opportunity to define acquisition reform, including the performance specification process, in a way that is understood and gains the confidence of industry. Flat panel displays in one form or another--whether currently well advanced amorphous-silicon-AMLCD and new generation EL (AMEL, TFEL), or some future contender, such as polycrystalline-silicon-AMLCD, or FED, or OLED–will be installed as part of standard military avionics, vetronics, or shipboard electronics throughout DoD. This situation is not merely because FPDs have the readily apparent advantages of less weight, volume, and power consumption relative to the out-going cathode ray tube (CRT) and electro-mechanical (EM) displays, but also by virtue of a 10-100X reliability and performance increase. Simply put, FPDs improve availability and cost less to own and operate. For this reason FPDs will eventually find their way into even benign-environment DoD-unique applications such as weapon system trainers and command and control stations. It is important to facilitate the decision process, by DoD and industry, which leads to putting the requisite size, number, and kind of FPDs into military platforms in a timely manner.

All DoD science and technology (S&T) organizations recognize a responsibility to the warfighter, the maintainer, and the taxpayer. Bringing military FPDs into the DoD inventory on a timely basis will serve the warfighter by providing a more mission-capable piece of equipment which reduces crew/soldier/sailor workload while improving situational awareness and combat kills. The maintenance establishment is served (1) by reducing workload and need for spares due to a FPD mean time between failure (MTBF) rate 30-100 times better than the out-going technologies of EM and CRT and (2) by addressing the vanishing vendor syndrome (VVS) for military EM and CRT displays. The taxpayer is served first (1) by decreasing DoD budgeted expenditures relative to LCC and (2) by ultimately reducing the projected number of persons and platforms necessary to achieve availability and sortie rates sufficient to provide the defense capabilities required by national military objectives.

The overall DoD flat panel challenge is to develop capable crew display systems for all classes of air, land and water vehicles, with spin-off to and spin-on from other federal, university, and civil dual uses. The primary goal is to develop affordable, capable crew station display technologies. A second goal is to conceive human system interfaces that use all the warfighters' sensory modalities -- vision, touch, hearing, etc. -- in order to 'embed" them in the information flow. The third goal is to establish tri-service display hardware and symbology standardization for economy of scale production runs, reduced logistics "tail", and safety. Objectives include display technologies not subject to the VVS disease and resolution increases to 1280 x 1024 and higher color pixel video Vehicle-Mounted Displays (VMD) and Head-Mounted Displays (HMD) systems. Tri-service logistics centers, depots, and system program offices are requesting S&T help at an ever-increasing rate for retrofits at the 1.3 megapixel and less regime. A key role of the service laboratories is to make DoD a "smart buyer" of new display technologies in retrofitting current as well as new systems. Many display retrofits are made mandatory by the VVS. Long range goals include the capability to put pixels on the head, vehicle/console, or wall according to the following timeframe (full color, full motion video in all cases): 4-6M, 10M, and 35-210M by 2000, 2005, and 2010, respectively. As agents for the DARPA-led National Flat Panel Display Initiative, the Army, Navy, and Air Force laboratories ensure that service S&T priorities are known to DARPA as it makes its investment decisions on behalf of DoD. Leadership by DARPA is central to meeting the DoD flat panel challenge.

For aircraft cockpit applications in 1998 the technology that is usually selected is avionic-grade color AMLCD. Some aircraft instruments are being replaced with other technologies, such as TFEL for EM or CRTs. Thus, symbolically,

$\mathbf{V}_{PS}$ (1998, fielded, aircraft cockpit multifunction display) is defined by full color avionic-grade AMLCD technology;
$\mathbf{V}_{PS}$ (1998, fielded, military a/c cockpit radar warning display) is defined by 1960s avionic-grade CRT technology;
$\mathbf{V}_{PS}$ (1998, production, military a/c cockpit radar warning display) is defined by avionic-grade monochrome TFEL;
$\mathbf{V}_{PS}$ (1998, production, military battle tank FLIR display) is defined by vetronics-grade monochrome TFEL;
$\mathbf{V}_{PS}$ (1998, initial production, Land Warrior solder head-mounted display) is defined by military-grade AMEL;
$\mathbf{V}_{PS}$ (1998, laboratory, low power handheld personal warfighter display) is defined by ruggedized reflective-Ch-LCD;

Hopper [11] introduced a performance specification vector for displays in 1993 and compared the AMLCD in a 1991 Apple PowerBook to four more demanding applications, two of which were commercial (automotive instrument panel and transport aircraft cockpit) and two, military (field notebook and fighter aircraft cockpit). An updated version of this table is included here in Table I to complete the use of displays as an example of the performance specification definition given above.

2.3 Aggregate metrics

Overall metrics are needed for each general technology. Such an aggregate metric is to a technology what the gross domestic product (GDP) is to the economy: a barometer which can be monitored both by those within and those outside the particular field of economic or technological endeavor. Such a metric combines several independent variables in the performance specification into an overall figure of merit. The aggregate metric is defined such that increases represent increased desirability from the perspective of humans. These overall metrics can then be used by a particular technology community to represent its technology challenges, plan investment strategies, establish roadmaps, and ascertain progress. For engines a key aggregate metric is thrust (lb) and specific thrust (lb/kg). Similar metrics may be defined for other technologies and two created by the author for display technology are introduced in the next section.

Table I. Comparison of specifications for commercial and military applications of flat panel displays (baseline = AMLCD).

Performance Specification Variable	Civil Office Notebook (1991,productn)	Mil.Truck-Auto. Instrumt Panel (1993,research)	Bomber/Transpt Aircraft Cockpit (1993,laboratory)	Military Field Suitcase/Notebk (ideal)	Bubble Canopy Cockpit (ideal)
Critical technology -- a key availability driver for weapon systems with human system interfaces based on flat panel displays					
Domestic vendor required	No	Yes	Yes	Yes	Yes
Foreign vendor allowed	Yes	Yes	Yes	Yes	Yes
Design control available to niche market (e.g. military/avionic) -- a key cost driver of 20-year life cycle cost (LCC) analyses					
Hi vol. low rqmt vendor	No	No	No	No	No
Low vol. hi rqmt vendor	Yes	Yes	Yes	Yes	Yes

Luminance in nits (nt), where 1 nt = 1 cd m^{-2} (fL, where 1 fL = 3.42626 nt), and contrast ratio, [CR]					
maximum	70 (20)	750 (220)	750 (220)	1370 (400)	1370 (400) [50:1] *
minimum	7 (2)	0.0274 (0.008)	0.0274 (0.008)	0.0274 (0.008)	0.0274 (0.008)
Video (full color and monochrome)					
Frequency, Hz	24	48	48	30	60
Grayshades / primary	2-16	8-128	8-128	8-128	16-256
Viewing range (H^o, V^o)	40, 30	30, 30	120, 30	60, 60	30, 30
Altitude, m (ft)					
Storage/Shipping	4572 (15000)	15400 (50000)	15400 (50000)	15400 (50000)	30800 (100000)
Operational	3048 (10000)	3048 (10000)	15400 (50000)	3048 (10000)	30800 (100000)
Temperature, ^{o}C					
Storage	-25 to 60	-54 to 90	-54 to 90	-54 to 90	-54 to 110
Operational	10 to 40	-40 to 85	-40 to 85	-40 to 60	-40 to 85
Startup transient	up to 60	up to 175	up to 175	up to 175	up to 175
Times					
Storage-to-operation, m	20	1	20	20	1
MTBF, h	300	200,000	30,000	20,000	20,000
Lifetime, y	3	20	40	20	20
Acceleration, g					
Constant (RMS)	1	15	15	15	15
Shock (impulse)	1	30	15	60	30
Adverse condition operation					
Relative Humidity, %	20-80	0-100	0-100	0-100	0-100
Salt spray	No	Yes	No	Yes	Yes
Blowing fine sand	No	Yes	No	Yes	Yes
Immersion in mud, water	No	Yes	No	Yes	Yes
Bullet hole in inst.panel	No	Yes	Yes	Yes	Yes
Filters					
IR cut-off filter	No	Yes	Yes	Yes	Yes
EM interference	No	Yes	Yes	Yes	Yes
HUD compatible	No	Yes	Yes	No	Yes
AR & UV coatings	No	Yes	Yes	Yes	Yes

* Some now say that the maximum luminance should be greater than 3400 nit (100 fL).

2.4 Display information thrust (DIT) and specific information thrust (SIT)

For displays the aggregate metrics of "display information-thrust (DIT)" in bits/s and "specific info-thrust (SIT)" in bits/kg-s are herein introduced. * Info-thrust is computed for a particular display by multiplying the resolution (pixels per frame), grayscale and color (bits/pixel), and frame rate (frames/second, or Hz):

Display Info-Thrust (bits/s) ≡ Resolution (pixels/frame) x Grayscale&Color (bits/pixel) x Frame Rate (frames/s)

Specific Information-thrust is defined to be DIT divided by the weight (mass in kilograms in a 1 G gravity field) of the display:

Specific Info-Thrust (bits/kg-s) ≡ DIT / Weight (kg) .

where the weight is that of the display plus the energy to drive it. Examples for large displays are provided in Table II. Examples for miniature displays and commercial notebooks are provided in the next paragraphs. Note that the SIT mass unit is grams for miniature displays but kilograms for large (direct-view and projection) displays.

The energy can be computed as a portion of the power generation weight attributable to the display. The energy is defined for a given application to be a profile over time of power of a specified type (voltage, current, frequency, waveform). For an aircraft the weight contribution includes fuel and the auxiliary power generation unit driven by the turbine in the engine. For a portable display device (e.g. for a dismounted soldier or downed pilot) the weight contribution for power generation includes such things as batteries, solar cells, kinetic energy devices to capture motion fueled by having eaten K-rations or ants, and even eventually a 30-gram butane-fueled micro-electro-mechanical 3-mm long turbine generator producing 100 W for 20 hours.

For the Land Warrior program a miniature TFEL display (monochrome VGA with 32 gray levels, 60 Hz, 2.1 g) is entering production; here V(1998, production, dismounted soldier) would have DIT = 92 Mb/s and SIT = 44 Mb/g-s. For the Comanche helicopter pilot a miniature CRT display (monochrome 1000x1000 with 256 gray levels, 60 Hz, 6.5 g) is entering production; here V(1998, production, helicopter pilot) would contain DIT = 480 Mb/s and SIT = 74 Mb/g-s.

Early commercial notebook computers are well exemplified by the 1991 production of the Apple Macintosh PowerBook 170 weighing 3 kg (6.5 lb), which included a monochrome VGA (640 x 480 pixel) AMLCD with 2 gray levels at 30 Hz; here, V(1991, production, consumer notebook) would have DIT = 9 Mb/s and SIT = 3 Mb/kg-s . Five years later the state-of-the-art of notebooks at the production level could be represented by the 1996 Toshiba Tecra730CDT weighing 4 kg (8.5 lb), which included a color XGA (1024x768 pixel) AMLCD with 64 gray levels at 60 Hz; here, V(1996, production, consumer notebook) would have DIT = 283 Mb/s and SIT = 72 Mb/kg-s . One sees that over the five-year period from 1991 to 1996 for an office civil commercial notebook computer, DIT increased a factor of 31 and SIT increased a factor of 24.

Table II. Combination multi-variable metrics (displays): display information thrust (DIT) & specific information thrust (SIT).

Variable	Fighter Cockpit, 1998		C4I Mission Crew Station, 1998		Simulator for Training, 1998	
or Metric	V(fielded)	V(prod)	V(fielded)	V(production)	V(fielded)	V(ideal) #
Resolution, pixels/frame	512x512	512^2	1024x1280	1024x1280	1600x1200	5120x4096
Color&grayscale, bits	4	5	12	24	24	24
Frame Rate, Hz	80	80	66.6 ni	72 ni	80	80
DIT, Mb/s	84	105	1047	2265	3686	40265
Weight, kg (lb)	18 (40)	9 (20)	53 (116)	11 (25)	23 (50)	23 (50)
SIT, Mb/kg-s	5	12	20	199	162	8850

Ideal based on 20-20 *Homo sapiens* vision acuity of about one pixel per 50 arcseconds subtended at the pupil of the eye.

* DIT and SIT complement traditional key aggregate variables for displays, like power efficiency in lumens/Watt (lm/W).

2.5 State of the art: level

The level of knowledge ranges from theory, laboratory proof of principle, laboratory working breadboard model, demonstration brassboard model, production prototype, low rate initial production, production, fielded, accepted by market. More or less of these levels can be identified as may be necessary for a particular general technology. Three levels are used herein for purposes of illustration: laboratory, production, fielded. Beyond all such levels is the "ideal," which is used to identify what humans would like if their level of knowledge (of how to mine the earth for atoms and reassemble them) were not limited. At the research level enough is known to believe a particular instantiation of a general technology can eventually (in, say, 30 years) be brought into existence. At the laboratory level enough is known to believe an envisioned technology can become a realistic option within, say 10 years. At the developed level sufficient knowledge is amassed so that models will have passed initial test marketing (civil or military as the case may be). At the production level sufficient knowledge exists on the pertinent processes (atom re-assembly from raw materials to product) to put significant quantities of the products including the technology into the hands of users (customers, warfighters) who pay for functionality and have no particular attachment to the particular technology used to achieve that performance. Once the market has had a suitable period to barf on the new "want-to-be (WTB)" technology (say 1 to 18 years) it may be termed a technology. A technology is herein defined as a body of knowledge that supports products. Two comparisons of ideal versus fielded performance specifications,

V(ideal,combat fighter aircraft multifunction display) vs. V(1995, fielded, F-16 multifunction display)

and

V(ideal, C4I mission crewstation display) vs. V(1995,fielded, AWACS mission crewstation display)

are included in a previous paper. [12]

2.6 Application group: phylum

Performance specifications for applications naturally cluster into groups, or phyla. One phylum may be conveniently distinguished from another by one or more significant differences in the required values of key variables. For example, sunlight readability is mandatory for applications including aircraft cockpits, automobiles, and automatic teller machines, but is not needed in darkened lighting conditions such as C4I crew stations, wall displays, or standard accepted home and office ambient lighting conditions for computers, movies, and television. Thus, the variable of luminance may need to reach a maximum of 1600 nt or more for a bubble canopy combat fighter aircraft, but only 100 nt for dimmed office environments. The level of knowledge needed to fabricate sunlight readable displays drives the cost for these applications. Other variables, such as total resolution, are more important for non-sunlight readable applications. We then have a phylum of sunlight readable displays.

Similarly, the conditions of use in military combat are often significantly more demanding and require a higher level of knowledge to fabricate and operate for a system life of 10-30 years than a similar non-military (civil) application. For example, an advanced forward infrared imaging sensor may require higher resolution (4X) and gray scale (16 bit vs. 8 bit per color) than a similar display used for viewing television and must be packaged to survive kicks, mud, high-pressure hoses, and hermetic sealing (which makes heat dissipation a bear). The level of knowledge needed to fabricate the 4X resolution displays (in the same viewing size) with 8 bit and higher gray scale response in an adversarial hostile combat environment drives the cost for these applications. One may then distinguish between combat and non-combat applications to define phyla.

Phylum means the application group, where three military and five civil examples are as follows: combat-shooter, combat-C4I, combat-support, civil electronics-notebook or monitor or television, commercial/general aviation-flight deck and in-flight entertainment, civil-automotive or train or banking ATM machine, consumer-personal digital assistants, civil-Space Shuttle and Space Station. The first four of these example phyla are used to illustrate the concept of application group in the following sections in terms of types of military systems: combat-shooter, C4I for combat, support (transportation, intelligence, communication) for combat, and consumer electronic for notebook computers.

Performance specifications for each phylum, or class of application, need to be established by users (DoD) and industry together in an iterative process with sub-processes that are government only (issuance of specific PS for a specific acquisition from time to time) and that are joint (development of baseline PS for each application class and level within that class). Much work has been done in the example technology of FPDs used in this paper, but far more remains to be accomplished.

2.7 Pathway invariance

The performance specification is independent of the pathway from atoms to product. This concept is illustrated in Figure 1. The pathway chosen is the one with the expected lowest life cycle cost (LCC). Initial acquisition cost is but one LCC factor. Some display applications not related to combat can be met with products similar to those designed for civil markets. Some applications require a degree of display ruggedization, but can then work even in many combat-related applications. However, the most severe applications require unique military display development as part of the process of optimizing the weapon system for combat, with a $100K display unit in a $100M aircraft. If because of the introduction of custom design displays such an aircraft-pilot system is 30% more effective and the display itself is 100X more reliable than a consumer display, the custom display is a bargain as fewer aircraft are required to provide needed capability to a fielded force commander. Some typical FPD concerns in using custom vs. consumer starting point are summarized in Table III.

Start Point	**Develop**	**Mid-Point**	**Acquisition**	**Operate**	**$LCC**	**End Point**
custom	design	manufacture	integrate	maintain	$X	product
consumer	re-design	re-manufacture	integrate	maintain	$Y	

Figure 1. The product is defined by the performance specification, which is independent of the manufacturing pathway.

Table III. Comparison (custom versus consumer-grade) at State of Production (manufacturing) level for LCD technology.

Problem	Design features that solve problem	Custom Incorporates feature(s)	Consumer Commercial Does NOT use features	Reason feature missing from commercial
Submarining	Thin cell gap In-plane switching Cell uniformity Ferroelectric LC	Yes	No	Value-added engineering (market will not support in 1996—projected for 1998)
Wide angle viewing	Compensation layers	Yes, if product needs	No	Value-added engineering (market will not support in 1998—projected for 2000)
Sunlight viewability	Hi-luminance backlight including wide >20,000:1 dimming range electronics	Yes, if product needs	No	Value-added engineering
Full 256 grayscale	Driver chips	Yes e.g. Comanche	No	Value-added engineering (market will not support in 1998—projected for 2000)
Full motion video	See submarining	Yes e.g Shuttle,Comanche	No	Value-added engineering (market will not support in 1998—projected for 2000)

3. CLASSIFICATION SYSTEM

The principal of a PS classification system is introduced herein, comprising (a) the definition of the PS as a vector V of N performance variables X_i that is time dependent, $V(X_i(t)$, i=1-N : level, phylum); (b) the concept of a PS spectrum of knowledge level ranging from the fielded baseline down through production to laboratory towards ideal; (c) the concept of a PS phylum, or application, with phyla ranging from combat (shooter, C4I, support) to civil consumer electronics (computer laptops, monitors); (d) the concept that the rate of PS change varies from every 18 months for fielded consumer electronics products to infinity for ideal. The time dependence of the PS level of knowledge may be viewed from the perspective of an individual technology coming into existence over a period of years (5-30) from discovery of phenomena in the research laboratory through prototyping and production (limited, full) to market acceptance of products—a graphical method is introduced as a tool for the analysis of this time-cycle aspect of performance specifications.

The classification system is exemplified for selected levels and applications in Table IV.

Performance specifications provide guidance to industry for needed products without dictating the detailed design of that product. Such specifications must emanate from government but must also be developed in concert with industry. It is recommended here that the problem be broken down into two main parts or phyla, each of which is divided into subparts or levels (see Table III). The Phyla for displays should differ little from those for other technologies. The initial Phyla set might be limited to four: combat, C4I for combat, combat support, and commercial. The Combat Phyla includes systems that shoot and get shot at. The C4I Phyla includes systems that do not shoot but will get shot at because they direct shooters. The Support Phyla includes applications removed from the battle zone but necessary to the support of combat; such support systems include logistics chains and may get shot at, especially when they arrive in a battle area to dispense men & equipment.

Value added engineering (VAE) involves the deletion of design features to decrease the cost of production. Features deleted are based on market analysis. Right now, the LCD producers can sell more than they make even though features needed in high requirement applications are deleted. The same logic causes Delco Electronics to delete a resistor in an automotive radio tuner circuit if it can be shown that the radio gets to the right frequency say 90% of the time without it. Table III helps explain VAE for custom vs. consumer applications of LCDs for V(production). Also, VAE strongly impacts V(production) vs. V(laboratory).

Table IV. Classification system for performance specifications.

Kingdom: **Performance Specifications**	**Technology:** Displays	**Key * Performance Variables:**	**Aggregate:** LCC ($), Efficacy (lm/W) Specific Info-Thrust (Mb/kg-s)	**Specific:** weight, power, volume, all of the -ilities, luminance, resolution, contrast, chromaticity, etc.
Starting Point:	**Custom Display**	**Custom and / or Re-engineered Consumer**	**Re-engineered Consumer and / or Custom**	**Consumer Display**
Phylum	**Combat–Shooter**	**C4I for Combat**	**Support for Combat**	**Civil Electronics-Monitor**
Level of Knowledge				
Ideal (humans on earth)	Vector (I, Shooter)	Vector (I, C4I)	Vector (I, Support	Vector (I, Office Monitor)
Laboratory	Vector (L,Shooter)	Vector (L,C4I)	Vector (L, Support)	Vector (L, Office Monitor)
Production	Vector (P,Shooter)	Vector (P,C4I)	Vector (P, Support)	Vector (P, Office Monitor)
Fielded	Vector (F,Shooter)	Vector (F,C4I)	Vector (F, Support)	Vector (F, Office Monitor)

* In other contexts the term "performance parameter" has been used for what is here termed "performance variable." The use of the word variable has two advantages in the present context: (a) this paper views all performance specifications for all human applications as a rapidly expanding hyperspace from which applications are selected and products made; (b) the use of the term variable helps one keep the perspective that the performance specification is not a single point in an N-dimensional hyperspace, but instead an N-dimensional volume in that hyperspace and that trade-offs can be made in that volume. That is, each element of performance is not to be viewed as a done and selected parameter, but as a variable to be explored in concert with all others to optimize and achieve the overall performance specification to be realized in the fielded product.

4. PERFORMANCE SPECIFICATION EVOLUTION

4.1 DoD technology strategy

The Director of Defense Research and Technology has endorsed a systematic analysis of technologies for their value-added in constituting the national defense. An example of such an analysis applied to displays as a core competency is illustrated in Figure 2. Slight modifications of Figure 1 yields similar charts for other classes of military applications, such as land combat vehicles, shipboard electronics, dismounted soldiers, land/sea/aerospace C4I, et cetera. The method used is a quality function deployment approach with metrics. First, one states at the top left the payoffs from an operational perspective. Then the engineering goals, which if achieved will provide the opportunity to achieve the operational payoffs, are listed in the top right. Individual investments in particular science and technology projects are shown at the bottom. If a significant portion of the individual investments work out, the previously unattainable engineering goals become reality, thus contributing to affordable national defense. The DoD must leverage the trends in the civil commercial market. The performance specification at any given time (year) must be based on an interaction between the operational needs and the technological possibilities. Both need and possibility evolve as the technologies are invented and improved. This concept of an evolving performance specification is a basic feature of the commercial markets. Recognition of this process and, especially its rapid pace, will enable DoD to capitalize on leveraging opportunities based on new commercially viable technologies, such as FPD, for which the present growth phase is exponential.

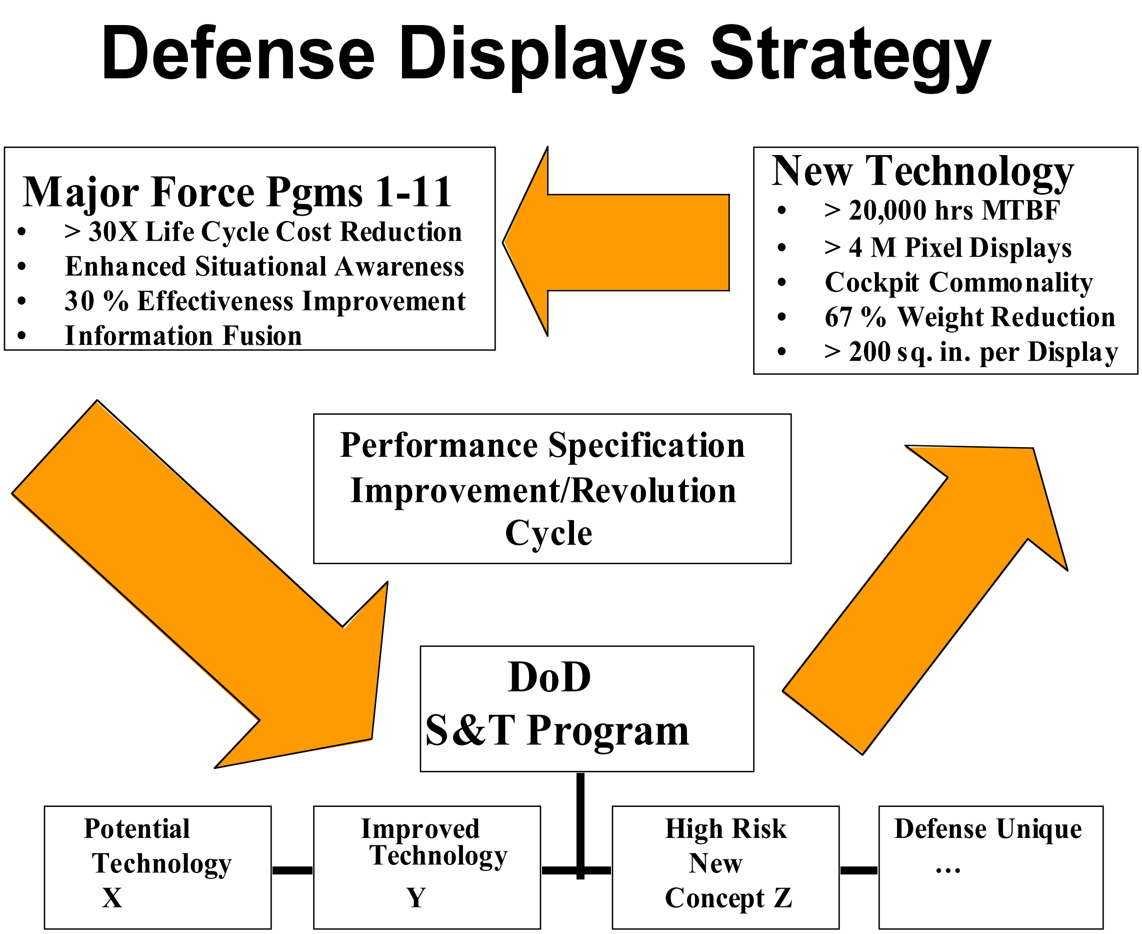

Figure 2. Defense displays strategy: goals based on payoffs drive evolution of performance specifications.

4.2 Graphical metric

A metric called "technology status" is introduced along with a graphing approach for its use as a tool to measure the progress of a given potential technology through each of the levels of performance shown in Table IV. The plot shows the progression in time of a "want-to-be" technology from laboratory through production to use. Once the marketplace of users have accepted products incorporating the "want-to-be" technology, it is declared to have technology status. This market acceptance time is defined to be the period of years needed for initial year sales to quadruple; that is, when annual sales are 400% of those achieved in the introduction year, the market has "accepted" the new technology. By this metric it took 18 yrs for the refrigerator as presently designed (compressor/insulated walls) to be accepted, but only 6 yrs, for VCR.

An April 1998 report on acquisition reform indicated "DoD still has much to learn from the dynamic changes in business practices and support systems that characterize the best of American business. [6] The graphical metric of technology status provided here is intended as a contribution to that end. Both consumer commercial and military target markets are included because affordability dictates that DoD must leverage the private-sector market paradigm. Seed research and development investments by DoD in areas of concern to it will encourage industry to examine new potential technologies and markets. However, only private capital decisions can lead to the creation of products and markets that are viable over the planned life of the weapon system. Consumer product cycles for displays and other electronics are 6 to 12 months; thus, DoD plans for 20 years of system life must take the underlying consumer electronics paradigm into account via flexible and open systems design and interface standards that exist at least over the required 20 year period. The pre-planned product improvement (P3I) process is a tool already in the DoD acquisition toolbox; this tool may have to be updated to accommodate technology insertions continuously, or perhaps every 18 months, rather than every 5-15 years as at the present time. The technology insertion process needs a large dose of reality, however. As shown in Figure 3, it takes years for the required knowledge level for an envisioned technology to emerge from the research through manufacturing to the using community. Much hype typically accompanies an envisioned technology: proponents use the word technology without qualification (envisioned, laboratory, manufacturing) as if original equipment manufacturers could order up as many as they want (which might be millions) whereas the proponents have not demonstrated the first working prototype or cannot produce but ten.

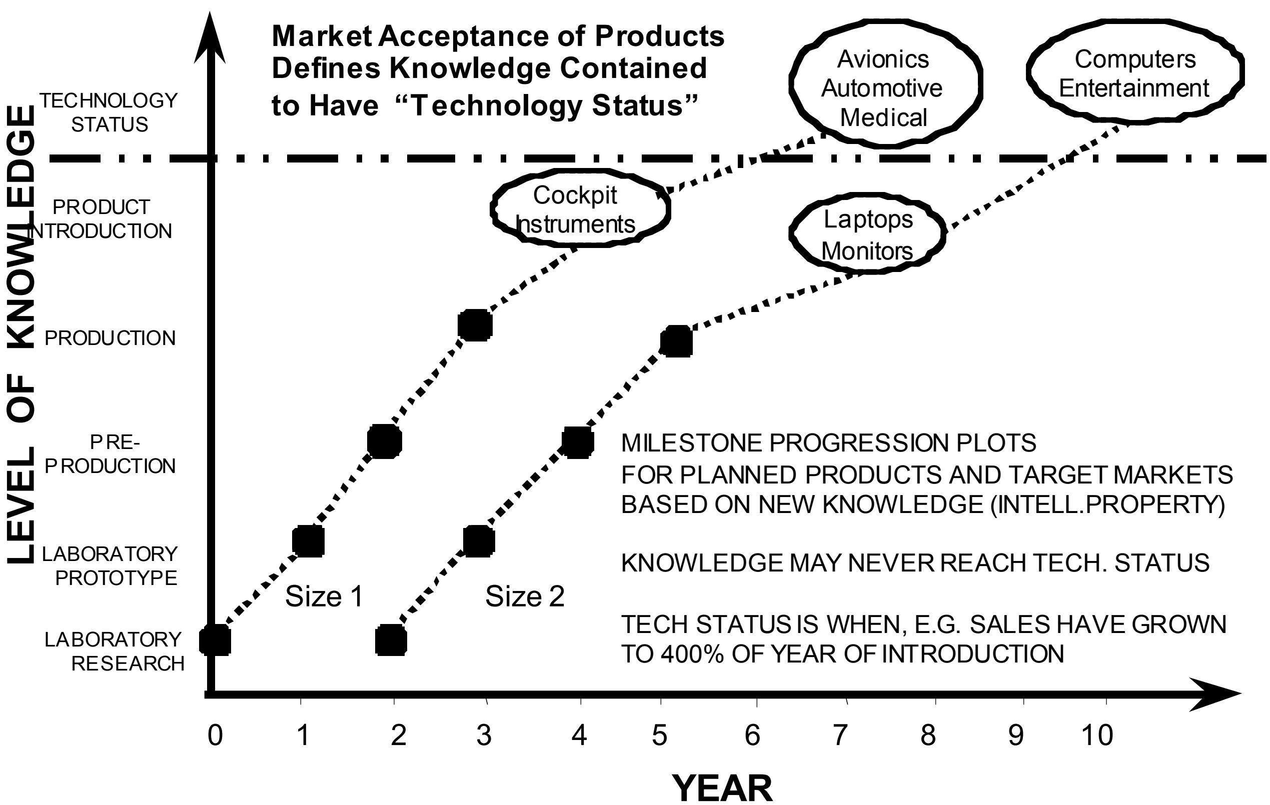

Figure 3. Evolution of knowledge aggregation "X" towards technology status.

5. DISCUSSION

The DoD strategy is to continually obtain the best technology affordable and keep our forces in a position of dominance. [6] There is a condition on acquisition reform: it must deliver systems to the combat commands that work under the condition attendant to combat. These systems must lower the cost of operating current systems and must, over time, dramatically decrease the cost of force projection capability. For example, air superiority must be provided by ACC or NAVAIR to a Unified Command at less cost; this means fewer planes, airfields/carriers, pilots, and support personnel than now.

The DoD S&T investment strategy is guided by the differences in fielded and ideal performance specifications, but tempered by the realities of current development and anticipated manufacturing performance possibilities. In each application class, or phylum, for a technology, the variables of the performance specification must be prioritized so that application of the budget process places limited resources against the most advantageous technology challenges.

This paper provides a suggested methodology for performance specifications, comprising definitions, concepts, principals and a classification system. The notion here is that such a methodology, especially the classification system, is a mandatory tool to the analysis of where and how DoD can meet the challenge of acquisition reform by maximizing its reliance on the commercial market place. The classification system introduced has two key orthogonal dimensions: level and phylum. Level means level of knowledge (state-of-the-art), and four are used to illustrate the present discussion: laboratory, manufacturing, fielded and ideal. Differences among these levels constitutes a basis for identifying technology challenges. Phylum means the application group, where three military and six civil examples are as follows: combat-shooter; combat-C4I; combat-support; civil electronics-notebook or monitor or television; commercial/general aviation-flight deck; cabin in-flight/in-train/in-auto entertainment; civil-automotive or train or banking ATM machine; consumer-personal digital assistants; civil-Space Shuttle and Space Station. The phyla are defined such that the performance specification differs so much that the highest priority variables or parameters in one are not the same as in the others; the top priority variables are those that drive the cost or technology or both for a particular phylum. All combat applications are distinct from most civil applications in terms of the –ilities (reliability, maintainability, sustainability). However, integration and packaging techniques might enable a consumer-electronics product to act as the starting point for combat-C4I (mission crewstations in AWACS, E-2C) but not for combat-shooter (e.g. cockpits of F-22, M1A2, AH-64D, F/A-18E/F, AAAV). If there is more than one starting point by which the performance specification can be met, the one selected is the one with lowest LCC, which includes the effects of 18-month commercial product cycles and the vanishing vendor syndrome (VVS) for sunset technologies, such as electromechanical and CRT in cockpits.

The baseline for a performance specification at the *fielded* level must start with what is already bolted onto systems comprising DoD capability. Fielded performance specifications for 1997, for example, can be written in 1998, for reference in on-going acquisitions. The fielded performance specification is good from the time it is bolted onto the platform until (a) a technology insertion project comes along or (b) the platform is removed from service. The fielded performance specification must represent what the user (warfighter) actually gets in terms of performance in every day use in all operational conditions (normal and extraordinary). Fielded performance specifications often are fixed or slowly varying for 15 years for electronics components like displays. The military display market has been surveyed from within DoD by Desjardins and Hopper. [13,14] The U.S. Displays Consortium has issued an industry-view roadmap for the military and avionics market. These two efforts, one inside and one outside of DoD, should lead to a realistic common view for all concerned parties of the DoD niche market for displays and aid the establishment of a set of consensus fielded performance specifications for application classes, or phyla.

The maximum for a performance specification at the *ideal* level must start with the limitations of humans on or near earth. As evolution both of *Homo sapiens* and the planet earth is an ultraslow process, ideal performance specifications, once identified, are essentially constant over a planned life of 20 years for a system. However, humans do not know all of their capabilities nor do they understand all aspects of the environment on/near earth. Thus, improvements in knowledge on the operator/environment side of the interface may drive changes as much or more than the hardware side from one 20 year planning period to the next (new system or major upgrade), or even from within such a period (technology insertion).

A vetting process is required to develop performance specifications. All concerned DoD and industry components must be involved in this vetting process. Operators are vital to the establishment and evolution of the fielded performance specifications. Technologists are vital to the establishment and evolution of the laboratory level PS. Manufacturers are vital to the establishment and evolution of the manufacturing level PS. All are vital to the vetting to establish the ideal performance specifications, and to interact with the other two communities. A DoD-industry team structure with three subcommittees would be necessary to address such a vetting process. In the end, each PS must be issued by the customer (DoD) to industry.

The performance specification methodology introduced here, or something like it, is a tool necessary to the efficient organization of DoD efforts to win the cycle time race.[15] As military programs come to rely ever more on the commercial market place, the well-spring of innovation available to DoD becomes more accessible to all potential adversaries as well. Progression of an envisioned technology from the laboratory to everyday use may be viewed as a time-dependent metric: technology status. A graphical metric for technology status is provided to help assess the evolution of research ideas toward products—civil or military. The classification system and technology status may be used in future efforts to establish a model of change (cycle time) for technologies like flat panel displays in defense applications.

6. REFERENCES

1. W. J. Clinton, "Technology for America's Economic Growth, A new Direction to Build Economic Strength," Federal Technology Policy issued February 22, 1993.

2. Defense Department Acquisition Law Panel (the "800 Panel"), established under section 800 of the 1991 Defense Authorization Act, recommended reform of 889 laws and regulations governing defense acquisition (1991).

3. D. Silverberg, "U.S. Pushes Radical Procurement Policy Reform," Defense News **8** (8), p.1,28 (March 1-7, 1993).

4. W. Perry, acceptance speech upon receipt of the Annual Defense Achievement Award from SPIE (April 1997).

5. Department of Defense Directive (DoDD 5000.1 and Department of Defense Instruction 5000.2 (1996).

6. W. Cohen, letter and report to Congress on DoD implementation plan to streamline the acquisition organizations, workforce, and infrastructure IAW Section 912 (c) of Natl Def Authrztn Act for Fiscal Year 1998. www.acq.osd.mil/ar/

7. D.G. Hopper, "Military Flat Panel Display Technology," Abstract of presentation at the *U.S.-Japan Meeting on Flat Panel Display Technology (FPDT)*, Defense Research Center of Japan, Tokyo (5 October 1993).

8. "National Flat Panel Display Initiative," prepared and issued under DoD leadership (October 1994). This policy equated economic security to national security in the U.S. pursuit of a domestic portion of the growing FPD industry.

9. "Acquisition of Flat Panel Displays for Military Applications," Report to Congress (Mar 98), www.osd.acq.mil/es/dut

10. R.Van Atta et al., "Acquisition of flat panel displays for military applications," in ***Cockpit Displays V: Displays for Defense Applications***, Darrel G. Hopper, Editor, Proc. SPIE 3363, 1-7 (1998).

11. D.G.Hopper, "Cockpit display requirements and specifications," in ***Display Systems***, Chris Bartlett, Editor, Proc SPIE (1993). Paper in the proceedings volume for the EOS/SPIE "EUROPTO" International Symposium on Electronic Imaging Device Engineering held at Munich, FR Germany, 21-25 June 1993.

12. R.A. Michaels, D.D. Desjardins, R.Daniels, and D.G. Hopper, "Applications of AMLCDs in U.S. military cockpits," in ***Cockpit Displays III***, Darrel G. Hopper, Editor, Proc. SPIE 2734, 258-267 (1996), pp. 262,263.

13. D.D. Desjardins and D.G. Hopper, ***Military Display Market: First Comprehensive Edition***, Technical Report Number AFRL-HE-WP-TR-98-0017 (March 1998),296p. Available to qualified recipients from AFRL/HECV, WPAFB OH 45433.

14. D.D. Desjardins and D.G. Hopper, "Defense displays market assessment," in ***Cockpit Displays V: Displays for Defense Applications***, Darrel G. Hopper, Editor, Proc. SPIE 3353, Paper 3 (August, 1998).

15. W.B. LaBerge, "'Cycle time'—a military imperative as well," Acquisition Review, **3** (2), pp. 79-82 (Fall 1996).