ORNL/TM-12497

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

CALSETS 2000 Assessment Study

J. A. McEvers
R. L. Anderson
J. O. Hylton
T. J. McIntyre
M. R. Moore

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/TM-12497

Instrumentation and Controls Division

CALSETS 2000 ASSESSMENT STUDY

J. A. McEvers
R. L. Anderson
J. O. Hylton
T. J. McIntyre
M. R. Moore

December 1993

Prepared for
United States Army
Test, Measurement and Diagnostic Equipment (TMDE) Activity (USATA)
Redstone Arsenal, Alabama

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

CONTENTS

ACRONYMS

ACT	acoustic charge transport
ANA	automatic network analyzer
ASIC	application-specific integrated circuit
ATE	automated test equipment
BAW	bulk acoustic wave
BJT	bipolar junction transistor
CAE/CAD	computer-aided engineering/computer-aided design
CASE	computer-aided software engineering
CASS	Consolidated Automated Support System
CBU	calibrate before use
CD-ROM	Compact Disk-Read Only Memory
CMOS	complementary metal-oxide semiconductor
CNR	calibration not required
CVD	chemical vapor deposition
DMM	digital multimeter
DSP	digital signal processing
DUT	device under test
DVM	digital voltmeter
emf	electromotive force
EO	electro-optics
FED	field emission display
FET	field-effect transistor
GPS	Global Positioning System
HBT	heterojunction bipolar transistor
HEMT	high electron mobility transistor
HP	Hewlett-Packard
I/O	input/output
IC	integrated circuit
IFTE	Integrated Family of Test Equipment
IMRF	Instrument Master Record File
IOC	instrument-on-a-card
IOc	instrument-on-a-chip
ir	infrared
LCD	liquid crystal display
LRU	line-replaceable unit
LSI	large-scale integration
LZW	Ziv-Lempel-Welch compression
MAP	Meaurement Assurance Program
MCM	multichip module
MEMCAD	MicroElectroMechanical CAD
MESFET	Metal Semiconductor Field Effect Transistor
MMIC	Monolithic Microwave Integrated Circuit
MMS	modular measurement system
MODFET	Modulation Doped Field Effect Transistor
MSPM	monolithic six-port module
MTS	multifunction transfer standard

MTS	multifunction transportable reference standard
NBS	National Bureau of Standards
NEP	noise equivalent power
NIST	National Institute of Standards and Technology
ORNL	Oak Ridge National Laboratory
PAE	power-added efficiency
PATEC	Portable Automatic Test Equipment Calibrator
PBT	Permeable-Base Transistor
PC	personal computer
PCN	personal communication network
PDA	personal digital assistant
RAM	random access memory
rf	radio frequency
SAW	surface acoustic wave
SPC	statistical process control
TEMOD	Test Equipment Modernization
TMDE	Test, Measurement, and Diagnostic Equipment
TPS	test program set
USATA	U.S. Army's TMDE Activity
UUT	unit under test
VGA	video graphics adapter
VLSI	very large scale integration
WORM	write once, read many
WWV	NIST Time Standard

EXECUTIVE SUMMARY

The U.S. Army's Test, Measurement, and Diagnostic Equipment (TMDE) Activity (USATA) at Redstone Arsenal, Huntsville, Alabama, is developing appropriate response to the long-term changes from anticipated decreases in defense spending resulting from the end of the Cold War. This effort has been collectively designated as TMDE CALSET 2000 or just CALSET 2000. This is in reference to the recommended form which TMDE calibration equipment should take by the year 2000. Two immediate results include a decrease in armed forces personnel and a shift in focus from a massive European ground war to relatively localized conflicts anywhere in the world. With decreased procurement budgets, it is anticipated that the Department of Defense (DOD) will place a greater reliance on research and development coupled with technology demonstrations. Few new technologies will go into full-scale production. This scenario assumes an establishment of a U.S. *agile manufacturing* capability that can be brought into full production on short notice.[1] Overall, fewer systems will be acquired, but they will be modular designs. Weapon systems will be retained in service longer by updating through modular upgrades.[2] As a part of this effort, Oak Ridge National Laboratory (ORNL) was asked to assess technology trends, to forecast where test and calibration technology would be by the year 2000, and to recommend how new technology can be efficiently incorporated into USATA's field calibration units. This study is focused on assessing applicable technologies rather than attempting to address all of the detailed issues involved in an actual development of the next-generation field calibration set.

In the course of this study, ORNL staff interviewed members of the USATA staff to develop an understanding of the organization's specialized activities and needs, reviewed appropriate literature, attended conferences, and made visits to several manufacturers of test and calibration equipment.

Some basic assumptions used in this study were as follows:

1. The study was primarily aimed at identifying and assessing revolutionary and emerging technologies rather than *evolutionary* technology. The term *revolutionary* as used in this report refers to technology trends and advances that, while not directly applicable in the near term, may come to fruition and be used by USATA within a 10-year time frame. With this information USATA may be able to influence and accelerate the development of some of these technologies. In contrast, the term *evolutionary* as used in this report refers to technology that will be available in the near term (present to 1 year) and that is relatively well established in the marketplace.

2. The U.S. Army and therefore USATA will be expected to maintain a high level of readiness and performance, with fewer resources, both in equipment and in personnel.

3. An increasing variety of weapons and weapon systems will have to be maintained. New generations of hardware as well as existing and older systems will need to be maintained.

4. The study addressed technologies that would impact several families of equipment to be calibrated [DC and AC to 500-MHz (Low-Frequency) Calibration Equipment, Microwave, and Physical / Mechanical Calibrations].

5. The study was not solely limited to calibration equipment but included related technologies that may improve the efficiency, reliability, and accuracy of the test and calibration activity.

6. To a limited extent, the study encompassed technologies that can have immediate application to downsizing the AN/GSM 286/287 calibration vans.

TECHNOLOGY FORECASTING

Forecasting the future direction of instrument science and calibration technology for any extended length of time into the future is likely to fall short of the mark because the rapid rate of progress in sensors and instrumentation can make possible many things we cannot even imagine. In spite of the inherent uncertainties in technology forecasting, it remains a useful exercise since, by anticipating future developments through extrapolation of what is now known and what may be learned in the next 10 years, USATA can plan and influence a desirable outcome.

For instance, extrapolating trends from today's stand-alone instruments and modular instruments-on-a-card (IOC), one can predict that in 10 years it is plausible to expect the development of instruments-on-a-chip (IOc). This will have a major impact on how instruments are used. Calibration intervals will be extended and simplified drastically since, with instruments composed of triply redundant, inexpensive IOc, the IOc can also spend a part of their time checking each other. IOc will greatly reduce volume and power requirements. The IOc will be fabricated from mostly standard libraries of chip-level modules. Custom or special purpose IOc will be affordable and easily made as short-run application-specific integrated circuit (ASIC) chips. This is but one, albeit significant, example of a desirable future that USATA could begin to encourage today.

CONCLUSIONS

The ORNL technology studies were subdivided into the following three areas:

- DC and AC to 500-MHz (Low-Frequency) Calibration Equipment.
- Microwave.
- Physical and Mechanical Calibrations.

Some major conclusions from each of these areas are given below.

General

- Calibration and standards technology developments must be made in the context of shrinking defense budgets and forces.

- Calibration and test systems must become agile—they must be easily adaptable to new technologies.

- The trends in miniaturization of electronic instruments in which single, stand-alone instruments are evolving into modular IOC will continue and will result in IOc.

- Virtually all instruments and sensors will contain at least one microcomputer as well as environmental sensors. They will be self-correcting, self-checking, and self-validating. Traceability will be provided through a single, stable, transportable standard.

- Because IOC and IOc have essentially no space for controls or readouts, instrument front panels will be simulated and displayed on computer screens (probably flat panel displays), creating *virtual instruments*.

- Computer technology—including displays and software—will be increasingly important. It will define how the user interacts with the instruments.
- The virtual instrument display can be designed to simulate any desired hardware configuration.
- Many existing calibration procedures will not have to be rewritten because any needed instrument setup can be simulated using the available set of core instruments.

DC and AC to 500-MHz (Low-frequency) Calibration Equipment

- Some of the existing DC/LF (low-frequency) AC equipment is outdated,* occupies substantial space in the calibration vans, and could be more highly automated.†
- There are too many different kinds of instruments in the vans. (The virtual instrument interface can be used to provide a uniform interface.)
- Many instruments needed for the van are becoming available as modular IOC.
- Self-checking devices and check measurements can extend calibration cycles.‡

Microwave

- Microwave calibrations will grow in numbers, and frequency will increase to approximately 100 GHz by 2000.
- Cabling will replace waveguides (for short paths).
- Much microwave instrumentation will be available in modular form on chips.

Physical and Mechanical Calibrations

- Mechanical measurement devices will be replaced by "smart" electronic devices with self-monitoring and diagnostics that can drastically extend the calibration intervals.§
- Smart, inexpensive, silicon-based sensors will be standards quality and drastically smaller.
- Field sensors with self-monitoring and diagnostics will reduce (or eliminate) the need for scheduled calibration.
- Field sensors will have nonvolatile memory and digital communications interface for storage and retrieval of calibration history.

---

*The equipment is continually being updated, e.g., a new CORE (meter calibration) Workstation and Signal Generator Calibration Workstations have been installed since 1990.

†Bar code scanners, CD-ROM containing Calibration Technical Bulletins, and administrative data are being added.

‡Instrument standard cross-checking has been employed in the calibration vans for many years.

§Stimuli would still need to be monitored which would still result in additional bulk.

- Miniature, high-performance, ASIC monolithic sensors will permit incorporation of a much smaller and highly automated "physical calibration" subsystem into CALSET 2000. (Although a large number of the existing physical/mechanical equipment is already small, automation would improve calibration efforts. In addition, electronically compensated-controlled actuators would be highly desirable within the physical/mechanical workstation.)

- Electro-optics (EO) calibrations are a very small fraction of the current workload, but the use of EO technology is expected to expand significantly over the next few years. Additional CALSETS support will be required.

Finally,

- A test bed is needed to keep the CALSET current with the Army's changing needs—like TEMOD.*

- A test bed can be used to develop and maintain hardware and operator interfaces for present and future modular instrumentation.

- The test bed should employ virtual instrument technology to allow the CALSET to adapt easily to technology developments.

- The test bed can be used to develop efficient workstation configurations.

- The test bed is needed to develop instrument timesharing.

- The test bed (or additional test bed) could be used for training, repair, and diagnostics.

RECOMMENDATIONS

General

USATA should

- Continue to follow Army and DOD R&D programs closely to anticipate technology requirements.

- Follow commercial and industrial instrument and calibration technologies to identify those which can be transferred directly to USATA applications.

- Participate in consortia [VXI, modular measurement system (MMS)], working groups, and standards committees.

- Drive the IOc technology by teaming with ORNL and industry to put together an R&D program, possibly with Defense Advanced Research Projects Agency (DARPA) support.

*Test Equipment Modernization Program; please see discussion in Sect. 3.2.2.

- Expand the use of expert systems, knowledge-based systems, and fuzzy logic.
- Establish a "technology 2000 test bed."
- Apply Object Oriented Programming (OOP) techniques in software development.
- Install networking capabilities for USATA's calibration and standards community (link labs, units in the field, and databases worldwide).
- Begin implementation of field-set size reduction using VXI and MMS modular instruments.
- Tie time and frequency calibrations to National Institute of Standards and Technology (NIST) via the Global Positioning System (GPS).*
- Incorporate the use of software-generated virtual instruments, which communicate to VXI- and MMS-type DC and low-frequency instrumentation.
- Identify the requirements for the development of multifunction, transportable standards to support current and future CALSETS.
- Move toward automating the DC and low-frequency calibration activities wherever possible.
- Implement self-checking instrumentation through the TEMOD program so that information may be used to monitor and adjust calibration intervals.
- Try to influence the standardization of the communications bus hardware and protocols.
- Initiate a working group to investigate and follow the rapid developments in imaging, image storage, document indexing, and document retrieval.

Microwave

- Minimize power requirements of the van, especially below 2 GHz.
- Replace waveguide with cables where feasible.
- Take advantage of amplifier advancements (decreasing size), especially above 1 GHz.

Physical and Mechanical Calibrations

- Initiate a program to determine possible reductions in calibration support requirements due to technology improvements to "smart" field devices.
- Incorporate an automated "physical calibration" subsystem into the CALSETS 2000 concept based on monolithic sensor technology.

*Some work in this area has already been accomplished; a GPS-disciplined rubidium standard is currently undergoing First-Article tests.

- Possibly consider a modification to variation of the existing TEMOD program to introduce new technology in this area.

Test Bed

- Assemble a working test bed to simulate a CALSET 2000 with off-the-shelf instrumentation.
- Use the test bed to solve hardware and software integration issues.
- Use the test bed to demonstrate the application of virtual instruments to simulate any desired instrument or test set.
- Develop a model graphical user interface based on human factors considerations.

This survey has indicated from the standpoint of this time and place several of the most likely trends in calibration and standards technology over the next 10 years. Both instrumentation and sensor technologies, including the user interface, will be dominated by microcomputer technology. The logical extrapolation of instrumentation technology from individual instruments through modular instruments-on-a-card will eventually result in instruments-on-a-chip.

USATA's goal of reducing the size and weight of the field calibration sets will be made quite practical as the miniaturization of instruments and standards becomes widespread. Integration technologies are already available to begin development of modular, compact field calibration sets. ORNL recommends that USATA begin now with an integration test bed to develop and demonstrate the test sets that will be fielded by the year 2000.

1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) was engaged to conduct an assessment study for the U.S. Army Test, Measurement, and Diagnostic Equipment (TMDE) Activity (USATA) located at Redstone Arsenal, Alabama.

The members of the ORNL assessment team are listed in Table 1 (in alphabetical order) with their academic qualifications and areas of responsibility within ORNL.

Table 1. Assessment team background

Team member	Academic credentials	Area of responsibility (at ORNL)
R. L. Anderson	Ph.D., Physical Chemistry	Section Chief Scientist
James O. Hylton	B.S., Engineering Physics M.S., Mechanical Engineering	Group Leader, Measurement Research
Jim A. McEvers	B.S., Electrical Engineering M.S., Engineerng Science and Mechanics	Group Leader, Instrument Development
Timothy J. McIntyre	M.S., Physics	Manager, ORNL Metrology Laboratory
Michael R. Moore	B.S., M.S., Electrical Engineering	Development Engineer

All team members are members of the Measurement and Controls Engineering Section of the Instrumentation and Controls Division at ORNL. This section is a multidisciplinary organization composed of ~80 staff members. Virtually all of the section staff possess bachelor's-level technical degrees with many possessing advanced (M.S. and Ph.D. level) degrees. The technical areas include electrical, mechanical, and chemical engineering as well as computer science.

The section and division have long and successful histories of developing complex instrumentation and instrumentation systems for the nuclear power industry and virtually all branches of the U.S. military.

Areas of expertise include

- metrology,
- real-time computing applications involving data acquisition, storage, analysis, and presentation of information,
- electronic and software instrumentation systems design, development, and fabrication,
- real-time image processing,
- digital signal processing,
- noise analysis,
- modeling,
- hardware/software systems integration,
- expert systems development, and
- electromagnetic technologies.

As evidence of the degree of change that can occur over a 10-year time frame, Fig. 1 shows a conventional process control room as implemented at a facility within ORNL.

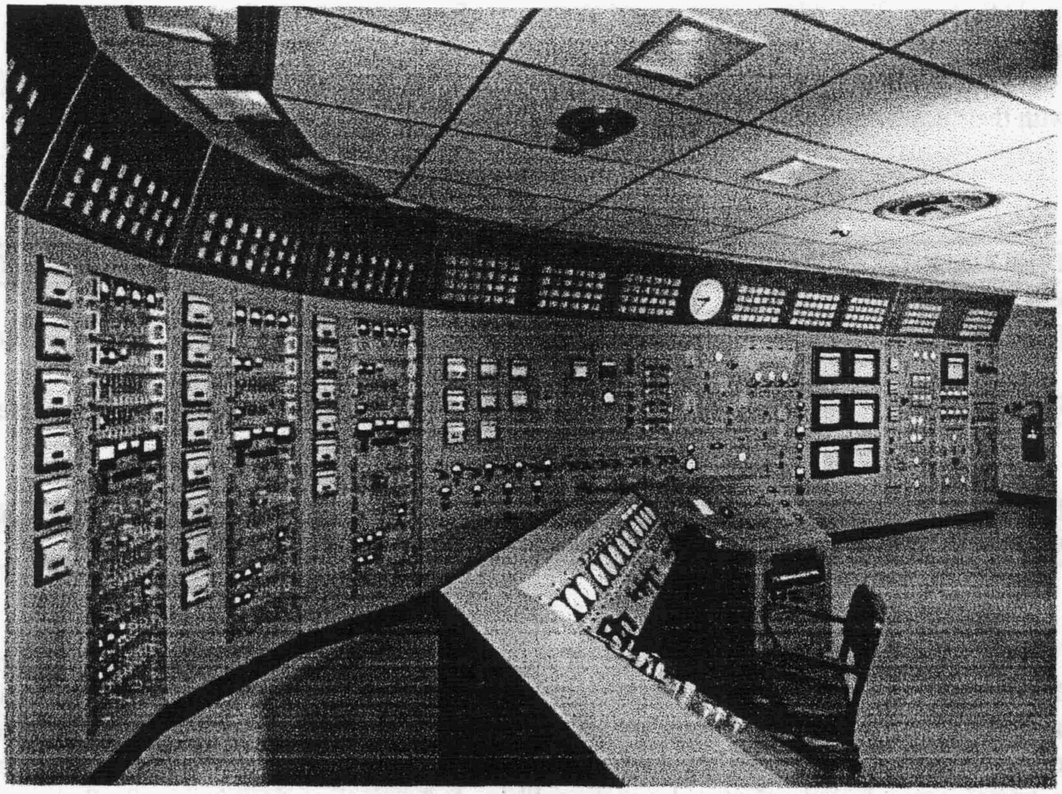

Fig. 1. Control room implemented with discrete instruments.

This facility uses discrete measurement and control instruments, with any data recording being done manually. Figure 2 shows a similar control room, implemented at ORNL within a 10-year period, using distributed microprocessor technology.

All control, data acquisition, and information recording is accomplished automatically. All control functions are accomplished through software. Information required by the operator is accessed through color graphic display consoles. The authors of this report feel that this is indicative of the kind of transition that is possible within test and calibration instrumentation given the emerging technologies discussed in this report.

The objective of this study was to assess and extrapolate key technologies that could be applied to the U.S. Army's calibration needs and to advise USATA of the trends in technology that may impact calibration methodologies within a 10-year time frame, that is, CALSETS 2000.

The activity was initiated in response to anticipated changes in levels of personnel and training, field equipment configurations, and levels of documentation required for proper field support.

The actual study activity was carried out in four phases:

1. Orientation and Assessment,
2. Technology Assessment,
3. In-process Review, and
4. Preparation of the Final Assessment Report.

The Orientation and Assessment phase consisted of visits by the ORNL assessment team members to the USATA facilities located at the Redstone Arsenal, Alabama. Discussions were held with several of the staff members regarding the Army's calibration needs and methodologies used.

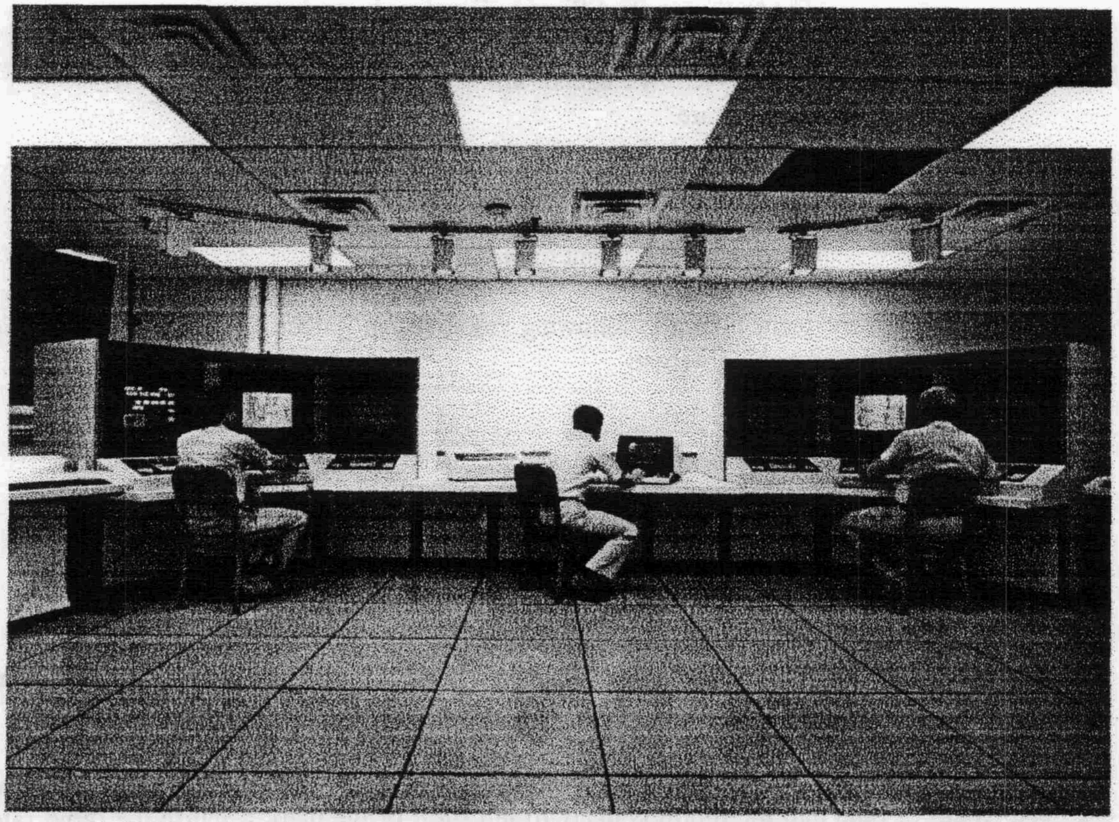

Fig. 2. Control room implemented with distributed microprocessor and color graphic display technologies.

The Technology Assessment phase consisted of reviewing appropriate technical literature, attending relevant conferences, and visiting several major vendors of test and calibration equipment of the types generally used by the TMDE Activity.

The In-Process Review consisted of providing the TMDE Activity principal contact with a written outline of the proposed final report for review and comment as welll as discussions relating to the general progress and direction of the activity. Several suggestions were made and incorporated into the report outline. Visits were also made by members of the ORNL assessment team to the TMDE Huntsville site, and a visit was made to the ORNL facility by TMDE project management staff to discuss the project and its direction.

This document is the Final Assessment Report for this activity as well as the final deliverable for the assessment activity.

As indicated earlier, a primary objective of the assessment study and therefore the report was to attempt to forecast the state of test and calibration equipment and technologies in a nominal 10-year time frame. Forecasting is based on a rational study and analysis of pertinent data or information and is aimed at predicting some future condition. To quote from the Future World Society regarding the Art of Forecasting,

> There's a popular myth that futurists are in the business of predicting what will happen in the future.
> The truth is quite different. Futurists know better than most people that the future is not predictable. We cannot ***know*** what will happen in the future.
> Then what ***do*** futurists do?
> Quite simply, they try to suggest things that ***might*** happen in the future, so that people can decide what they want to ***make*** happen.[3]

The assessment team used the following resources in gathering information to aid in attempting to make a reasonable forecast:

- personal interviews,
- review of applicable industry literature,
- review of government-furnished documents,
- vendor site visits,
- industry conferences,
- vendor-supplied literature,
- assessment team experience and background, and
- previous calibration studies for other agencies (e.g., "Propulser System Instrumentation Calibration" for the Navy's Engineering and Calibration Laboratory).

A forecast of the future direction of instrument science and calibration technology for any extended length of time into the future is likely to fall short of the mark because the rapid rate of progress can make possible many things we cannot even imagine. Arthur Clarke, who has an enviable record in successful technology forecasting, expressed this in his three laws:

Clarke's Laws[4]

1. **When a distinguished but elderly scientist states that something is possible, he is most certainly right. When he states that something is impossible, he is very probably wrong.**
2. **The only way to discover the limits of the possible is to go beyond them into the impossible.**

3. Any sufficiently advanced technology is indistinguishable from magic.

In spite of the inherent uncertainties in technology forecasting, it remains a useful exercise since we can probably anticipate many future developments by extrapolating what we know and what we think we will learn in the next 10 years.

J. M. Connell carried out such an exercise for electronics in a paper presented in 1981.[5] He showed that in each new generation of technology for electronic components, the systems or assemblies of the preceding generation evolve into the components of the next. For instance, individual components, transistors, resistors, capacitors, inductors, etc., were combined into a single entity in the integrated circuit (IC). Integrated circuits became components in the next generation of technology. As a result, each new generation of technology requires a new method of thinking to take full advantage of the opportunities offered by the new technology (see Table 2).

Just as the development of electronic components has evolved over the past century and a half, the science of calibration has undergone a steady evolution from primarily mechanical-based calibration techniques to much more sophisticated electronics and software-based techniques.

Table 2. Evolutionary development of electronic component technology

Cycle	1	2	3	4	5
Period:	1840-1910	1910-1960s	1960-1980s	1975-1981	Future
Systems-designer skill base	Electricity, electric machinery	Electronics, circuit design	Logic design	Software design	Computer science (Systems analysis)
Component types	Conductors, magnets, coils, relays	Tubes and transistors	Logic families	Microprocessors	Standardized language and network processors
Internal signals	"Large" signals	"Small" signals	Coded switching signals	Data stream	Data and program packets
Synthesis tools	Basic laws of electricity and magnetism	Circuit network theory and equivalent models	Boolean algebra, minimization	Programming languages	Software partitioning methods
Analysis tools	Meters and bridges	Oscilloscope	Logic analyzer	Software development systems	Network modeling systems
Component-design skill base	Material science	Electricity and physics	Circuit design	Logic design	Programming
Component technology	Passive devices	Active devices	Integrated circuits	Large Scale Integration (LSI)	Very Large Scale Integration (VLSI)

We have tried to carry out a similar exercise on the evolution of instrumentation and calibration technologies. This is summarized in Table 3.

The *Technology Cycle* is a fairly arbitrary designation of when a new generation of technology becomes dominant. Others would probably draw the lines differently. The exact delineation is not important to the main feature of the table, which is to determine the trends in technology. Historical exactness, while desirable, may not always be possible. The important generalization that is illustrated by this table is that *the systems of one generation tend to become the components of the next.*

The *Instrument Generation* is an attempt to describe an overall major characteristic of the instruments in each technology cycle. For instance, in the first, or electromechanical, generation, which spans most of history up to the late 1800s, DC instruments were dominant before the invention of rotating machinery and AC power generation. Many of these early instruments used the Weston or d'Arsonval meter movements with mirrored meter scales and were often housed in fine wooden cases. Insulation was often marble or hard rubber. The artistic nature of the wood and metal craftsmen often found expression in these instruments.

The components used to fabricate the instruments in the first generation were mostly hand made. Coils or resistors were hand wound. Standard cells were made by glass blowers and then filled by chemists. The electrical signals in instruments were all either steady state or pulsed DC. The operation was manual. Automation from the "Herr Professor's" standpoint was setting a technician in front of the apparatus to operate it and write down the data.

The tools used to design first-generation instruments were the basic laws of mechanics, electricity, magnetism, and optics (so far as they were known at that time). The tools used to analyze the operation of the instruments were basically other electromechanical instruments, perhaps fabricated with greater care. Very sensitive galvanometers were made by using long optical lever arms, often several meters long and requiring elaborate mechanical suspension systems to isolate and damp vibrations. For this reason, some of the most accurate work at the National Bureau of Standards (NBS) in the 1920s and 1930s was carried out after midnight after the street cars had stopped running on Connecticut Avenue in Washington, D.C.

The basis of the measurements made in this period was essentially the same as the design tools, the basic mechanical, electrical, magnetic, and optical laws. Prior to the founding of the NBS, there was no formal structure for standards in the United States except for an Office of Weights in the Treasury Department. This was essentially a one- or two-man operation that was concerned with standardizing weights for customs purposes. Formal national standards did not come into play until the establishment of NBS in 1901. Standards that did exist tended to be local, probably within one company.

> Ford's 1908 Model T was his twentieth design over a five year period that began with the production of the original Model A in 1903. With his Model T, Ford finally achieved two objectives. He had a car that was designed for manufacture, as we would say today, and that was also in today's terms, user-friendly. These two achievements laid the groundwork for the revolutionary change in direction for the entire motor-vehicle industry.
>
> The key to mass production wasn't—as many people then and now believe—the moving, or continuous, assembly line. *Rather it was the complete and consistent interchangeability of parts and the simplicity of attaching them to each other.* These were the manufacturing innovations that made the assembly line possible.

Table 3. Adaptation and extension of Connell's work to instrumentation

Technology cycle	1	2	3	4	5	6	7
Instrument generation	Electromechanical	Electromagnetic	Solid state (transistorized)	IC-Based	Smart instruments	Instruments-on-a-card (IOC)	Instruments-on-a-chip (IOc)
Time period	To ~1890	1890 to 1960	1960 to 1975	1975 to 1984	1984 to 1988	1988 to 1995	1995 to 2000+
Component-design skill base	Mechanics, DC electricity	Electricity and physics	Solid state physics, semiconductor physics	CAE/CAD[a], Device physics	Circuit design, Programming	Instrument modules	VLSI design, semiconductor fabrication
Component technology	Machine shop, Electrochemical	Rotating machinery, active devices	Integrated circuits, hybrid circuits	Microcomputers, digital signal processing	Integrated microprocessors	Standards modules, card cage, data bus	Solid state instrument function modules integrated on an ASIC chip. MCMs[a]
Component types	Resistors, capacitors, batteries, galvanometers	Coils, transformers, vacuum tubes, transistors	Logic circuits, analog amplifiers	LSI	VLSI, integrated analog modules	Function modules, virtual interface	Standard library of integrated instrument component designs
Internal signals	DC	DC and AC	AC + DC + logic	AC + DC + logic	AC + DC + programs	Data bus, analog input/output	Data bus, analog bus, optical
Operation	Manual	Manual	Manual	External computer control	External/internal computer control	Virtual instrument graphical user interface	System-level graphical user interface
Synthesis tools	Basic laws of mechanics, electricity, and magnetism	Circuit and network theory	Circuit and network theory + Boolean algebra	CAE	Self-diagnostics, self-correction, virtual instruments	Virtual instrument interface	Self-organizing system, self-programming
Analysis tools	Balances, meters, galvanometers, bridges, kites, frogs	Tuned detectors, oscilloscopes	Tuned detectors, oscilloscopes + logic analyzers	Circuit simulation, circuit testing	Built-In Test, automated testing	Automated testing	Systems-level analysis, expert diagnostics
Measurement basis	Electrical and physical measurements	AC and DC measurements, electronics	Counter-timer, signal analysis	Network analyzers, IC testers	Internal standards	Self-test	Self-test through redundant IOc

Table 3 (continued)

Technology cycle	1	2	3	4	5	6	7
Standards, NBS/NIST[a]	NBS not established until 1901	Meter bar, kilogram, electrochemical cells, standard resistors, capacitors, pendulum clocks	Computable capacitor, ratio-transformer bridges, wavelength of light (time and distance)	Josephson junction	Quantum Hall effect	Molecular standards, single electron pumps	Measurement assurance programs, broadcast standards
Standards, working	Local or informal, no national standards	Standard cells, WWV, standard resistors, calibrated artifacts	Zener diode, laser interferometer, cesium clock	Transfer standards	Verification by means of standard resistors and voltage standards	Verification by means of standard resistors and voltage standards	Frequency- and time-based standard via electron pump
Standards, Basis	Statics, mechanics, electricity	Maxwell's equations, Steinmetz, Tesla, Heavyside, Westinghouse	Fundamental physical constants	Quantum physics	Statistical process control (SPC), measurement system comparison	SPC, measurement system comparison	Counting electrons tied to NIST by frequency and time broadcast (WWV)

[a]CAE/CAD = computer-aided engineering/computer-aided design; ASIC = application specific integrated circuit; MCMs = multichip modules; NBS/NIST = National Bureau of Standards/National Institute of Standards and Technology; WWV = NIST time Standard.

> To achieve interchangeability, Ford insisted that the same gauging system be used for every part all the way through the entire manufacturing process. His insistence on working-to-gauge throughout was driven by his realization of the payoff he would get in the form of savings on assembly costs. Remarkably, no one else in the fledgling industry had figured out this cause-and-effect; so no one else pursued working-to-gauge with Ford's near-religious zeal.[6]

With the invention of rotating machinery (i.e., generators and motors), AC signals abounded. This new development required an entirely new generation of instruments. The development of vacuum pumps and then vacuum tubes, eventually leading to radio, expanded the range of physical theory to the application of Maxwell's equations to component design. At the end of this period, solid state physics technologies began to play an important role in instrument application after the invention of the transistor. With the development of electronics, electronic instruments made their appearance. Tuned detectors for AC bridges and oscilloscopes were developed for AC measurements.

NBS was established and began to develop national standards. Many of the early standards were artifacts against which other standards were compared. The standard volt was maintained at the Bureau during this period by a bank of about 50 unsaturated standard cells. Similarly, the ohm was maintained by a bank of 50 one-ohm standards. Preparation for standards based on physical constants began near the end of this period with the development of atomic clocks.

The third generation of instrument technology corresponds to the introduction of solid state electronics. The biggest gains were in the area of digital electronics since the early solid state analog electronics were somewhat noisy. With the development of low-noise, solid state, operational amplifiers, solid state electronics began to make inroads into the instrumentation field. Near the end of this period, simple ICs were introduced, mainly as logic gates.

In the field of electrical standards, uncertainties on the order of a few parts in 10^9 began to be realized with the development of ratio-transformer bridges for use with computable capacitor impedance standards at NBS. Many of the initial uses of the laser were in the field of metrology for length and time standards.

The fourth generation in the development of instruments and standards coincides with the application of computers to control instruments and to acquire and analyze data. This was made practical because the ever-more-capable IC technology evolved into VLSI, which, in turn, brought the cost of computing down to levels that allowed widespread use in instrument control.

The electrical standards were tied to fundamental quantum mechanics through the development of Josephson junction voltage standards at the national laboratories. Improved, stable Zener diode voltage references were brought into use as transfer standards. It was during that time period that NBS began to develop MAPs, or Measurement Assurance Programs.

By the fifth generation, the cost of microcomputers was so low that several instruments, in particular, top-of-the-line digital multimeters, contained up to three microprocessors. With internal microcomputers, some signal processing could be done locally by the meter before being transmitted to the system controller. The internal computer also allowed self-checking and autozeroing.

The first version of LabView* was introduced around the summer of 1987. This introduced the concept of virtual or simulated instruments and the user-designed interface or control panel.

In standards, quantum physics-based standards were extended to resistance through the quantum Hall effect. At the secondary level, more instruments included self-verification that

required only a single external resistance standard and a single external voltage standard for routine calibration. More rigorous and complete calibrations were necessary only at greatly extended intervals.

The following, or sixth, generation saw the introduction of instruments-on-a-card (IOC) and such standards as the VXI bus. With the VXI modules, the graphical user interface was essential, since VXI-based instruments, for the most part, have no room for controls. Quantum electronics developed the single electron pump[7]. A standard ampere can be envisioned in which each unit of charge (each electron) could be counted as it passed through the pump.

The trend from stand-alone instruments to IOC, when extrapolated 10 years into the future, can plausibly lead to IOc. This development would have a major impact on how instruments are used. Calibration intervals could be extended drastically since with inexpensive IOc, triply redundant instruments can spend a part of their time checking each other. The volume and power requirements would be greatly reduced both because of the necessity to minimize the need to dissipate heat energy and the ability to reduce size through miniaturization. An additional benefit should be increased stability since all components are contained upon the same substrate, thereby minimizing thermal gradients. The IOc will be fabricated from mostly standard chip level modules. Custom instruments will be affordable and easily made as short-run application-specific integrated circuit (ASIC) chips.

More instruments and standards will be tied directly to National Institute of Standards and Technology (NIST) through WWV or GPS broadcasts. Time and frequency standards are now broadcast. With the quantum electron pump, the ampere can be directly realized in the field by using the time and frequency signals to count electrons directly. The practical embodiment of the electron pump ampere standard would probably consist of several thousand pumps on a single chip, all operating in parallel. By passing the ampere through a resistor, a value for the standard volt that depends only on the stability of the resistor can be realized.

The remainder of this report is aimed at identifying areas of need, assessing technologies that can have a possible impact, and attempting to provide a migration path to permit USATA to make the most use of the technology.

*National Instruments, 6504 Bridge Point Parkway, Austin, TX 78730-5039.

2. SPECIFIC STUDY AREAS

The specific calibration-related areas to be considered during the assessment were

- DC and Low-Frequency AC Equipment Calibration
  DC and low-frequency AC equipment calibration accounts for 34.4% of the worldwide equipment density and 42.6% of the TMDE worldwide calibration workload. In light of these high percentages, any reductions in the number of items to be calibrated, extension of calibration intervals, or decreased instrument size would yield considerable savings in the form of decreased density, equipment volume, and workload.

- RF/Microwave Equipment Calibration
  This technology represents 9.7% of the worldwide TMDE calibration equipment density and 9.5% of the worldwide TMDE calibration workload. This area was investigated since it is a critical but relatively difficult technology to support in the field.

- Electro-optics Device Calibration
  The present worldwide TMDE calibration density and calibration workload for electro-optics (EO) calibrations are very small (less than 1% in both cases). However, because of the importance of this technology in modern military and industrial systems, it must be expected to increase rapidly over the next few years. Therefore, calibration support for this technology must be considered in the CALSETS 2000 concept.

- Physical Sensor Calibration (e.g., pressure, temperature, mass, viscosity)
  Physical and mechanical calibrations make up 35.9% of the worldwide TMDE calibration density and 33.4% of the worldwide calibration workload. The standards associated with physical and mechanical calibration often consume more space than electronics calibration equipment and can be awkward to store and transport. A goal of the assessment study in this area was to determine how to reduce the size of the calibration equipment, reduce the number of devices required, and/or extend the calibration intervals through more stable technologies.

- Documentation Storage and Retrieval
  The proper calibration of equipment requires access to the appropriate supporting documentation. In a laboratory setting, this is generally not a problem. However, considering the variety of equipment to be calibrated, the equipment complexity, and the need for a high degree of manual intervention, availability of sufficient, high-quality documentation is mandatory. This can present a significant burden to the mobile calibration van configuration.

- Documentation Updating
  In the course of supporting any type of equipment, there will be necessary changes to existing documentation. Such changes arise as a result of changes to the hardware through engineering change orders, as they are referred to in industry, and changes to the actual document to correct errors or provide clarification. Technologies that provide a means for maintaining accurate and up-to-date documentation would be of value.

- Personnel Training
  The reduction of the military and the resultant loss of personnel make it much more important that the remaining resources be as efficient as possible. Technologies that aid calibration (including test and repair) personnel in the rapid and accurate execution of their function will allow the military to maintain a high degree of readiness, even with reduced, lower-skill-level manpower resources.

- Equipment Troubleshooting Aids
  The primary purpose of the calibration and test personnel is to make certain that accurate and properly functioning equipment is available to those who need it with the shortest possible delay. Technologies that enable a technician to spot and diagnose the cause of equipment malfunction (and propose a possible approach to repair) will improve the overall efficiency of the operation.

Additional technologies that were to be addressed as candidate technologies (those which could also support the goals and objectives of USATA) include technologies that

- Impact calibration and repair equipment size.
- Impact equipment interchangeability.
- Impact equipment functionality.

3. U. S. ARMY TMDE ACTIVITIES

3.1 UNIQUE REQUIREMENTS

USATA is responsible for the calibration of a wide variety of electronic and physical/mechanical equipment both in the field and in the secondary and primary laboratories. The particularly unique aspect of the field calibration activity is that it must be performed in locations that are remote from many of the services normally taken for granted in an industrial or commercial environment and even some of the other branches of the military. Today the field (or transfer-level) calibration activity is housed and transported in 5-ton expandable vans. The entire assemblage of calibration equipment is designated AN/GSM 286 and AN/GSM 287. For the remainder of the report, these will be referred to simply as 286 and 287 respectively. The vans can be deployed as a single 286 that contains DC calibration equipment or as a two-van, 287 configuration that includes microwave and physical/mechanical calibration equipment in addition to the 286. A small step van is also considered a part of the configuration. One of the vans tows a 30-kW generator to supply power to the vans in the field.

A representative illustration of an expandable 286 van is shown in Fig. 3.

The test and calibration equipment is mounted (generally) in 19-in. racks located in and around four workstation areas (this form factor is commonly referred to as "rack and stack"). Each work station has a complement of equipment best suited to the type of work to be generally performed at the particular station. Representative, current calibration van configurations for both the 286 and 287 configurations are shown in Figs. 4 to 7. The numbers refer to manufacturer's model numbers. The model numbers, ranges, and accuracies of the equipment are given in Appendix A.

3.1.1 Calibration Equipment Capability

As can be seen from Figs. 4 to 7, the calibration vans contain an inventory of rack-mounted equipment selected to meet the majority of field calibration needs. In addition, there are loose (not permanently mounted) calibration equipment items. The complement of calibration equipment, including the corresponding ranges and accuracies of the equipment carried by the two van configurations, is listed in two documents titled: (1) Army Calibration System Transfer Limited Deploy Capability Available to Army Area TMDE Support Teams (ATST), TMDE Support Operation (TSO), or TMDE Support Center (TSC), and (2) Army Calibration System Transfer AN/GSM-287 Capability Available to Army Area TMDE Support Teams (ATST), TMDE Support Operation (TSO), or TMDE Support Center (TSC). Copies of these documents are provided in Appendix A. The information for AN/GSM-287 includes both the 286 and 287 van configurations. Information defining the components required to calibrate all of the general-purpose TMDE is contained in two additional documents or catalogs. The first catalog lists the components carried by a 286 configuration that are sufficient to calibrate ~85% of the general-purpose TMDE. The second catalog lists the components carried by a 287 configuration and is essentially what is required to calibrate 100% of the general-purpose TMDE. These catalogs are (1) Draft Sets, Kits, and Outfits Component List Calibration Set: Secondary Transfer Standards (Basic) AN/GSM-286 (6695-01-081-0960) (LIN C72669), 1 October 1989, and (2) Draft Sets, Kits, and Outfits Component List Calibration Set: Secondary Transfer Standards AN/GSM-287

(6695-01-081-4873) (LIN C72601), 1 October 1989. Because of the size of these documents, copies are not provided with this report. The reader is urged to obtain copies if needed from Commander, U.S. Army TMDE Support Group, Attn: AMXTM-LML, Redstone Arsenal, AL 35898-5400.

3.1.2 Army Fielded Test Equipment Distribution by Type

The information provided in this section is intended to give the reader an appreciation for the types and distribution of equipment that must be supported. The fielded test equipment to be calibrated falls into several categories: (1) RADIAC (radiation monitoring equipment), (2) physical measurement, (3) infrared (ir)/optics, (4) DC/low-frequency AC miscellaneous, (5) DC/low-frequency AC oscilloscopes, (6) DC/low-frequency AC meters, (7) DC/low-frequency AC generators, (8) DC/low-frequency AC counters, (9) microwave, and (10) all other.[8]

In the following tables, derived from information supplied to the ORNL assessment team, the term density is defined as the total number of items of TMDE supported by a specified unit. This includes CNR (calibration not required) items, CBU (calibrate before use), as well as items evacuated to the support site from other scheduling units' Instrument Master Record File (IMRF). The density does not include items from the supporting units' IMRF that are evacuated to other areas for calibration or repair. Workload is defined as the actual number of calibration actions required annually to support the TMDE for which a unit is identified as the performing site. The workload does not include repair actions.

The information relating to the worldwide TMDE density* distributions obtained from the CARES book[9] is shown in Table 4.

Table 5 shows the worldwide TMDE workload distribution as obtained from the same source.

The military calibration activity is carried out by the 95th Maintenance Company in the United States, the 517th Maintenance Battalion in Europe, and the 74th Maintenance Battalion in the Pacific Area (Korea, Japan, etc.). An approximate distribution of percentage calibration workload for each of these units is shown in the Table 6.

This equipment is normally to be calibrated using equipment with a 4:1 accuracy ratio, that is, the instrument used to calibrate an item must be at least four times more accurate than the item being calibrated.

3.2 END-ITEM TEST AND REPAIR EQUIPMENT

End-item test and repair equipment is the equipment used to diagnose and repair the various weapons systems and field support equipment. The following subsections describe the two major types of end-item test and repair equipment. The Integrated Family of Test Equipment, or IFTE, consists of automated test equipment (ATE) configurations generally used in support of complex weapons systems; and the equipment addressed by the Test Equipment Modernization Program (TEMOD), which is primarily general-purpose test equipment such as scopes, meters, bridges, etc., is intended to (1) ensure that the Army's inventory of test equipment remains current and (2) minimize duplication of function.

---

*Note: the use of the term density in this context refers to equipment concentration and is used in this manner in the CARES book (see above).

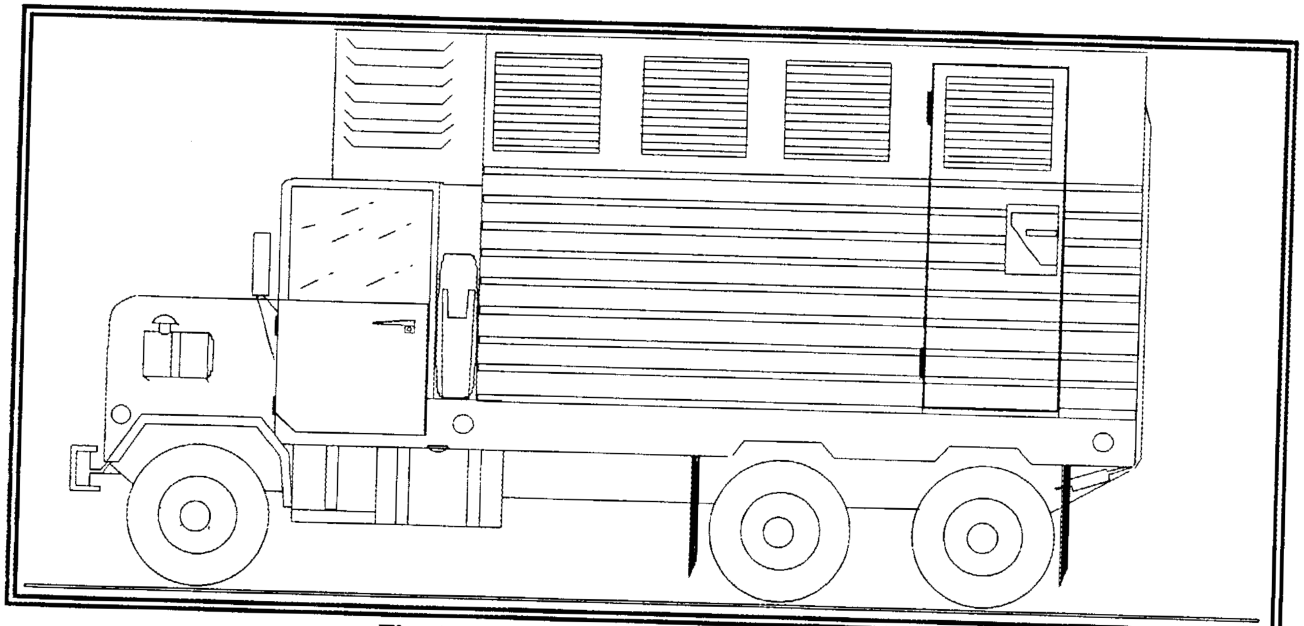

Fig. 3. TMDE activity field calibration van.

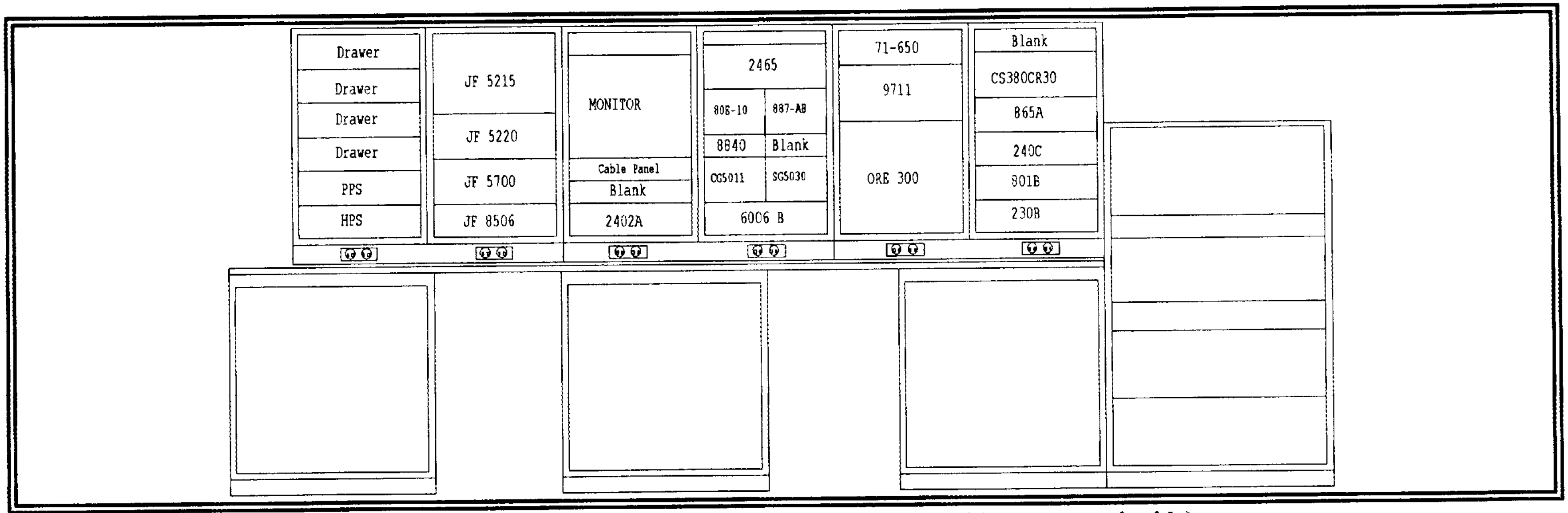

Fig. 4. AN/GSM 286 calibration van work area (right side, passenger's side).

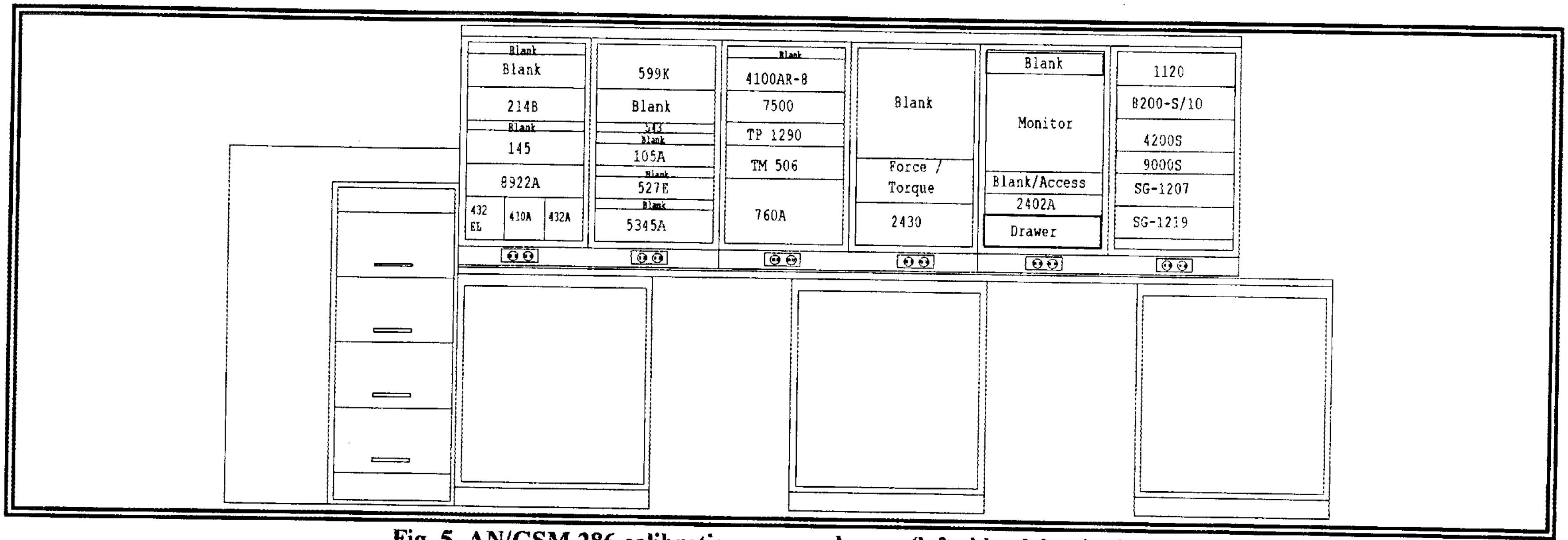

Fig. 5. AN/GSM 286 calibration van work area (left side, driver's side).

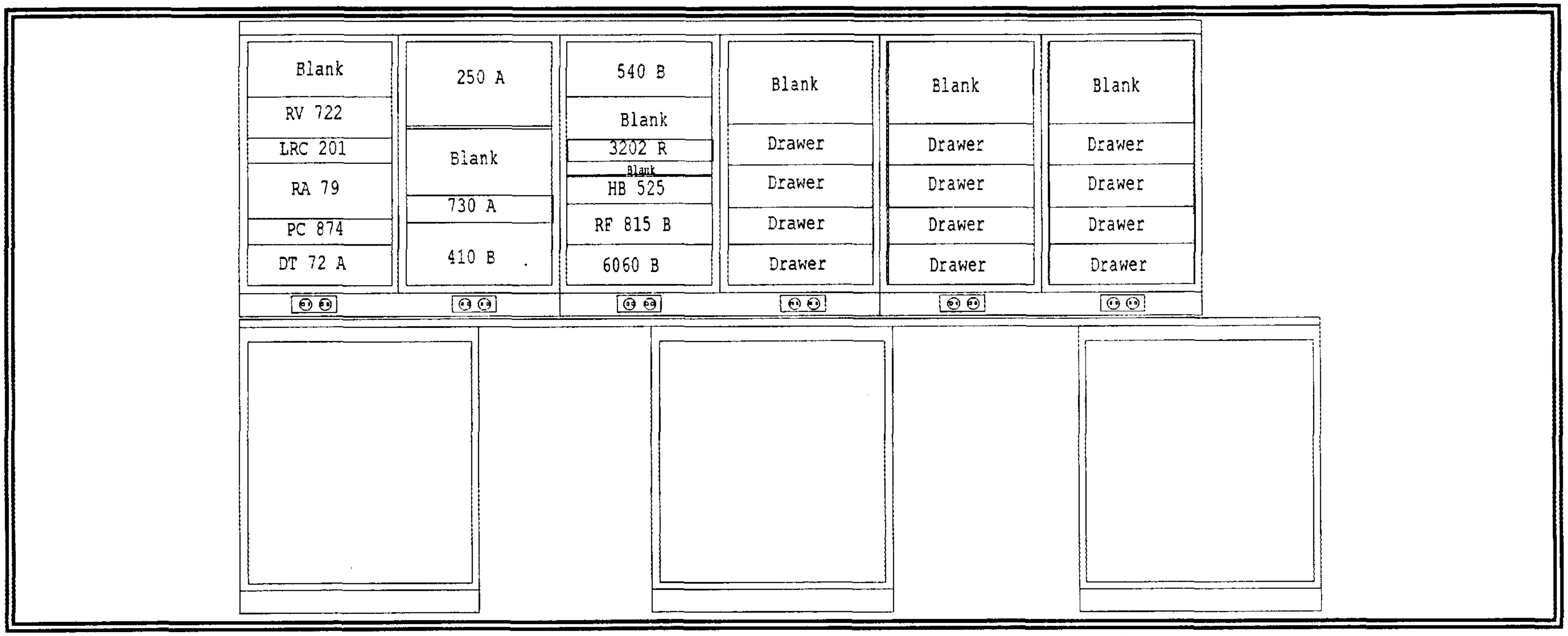

Fig. 6. AN/GSM 287 calibration van work area (left side, driver's side).

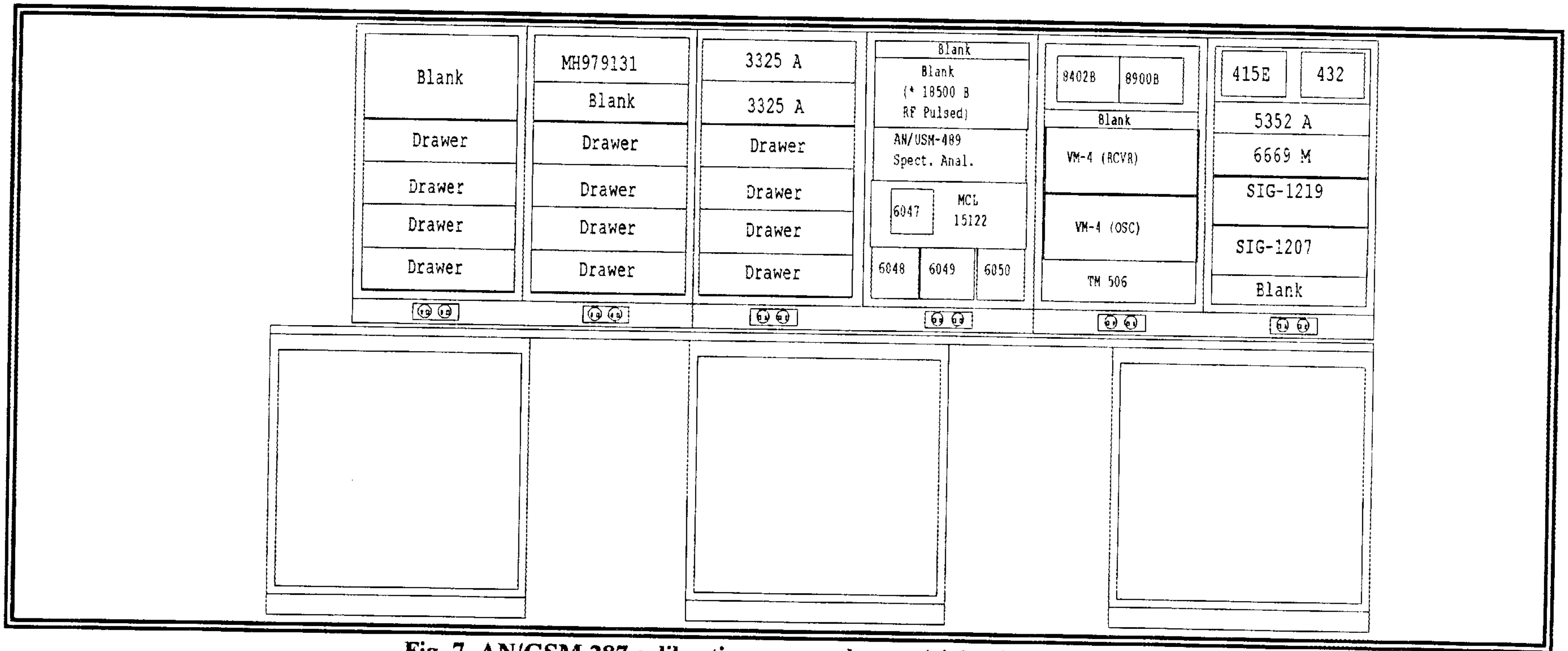

Fig. 7. AN/GSM 287 calibration van work area (right side, passenger's side).

Table 4. Worldwide TMDE percentage density distribution by measurement type

RADIAC	Physical	IR/Optics	DC/Low, misc.	DC/Low, scopes	DC/Low, meters	DC/Low, generators	DC/Low, counters	Microwave	Other
15.5	35.9	0.1	12.3	4.9	12.3	3.3	1.6	9.7	4.6

Table 5. Worldwide TMDE percentage workload distribution by measurement type

RADIAC	Physical	IR/Optics	DC/Low, misc.	DC/Low, scopes	DC/Low, meters	DC/Low, generators	DC/Low, counters	Microwave	Other
9.6	33.4	0.1	10.4	9.3	15.8	4.5	2.6	9.5	4.8

Table 6. Percentage distribution of military calibration workload by equipment category and supporting organization

Equipment type	95th Calibration Company	74th Calibration Battalion	517th Calibration Battalion
General Electronic (DC/AC low)	33	47	42
Microwave	10	10.5	10
Physical	40.6	28.6	30.7
RADIAC	15	14	19

3.2.1 Integrated Family of Test Equipment

Personnel from ORNL/Energy Systems attended a briefing on the Army's IFTE held at the Redstone Arsenal on April 22, 1992. The briefing was hosted by Major Jim Burgess of the Training and Doctrine Command Ordinance, Missile, and Munitions Center and School, and attended by Major Fecteau (TMDE), Jim Hylton (ORNL), Tim McIntyre (ORNL), and Jim McEvers (ORNL). A demonstration of the IFTE was given by Sgt. White and included an actual diagnostic session on a component of the HAWK missile system.

The IFTE systems are based on commercial-grade equipment that is integrated and assembled by ATE vendors such as Grumman (Grumman is the prime contractor for IFTE). IFTE is a single set of ATE which is configured for each weapon system through the test program sets (TPSs) and any system-peculiar interface connection devices. It is the ORNL assessment team's understanding that there are to be 205 additional IFTE systems deployed. These units will contain militarized equipment. The particular system demonstrated consisted of primarily Hewlett-Packard (HP) instruments, with some special components (assemblies) being provided by Grumman. The system's intersubsystem communication links are accomplished using the IEEE-488/General Purpose Interface Bus. The test procedures for the IFTE station were contained on Compact Disk-Read Only Memory (CD-ROM) disks. The point was made that a major cost in the deployment of an IFTE station was in the authoring of the software routines referred to as TPSs (as stored on the CD-ROM) that perform the diagnostics and "pinpoint" the problem. With the application of commercial-grade equipment, thereby eliminating the cost of military hardware qualification, the most significant cost in fielding such a system is in the production and distribution of the software.

3.2.2 Test Equipment Modernization Program

As a part of the familiarization portion of the assessment study, ORNL project personnel were also given a briefing on the U.S. Army's TEMOD program. This briefing was presented by Dick Maryanski and Russ Fleming. The briefing was attended by Major Fecteau (TMDE), Jim Hylton (ORNL), Tim McIntyre (ORNL), and Jim McEvers (ORNL).

The briefing addressed the TMDE problem and proposed solutions based on the 1970s time frame, the TEMOD program, and the status of various TEMOD projects.

It was pointed out that at that time the Army had ~2500 different makes and models of test and calibration equipment in the field.

The problems identified included

- technical adequacy of the maintenance capability,
- obsolescence of field equipment, i.e.:
  - —age
  - —availability of replacement parts
  - —procurability of additional units
- proliferation of equipment
- need to provide training on a large and varied population of equipment.
- general support costs

The outcome was the establishment of the TEMOD program with the charter to procure state-of-the-art, commercial, off-the-shelf equipment, with a primary goal of reducing the proliferation of model numbers. The assessment team was informed that the TEMOD program goal is to reduce the model numbers from 2500 to ~70. The TEMOD program is an ongoing program.

4. CHANGES IN OPERATIONS

4.1 GENERAL TRENDS

With the cessation of the Cold War and the perceived lack of need for a standing military force of the size required for a major (global) military confrontation, the general trend is to decrease expenditures for both manpower and equipment throughout the military. This trend results in a perceived decreased need for direct support services as well.* While the need for calibration certainly remains, there is a driving force to provide the same capability with fewer resources. The need for large quantities of serviceable equipment can arise on very short notice. A good example of this is the need for a large number of heavy transport vessels during Operation Desert Storm in 1991. The necessity for rapid deployment of tanks and other heavy armor placed a significant burden on the Navy's ability to respond with adequate transportation resources. While equipment will be taken out of service, it cannot be stored without regard to short-term needs. A study prepared by ORNL for the Navy Calibration Laboratory at Seal Beach, California,[10] found that, with a simple but effective procedure, stored instruments could be maintained in good operating condition. This procedure consists of powering up the equipment and exercizing the controls each 90 days. Using this technique, the Navy found that storage related failures were reduced from >20% to <1% for a large sample of calibration laboratory instrumentation provided to the Saudi Arabian navy.

Therefore, it could be a serious mistake to consider passive storage for instruments and systems. With a smaller force, it will be even more critical for a fast response to keep the equipment in good operating condition. So even if the United States is not currently involved in a high-intensity conflict, the reduction in personnel and services must not result in dropping the level of maintenance below that at which the equipment would begin to deteriorate.

4.2 DOWNSIZING

As referenced above, a real emphasis is being placed on downsizing the resources used to support calibration activities provided by the TMDE Activity. This is seen as being accomplished on two fronts: (1) decrease the number of personnel required for direct support of the calibration activity and (2) decrease the size and weight of equipment needed to carry out the calibration function. The figures related to the ORNL study team were that there were currently seven people assigned to a field calibration van set: two sets of two people each to work two 12-h shifts (two people are required on each shift for safety considerations) and three support personnel, including a "crew chief." Comments have been made concerning the possibility of decreasing this team to five. At this point, this would only seem to be conjecture. This would still provide two teams of two calibration technicians to work two 12-h shifts while removing two people from the overall team. To accomplish this goal, it is necessary that the overall calibration function be examined as well as the equipment to be calibrated.

*Of course, a smaller Army (total) means less quantities of weapons systems, i.e., less maintenance, calibration, etc. Therefore, the decreased need is, in this sense, real.

4.3 NEW TECHNOLOGIES TO BE SUPPORTED

The TEMOD program referenced earlier is indicative of the constant need for review of the types of equipment to be supported and the appropriate equipment for calibration.

Obviously, the weapons systems will continue to take advantage of more and more sophisticated technologies as they become available. This dictates that the types of equipment needed for the maintenance and calibration of advanced technologies will have to take advantage of advanced technologies. At the same time, older equipment will still be used, especially by reserve and National Guard units. If the reserve units are called up, the calibration function will have to support their equipment as well. The reserves are rarely equipped with the latest equipment; therefore, the calibration vans are called on to support several generations of weapons systems.

4.4 TRAINING

The calibration activity requires a substantial understanding of the function of the equipment to be calibrated as well as how it is ultimately used. To date, this information is instilled into the labor force through formal training programs: basic 35H training is 34 weeks; advanced training is 43 weeks. This is a very time-consuming (and therefore costly) activity, and its effectiveness is highly dependent upon the caliber of the person being trained. The more sophisticated systems of the future will either require an even more highly qualified labor force or significantly more sophisticated and comprehensive calibration and maintenance equipment. Based on discussions with USATA personnel, indications are that training will take a lower priority in light of the personnel reductions and budget decreases. There is expected to be increased emphasis on on-line training and interactive training. There seems to be some question as to whether the skill level of the technician force will drop as the overall manpower levels decrease or if the military can afford to be more selective and thereby obtain more highly skilled personnel. A final point to consider is that the calibration technician is a soldier first and a calibration technician second. He must therefore be trained to fight well and be available to fight rather than just perform calibration.

4.5 EQUIPMENT CONFIGURATIONS

The equipment configurations presently in the field contain some ATE, but it is not yet widely distributed. Much of the test and calibration work is still carried out with discrete instruments and, in light of decreasing budgets, may tend to remain this way. In many cases the test and calibration equipment must be taken to the field equipment requiring attention. This adversely impacts the concept of conventional ATE since the equipment is designed to operate as an integrated system with the components being integrated as a functioning system. Additional factors that impact the test and calibration task are the increased use of ATE in end-item testing, the need to remove equipment from the calibration van and take it to the equipment to be calibrated, and the need to get equipment into an S-280 shelter (the IFTE ATE is generally located in a transportable S-280 shelter). Because of the distributed nature of equipment requiring test and calibration, there is a significant need for transport standards.

4.6 CONFLICT DURATION

Past military conflicts, with few exceptions, have lasted in excess of a year and in most cases several years. The U.S. participation in the Vietnam War (conflict) lasted for several years, while Operation Desert Storm lasted only a few weeks. While they were certainly not on the same scale, it is indicative of the types of conflicts that the United States may become more involved in, at least in the near term. The world seems to be emerging into a period whereby third world countries, which possess a much inferior military presence than the United States and many other major forces, still present a significant threat to world and regional peace. These types of conflicts, at least in the short term, seem to have a higher probability than long, drawn-out conflicts. These types of conflicts require that equipment be available on relatively short notice, be deployed in a matter of weeks if not days, and be present in the field for months rather than years.The ability to calibrate equipment in the field will always be needed; however, the degree to which it is used certainly depends upon the duration of the conflict. The types of equipment needed and the frequency are subject to close examination.

5. FUNDAMENTAL DIFFERENCES

The following definitions are provided in an effort to clarify some fundamental differences between terms that have been used during various discussions in the course of this assessment study.

5.1 CALIBRATION

Calibration is defined as "to standardize [a measuring instrument] by determining the deviation from a standard so as to ascertain the proper correction factors." This generally implies that the standard is traceable to national or fundamental standards. In the context of the work performed by the TMDE Activity, this equates to the comparison of values obtained from a reasonable quality instrument (i.e., one that is considered capable of maintaining a known degree of accuracy for a reasonable period following the calibration activity) to those obtained from a standard reference. In the case of the TMDE calibration the standard is expected to be at least four times more accurate than the instrument being calibrated. If this is not the case, then the unit under test tolerance must be restricted to less than specified tolerances to account for the standard uncertainty. In addition, "procedure limitation" is annotated in the unit's calibration procedure.

5.2 VALIDATION

Validation by definition is "to grant official sanction to [an instrument] by marking" or "to support or corroborate on a sound or authoritative basis." In the context of TMDE, this corresponds to officially sanctioning that an instrument (or instrument system) is performing at a level that is acceptable for the intended purpose. It does not explicitly signify calibration.

5.3 DIAGNOSIS

Diagnosis involves the investigation or analysis of the cause or nature of a condition, situation, or problem. This can be a time-consuming effort, especially if there is inadequate support equipment in the form of easily accessible and up-to-date documentation, proper test equipment, and well-trained personnel. This is especially critical in a field environment where the technician may not have a proper inventory of substitute components or modules to insert in the failing equipment in an effort to conduct a "process of elimination" diagnosis. Problem diagnosis is probably the most complex activity relating to any piece of equipment, exceeded only by the actual designing of the equipment. The operation of the equipment follows a well-prescribed, well-documented procedure with known results. Diagnosis, while it can follow a prescribed procedure, still can have a high degree of uncertainty associated with it since the equipment is generally not responding in a known manner.

5.4 REPAIR

The act of repairing inoperable equipment, assuming that the diagnosis has been accurately carried out, is key to the subsequent calibration activity. Repair requires a comprehensive inventory of spare parts. It also requires a reasonably high degree of competence on the part of the repair technician since poor repair practices can result in more and possibly irreparable damage to the equipment. In a field environment, the most effective repair procedure is direct replacement at the module level. That is, replace the largest assembly that will make the equipment fully operational in the shortest amount of time.

6. TECHNOLOGY ASSESSMENT ACTIVITIES AND FINDINGS

The intent of this section is to report the key findings of the ORNL assessment study team. Any references to commercial products within the body of this report do not constitute an endorsement by ORNL or Martin Marietta Energy Systems, Inc.

6.1 DC AND LOW-FREQUENCY AC EQUIPMENT CALIBRATION

This section of the report deals primarily with existing and emerging technologies that have greatest impact on the AC/DC low-frequency regime of metrology and maintenance services. Areas of focus will be size of the DC/AC low-frequency CALSET, CALSET functional versatility, and CALSET architecture. Each of these areas is dictated by the technology, and hence optimization depends solely on technological advancement and utilization.

Historically, precision electronic equipment that functions in the DC, low-power regime has been the first to benefit from advances in technology. This type of equipment is generally the most accurate of all metrological equipment. John Fluke, Hewlett-Packard, Datron, and others currently make precision digital multimeters that challenge even the best reference standards. Hence, to truly speak of revolutionary advancement in the DC, low-power regime, one has to begin exploring the realm of miniaturization. The Josephson array and quantum effect transistor are prime examples of such miniaturization (note: these are totally new technologies offering significantly more than just miniaturization). Their full impact on the capability one might realize in a chip-size or IOC package is just beginning to be explored.

"What would happen if we could arrange atoms one by one in the way that we would like to arrange them?"[11] Feynman argued about 30 years ago that with such a capability and within the laws of physics, all the books written in history, some 50 million volumes, could be stored within a volume less than a speck of dust. We could take mechanical systems as complex as an automobile and reduce them by a factor of 4,000–10,000. We could build layered and checkerboard arrays of atoms upon order and tailored to our needs. Then, finally, we could make molecular computers with biological-like capabilities for image processing and memory storage.[12] Layered structures have already been built, and we are closing fast on checkerboard arrays. One can only imagine what impact technological advancements such as these might have on the world of measurement and information processing.

Nanotechnology,[13] the science of positioning, measuring, or fabricating with a dimensional precision on the nanometer level, will be the primary technology responsible for the revolutionary advancement of metrological capabilities in the DC, low-power regime. As systems become more highly autonomous, because of the ability to manufacture whole instruments on a single chip, software, signal processing, and interfacing will become critical issues. The capability to produce whole measurement systems on a single chip will make the greatest apparent impact, while the software and signal processing gains will allow the technology to remain transparent to the user.

For higher power applications, current and voltage measurement in particular, divider networks will still be necessary. However, substantial size reductions are possible but are limited by the physical space limitations imposed by high currents or potentials. Again, developing technologies in microelectronics (i.e., high current density heterojunction devices and superconducting materials) and materials science will have some impact. High-power sourcing will rely on novel implementation of highly regulated power supplies that also serve to drive the measuring system as a whole. Turbine technologies have already made substantial strides in the areas of total output power, generator efficiency, and power regulation as evidenced by the portable gas-turbine-powered power supplies that the U.S. Air Force has used for deployable radar installations for several years.*

Finally, a philosophical change regarding DC resistance sourcing will have the most significant impact on device requirements. Once it is accepted that only a few cardinal-point resistance measurements are necessary to verify operational integrity, the equipment requirements shrink down to a very small package. Resistance measurement will be handled by the precision measurement equipment on a chip. Again, only a select group of cardinal-point assessments will be necessary.

Areas of assessment include those which might impact low-frequency AC current, voltage, resistance, capacitance, inductance, and distortion. As with the DC functions, it is anticipated that many improvements will be made through the miniaturization of the IC components. However, the higher power applications will be addressed through the use of modular measurement systems (MMSs). VXI or MMS architectures already show some promise as the core instruments that would be critical to a highly compact and versatile CALSET 2000 (more detailed discussions of VXI and MMS are provided in Sects. 7.2.1 and 7.2.2). Progress in this area will lead to products that gain the advantage of solid state miniaturization on the front end (interface, processing, and control hardware) but still must interface to more powerful supply modules for the currents and voltages necessary. A revolutionary approach here would be to communicate to sources, measurement devices, and reference artifacts through a virtual instrument environment (a more detailed discussion of the virtual instrument interface is provided in Sect. 10.3.2). These virtual instruments would be generated through software to simulate either an instrument in inventory or reconfigured to simulate a newly available instrument. The reason one would choose to simulate a commercially available instrument, assuming it was one in prior inventory, is that all of the technical literature concerning operation, maintenance, and calibration would already be in hand. Given that the documentation and operational familiarity are incumbent upon this simulated instrument, a substantial saving in space will be realized with the new modular devices. Many modular components to support such an architecture are already becoming viable; signal generators, timer/counters, and scopes for the lower power end are available[14,15] for both sourcing and measurement. Higher power applications will require some development. The supplies would be nested in a convenient space with communication and manipulation interfacing remaining in close proximity to the test space in this architecture. Having only the necessary cabling links, displays, and control interface occupying critical bench-top space, the user-interactive segment of the DC/AC low-frequency CALSET 2000 may become as small as a flat-panel/touch-sensitive display mounted on top of an interconnect module (0.03 m^3).

With regard to the approach to the reference capacitance, inductance, and resistance artifacts required, these devices will be few in number such that only a core set will be required to calibrate most field instrumentation. However, fiscal trends might preclude reduction of the reference artifact set so that older equipment, still in service, remains supported. The reference artifacts will also be nested within the core of the CALSET 2000, with access via the virtual instrument interface. Hence, additional artifact inventory would not dramatically impact the set's perceived size or operation.

The DC/AC low-frequency electrical CALSET 2000 objectives were driven by a need to significantly reduce the size and increase the mobility of an AN/GSM-286/287 vehicle. These needs are to be met, however, without a compromise in current capability. As more and more complex systems come on-line, the diversity and complexity of the CALSET will be augmented to

*Personal experience and observation by J. A. McEvers.

include higher frequencies and EO applications. Hence the foremost concern was to provide measurement/source test, verification, and calibration capability for all device-under-test (DUT), line-replaceable units (LRUs), transfer standard, and/or working standard item or any other field-supported device maintained by the current CALSET as well as any new capabilities that may appear (e.g., TEMOD program or changes in the IFTE). Secondly, the DC/AC low-frequency equipment area offers the greatest potential for space savings. This would consist of an instrument interface, which involves the means for interconnecting to source stimuli and measurement sensing; a communication interface, which controls the selection, configuration, and input/output posture of the core components; and a display/user feedback device, which will occupy no more than 0.03 m^3 (30 cm on a side or 1 ft^3) of test bench space. This tentative size was arrived at through thorough analysis of instrumentation and computational hardware specifications available today as well as technical discussions with design and metrology engineers at both ORNL and private vendors. Thirdly, the man–machine/machine–machine interfaces should allow high speed, high reconfigurability, high durability, and low operational complexity (machine intelligence). Finally, this CALSET should be supportable in the field via multifunction transfer standard (MTS) and intrinsic standard-type instrumentation that is maintained at the primary laboratory level.

For the CALSET 2000 to be able to assume the necessary posture for performing such varied tasks as a diagnostic test on a missile system LRU to the complete calibration of a portable working standard, the system must include both solid state cardinal-point reference source devices as well as signal excite-and-receive diagnostic hardware for fault detection and assessment. The beauty of such an architecture is the multitasking functionality that will be included. Multitasking means that diagnostic signal generation and detection can be performed by the same source and detection hardware that is capable of calibrating voltmeter inputs to tens of parts per million. Clearly, this source/measurement hardware would also have to provide a multiplexed, time-share capability so that one instrument technician may diagnose and repair a device while another technician calibrates a completely different piece of equipment simultaneously. Viability of such an architecture will necessitate an almost ubiquitous use of microcomputers that would control operation and communication between devices in a relatively transparent fashion to the user. The CALSET hardware will be able to excite an end item as it would operate in its system while monitoring for the required outputs. If operational faults are detected, noncontact magnetic probing would then be used to identify the malfunctioning device. However, rather than fault detection and remediation, high-speed pass/fail LRU or DUT operational verification will be the desired mode of operation. (This mode of operation is driven by the nature of the conflict situation; more thorough fault detection/remediation is available if necessary.)

As instruments become smaller, smarter, and more accurate, much of the same capability seen in a laboratory-standard-type instrument today will be miniaturized to the "device on a card" or "device on a chip" level. This miniaturization will facilitate development of a full field CALSET 2000 that may be helicopter or even high-mobility multipurpose wheeled vehicle transportable. Such a system will require only a core set of modular devices and instruments that are nested within a mainframe/graphical user interface structure that provides computer control and data/instrument display. The data/instrument display or graphical user interface allows the CALSET 2000 system user to reconfigure the core device set to be whatever standard, calibration device, or diagnostic tool required. This is done through the use of a virtual instrument interface software package like National Instruments' LabView. Hence, simply reprogramming the CALSET 2000 for a different application adjusts the core set to meet the requirements. This high degree of versatility has several important consequences. First, the total weight, volume, and power burden of the CALSET may be significantly reduced. Second, any calibration or maintenance setup can be simulated; hence a dramatic reduction in the necessary technical briefs, procedures, etc., can be realized. This reduction in paperwork occurs because instrumentation that is already in inventory is the equipment simulated. For example, documentation for Fluke 8000 series multimeters as well as Hewlett-Packard 3400 series meters would be redundant since all CALSET 2000 systems would only simulate multimeters at the instrument interface. Finally, the maintenance and repair aspects of field device support may be combined with the calibration service group since the reconfigurability of the CALSET 2000 permits precision calibration as well as diagnosis and repair if necessary.

To realize such a versatile instrument group as the CALSET, certain measurement parameters will need to be covered by precision or intrinsic reference sources or measurement capability. Those parametric areas will have to be volts (AC/DC), amps (AC/DC), ohms (AC/DC), capacitance (AC), inductance (AC), impedance (AC), power (AC/DC), and time/frequency. Each of the parametric areas is addressed in detail in Table 7.

This capability summary describes a minimum set of equipment that provides a system with which both diagnostic measurement and calibration can be handled. A few additional pieces of diagnostic equipment may be necessary, such as magnetic probes[16] and hand-held logic analyzers and oscilloscopes,[17] all of which are of a similar technological genre. These modules or devices can then be periodically tested or replaced if the performance checks using multifunction transfer standards or portable intrinsic standards so warrant.

The technologies that afford such an architecture as described above either exist or are maturing quickly. High electron mobility transistors (HEMTs) and resonance tunneling diodes[18] are the type of quantum-well structures that will facilitate the necessary size reductions to realize such things as a digital voltmeter (DVM) on a chip. However, because of their small sizes, speed, power, and current density enhancements will also be gained as mutual benefits. Jaeggi and Bates[19] describe a complementary metal-oxide semiconductor (CMOS) thermoelectric AC power sensor that occupies but a few microns because of the current CMOS IC and micromachining technologies. Several other areas, when mature, will yield marked improvements in circuit speed, signal detection, and power handling capabilities.[20,21,22] The heterojunction and quantum-well device technologies will be the ones that legitimize the technological push toward whole instruments of standards quality level being built on a single chip.

With the standard, cardinal-point, and low-level sourcing being handled by the microelectronics, the higher power requirements along with the interfacing to actual field devices via virtual instrument simulation would be accomplished through the use of the graphical user interface. This graphical user interface would access things such as (1) ultrahigh-density memories and high-speed switching and communication networks,[23,24,25,26] (2) microcomputing capability, including some parallel processing,[27,28] (3) "device on a card" assets[29] to fill in where "device on a chip" has a shortfall; and (4) the mind behind the hardware, namely, the virtual instrument interface itself, the software.[30] Given the former in combination with measurement techniques that optimize the accuracy, precision, and repeatability of the system, the CALSET will be the most versatile and precise measurement system ever conceived.

An ancillary benefit to having electrical cardinal-point reference artifacts onboard is that the maintenance required to keep the CALSET up and running will be minimized. Self-checking routines can be implemented in software. During any performance test or calibration, an additional measurement will be inserted into the measurement cycle. This measurement will amount to the virtual instrument used at the time, assessing its own performance by making a reference artifact reading. The reference reading, for example, may just be the virtual DVM assessing the value of a reference metal-film resistor to verify that a four-wire ohm measurement of a resistance temperature detector is indicating properly. In this scenario, both forward and reverse readings should be performed so that cancellation of any thermal electromotive forces (emfs) will result.

Table 7. DC and AC low-frequency parameters with required source and measurement ranges vs applicable emerging technologies

Parameter	Range	Technology/[Availability][a]
Volt (DC) — Source	10^{-6} to 10^{4} V; cardinal-point value @ 10 V.	Solid state voltage reference (Josephson type), high-temperature superconductors (10^{9} junctions/array), variable frequency excitation (5×10^{8} - 5×10^{9}Hz) [~2000]
Volt (DC) — Measurement	10^{-6} to 10^{4} V	Solid state 8 1/2-digit DMM on a chip. [Now]
Amp (DC) — Source	10^{-12} to 1 A; cardinal point @ 10^{-3} A.	Solid state reference (heterojunction transistor array to 1 A), coil multiplication to 10^{2} A. [~2000]
Amp (DC) — Measurement	10^{-12} to 10^{-3} A Higher currents measured using precision shunts and Ohm's Law	Solid state electrometer on a chip. [Now]
Resistance — Source	10^{-3} through 10^{12} Ω (decades); cardinal-point values @ 1 and 10 k Ω.	Solid state decade reference on a card (X-ray lithograph precision metal film) [Now]
Resistance — Measurement	10^{-3} to 10^{12} Ω	Use voltage reference source & current measurement, apply Ohm's Law. [Now]
Volt (AC) — Source, RMS	10^{-6} to 10^{3} V, frequency range: 0 to 100 kHz, 0 to 50 mA.	Solid state DC reference, digitized and synthesized to AC [1995]
Volt (AC) — Measurement	10^{-6} to 10^{3} V	Solid state 8 1/2 digit DMM on a chip [Now]
Amp (AC) — Source	10^{-6} to 10^{2} A	Solid state DC reference digitized and synthesized to AC [1995]
Amp (AC) — Measurement	10^{-6} to 10^{2} A	Solid state thermal device. [1995]
AC IMPEDANCE — Resistance — Source	Cardinal points: 1 and 10^{4} Ω	Solid state reference resistors [Now]
AC IMPEDANCE		Precision impedance bridge device on a card. [Now]
Resistance measurement	10^{-6} to 10^{7} Ω	
Conductance measurement	10^{-11} to 10^{2} S	
Reactance measurement	10^{-6} to 10^{7} Ω	
Susceptance measurement	10^{-11} to 10^{2} S	
Q factor measurement	10^{-2} to 10^{4}	
Dissipation factor measurement	10^{-6} to 10^{1}	
Phase angle measurement	-180 to 180 °	
% deviation measurement	-10^{3} % to 10^{3}% (deviation from nominal values of L,C,R, used for batch testing)	
AC IMPEDANCE — Capacitance — Source	Cardinal points: 10^{-12} and 10^{-6} F	Precision air gap and dielectric film capacitors [Now]
AC IMPEDANCE — Capacitance — Measurement	10^{-17} to 10^{1} F	Precision impedance bridge device on a card. [1995]
AC IMPEDANCE — Inductance — Source	Cardinal points: 10^{-3} and 10^{2} H	Precision wire wound inductors [Now]
AC IMPEDANCE — Inductance — Measurement	10^{-11} to 10^{6} H	Precision impedance bridge device on a card. [1995]
AC/DC POWER — Power factor — Source	CALSET power supply will also serve as calibration. Power source to 100 W.	Ultrahigh-speed ceramic turbine generator. [Now]
AC/DC POWER — Power factor — Measurement	0.7 to 1.0	[1995]
AC/DC POWER — Current — Source	CALSET power supply will also serve as calibration. Power source to 100 W.	Ultrahigh-speed ceramic turbine generator. [Now]

Table 7 (continued)

Parameter	Range	Technology/[Availability][a]
AC/DC POWER — Current — Measurement	10^{-3} to 10^{2} A	[1995]
AC/DC POWER — Voltage — Source	CALSET power supply will also serve as calibration. Power source to 100 W.	Ultrahigh-speed ceramic turbine generator. [Now]
AC/DC POWER — Voltage — Measurement	10^{-6} to 10^{3} V	[1995]
AC/DC POWER — Phase — Source	CALSET power supply will also serve as calibration. Power source to 100 W.	Ultrahigh-speed ceramic turbine generator. [Now]
AC/DC POWER — Phase — Measurement	0 to 360 °	[1995]
AC/DC POWER — Frequency — Source	CALSET power supply will also serve as calibration. Power source to 100 W.	Ultrahigh-speed ceramic turbine generator. [Now]
AC/DC POWER — Frequency — Measurement	0 to 10^{7} Hz	
Time and Frequency — Source	Global Positioning System	Global Positioning System link to local universal timer/counter on a chip. [Now]
Time and Frequency — Measurement	10^{-12} to 10^{3} s/10^{-3} to 10^{12} Hz	Heterojunction type devices with virtual interface.

[a] The term "[Now]" refers to technologies which exist; however, the actual availability is driven by specific requirements. Therefore, they are typically associated with high cost.

The result will then be stored in system memory so that SPC may be used to maintain the CALSET performance. With each field unit having this attribute, a worldwide Army CALSET data base can be generated so that SPC can be monitored on all CALSETS.

Many technologies currently exist that could dramatically impact the level of capability, size, and cost of a CALSET-type instrument system. However, the maturation rate in some areas of technology will be strongly influenced by the current demand for measurement device improvement. The U.S. Army TMDE Activity has a unique need in the area of test, calibration, and maintenance of field deployable measurement and test equipment. Following discussions with several precision test equipment suppliers (e.g., Fluke, Datron/Wavetek, and Hewlett-Packard), it is the opinion of the ORNL assessment team that the most effective way for the Army to make a revolutionary change in capability relative to the size of the package is to commit to designing and building a CALSET of the kind described herein. The development of such a test bed will require the technical wherewithal to integrate the many devices and instruments that make up just the DC/AC low-frequency aspect of the CALSET 2000. Also, thorough knowledge of advanced control techniques and architectures is critical to the success of a system like the CALSET 2000. Perhaps a system like this will be available through the many advances in VXI- and MMS-type technologies, but to wait for the market to drive the technology far enough to render this type of capability commercially available would result in a time frame well beyond the scope of this assessment's forecast. Henceforth, a supplier who can draw on many technological resources will likely have to build a CALSET 2000 because truly unique requirements demand truly unique systems, and the CALSET 2000 is truly a unique system.

6.2 RF/MICROWAVE EQUIPMENT CALIBRATION

As mentioned earlier, rf and microwave equipment makes up 9.7% of the worldwide TMDE density distribution and 9.5% of the worldwide workload distribution. The AN/GSM 287 calibration van configuration consists of the 286 van containing the DC and low-frequency AC equipment and a second van containing rf and microwave (as well as physical and mechanical calibration equipment).

The need to have a separate van configuration to support microwave is driven by two factors: (1) all of the equipment needed to support DC and low-frequency, microwave, and physical/mechanical equipment will not fit in a single van and (2) not all calibration sites have need of microwave calibration.

In the first case, if there are technologies that can reduce the size and complexity of rf and microwave calibration equipment, it might be that two vans would not be needed. An overall 50% reduction in size would be a significant accomplishment. This is the motivation behind seeking out microwave-related emerging technologies.

This section attempts to discuss specific trade-offs with regard to integration, to identify technology trends that could aid in downsizing the 287 configuration, and, finally, to identify products or devices that already exist that serve to reinforce the feasibility of the CALSETS 2000 design. Table 8 addresses specific technologies and the impact they are expected to have on microwave device calibration.

Table 8. Impact of emerging microwave related technologies on calibration

Technology	Impact
GPS time/frequency standard	Time/frequency transfer; time within 10 ns; frequency 1 part in 10^{14}; avail. on VXI
Cabling to 60 GHz	Replaces several bands of waveguide with one cable
GaAs MMIC[a] devices	Multiple functions integrated on substrates less than 1 in.^{2} Increased frequency of operation to about 100 GHz.
Acoustic wave devices	Improved BAW[a] resonators up to 10 GHz; improved DSP[a] devices to above 1 GHz; lower cost, more rugged
Superconducting devices	Greatly reduce noise level; increase frequency of devices to about 1 THz; reduce size if not for required cryogenics
Heterojunction bipolar transistors	Increased efficiency and reduced size of microwave amplifiers (1 GHz to above 100 GHz)
Heterojunction field effect transistors	Higher frequencies of operation, lower noise figures, oscillators to several hundred GHz.
Diamond semiconductors	Superior thermal characteristics allow much greater packing densities for microwave amplifiers
Band-gap engineering	Record current density of 67 mA/mm and increased frequency of operation to well above 100 GHz

[a] MMIC = Monolithic Microwave Integrated Circuit; BAW = bulk acoustic wave; DSP = digital signal processing.

A major concern for the microwave and rf calibration equipment will be the power requirements for the various frequency ranges. Currently, the assessment study has identified power needs in excess of 200 W up to about 2 GHz, but the van is only capable of 50–100 W.* Above 2 GHz the requirements are probably not above a few watts. To reduce the size and weight of the equipment on the van, careful consideration must be given to the actual "mission essential" power requirements below 2 GHz. Downsizing would be greatly aided by reductions of the overall power requirement or at least reduction in significant portions of the frequency spectrum.

*Based on discussion between M. R. Moore (ORNL) and J. Christian (TMDE).

The advances in microwave detection and generation involve several new technologies. Superconducting materials are being used to increase current densities and decrease noise levels. Heterojunction bipolar transistors (HBTs) and similar field-effect devices are being used to reduce the size of microwave amplifiers. Improved cable and connectors are allowing flexible cabling to replace waveguides at frequencies up to at least 60 GHz if only for short distances. Finally, the advances in developing IOC have greatly reduced the size of overall systems.

A technology that is already available can be used as an aid in transferring time and frequency standards. NIST provides a service via the Global Positioning System (GPS) that performs precision time and frequency transfer.[31] The service has time stabilities of a few nanoseconds, time accuracies of the order or 10 ns, and frequency stabilities of 10^{14}, or better, for measurement times of about 4 days or longer. This system could replace or enhance time calibration equipment needed. In some instances, a GPS setup at a site could negate the need for the van to carry this equipment.*

The replacement of waveguide with cable is presently feasible up to about 60 GHz. Cable with losses as low as about 0.6 dB/ft at 40 GHz are currently manufactured which employ low-density polytetrafluoroethylene (PTFE) dielectric and are equipped with either 2.92-mm K or 2.4-mm connectors. 1.8-mm connectors for 60-GHz work are available, and connectors as small as 1 mm are being developed. The replacement of waveguide with cables has the obvious effect of reducing the size, cost, complexity, and weight of the interconnecting systems. This also means that the interconnecting equipment such as switches can be broader banded since one cable could replace several bands of waveguides.

To provide a user interface for IOC, standard buses and interface software are needed. The VXI bus solution is already being investigated by the various commercial laboratories.[32] Currently, VXI products provide power detection to about 50 GHz and 100 mW, frequency counters to about 170 GHz, and generators to about 20 GHz. In MMSs, the products are mostly made by HP; however, the standard is open and available to all vendors. The capabilities of current MMS products include power detection to 50 GHz and about 20 W, generators to 20 GHz, and, most significantly, a spectrum analyzer. This spectrum analyzer has a frequency range of 26.5 GHz and a sensitivity that varies from -138 to -128 dBm. Various software packages exist that are useful as user interfaces to instruments that have no "front panel." These products will allow the integration of many of the function blocks and will provide a virtual interface that does not have to be updated with each equipment improvement.

Several acoustic phenomena are being used to advance the state of the art in microwave devices. These phenomena include surface acoustic waves (SAWs), bulk acoustic waves (BAWs), and acoustic charge transport (ACT). Many developments in SAW technology have taken place over the last 25 years, especially in DSP devices.[33] SAWs are employed as filters, correlators, convolvers, delay lines, and as other signal processing devices. Research in the area of acoustic wave devices is advancing the state of the art in smaller, lower cost, more rugged uhf oscillators that are well suited for mobile applications up to about 1 GHz.[34] These oscillators have a major advantage over bulk crystal oscillators in that they resonate at higher frequencies and thus do not need to be frequency multiplied. Advances have also been made in materials that have lower phonon absorption and thus provide a significant increase in *Q (quality factor)* for BAW resonators.[35] These advances are bringing the advantages of acoustic devices to the microwave range (upwards of 10 GHz.) These advances in acoustic devices will greatly increase filtering capabilities, reduce cost, and lead to more rugged devices in the microwave region.

---

*USATA is in the process of First Article Testing of a GPS-disciplined rubidium standard; it is smaller and more lightweight but is not based on VXI. It is designated as the Time and Frequency Workstation.

One technology that should aid in reducing the size of some rf components is the field of superconducting electronics. One student is already developing a superconducting field-effect transistor (SUFET).[36] Also YBCO ($YBa_2Cu_3O_x$) filters are being developed that will be orders of magnitude smaller than their cavity counterparts. Superconductors are also being used to increase the sensitivity and decrease the noise equivalent power (NEP) of microwave signal detectors.[37] Another reference[38] discusses improved microwave response in the 10–100-GHz range at temperatures up to 82 K using a film of MgO between two superconducting electrodes. Finally, superconducting devices are emerging that can be used in microwave products operating in the 1000-GHz (THz) range.[39] These devices will reduce the size of some electronics, but their application will be limited until their temperature of operation is raised nearer to room temperature or the size of cryogenics is reduced. Presently, the superconducting devices are already reducing noise figures and increasing the frequency of operation of some devices from about 100-GHz to about 1000 GHz.

"Heterojunction Bipolar Transistors (HBTs) fabricated in the AlGaAs/GaAs material system offer excellent potential for power application in the microwave spectrum."[40] These transistors employ a heterojunction of materials such as AlGaAs/GaAs rather than the *n* and *p* doping of the silicon bipolar junction transistors (SiBJTs). This results in higher output-power density, higher power gain, and higher power-added efficiency (PAE). A range of devices has been developed that range from 2 W at 1.5 GHz with 72% PAE to 1/3 Watt at 18 GHz with 11.4% PAE. These power HBTs can also "operate from the L-Band to K-Band (17–33 GHz) and even into the Q-band (33–46 GHz)." Also, another HBT amplifier that operated up to 59 GHz "exhibited a maximum oscillation frequency, $f_{max,}$ of 218 GHz which is the highest reported for any AlGaAs/GaAs HBT to date." Another source[41] describes future amplifiers in the range of 1 GHz to well over 100 GHz. This article discusses various millimeter-wave solid state research advances driven by material and fabrication advances. Another source describes new millimeter-wave sources (60 GHz) that are being developed using HBTs and mode-locked lasers.[42] "Because of the intrinsic gain of the high frequency HBTs and the ease in which amplifying MMIC circuits can be incorporated, substantial radiated powers can be obtained with this approach." This is part of an effort to develop large bandwidth systems that require low-loss, lightweight, interference-free transmission mediums. In summary, HBTs are greatly increasing the available power, gain, and frequencies of microwave amplifiers while increasing the efficiencies and reducing the size of devices.

A similar class of transistors has been proposed that make field effect transistors (FETs) operating beyond 200 GHz a possibility.[43] The devices include MODFETs (f_{max} = 350 GHz), PBTs (f_{max} = 500 GHz), and MESFETs (f_{max} = 450 GHz). Another member of this class is the High Electron Mobility Transistor (HEMT).[44,45] These FET devices offer operation at much higher frequencies than do their doped silicon counterparts. In fact, the HEMT devices offer higher frequencies of operation and higher gain-bandwidth products than those of HBTs. The literature[46] states that the "principal interest in HEMTs, however, is in low-noise applications, with a number of investigators reporting extremely low noise figures; 0.68 dB at 12 GHz, and 0.83 dB at 18 GHz." A class of tunneling devices that uses the same technology as the HEMT has been developed that includes two-terminal oscillators that have been tested up to several hundred gigahertz. These heterojunction FET-type devices are greatly increasing the frequency of operation of MMIC devices and are decreasing their noise figures and size.

Recent advances have also been made in the area of diamond film semiconductors.[47,48] The greater thermal conductivity of these films will allow greater packing densities for microwave electronics in power devices. This could greatly reduce the size of future microwave amplifiers as well as optical electronic devices. The diamond films still require development to make them more useful in room temperature devices (they currently work at temperatures such as 300°C). However, advances in doping, chemical cleaning, and hydrogen plasma treatments have been found to enhance the electrical characteristics of these CVD (chemical vapor deposition) diamonds.

The ability to form a layer of material one atom thick has enabled "band-gap engineers" to change the physics of new semiconductors.[49] Typically, semiconductor layers are hundreds or thousands of atomic planes in depth. The physics of these materials is well documented. However, the application of layers of materials that are only a few atoms thick allows the formation of heterojunction sandwiches, reflecting layers, quantum wells, and other structures that have special properties. For example, a strained-quantum-well field-effect transistor (SQWFET) has been developed using two thin strained quantum wells on InGaAs embedded in a host crystal of GaAs. This device has achieved a record current density of 67 mA/mm of gate width while maintaining a respectable transconductance of 60 mS/mm. Additionally, theoretical models suggest that a single layer of dopant applied to a multiple quantum-well structure such as GaAs/AlGaAs might produce FETs that are an order of magnitude faster than the present modulation-doped FETs that operate at 100 GHz. Early measurements on some of these devices show "hot" electrons with "velocities of about 10^8 cm/sec., which is about five times faster than low-temperature measurements of velocity in conventional devices." Thus, band-gap engineering is making great strides in pushing the frequencies of operation toward 1000 GHz and improving efficiencies and speeds of various devices in the hundreds of gigahertz.

"System applications will benefit not only from the improvements in performance of individual devices but also from the rapidly increasing levels of integration. The DOD MIMIC program is giving a big boost to the practical [use] of monolithic circuits."[50] Combining microwave circuits into monolithic packages has increased speed and efficiency and decreased size, as shown by the devices described below. In fact, one source [51] states, "The next generation of portable communications systems ... will require ultra low-noise and low-power electronics technology ... GaAs based MESFET MMIC receivers will lead to a continued reduction in the number of parts and interconnects, thereby reducing the size and weight." Also, a personal communication network (PCN) developed at 38.5 GHz [52] has demonstrated that "MMIC costs are now competitive with the lowest priced hybrid alternatives and will shortly have a clear cost advantage."

Many of the MMIC advances have been used in producing amplifiers with higher gains, powers, and bandwidths. For instance, Avantek has developed an X-band amplifier that produces 10 W (9–10 GHz) on a 20.8- by 7.6-mm substrate.[53] This device has a gain of 19 dB and a PAE of 32%, which helped it meet the limited power and space requirements of an airborne system. Another device that is much smaller delivers 14 dB of gain and about 1 W of output power for the range of 6–18 GHz on a 4.35- by 5.1-mm chip.[54] A 2- to 20-GHz amplifier has also been developed which is based on a 0.5-μm ion-implanted MESFET process.[55] This amplifier is 3.1 by 4.0 mm, has a gain of about 24 dB, and a 1-dB compression point of about 23 dBm. As shown, there have been many advances in increased power and bandwidth for the 1- to 20-GHz range.

At the higher frequencies, MMIC technology has been especially successful in increasing the amount of gain and power that could be achieved. This opens up new applications, as discussed in the literature.[56] In this case, a 47-GHz 1/2-W amplifier was developed in MMIC using MESFET technology. This device can be applied "as a driver for a monolithic doubler circuit to reliably produce greater than 80 mW of output power at 94 GHz for missile seeker applications." The article also mentions that this device will provide the power needed for W-band (56 to 100 GHz) phased array radar transmitters, which were not previously readily available. Another W-band MMIC device has been developed by researchers at TRW.[57] This device operates at 91–95 GHz with a gain of 50 dB and has the "highest gain ever achieved by a single amplifier at these frequencies." This amplifier, which is about 1 in.^{2} in size, has a 6-dB noise figure and is well suited for low-noise receiver and radiometer applications.

A prime example of how some of the advancements in technology can benefit the calibration effort is demonstrated by the development of a monolithic six-port module (MSPM) MMIC device.[58] The six-port network is the main component of automatic network analyzers (ANAs). A "full-up" ANA typically costs about $200,000 and occupies an entire equipment rack. The MSPM is a 3- by 3-mm GaAs chip and operates from 7 to 9 GHz. The MSPM has demonstrated good agreement with NIST standards. This device could be the primary building block for a new class of low-cost, very small ICs used for test and calibration of microwave equipment. The comparison of the MSPM with two commercial ANA setups showed amplitude agreement within 0.2 dB and phase agreement within 3°.

The "noncontact" connections involve technologies that exist but are not presently being used for this purpose. One magnetic pickup that operates to 33 GHz has been developed.[59] This probe, however, is only accurate enough for general-purpose testing, not for calibration. Other noncontact methods include systems that communicate via rf or EO links rather than by hardwire or coax. The existence of such systems is still a subject of investigation.

The following items are representative of the technologies available today:

- Micro-Coax Components makes an Ultiflex cable that has 0.61 dB/ft loss at 40 GHz.
- Engineers at Avantek have developed a 10-W, class AB amplifier that operates in the 9- to 10-GHz range.[60] The amplifier has a gain of 19 dB, 32% PAE, and is 20.7 by 7.6 mm in size.
- Another class of products consists of in-line devices that include noise sources (comb generators) by NoiseCom for frequencies up to 110 GHz and passive devices such as waveguide kits for calibrating network analyzers by Maury Microwave.

6.3 PHYSICAL SENSOR CALIBRATION

Approximately 35% of the field instruments supported by the AN/GSM-286/287 calibration vans measure physical or mechanical, rather than electrical, parameters. Although in many cases the field instrument produces an electrical signal that can be measured by electrical standards, a physical standard and a stimulus are still required to perform the calibration. In many cases, both the physical standards or field instruments are completely mechanical, and the "signals" must be read visually by an operator. The potential for downsizing of physical standards and integration into the flexible and highly automated systems envisioned for CALSET 2000 is not quite as amenable to technological advances in electronics and computers as are electrical or microwave instruments. This section reviews the current CALSET capability and discusses technology trends that may be applicable to the CALSET 2000 system.

As evidence of the improvements that are possible in the area of physical sensors, Fig. 8 shows the evolution of pressure sensor technology as used at ORNL over the past 10–15 years. The items shown in this figure are all pressure sensors, all performing essentially the same function. The reductions in size and weight have been dramatic.

The present calibration sets provide calibration capability for a range of physical parameters such as pressure, temperature, force, torque, mass, length, flow, and viscosity. In some cases the CALSET reference standard is a sensor that provides an electrical signal. In other cases the standards are artifacts such as weight sets or gauge blocks, or they are mechanical devices such as piston gauges, pressure gauges, or dial indicators. Also, in most cases, several different sensors or devices are required to cover the supported calibration ranges to the required accuracy. Because of the variety and the "mechanical" nature of many of the physical standards and the field equipment that they support, neither a significant reduction in size nor an improvement in the degree of automation is possible at this time. However, there are some trends in sensor technology that will change this situation over the next few years.

One technology advancement that has matured over the past decade and has significantly improved the performance of physical sensors is referred to as "smart" sensors. A smart sensor is one that incorporates signal conditioning electronics and a dedicated microprocessor in a package, often built into a single assembly with the sensor. This permits many performance enhancement features (linearization, temperature compensation, autoranging, autozero, etc.) to be performed digitally. These instruments can also perform self-monitoring and diagnostic functions that greatly improve their reliability.

One of the first commercially available "smart" sensors was a differential pressure transmitter (dP cell) manufactured by Honeywell primarily for the chemical process industry. This was a conventional dP transmitter with a built-in microprocessor that performed many of the

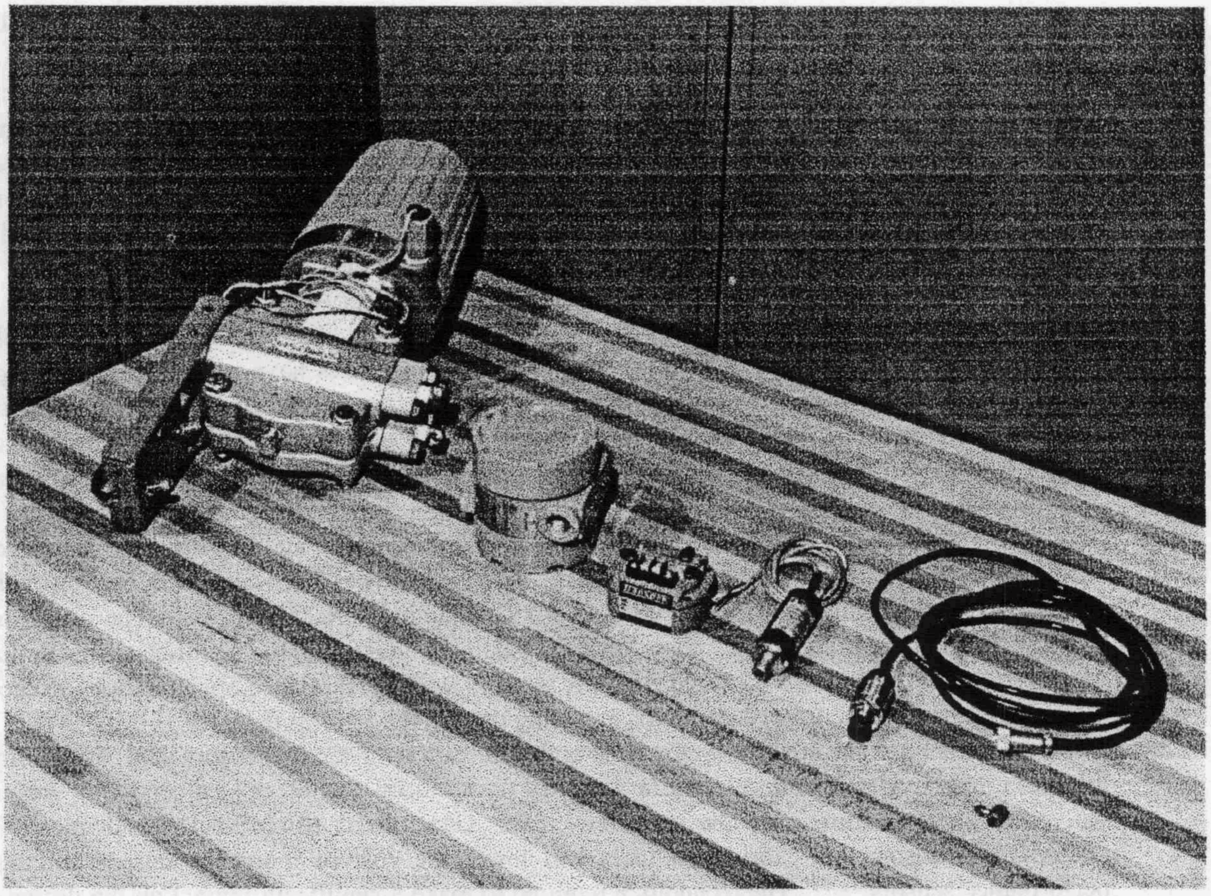

Fig. 8. Evolution of pressure sensors over a 10- to 15-year period.

operational adjustments that previously were done manually. The output was a standard analog signal (0 to 10 V, 4 to 20 mA, etc.), but the signal wires also served as a carrier for a digital communication link. This instrument and others like it provided an enormous improvement in the performance and reliability of process transmitters.

The smart transmitters first appeared in the mid-1980s, and their development has been analogous to that of electronic instruments such as the digital multimeter. The need for manual adjustment and periodic calibration in the conventional sense has been virtually eliminated. One device can cover measurement ranges and perform functions that formerly required several different devices. The sensors contain digital and conventional analog communications. Signals are digitized at the source and can be transmitted digitally as well as analog.

A variety of smart sensors is now commercially available for most normally encountered physical measurements.[61,62,63,64] While their advantages and benefits are fairly obvious, they have created some new problems from the calibration laboratory's perspective. Like their digital multimeter counterparts, the improved functionality and performance of smart sensors have made it more difficult to perform a traditional calibration. In some cases the accuracy of field devices equals or exceeds that of laboratory standards. Instead of offering possibilities for downsizing and simplification, it just places more stringent requirements on the calibration standards.

At the present state of the art, smart sensor technology does not provide many solutions for meeting the CALSETS 2000 objectives. However, in combination with other rapidly emerging technologies such as semiconductor-based monolithic sensors, sensor fusion, and "intelligent control" techniques (such as fuzzy logic [65]), there will be a significant impact.

Semiconductor processing technology for VLSI has provided a valuable spinoff in the area of high performance, low cost, miniaturized sensors for a wide variety of physical measurements. The ability to fabricate silicon structures with dimensions on the micron scale and incorporate VLSI electronics on the same structure has produced a revolution in sensor technology. Microscopically sized "smart" sensors that can measure multiple physical parameters and can replace several conventional instruments are now appearing on the market.[66]

Solid state pressure or load sensors utilizing monocrystalline silicon structures with diffused semiconductor (piezoresistive) strain guages and integrated electronics have been available for several years. Their low cost and potentially microscopic sizes have made them very popular for high-volume applications in the automotive industry and for biomedical applications requiring extreme miniaturization.[67,68] Because of the sensitivity to temperature and other environmental factors, the majority of the presently available sensors are directed toward low-cost, moderate-performance applications.

The technology is now moving toward higher performance and more specialized needs in the medical and aircraft industries. ASIC technology, which has been available for low volume specialized IC fabrication for several years, is now available for microsensors.[69] The use of built-in digital compensation rather than analog trimming has led to significant performance improvements.[70] "Matchbook" sized pressure sensors with performance specifications exceeding many of our present laboratory standards are being used in the aircraft industry.[71]

Current trends in the development and application of smart sensors and the ability to fabricate integrated monolithic sensor assemblies from silicon and other semiconductor materials will continue to mature over the next few years. Generalized MicroElectroMechanical CAD (MEMCAD) design and fabrication tools will lower the cost of more specialized and higher performance sensors.[72,73] The technology required to make a significant impact on the design of a CALSETS 2000 system will almost certainly be commercially available by the mid-1990s.

6.4 DOCUMENTATION STORAGE AND RETRIEVAL

As indicated in several other sections, particularly regarding mass storage, the emerging technologies regarding the storage of documentation will be rooted in optical storage. The advances in document scanning and storage have increased significantly within the past few years.

Automated indexing and referencing of elements of both text and illustrations within a document are already realities. More capable computing and imaging equipment has brought the technology of imaging, optical character recognition (OCR), and documentation to the desktop.[74] There is no question that within 10 years, document storage and retrieval will be advanced to the point that a large portion of the field documentation can be stored on optical media and rapidly retrieved by computerized equipment. USATA may want to initiate a working group to investigate and follow the rapid developments in imaging, image storage, document indexing, and document retrieval.

6.5 DOCUMENTATION UPDATING

Documentation updating can be accomplished through the issuance of new storage media (most likely optical) and, in the case of field installations, through satellite down links. The updated information would be stored on writable optical storage media. Some updating could still be accomplished by paper, but this should be discouraged in favor of more permanent and accessible media.

6.6 PERSONNEL TRAINING

The direction that personnel training takes will depend upon the direction USATA takes toward adopting some of the emerging technologies reviewed in this report. If, for example, the increased use of expert systems, fuzzy logic, color graphic display technology, and software driven test and calibration systems is adopted, the type of training would certainly differ from the present norm. In many regards the technologies referenced in this report could be used in the actual personnel training process. A unit referred to as KATIE,[75] developed at ORNL for diagnosing equipment malfunctions and recommending a repair procedure, could be applied to the training of personnel in how system or unit malfunctions manifest themselves and how the systems determines the best course of action.

6.7 EQUIPMENT TROUBLESHOOTING AIDS

Expert systems probably show the most promise as an emerging technology that has direct application to the troubleshooting of equipment. Such systems follow probability-based procedures to systematically arrive at the probable cause of a problem and suggest the appropriate repair procedure. The advantages of this approach is that it does not "hop" from possibility to possibility but rather follows a reasonable and logical path to diagnosis. USATA should investigate the application of expert systems and related technologies to the area of equipment troubleshooting for the CALSET 2000 Repair Workstation.

6.8 TRANSPORT STANDARDS

The CALSET 2000 system proposed herein is a highly modular and reconfigurable system that is based on a core set of "device on a chip"/"device on a card" assets. These assets include several highly precise cardinal-point reference devices as well as microprocessor-controlled instruments that, through the use of an expert system and graphical user interfaces, are able to sustain themselves by continually performing self-assessments. These self-assessments are used to monitor CALSET 2000 performance through statistical process control techniques. However, periodic calibration of the CALSET 2000 internal reference set will be necessary. CALSET 2000 reference set calibration may be accomplished by interchanging the main core module that includes the Josephson voltage standard, the resistance cardinal points, a capacitor and inductor standard, and a local rubidium frequency standard with a multifunction transfer standard (MTS) module that includes identical artifacts as well as a microprocessor control center, nonvolatile memory, battery power pack, and an interface test kit that looks at the CALSET 2000 interface outputs while being excited by the MTS module artifacts. The test routine, which is controlled by the MTS onboard computer, once elicited by the CALSET operator, performs a series of tests that include reconfiguring the core to simulate a calibration in all parametric areas. Once this system check is completed, the MTS module is connected to the CALSET main core module to generate a reference and drift assessment of the main module. This reference and drift assessment is used to determine an artifact ratio set that is then stored by the CALSET 2000 as a system core-coefficient file. This file is then used to both update the system parametric outputs as well as serve as a historical record of CALSET main core module performance. The MTS device that enables this performance update will be a ruggedized, self-contained unit of suitcase proportions that gains its calibration traceability directly from the primary laboratory.

7. CALIBRATION-RELATED TECHNOLOGIES

The following technology areas are included as supporting technologies through the concepts put forth as a result of the assessment activity. The shifts toward more complex systems, the proposed inclusion of expert systems, advanced documentation storage and retrieval systems, and the introduction of new equipment configurations have resulted in the necessity to discuss these areas in specific detail.

7.1 VIRTUAL INSTRUMENTS

The physical space constraint relating to placement of such a wide variety of calibration equipment in the 286/287 vans leads to consideration of (1) ways to share equipment and (2) ways to reduce the physical space requirements. The concept of virtual instruments seems to be directly applicable in this situation.

The term *virtual instrument* refers to replacing a conventional, discrete, rack-mountable (or bench-top) instrument with a functionally equivalent representation of the instrument. Generally speaking, most of the panel space for an instrument is associated with the display and manual controls (i.e., switches, knobs). The actual functional portion of the equipment (electronics) can be placed in a much smaller volume. This is particularly true with the advances being made in miniaturization.

An example of this concept would be the replacement of a Hewlett-Packard Model 5345A Universal Electronic Counter such as used in the present calibration van configuration with the HP Model E1420B VXI format High Performance Universal Counter module in conjunction with appropriate display software. While this is not an exact replacement with regard to input sensitivity and frequency range overlap, it is very representative of the possibilities.

The space normally occupied by the front panel of the instrument is multiplexed on a common display monitor with the space required by other instruments. This is the origin of the term "virtual instrument"; all of the functionality of the instrument is retained without the need to accommodate the physical space for the entire instrument, and a single instrument can be shared by several users. If appropriate methods are employed, a single instrument such as a DC voltmeter can be multiplexed between several users simultaneously.* An advantage of the virtual instrument and associated display is that the representation of the instrument can be minimized or maximized on the display screen depending on whether or not the instrument is needed or needs to be viewed at the time. The input to the actual voltmeter is multiplexed between each of the workstations and the corresponding data synchronized with the appropriate display monitor. This allows one instrument to be shared by all workstations and effectively decreases the required equipment by 75% (based on the premise that there are four workstations and each of the stations can use a single instrument, i.e., a 3:1 reduction).

---

*It is understood that there is a significant concern regarding the feasibility of multiplexing such signals, especially precision low-level signals and source signals. However, low-level signals are routinely sampled in data acquisition systems to a resolution of ~1:32,000. The multiplexing of sourcing or driving signals can be accommodated if appropriate settling time is provided.

7.2 MODULAR INSTRUMENTS (E.G., VXI, MMS, IOC)

The term modular instrument refers to the arranging of the electronics for a particular instrument into a standard form factor. This form factor is usually based on the card or module being inserted into a slot and accessing a common backplane. This backplane provides at least the following; (1) module power (this may take the form of multiple DC levels or a single AC source that must then be conditioned by the individual module) and (2) a common digital communication bus for the transmission of information to a common point, usually a central controller and display. There are two major competing modular instrument technologies currently in the marketplace: VXI and MMS.

7.2.1 VXI

The most popular modular instrument format currently appears to be VXI. This standard grew out of the computer industry and is based on an extension of the VME computer backplane. Development of the VXI bus specification was inspired by the U.S. Air Force and its IOC standardization efforts.[76] The first VXI bus specification was introduced in July of 1987. This specification was the result of work performed by a consortium consisting of Hewlett-Packard, Tektronix, Wavetek, Racal Dana, and Colorado Data Systems. The consortium is now incorporated and currently has ten voting members with a large number of nonvoting members. The VXI bus standard is intended to be a completely open, nonproprietary bus architecture that provides a multivendor environment for modular instrumentation. A VXI configuration consists of a backplane, a system controller, an array of modular instruments based on the VXI module standard, and the supporting software to make the assembly operate as an integrated system. The primary advantages over conventional instrumentation include (1) smaller size (for individual instruments), (2) a common form factor, and (3) improved vendor interchangability. The VXI bus specification defines a scalable family of four module sizes. These are designated A, B, C, and D, with the D size being the largest. The A and B sizes are compatible with the original VME module sizes. The two larger sizes, C and D, are specifically aimed at providing support for higher performance instrumentation systems.

As mentioned earlier, the VXI bus standard grew out of the VME computer backplane bus. The VME bus has been a very popular industry standard architecture for the computer industry and was considered to be a technically sound foundation for instrument extensions. Now more than 200 companies are manufacturing in excess of 2000 VME-based products. The VME bus supports high-speed data transmission (theoretically to 40 MHz), which is ideal for high-performance instrumentation and measurement systems. Key features of the bus include coordinated communication between a common controller and the individual instrumentation modules. These include handshaking, arbitration, and interrupts. Also, since the VXI bus standard is so closely related to the VME bus, VME modules can be used in the VXI bus backplane in the case of the A and B size modules.

There are ~50 manufacturers of VXI bus compatible instrumentation with more than 500 VXI bus instruments available.* Hewlett-Packard's latest catalog of VXI bus-based instruments lists 83 types of instruments and special interface modules based on the VXI bus specification.

---

*From information made available during discussions with Hewlett-Packard.

7.2.2 MMS

MMS technology is based on an open system into which instrument manufacturers and system integrators can design and develop modular test and measurement instrumentation, as well as complete test systems.[77] MMS was initially developed by Hewlett-Packard for use in the rf and microwave instrumentation applications. It is now considered by many to be a competitor to VXI bus. The basis for this thinking seems to lie primarily with HP since although there is an MMS consortium, HP has the most experience with MMS and therefore the best market position for introducing new products. Like VXI instruments, an MMS module significantly reduces the front panel space required for an instrument with modules being designated as one-eighth, two-eights, three-eights, half, and full-rack in size. This notation refers to the module occupying one-eighth, etc., of a 19-in.-wide, rack-mount MMS frame.[78] A feature included in the MMS architecture is a rack-mounted display. This has been touted as an advantage of MMS over VXI; however, proponents of VXI say that an "in-rack" display could be produced for VXI if the need were great enough. In the context of the virtual instrument concept, there is little need to consume precious instrument space with a "dedicated" display.

Current applications for MMS include rf and microwave instrumentation for the U.S. Navy's Consolidated Automated Support System (CASS), the U.S. Army's Intermediate Forward Test Equipment (IFTE) [this is currently referred to as the Integrated Family of Test Equipment within the Army], and the U.S. Air Force's Tactical Electronic Warfare System (TEWS) Intermediate Support System (TISS).[79]

While MMS enjoys acceptance in the rf and microwave applications, industry does not seem ready to embrace it for general modular instrumentation architectures. This stems from the concern by VXI-based suppliers that HP has such a significant lead in MMS technologies that it could quickly introduce lower cost versions of significant new products faster than newer, smaller players in the market.[80]

7.2.3 Applicability

The following subsections are provided to show the applicability of current modular instrument technology to the needs of USATA in the DC and low-frequency AC and microwave applications.

7.2.3.1 DC and low-frequency AC instruments

Technology has made available a varied assortment of modular devices which, if implemented, could have substantial and immediate impact on the CALSET configuration. However, it is important to note that although most areas of the DC and AC low-frequency parametric range have both source and measurement coverage, there is not a simple one-to-one exchange of devices possible at the current time. In fact, there are few, if any, "standard's grade" VXI instruments. In particular, there are no stimuli calibrators. Table 9 may be considered a thorough but not comprehensive synopsis of equipment availability and will serve as a handy tool for orienting oneself to the assortment of instrumentation currently available.

As is evident from Table 9, some parametric areas are lacking. In addition, full measurement and sourcing ranges are also not provided. Hence, supplemental coverage or synthesis of cardinal-point values such as DC currents remains necessary via conventional stand-alone instrumentation. However, benefit may be gained from limited implementation of modular equipment wherever sufficient parametric range overlap exists. The size savings as well as the experience gained in utilizing this equipment will be invaluable.

Table 9. Component list of mature DC/AC low-frequency equipment

Description	Manufacturer's model number	Parameters	Cost ($K)
Voltage			
DVMs (AC/DC)	HP E1410A,E1326B	0-300 Vdc,Vac	3.5
	Wavetek 1362	0-300 Vdc,Vac	1.5
	Tek. VX4236	0-300 Vdc,Vac	5.0
		6 1/2 digit DMM	3.0
Sources (AC)	HP E1440A	0-21 MHz sweep	5.7
(DC not avail.)	E1445A	0-43 MHz arbitrary function generator	7.0
	Wavetek 1378	0-12 MHz function generator	3.3
	Tek. VX4750	Function generator	4.5
	Tek. VX4790	Waveform generator	7.0
Current	N/A		
Resistance/impedance	Tek. 73A-342	Programmable resistance	2.5
Time/frequency	HP E1420B	Univ. counter	4.0
	Tek. VX4223	Univ. counter	5.0
Power	HP E1416A	25W, 0.1-50 GHz	2.5
	Tek. VX4281	power meter	N/A
Oscilloscopes	HP E1426A	Digital oscillator	8.0
	Tek. SC504	Digital oscillator	10
	Tek. VX4250	Waveform analyzer	10

7.2.3.2 Microwave

MMS is by far the leader in rf and microwave modular instrumentation.

Table 10 is a list of VXI equipment. Similar equipment can be found from other manufacturers. The representative of one vendor said that all instruments may not be available in VXI in the next 5 to 10 years because of the small demand for calibration quality equipment. He said that some products may be developed on the MMS format and that some may not be produced as IOC in any format.

An obvious concern in deciding between the two modular architectures is cost. Tables 11 and 12 show cost data for configurations implemented in VXI and MMS. Direct comparisons (for cost purposes) between equipment shown in the two tables is only valid for the chassis, mainframe, and the power meter. The tables reflect the increased capabilities of MMS in the gigahertz regions.

Table 10. Sampling of available microwave-related VXI equipment

Description	Manufacturer	Parameters	Cost ($)
RF/Microwave Chassis w/ intermodule and backplane shields Model 1261E	Racal-Dana	101 lb	
Series C Mainframe	HP	With command module	8,750
Power meter (HP E1416A)	HP	100 kHz to 110 GHz -70 to +44 dBm	2,600
Oscilloscope (HP E142A)	HP	Digitizing 500 MHz	8,000
Frequency Counter (HP E1333A)	HP	0 -1 GHz	1,000
Generator, Function (HP E1440A)	HP	0-21 MHz	6,000
System Computer	HP		10,000
Gen., Microwave	Racal-Dana	2-170 GHz	
Gen., Microwave (1141A)	EIP	2-20 GHz	
Counter (2151)	Racal-Dana	Up to 20 GHz	
Counter, Univ. (Events, etc.) (2251)	Racal-Dana	Up to 1.3 GHz	
Counter, Pulse, Micro EIP 1230A	EIP	Up to 170 GHz	

Table 11. Component list and corresponding costs for VXI implementation

Description	Manufacturer	Parameters	Cost ($)
Series C mainframe	HP	W/ command module	8,750
DMM (HP E1410A)	HP	6-1/2 digit	4,000
Oscilloscope (HP E142A)	HP	500-MHz digitizing	8,000
Function generator (HP E1440A)	HP	0 to 21 MHz	6,000
Frequency counter (HP E1333A)	HP	0–1 GHz	1,000
System computer	HP		10,000
Gen., Microwave (1141A)	EIP	2–20 GHz	33,900
Counter, pulse, micro EIP 1230A	EIP	Up to 170 GHz	15,400

Table 12. Component list and corresponding cost for MMS implementation

Description	Manufacturer	Parameters	Cost ($)
System mainframe	HP	32 lb., 360 W	7,050
System display	HP	1024 x 400, color	10,400
Power meter (HP 70100A)	HP	100 kHz to 50 GHz, -70 to +44 dBm	3,080
Signal generator (HP 70322A)	HP	0.1 to 4.2 GHz	37,150
Spectrum analyzer (HP 71209A)	HP	100 Hz to 26.5 GHz	67,700
External mixer interface (HP 7990907B)	HP	Interface analyzer & external mixers	9,910
Millimeter mixers (HP 11970V)	HP	50 to 75 GHz	2,920
Millimeter mixers (HP 11970W)	HP	75 to 110 GHz	3,270
Precision frequency reference (HP 70310A)	HP	10, 100 MHz, 0 dBm	5,310

7.3 INTELLIGENT INSTRUMENTS

The widespread availability of microprocessor technology, the advances in software, and the advances in embedded memory have enabled instruments to become vastly more capable than those of a generation ago. The next generation of instruments will employ even higher levels of intelligence through the use of technologies such as those discussed in this section.

7.3.1 Fuzzy Logic

Fuzzy logic is a new and fascinating field. It was invented in the mid-1960s by Professor Lotfi Zadeh at Berkeley. Currently, fuzzy logic is a successful and most promising tool in a variety of applications ranging from consumer electronics and manufacturing to intelligent control and computer equipment. To understand fuzzy logic, consider Boolean logic, which allows only two values (False and True) that are indicated by the numerical values of 0 and 1 respectively. In contrast, fuzzy logic permits a continuous range of values between those two extremes. Contrary to the discrete degree-of-membership for Boolean values (i.e., 0—not a member to 1—definitely a member), fuzzy logic contains a much larger set membership. Correspondingly, the logical operators for fuzzy logic (i.e., AND, OR, and NOT) must manipulate their operands algebraically in order to derive the fuzzy truth value of the result.

Both the Europeans and the Japanese are at the forefront of fuzzy logic development with major projects underway in France, Germany, Italy, and Japan.[81] A key application is in the retrieval of information. This technology allows information to be retrieved based on incomplete or inferred information. This aspect is presented in more detail in Sects. 6.4 and 6.5, which deal with documentation. As evidence of the growing impact fuzzy logic will have on the electronics industry, according to some forecasts, the worldwide market for fuzzy logic semiconductors may total $10 to $13 billion by the year 2000.[82]

Since fuzzy logic has been incorporated into everything from washing machines to telescopes, it is only a matter of time before it appears in test and calibration equipment. The technology is well suited for diagnostic applications where a set of stimuli is applied to the equipment being diagnosed, and, based on a defined or inferred set of criteria, the responses are monitored and the equipment is judged to be operating properly or improperly or the probable cause of the improper operation may be determined. One company involved in the development of fuzzy-based diagnostic equipment is Array Analysis Corporation based in Ithaca, New York.

Fuzzy logic is also finding wide application in the area of control. This is generally in the form of control for multiple input systems, where control output is based on a set of rules or criteria operating on the input values. In this type of system, it is highly probable that there can be overlapping conclusions; that is, two rules consider the same inputs and arrive at two contradictory outputs. The key lies in the fact that the results are generally nonzero, unequal values. Fuzzy logic as applied to such situations determines the degree of correctness between the two outcomes. Essentially, a fuzzy processor accepts discrete (or *crisp*) input, maps it into fuzzy set-membership values, performs the desired processing, and then defuzzies output membership values to produce *crisp* outputs.

This type of processing is of most value when there is no clearcut choice based on the objective data, but rather a subjective assessment must be made. This is, in essence, the same methodology used by an experienced or expert calibration technician operating in the diagnostic repair mode. There is no clearcut answer; the calibration is based on the best compromise between a number of factors such as sufficient accuracy for the intended use, time available to spend on the calibration, etc..

7.3.2 Self-Diagnosis

There is no question that end-use equipment developed in the time frame that this study encompasses will incorporate significantly higher levels of self-diagnostic capabilities. The decreased size of components, the advent of expert systems, and improved microprocessor technology all enable the incorporation of very sophisticated diagnostic routines in equipment. The personal computer and precision digital volt meters of today incorporate a rather comprehensive set of diagnostic routines that are stored in ROM and are executed each time the unit is turned on. This capability provides the user with an almost immediate indication of the equipment's suitability for use. It will be a simple matter to extend this concept to more extensive diagnostic capability.

7.3.3 Diagnostic Equipment

Just as the equipment to be supported becomes more sophisticated, the diagnostic equipment used to support it will also need to be more sophisticated. The technologies available to the field equipment are likewise available to the diagnostic equipment manufacturers. While the systems to be supported will generally, if not always, cost more than the equipment to support it, similar technologies will be employed in both implementations. Therefore, the technologies referenced in this report relating to increased sophistication in the equipment being calibrated will manifest themselves in the calibration and test equipment.

7.3.4 Expert Systems

Expert systems are based on the premise that a large family of problems and the appropriate response can be defined by rules of the form IF/THEN/ELSE. This can better be visualized by an example:

```
voltage_out_of_limit := TRUE
DO WHILE voltage_out_of_limit
        IF (output_voltage .LT. high_limit .AND. output_voltage .GT. low_limit)
        THEN
                "instrument within specifications, calibration complete"
                voltage_out_of_limit := FALSE

        ELSE
                IF (output_voltage .GT. high_limit)
                THEN
                ADJUST VOLTAGE DOWNWARD
                ELSE
                ADJUST VOLTAGE UPWARD
                ENDIF
        ENDIF
END
```

Although the previous is more representative of the form that an expert system implementation takes, it may be easier to understand in the flowchart form, as shown in Fig. 9.

It is important to realize that practical expert systems generally utilize fuzzy logic principles while performing an assessment in order to provide a "region of acceptibility" for specific parameters and conditions rather than a discrete procedure.

This technology is particularly applicable to equipment that does not require direct manual adjustment and can be remotely accessed. While there are sophisticated instruments today that require absolutely no manual adjustment for calibration [e.g., Tektronix's latest model oscilloscopes (as well as others)], many systems in the future that are not quite as sophisticated could benefit from embedded expert systems technology.

7.3.4.1 Augmenting training

One of the most advantageous uses of expert system technology is in the augmentation of personnel training. In a manner of speaking, expert systems have been around in the test arena for quite some time in the form of the troubleshooting charts found in many test and calibration equipment manuals. The chart takes the form of a column containing a set of symptoms or conditions (the IF criteria), a corresponding column containing the course of action (the THEN action), and, finally, a corresponding column containing the alternate path or action to take if the symptom is not met (the ELSE action).

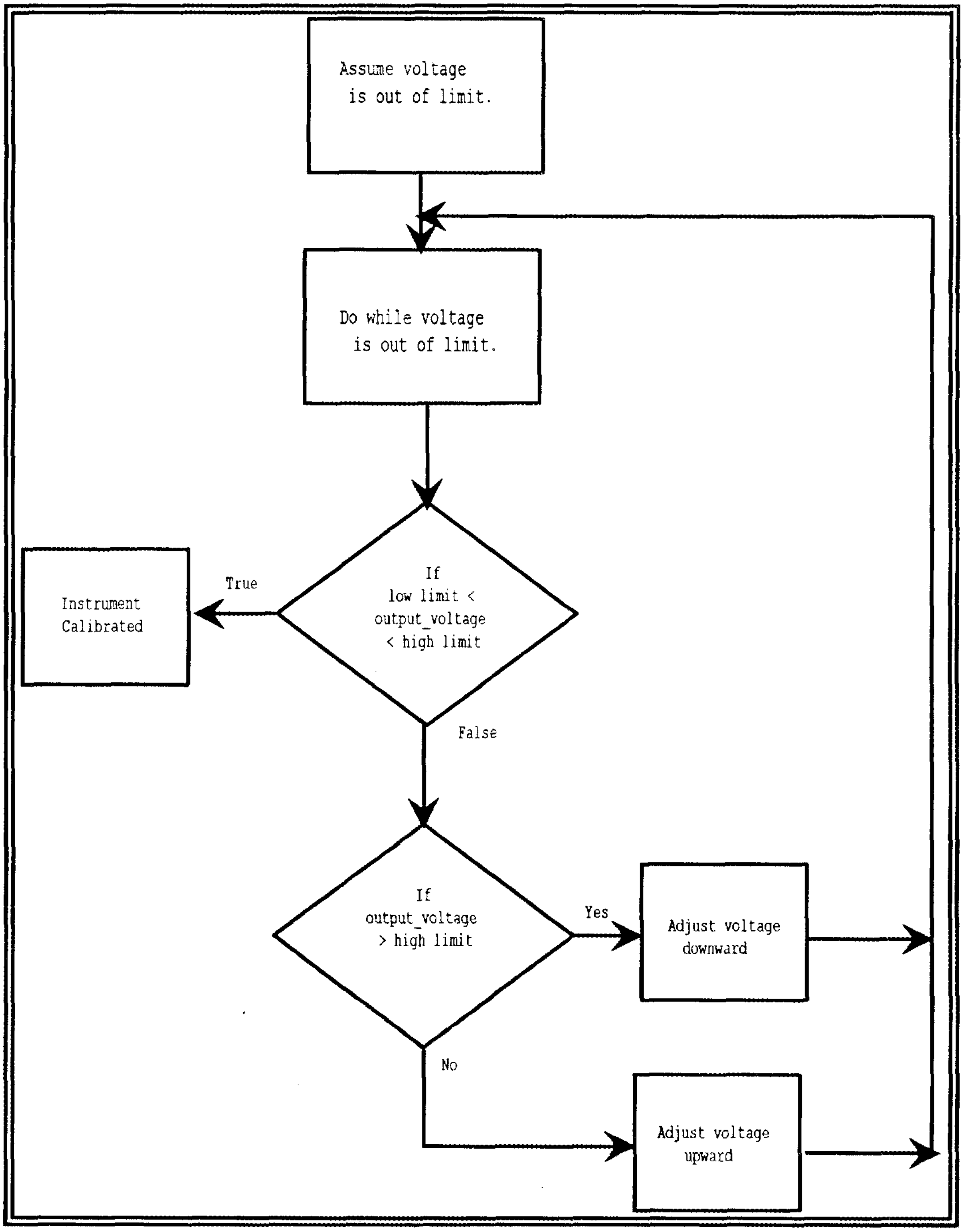

Fig. 9. Flowchart showing logic of expert system for voltage calibration.

Today's expert system implementations are certainly much more sophisticated and encompass concepts borrowed from fuzzy logic. Expert systems have been implemented for the purpose of capturing the knowledge base from individuals who possess a high degree of experience in a particular procedural activity. An automated, optical-disk-based expert system could be extremely useful in compensating for a less well trained support staff both in calibration and test (diagnostic) applications.

7.3.4.2 Impact on documentation and staff size

The absorbtion of diagnostic information into an expert system could have the effect of decreasing the level of documentation required on-site. The procedures needed to diagnose and, for that matter, calibrate equipment would be an integral part of the expert system implementation. Although a certain level of documentation would still be required, a large part of the detailed procedures would be resident within the software-based procedural libraries used to drive the expert system. Although additional personnel are required to initially implement expert systems (information assembly, etc.), the long-term effect can be to reduce personnel requirements in the "field," that is, the end user.

7.4 COMPUTATIONAL RESOURCES

The inclusion of microprocessors and related devices (e.g., memory and communication interfaces) into individual instruments and as the controller for more sophisticated instrumentation systems requires that some consideration be given to the direction that computer-related technologies are taking and will be taking in the next 10 years. The following subsections address these areas.

7.4.1 Processing

The past 10 years have witnessed a phenomenal growth in the application of microprocessors and microcontrollers in all types of equipment. The most obvious has been the personal computer, or PC. Ten years ago the nearest relative to the PC was a single-board computer with extremely limited capabilities. The systems in common use today incorporate billions of bytes of storage, in both random access memory (RAM) and disk, and operate at speeds of 50 MHz and higher. The fact that such systems exist is not as impressive as the fact that they exist in such profusion and at such low cost. The early predecessors of today's microprocessor technology (e.g., Intel 4004, 8008, 8080) contained on the order of 1,000 to 10,000 transistors. The current generation of microprocessors (e.g., the Intel 80386 and 80486 and Motorola 68040 microprocessors) contain 10,000,000 and more transistors. This represents a 1000-fold increase in the number of transistors in just 10 years. There is no reason to believe that the next 10 years will not experience the same (or larger) increase in transistor density. Systems with such capabilities as today's were not even considered by the general population even 8 to 10 years ago. The next 10 years will see an even more impressive integration of microprocessor technology into calibration and test equipment—even to the point that there will not be a single system of even minimal complexity that does not contain a fully operational microprocessor.

7.4.2 Communications

The advent of the PC heralded the availability of reasonable computational resources to the individual user. No longer was the user tied to the commonly shared mainframe system through a "dumb" terminal. The power available in the PC and the need to exchange large quantities of information resulted in the development of ways to allow PCs to communicate. This technology has progressed to the point where most communication between PCs is carried out over complex networks, some of which employ fiber-optic cables to increase bandwidth (there are other advantages such as noise immunity and security). The fact is that reliable, industry-standard mechanisms are being developed to allow microprocessor-based systems to communicate more freely. This technology will obviously have an impact on the overall utilization of computers in network configurations.

7.4.3 Display Technology

The emphasis on display technology may seem out of place in a report aimed at calibration technology; however, with the increased emphasis on the computerization of many of the operations and document storage and display, advances in information display technology become extremely important. The commercial drivers for display technologies include the laptop and notebook computers. These products require rugged, small, power efficient displays that are highly reliable and provide clear information display. In most, if not all, applications, color is becoming mandatory. As has been recognized for a long time, color adds a significant dimension to the display of information.

With the advent of optical storage of large volumes of documentation, high-quality, compact display technology becomes even more important for the display of calibration and test information.

The field environment in which much of the equipment must operate has traditionally dictated that the equipment be militarized. In the case of display technology, significant advances have been made and continue to be made. One of the most promising emerging technologies is the field emission display, or FED.[83] This technology is based on the "cold" emission of electrons from a microtip electrode onto a phosphor screen under the influence of an electric field. The microtip FED technology, which was pioneered by SRI International in the 1960s, is essentially a flat, matrix addressed cathode ray tube (CRT), with the large, bulky, hot cathode of the CRT replaced by large numbers of tiny semiconductor cold cathodes. It uses only a fraction of the voltage of a conventional CRT and is much more efficient than liquid crystal displays, or LCDs. However, it is much less efficient than a CRT.

Another contender in the display markets is the passive LCD. Passive LCDs have long suffered from limitations, including limited viewing angles, slow response time, low contrast, and nonuniformity in gray-scale display applications.

7.5 HIGH-VOLUME STORAGE TECHNOLOGY

The storage of large volumes of documentation, calibration information, and expert system information requires ever-increasing storage capacity, both read-only and read-write storage.

Data compression is receiving more and more attention as a parallel solution to the storage problem. Lossless data compression techniques such as Huffman coding and Ziv-Lempel-Welch (LZW) compression can reduce storage requirements by factors of 2 and even 3. For information such as photographs, lossy compression techniques may be applicable. Using these techniques, 50:1 compression ratios are possible.

7.5.1 Magnetic Media

Another area that may be enhanced by advancing technologies is high-density data storage. Near-field magneto-optics are being used to achieve data densities of about 45 Gbits/in.^{2}, which is

100 times denser than the best commercial magnetic-optic technologies and 300 times denser than the best magnetic media.[84,85]

7.5.1.1 Disk

The market for high-capacity, small-volume magnetic storage media is being driven by the PC market with significant advantages for applications directly or indirectly utilizing computer storage technology. While optical disk storage offers very high volume, it has traditionally been significantly slower than magnetic storage. In this regard, and considering the recent advances in magnetic storage, if the trend continues through the time period considered by this study, magnetic media will present a very attractive alternative.

The current state of the technology can be assessed from reports of 1-GB, 3-1/2-in. drives and 2-GB, 5-1/4-in. currently being available. As of the time of this report, Fujitsu Computer Products of America has announced a 2-1/2-in. drive with a capacity of 250 MB. Since the major problem with hard disk technology is head crashes when the drive is subjected to extreme mechanical shock, several companies are actively attacking the problem. A new line of 1.8-in. disk drives has a capacity to 85 MB and an operating shock rating up to 100 G's. Typical 1.8, 85-MB drives have operating shock ratings of 10 to 20 G's.

7.5.1.2 Tape

Although magnetic tape has been a mainstay for information processing for a number of years, newer technolologies appear to be surpassing magnetic tape. The assessment team feels that other technologies offer more advantages than magnetic tape.

7.5.1.3 Card

Magnetic card technology has advanced significantly during the past few years to the point where personal pocket planners are programmed directly from magnetic cards. Such technology could be applied to rapid configuring of equipment and to hold calibration requirements for specific equipment. In the course of configuring a calibration setup, all of the calibration information can be read from a magnetic card. The results of the calibration could be stored on a magnetic card, which could then be filed for later reference. This would be an alternative to equipment that did not contain internal memory for data storage.

7.5.2 Optical Media

The storage of information by means of magnetic recording has been the mainstay of recording technology for many years. However, recent advances in optical storage technology have swept the field, offering higher storage density, higher reliability, more rugged media, and noncontact read/write. The write-once, read-many (WORM) aspect of optical storage was a detracting factor for many applications that require updating of information. This was typically accommodated by taking advantage of the high capacity to completely rewrite the information being updated. Later advances support the rewriting of information.

7.5.2.1 Disk

The traditional advantages of magnetic disk storage have included rapid, random access to relatively large quantities of information. Optical disk storage provides the same advantages with the added advantage of higher capacity, more rugged media, and the lack of susceptibility to magnetic fields. The advances in optical storage technology over the past 5 years are a good measure of the advances that can certainly be expected over the next 10 years. As an example, Kodak Information Systems has made available an optical disk system that supports storage of 10.2 Gbits on a single optical disk.* The capacity of such systems should continue to increase in the future. A storage technique for application to optical disks, which provides for a factor of 1000 increase in capacity, has been developed and patented by researchers at ORNL.

7.5.2.2 Tape

Advances in optical tape storage have progressed to the point that off-the-shelf optical tape storage units are now available. A unit available from CREO Products, Inc., is claimed to store 1 TB (1,000,000 MB) on a single 12-in. reel of tape.† While this current physical size of the drive unit (77 in. tall, 19-in. rack mount) is prohibitive for location in a calibration van, it could certainly meet the needs of central documentation storage. The vendor claims that a single reel of optical tape is equivalent to 5000 standard reels of magnetic tape or 1000 5.25-in. optical disks. This technology may advance within the next 10 years to the point that smaller drives are available, making them suitable for inclusion in a calibration van. They would be used in a manner similar to optical disk (i.e., storage of documentation, technical manuals, software, etc.). The primary advantage is the lower cost of the media itself.

7.6 SOFTWARE

As can be seen from Table 3, although software technology already plays a key role in instrumentation, it is expected that software will become the dominant factor in systems of all types. In the recent past, the software costs associated with any given system were generally estimated at 75% of the associated hardware costs.‡ They have now reached at least 125% of the hardware costs and continue to increase as a result of lower hardware costs, higher software content, and increased sophistication and complexity of software. The fact is that a substantial portion of the cost of an IFTE system is in the preparation, updating, and distribution of the TPS software that drives the system. As a result of the continued concern over the ubiquitous nature of software, development cost, maintenance cost, and reliability, the software industry is continually trying to find better ways of implementing software. These have included structured software development methodologies (e.g., Yourdon), higher level programming languages (e.g., C, C++, Object Oriented Programming), sophisticated run-time source code debuggers, and a wide range of other computer-aided software engineering (CASE) tools. The fact that instruments have complex software (and will have even more complex software) embedded within them indicates that even more powerful and complex software will be required to maximize overall system capabilities. All of the systems such as IFTE and CASS will utilize more complex software as the systems are

*Kodak Optical Disk System 6800 - 10.2 GB, Eastman Kodak Company, Kodak Information Ssyetms, Rochester, NY 14653-4535.

†CREO Model 1003 Optical Tape Recorder. Product available through ICI Imagedata, Wilmington, Delaware 19897, Telephone: (302) 886-3000.

‡Based on past estimating procedures used by ORNL Instrumentation and Controls Division.

asked to perform more sophisticated tests and analyses. As an example of the rapid expansion of software, at ORNL, as little as 20 years ago, Digital Equipment Corporation PDP 8-e computers were used extensively for real-time data acquisition and control applications throughout the laboratory. These systems contained 8 kB of RAM memory and, if a system had a disk drive, it was a 32-kB, fixed-head (nonremoveable) drive. A complete system cost on the order of $100K. Contrast this to systems that are used in similar applications (with obvious increased functionality) today. Such systems typically have 4–8 MB of memory and 100 MB of disk storage as a minimum. This is a result of lower hardware costs and the increased functionality of the application software. Similar trends are occurring throughout industry. To anticipate these trends and be aware of their impact, USATA should maintain a very active role in software trends and assessment. Software will be the most expensive and all-pervasive component in instrumentation systems of the future.

8. SITE VISITS/THIRD PARTY CONSULTATIONS

A series of visits to third parties (other users of test and calibration equipment), trade conferences, and equipment manufacturers was planned as a part of this study activity. The purpose of these visits was to gather additional information from facilities that had similar interests and problems relating to test and/or calibration, assess the trends in equipment that relates to test and calibration (particularly physical and mechanical standards), and determine the directions key test and calibration equipment manufacturers were taking for the near future.

8.1 U. S. AIR FORCE CALIBRATION LABORATORY

This facility was selected as a third party site visit, particularly to discuss the Portable Automatic Test Equipment Calibrator (PATEC) program. A trip was scheduled for late September of 1992 and arrangements made to visit the facility; however, conflicts prevented this visit from taking place.

8.2 JOHN FLUKE INSTRUMENTS

A visit was made to the Fluke facility located in Everett, Washington. While Fluke is a member of the VXI bus consortium, they currently decline to produce products that conform to the standard. Fluke is a high-end "standard-grade" test and calibration equipment manufacturer. They believe that VXI is a commodity item and does not provide the high degree of quality commensurate with their corporate product goals. We were given a tour of the main office complex that includes the administrative offices as well as the fabrication/assembly area for Fluke's line of "hand-held" instruments, a market in which Fluke has a dominant position. These instruments are intended primarily for the industrial field environment. They are cased in plastic and are relatively low in cost.

We were also given a tour of the facility that assembles the Fluke 5700A High Precision Multimeter. Of particular interest was the procedure used for the calibration of the completed units. The units are compared with a set of field standard units rather than being sent off-site to a calibration laboratory. The reference units used for the calibration are not removed and sent to a separate calibration facility since this would impact production. Rather, a random sampling of units is sent to the calibration facility at the main facility and checked against standards. A record of how well the units perform is maintained and used as a gauge as to how well the "standard" units being used in the production facility are performing. Fluke maintains that this method ensures that the outgoing units are calibrated without having to have multiple test and calibration sets for the production site (so that the units can be rotated through the calibration facility) or having to suffer downtime while the standard units are being calibrated .

8.3 HEWLETT-PACKARD

The Hewlett-Packard facilities located in the following cities and the corresponding technology areas are

- Lake Stevens, Washington/VXI-Based Data Acquisition Input/Output Modules,
- Santa Rosa, California/Modular Measurement System Development,
- Loveland, Colorado/VXI-Based Instruments, and
- Atlanta, Georgia/Calibration Facility.

Although a visit was made to the Lake Stevens facility, schedule conflicts precluded having a meeting.

Specifics regarding the technology areas at each of these sites is provided in Sect. 7.2.

Hewlett-Packard is committed to the VXI standard and offers a comprehensive line of instruments in the VXI form. A catalog on the 75000 series of VXI instruments is available from HP under the publication number 5091-1587.

The visit to the Atlanta, Georgia, facility confirmed that HP is committed to the MMS concept, especially for higher frequency instruments. The visit also revealed that HP keeps their calibration function distinctly separate from the repair facilities. They are, however, located within close physical proximity. They have developed their own internal inventory tracking software that generates calibration reports. They are currently talking with a customer about marketing the software.

HP is also pushing the MMS technology, an HP-originated open standard. The MMS architecture was carefully thought through from an instrumentation and reconfiguration perspective and certainly offers a more rugged form factor.

8.4 TEKTRONIX

A visit was made to the Tektronix facility located in Beaverton, Oregon. This facility designs and manufactures Tektronix's line of test equipment. We were shown the assembly and test areas for Tektronix's TDS line of oscilloscopes. This is a very advanced product line and includes features like an analog front end that can be fully calibrated electronically, a high performance modular microprocessor, and a video graphics adapter (VGA) quality display. There are no potentiometers to adjust for setting gain, etc. The four-channel front end has been designed as a modular unit that can be used in a number of devices. It can be fully calibrated electronically with variations from nominal performance stored within memory as correction factors. This is a real advantage in a production line environment. The unit is connected to a calibration stand and a series of preprogrammed, calibrated signals are injected into the unit's inputs. The units are monitored electronically, and the calibration adjustment signals to the front end unit are adjusted in response to the excitation/response characteristics. This completely eliminates the laborious manual process of "twiddling" the calibration pots and watching the results. The final test and calibration check are performed using a rack of calibrated instruments designed to test all aspects of the instrument. Unlike Fluke, Tektronix has three sets of calibration equipment that are rotated out for calibration. While some of the older product line items still require hands-on calibration, it is very clear that Tektronix is moving rapidly toward, and has arrived at, equipment that can be fully calibratable electronically, multimicroprocessor-based instruments that incorporate internal diagnostics to verify proper operation on instrument power-up.

8.5 SENSORS EXPOSITION

A member of the ORNL assessment study team attended the 1992 Fall Sensors Exposition held in Chicago, September 29–30, 1992. This conference had been attended by ORNL staff members in previous years and is considered to be an excellent source of information on the current state of the art in the sensor manufacturing industry. The conference consists of 3 days of technical sessions with talks by representatives from industry, universities, and government research laboratories primarily in the United States. There is also an excellent hardware exhibit with over 300 industrial participants. Many of the exhibits were manned by technical as well as sales personnel, which provided a good opportunity to learn about new and impending products in the physical and optical sensor areas.

The exhibit illustrated the rapidly emerging nature of monolithic smart sensor technology. At least 30 U.S. companies now manufacture solid state sensors of various kinds. Sensors and transducers without at least built-in signal conditioning electronics are actually becoming hard to find. Smart sensors with internal digital compensation and communications interfaces are becoming more common. Some companies, such as Monolithic Sensors, Inc., are beginning to provide application-specific sensors designed (or specified) by the customer. This technology seems to offer some interesting possibilities for physical calibrations in a CALSET 2000 system.

The technical sessions were oriented toward emerging technology areas such as sensor fusion, smarter sensors, fuzzy logic and sensors, microfabrication techniques, and integrated sensor systems.

8.6 ARRAY ANALYSIS, INC.

A visit was made to Array Analysis, Inc., in Ithaca, New York, by ORNL and TMDE staff members. The main objective was to learn more about their automated test system called ExperTest 2000. This system is attractive because of a proprietary fuzzy logic-based diagnostic system that can be "trained" rather than "programmed" to perform automated circuit or system diagnostic testing.

The ExperTest 2000 consists of a hardware unit that combines conventional logic analyzer and digital oscilloscope functions and uses an Intel 80386/80486 based PC as the operator interface. The fuzzy logic diagnostic software runs on the PC and communicates with the analyzer by an IEEE-488 interface. There is also an optional PC interface card that extends the PC bus into the logic analyzer for high-speed data transfer.

Demonstrations of the fuzzy logic system are very impressive. The time to develop an automated circuit board test is greatly reduced in comparison with conventional ATE systems. Its ability to "learn" provides a possible means of developing an automated test for a complex system without extensive software development. The price range of the system (starting at about $25K) may make it attractive to consider using it as an auxiliary to existing ATE systems to perform additional maintenance diagnostics on DUT elements.

This fuzzy logic application, which is certainly an emerging technology, will be of significant benefit to the CALSETS 2000 system, at least in the Repair Workstation.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 CALIBRATION VAN CONFIGURATIONS

The assessment study was focused on emerging technologies that could have an impact on the CALSETS in the year 2000. Because of the emphasis placed on the downsizing of the calibration vans in light of current Department of Defense cutbacks, this area is being addressed specifically in relation to each of the technology areas.

Technologies that (1) extend the calibration intervals of equipment, including end-item, calibration, and test equipment; (2) aid in reducing the data or information to a more readily usable form; (3) reduce the physical size of the equipment; and (4) assist the technician with calibration, test and repair procedures, and data recording were all considered to be of key importance.

The first area addressed by the study was technologies associated with DC and low-frequency AC and the impact they could have on the calibration van configurations. The conclusions reached by the assessment study in this area are as described below.

A major impact will be made by increased use of instruments that perform statistical self-analysis (i.e., monitor their own data and parameters). Instruments employing self-analysis can extend calibration intervals and can eliminate the lost time spent checking instruments that are still within calibration limits. The same can also be said of the other instrument categories that were subjects of this study. Instruments that are able to self-correct or compensate for drift will minimize calibration uncertainties and extend calibration intervals. These self-assessment capabilities will result in decreased downtime for field standards-type equipment because end items do not have to be recalibrated when it is found that the standard was out of calibration (remediative calibration). This should result in a long-term decrease in field calibration costs. Continued technological advances will result in more stable instruments, and the increased use of microprocessor technology will mean "smarter" instruments. This makes the concept of a multifunction transportable reference standard (MTS) more feasible. These microprocessor-controlled transportable reference standards will facilitate more accurate field calibration. This will enable intrinsic standards to be taken to the field and entire systems calibrated in place rather than having to break the system apart to calibrate individual instruments.

Credibility is added to such a concept by examining the recent technological advances that make such an MTS closer to reality. For example, precision voltage, current, and resistance devices already exist, and VLSI technology is achieving the component and circuit densities required for such an instrument.

Probably the most immediate technological application for DC and low-frequency AC calibration would be a migration to the modular instrument technologies being expounded in the technical literature.

In the area of microwave technology, the following conclusions regarding USATA needs and technology advances seem reasonable:

1. Based on projected communications and radar needs, the current percentage of equipment will grow significantly beyond the current 10%.

2. On the basis of buy-cycle projections, the frequency coverage will most likely increase to about 100 GHz by the year 2000.

3. The power density of microwave amplifiers will continue to increase.

4. Within the time frame considered by this study, cabling should replace waveguides to 100 GHz, at least for low-power, short-distance paths. This will replace several bands of waveguide with a single cable.

5. Within the same time frame, IOc should be significantly impacting the size of microwave instrumentation. This will be achieved through MMIC technology.

6. Amplifier technology, through the application of such emerging technologies as HBTs, diamond semiconductors, and band gap engineering, will provide greater density and higher levels of performance.

The following conclusions apply to the area of physical and mechanical sensor and instrument technologies:

1. Field instruments that are purely mechanical in nature will gradually be replaced by instruments with built-in electronic "smart" sensors. This will occur by attrition even if the Army makes no active effort to facilitate the change. However, a concerted effort (e.g., by the TEMOD program) could definitely accelerate this process and, in turn, impact the CALSETS 2000 physical and mechanical workstation.

2. Smart field sensors with self-monitoring and/or redundant capabilities will be calibrated only when needed rather than on a routine schedule.

3. Smart field sensors will have on-board, nonvolatile memory that will store the calibration history of the unit. The CALSETS 2000 system will access this information via a digital communication interface.

4. Miniature "application specific" monolithic sensors will permit the incorporation of a small and highly automated "physical calibration" subsystem into the CALSETS 2000 concept.

The following conclusions relate to the area of electro-optical calibration:

- The use of EO technology for both military and industrial applications will expand greatly over the next 10 years. This will require increased levels of calibration support by CALSETS 2000. This topic is covered in more detail in Sect. 9.3.

Recommendations

In the area of DC and low-frequency AC, the assessment team believes that USATA should continue to follow the emerging standard modular instrumentation architectures since these can have a significant impact on physical size and on the common integration of the user interface. Because of the ever-increasing impact of software in this class of equipment, USATA should continue to become more knowledgeable in software-based integration and automation. This will impact not only DC and low-frequency AC but most other calibration areas as well. USATA should also become a very strong advocate of self-checking instrument technology, which can improve technician efficiency and instrument reliability.

Although it applies to all areas, it is particularly timely for DC and low-frequency AC that USATA assume a "major player" role in consortia and working groups in order to influence device miniaturization, foster exploration of novel techniques for communication with and between modular instrumentation, and influence the standardization of instrument and sensor bus hardware and protocols.

A focus should be established which outlines the requirements for MTS devices needed to support CALSETS 2000.

Recommendations in the area of microwave technologies include performing time and frequency calibrations by means of GPS; minimizing the microwave power requirements of the calibration vans, especially below 2 GHz; and monitoring developments in amplifier technology with the resulting decrease in size, especially above 1 GHz.

On the basis of trends in physical sensor technology discussed in the preceding sections and extensive experience in the calibration and use of process sensors in critical nuclear applications, the following recommendations are made for CALSETS 2000 application.

1. Reduce the calibration requirements (workload) through the use of improved sensor technology. The purely mechanical devices such as pressure gauges, torque wrenches, and dial indicators will gradually be replaced by smart devices with electronic sensors.[86] While many of the existing mechanical devices will still be in use 10 years from now, the trend will certainly be toward increasing the number of smart mechanical instruments containing electronics, sensors, and microprocessors.
   Smart transducers will be available that will measure or compensate for several different parameters. A common application is a flow sensor that also contains pressure and temperature measurements. Transducers that contain two or more independent redundant measurements of the same parameter are already available, which, combined with self-monitoring algorithms, can reduce or eliminate the need for scheduled maintenance and/or calibration. Some manufacturers are already claiming self-calibration features for their sensors.[87] Self-calibration will not, however, eliminate the need for calibration to establish traceability, but methods for in situ testing and calibration using new diagnostic techniques are being developed [88,89] for the nuclear and chemical process industries. This self-monitoring capability will permit scheduled calibration intervals to be extended or perhaps eliminated completely.

2. Further reduce the size and quantity of physical standards in the CALSET. Miniature sensors with performance comparable to that of many of our present laboratory standards can replace most of the present calibration set physical and mechanical standards. Nanofabrication technology for monolithic sensor systems will probably provide the capability for reasonably low-cost "application-specific" sensors[90,91,92] that could be designed specifically as a CALSETS 2000 physical standards subsystem. Artifact standards such as weights and gauge blocks can also be replaced by precision sensors, although the desirability of doing so would depend on the type of field equipment being supported.

3. Incorporate more automation for physical calibrations into the CALSETS 2000 "workstation" concept: Smart field devices will be easier to calibrate with an automated system. Both the DUT and the physical calibration subsystem will be monitored by the CALSETS 2000 computer. DUT sensors will have nonvolatile memory for storage of calibration constants and historical records. The calibration system (CALSETS 2000) might only have to access this information (via the sensor's digital interface) and automatically determine what, if any, calibration is required. If needed, a calibration could be performed either by bringing the DUT to the physical calibration subsystem or by installing a reference sensor in the field process and

analyzing the DUT signals while the system is operating. Wireless transmission (ir, rf, ultrasonic), which is becoming available in some smart sensors, might eliminate the need to physically connect the DUT to a CALSETS interface port. For example, the physical standards subsystem might include a torque calibration fixture consisting of a few torque bolts with built-in sensors. A torque wrench (DUT) would be calibrated by simply using it to tighten one of the bolts on the fixture. The DUT signal and the reference torque signal would be recorded and analyzed by the CALSETS 2000 data system. Similarly, the standard pressure gauges might be replaced with high-performance smart sensors that could be installed in the operating process to perform in situ calibration of field devices, aided by intelligent (possibly fuzzy logic) monitoring and analysis software in the CALSETS 2000.

9.2 COMMON TEST AND CALIBRATION EQUIPMENT

During the course of this study, several discussions have been held regarding the degree to which the accuracy of test equipment begins to approach that of calibration equipment. Not too many years ago it was believed or required that calibration equipment must have at least a factor of 10 higher accuracy than the equipment to be calibrated. This was in some cases achievable since there was an inherent gap between calibration-grade and general test equipment. In general, more money and effort went into the development of high-resolution, high-accuracy calibration equipment, and the equipment was certainly not used in a general test environment. Progress in solid state electronics design and fabrication methods provided improved accuracy of the general test equipment. Many of these improvements have resulted in significantly lower prices. The result has been a narrowing of the gap between high-accuracy, high-resolution calibration equipment and high-quality test equipment.

The ratio between calibration and test equipment is currently 4:1; that is, the equipment used to perform calibrations must be at least four times more accurate than the equipment to be calibrated.

For example, an HP 3458A Digital Multimeter has the following accuracies: 6 ppm for 24 h in dc volts, 2.2 ppm for 24 h in ohms, 100 ppm mid-band AC volts, and 8 ppm (4 ppm optional) per year voltage reference stability, yet costs only $7K. Why not use this type of instrument (or its VXI equivalent) for both test and calibration? While $7K may seem to be excessive for a piece of *test* equipment, that cost must be compared with the cost of maintaining separate equipment for each task.

It would seem prudent then to consider the general trends in test and calibration equipment and anticipate the coming developments. This merging of equipment could result in significant savings in space, support costs, documentation, and training. Of course, there are still instances when lower cost test equipment is more practical, especially for on-site maintenance external to the actual calibration van.

9.3 ELECTRO-OPTICAL DEVICE CALIBRATION

Already a large amount of visible and near ir optics technology is imbedded in military equipment. A limited deployment of an EO calibration set has been part of the current CALSETS for many years. A portable EO test set (AN/PSM 80 V4 Electro Optics Augmentation) is under development for eventual deployment as part of the IFTE. The use of fiber optics and integrated optoelectronic sensors will expand well beyond the present communications and "optical" applications.[93,94,95] Instruments of all kinds will use optical rather than electronic sensors. Some devices will utilize dedicated optical processors rather than conventional microprocessors for certain applications. There is no doubt that this technology will require higher levels of calibration and test support by CALSETS 2000.

In a sense, many of the technology trends and recommendations discussed in the previous section for physical sensors are applicable to EO calibrations. Radiometric calibration standards and methods are not as well established as are many of the other physical parameters. However, like the other physical sensors, optical sensors and systems are also becoming "smarter" and easier to calibrate, and similar concepts can be applied. An EO calibration "subsystem" can be incorporated into CALSETS 2000 along with, or as a part of, the physical calibration "subsystem."

9.4 TRAINING

The technologies reviewed in this report are aimed to a large extent at changes in equipment that affect the functionality, efficiency, accuracy, and reliability. The impact that these technologies will have on training will occur in two areas: (1) increased capabilities such as intelligence (expert systems) and self-monitoring within the instruments will make the instruments easier to use and therefore require less user training and (2) the technologies will aid in the training of personnel. The KATIE technology developed at ORNL demonstrates expert system technology applied to training. This expert system-based device can aid the user in diagnosing (or calibrating) equipment, but it can just as easily serve as a training aid in familiarizing personnel with equipment operation.

9.5 SUPPORT TEAM CONFIGURATIONS

An objective of the assessment activity was to examine the possibility of decreasing the 286/287 support team size. It is possible that reduction of the van configurations to a single van for all cases might allow reduction of the support team; however, there are other factors that influence this decision such as the types of equipment serviced, personnel safety, and workload. Therefore, a review of these issues should be undertaken by administration, in light of technical feasibility, to determine if it is reasonable to reduce the support team size.

9.6 EQUIPMENT SUPPORT PHILOSOPHY

The emerging technologies discussed in this report will affect the manner in which equipment is supported. As instrumentation becomes more reliable and is capable of going for longer periods between calibrations, the frequency at which it must be removed from service will decrease. This can result in more effective use of the equipment and a smaller logistics support organization. Maximum advantage should be made of technological advances that impact equipment support since these can have a cascading effect on personnel and material costs.

9.7 DOCUMENTATION SUPPORT

During the course of this assessment study, members of the ORNL study team made a visit to the logistics support teams' facility at the Redstone Arsenal and witnessed a demonstration of document transfer to optical storage media.

The demonstration was impressive, not so much from the technology standpoint, but rather from the initiative.

9.8 GENERAL CONCLUSIONS AND RECOMMENDATIONS

This report addresses emerging technologies that may have an impact on USATA within a 10-year time frame. To transition into these technologies, specific steps should be taken in the very near future to position USATA. This section contains conclusions and recommendations that are not keyed to specific technology areas but rather serve as a foundation proposal for the next steps that should be taken. The concept of a test bed is based on a longer term program to assess applicable technologies with a focus on instrumentation that will decrease the size of the 286 and 287 van configurations. As software becomes even more dominant in instrumentation and instrumentation systems, the need to keep abreast of, and actually influence the capabilities of, this software becomes extremely important. A test bed would provide the means for assessing appropriate technologies, both hardware and software based, and for actively influencing the direction the technologies take, particularly with regard to USATA needs.

A baseline proposal for test bed development is provided. This architecture presented in this proposal is intended to serve as a reference only. The actual configuration, equipment, and software would be determined as a part of the test bed development activity.

With regard to general trends in calibration and test equipment, the following assumptions are considered to be quite relevant to the reconfiguration of the calibration vans:

1. Computers, as microcomputers or microprocessors, will be ubiquitous but mostly invisible components of most, if not all, measurement systems and field units that are submitted for calibration.

2. The trend for instruments to become smarter, smaller, and more accurate will continue. Smart instruments and transducers will usually cost less to purchase and will certainly cost less to maintain.

3. The more compact instrumentation will allow downsizing of the calibration set into a helicopter-liftable field unit.

4. Calibration instruments and standards will be more compact. Miniaturization will progress from VXI and MMS modular IOC all the way to IOc.

5. Except for rare cases, instruments will no longer have manual controls, front panels, or displays. They will instead be modular units connected by a data bus through a computer-controller to a graphical user interface that will provide the controls and displays.

6. By means of a *virtual instrument* interface, such as LabView, a set of core instrument modules can be configured into many application-specific, virtual instruments by simply reprogramming.

7. All of the required instruments and test sets can be simulated as virtual instruments using the core set of instruments. There are several important consequences:

- The total number of different instrument modules that must be carried into the field will be reduced; thus the volume, weight, and power requirements of CALSETS 2000 can also be reduced.

- Since virtually any calibration or test setup can be simulated with the core instrument modules, older calibration procedures will not have to be rewritten since the required functions can be simulated through the a graphical user interface and virtual instruments.

8. Calibration procedures will be on optical storage and will be available on-line.

9. Read/write optical storage will be common and inexpensive. All field calibration units will be updated through satellite links so that all units will be using a common set of procedures and software.

10. With expert system technology, the progress of the calibrations can be monitored in the background, and the technician can be informed when test parameters are out of tolerance and told what to do about it.

11. Just as the digital controls share a common bus among instrument modules (e.g., IEEE-488 or RS-232), analog input and output buses will allow the multiplexing of instruments among the calibration workstations.

12. The units that are to be calibrated in the field will also become smarter with the addition of microcomputer controllers. Routine calibrations will disappear because these field units will also be self-calibrating and self-monitoring. At most, the self-calibrating units will require the use of one or two external standards that will commonly be used for a broad range of units (e.g., one 10,000-Ω standard resistor that will be used as an external standard for a wide number of different units).

13. "Smart" field units will have on-board, nonvolatile memory that will be used to record the calibration history of the unit. Thus, each unit or instrument will carry its own calibration record.

14. With self-monitoring and self-calibrating capabilities, field units will be calibrated only when needed instead of on a routine schedule. This will reduce the workload of the field calibration units, and hence the staffing can be reduced.

15. LabView or similar graphical interface controller software will be multitasking and be capable of operating in a multiprocessor local area network.

16. LabView is now implemented on both Macintosh 680xx-based computers and IBM or IBM clone 80X86-based computers. The joint Apple, IBM, and Motorola project to develop a common reduced instruction set processor and operating system will allow the successors to LabView to run on a wide variety of computers. In support of open architectures, additional real-time, multitasking, multiuser software must be investigated.

17. Displays will be color flat panels that will reduce the weight and volume required in the calibration set. The user interface will be graphical, in color, and will use flat-panel displays

and possibly touch-screen controls and will most certainly utilize some form of manual pointing device such as a mouse or pen.

18. Little or no manual data entry will be required. Field unit identification will be input by bar codes or similar technology. Data will be taken and recorded by the measurement system.

19. Each field unit will be included in a worldwide Army data base so that SPC can be monitored for each unit. Calibration and maintenance data will be uploaded during off-shift via satellite link to the central data base system for analysis and storage.

20. Fast fiber-optic data buses and cableless ir data links will supersede the IEEE-488 instrument bus (probably within the next 5 years).

21. With the downsizing of the defense budget, modernization of equipment and instrumentation will be spotty. As a result, several generations of instruments and equipment will have to be supported in 2000 and beyond.

22. Solid state micro sensors will be incorporated into equipment and instruments to measure and correct for environmental conditions.

23. Most of these smart, solid state sensors will be inexpensive because they will be mass produced for the automobile industry. Mil Spec versions will not be needed since the commercial sensors will be sufficiently ruggedized for military use. This will also be true of most of the instruments and standards used in CALSETS 2000.

One objective of the CALSETS 2000 is to reduce the size of the package that must be transported to the field. Presently, the calibration equipment is packaged on two large trucks and driven to the field location trailing a 30-kW motor generator set. The crew size is seven to nine, and it is desired that this also be reduced. The 286 set is presently overweight for off-road military requirements and is operating on a waiver. Therefore, weight reduction is essential. Volume and weight are, of course, correlated, but lightweight modules and chassis would also be helpful.

We assume that by the year 2000 most of the needed test equipment will be available as modules. This will provide the volume and weight reduction needed. Using LabView (for example) and existing IEEE-488 instrumentation, the CALSETS 2000 can be simulated today by means of virtual instruments and existing equipment that can be configured to resemble the instruments and standards we assume to be available and needed by 2000.

Because of downsizing and stretched-out procurements, CALSETS 2000 will have to support multigeneration technologies. With a LabView-like interface, the calibration and test procedures will not have to be rewritten unless it is desired to take advantage of the greater capabilities of the core instruments in CALSETS 2000.

However, some, but not all, calibration procedures will still need to be written or updated to take advantage of more capable instrumentation of the CALSETS 2000. The chief advantage of using virtual instruments is that a set of core instrument modules can be configured through software to simulate any needed instruments. In this way the Army could continue to use the older calibration procedures, but the actual measuring instruments would consist of the core modules programmed to resemble the instruments and standards called out in the procedures. Probably the majority of the procedures could continue to be used with the virtual instruments. This will provide a significant saving in time and cost in implementing the CALSETS 2000.

Although there is a significant initial cost associated with conversion to a virtual instrument environment, the use of virtual instruments will provide future flexibility and will reduce the need for specific hardware to support calibrations. The conversion cost must be weighed against continuing to do business as usual with the associated operating costs. Through the virtual instrument interface, the hardware needs only to provide the required functions. By divorcing the calibration hardware from the need for specific items, the calibration hardware can easily be modified and upgraded without affecting the remainder of the calibration interface, setup, or procedures.

Just as the digital signal and data lines are multiplexed through the successor to the IEEE-488 interface (which may be a fiber-optic-based system), the low-level analog signal lines will also be multiplexed (i.e., time shared) to reduce the number of pieces and volume of equipment needed for the calibration set. For instance, one DVM module would be time shared among two to four calibration technicians.

Each workstation will be provided with a standard interface panel for output and input connections. Similarly, instruments and modules under test would also be provided with standardized matching interfaces.

Figure 10 illustrates a general concept for a test bed implementation based on some of the above recommendations.

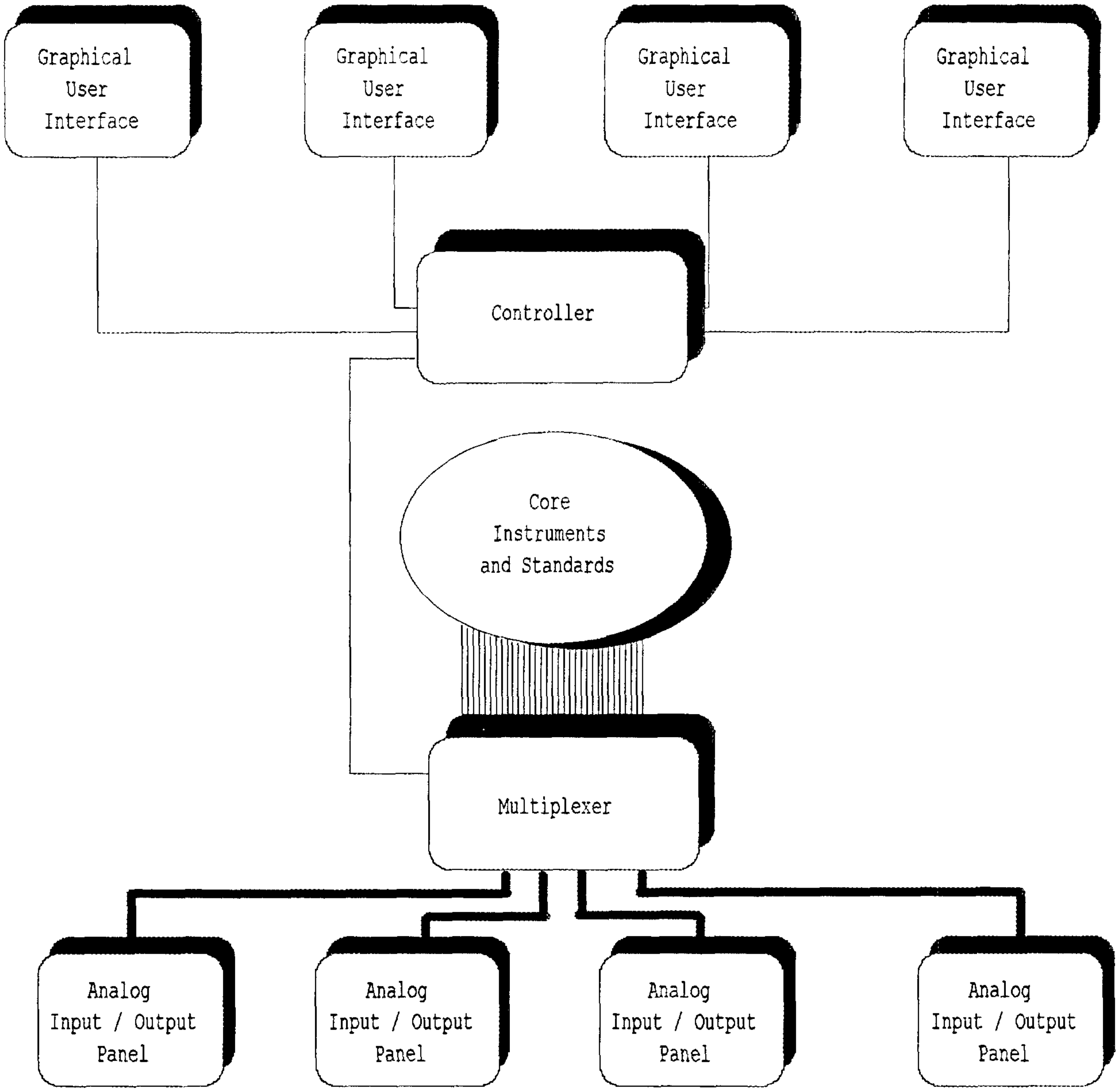

Fig. 10. Block diagram of CALSETS 2000 implemented through a virtual instrument interface, a set of core instruments, and standards with multiplexed inputs and outputs.

10. FOLLOW-ON ACTIVITIES

To benefit from the assessment study, the following work is proposed. USATA is urged to consider initiating a developmental effort to maximize an understanding of the advantages of the technologies presented in the body of this report.

10.1 OBJECTIVE

The objectives of this proposed work are to

1. Assemble a working test bed of CALSETS 2000 using off-the-shelf instrumentation.
2. Use the test bed to demonstrate the flexibility of virtual instruments to simulate any desired instrument or test set.
3. Develop a model graphical user interface based on human factors considerations.
4. Have USATA use the working test bed CALSETS 2000 system for evaluation of new equipment and concepts.

10.2 APPROACH

A flexible test bed system should be assembled to demonstrate and experiment with various options for the envisioned CALSETS 2000. The test bed should be a working system that can carry out actual calibration procedures yet be adaptable to varying needs as technology evolves. The test bed should be implemented with existing USATA equipment, modular instruments such as VXI or MMS, together with a state-of-the art controller and graphical user interface. The volume or area of the test bed will *not* be minimized. This must await the commercial development of smaller modules and the projected IOc. What can be demonstrated with the test bed system is the man–machine interface, the segmentation of the system using the virtual instrument interface into a set of core instrument modules and standards that can be used to simulate any desired instrument or test setup, and the limitations on the time sharing of the core set. The CALSETS 2000 test bed should be a breadboard system. That is, the various components will be spread out for easy access and experimentation. The exception will be the workstation area. The workstations must be arranged in a compact array so that people can experiment with possible physical arrangements that might be fielded (see Fig. 11). Once the test bed is set up and made functional, typical Army operators of this equipment could be brought in to get their reactions and suggestions for recommended configuration. Advice should also be sought from the Army's Human Engineering Laboratory.

Use of the virtual instrument interface would allow many possible arrangements of the workstation consoles and patch panels.

The approach to be followed would be to develop test bed specifications (e.g., system software, initial equipment complement, displays) and then design the system to meet these specifications. Some modules, particularly newer VXI modules, will have to be purchased. The system controller and display systems will be designed and assembled. A possible arrangement is shown in Figure 12.

Various configurations of the workstation console could be easily tried. The use of virtual instruments would allow the actual calibration instruments to be separated from the workstation console, giving great freedom in the arrangements of the displays and input/output panels.

A number of standard calibration procedures should be selected to exercise a variety of functions. The appropriate virtual instrument graphical user interface displays could be developed and the calibration procedures automated. After a shakedown period to integrate all the functions of the test bed, a series of calibrations will be performed using the system—first locally, then with Army military calibration personnel from TMDE, and finally with technicians who have had actual experience in using this type of equipment in the field. Any modifications that are needed will be made after these operational tests.

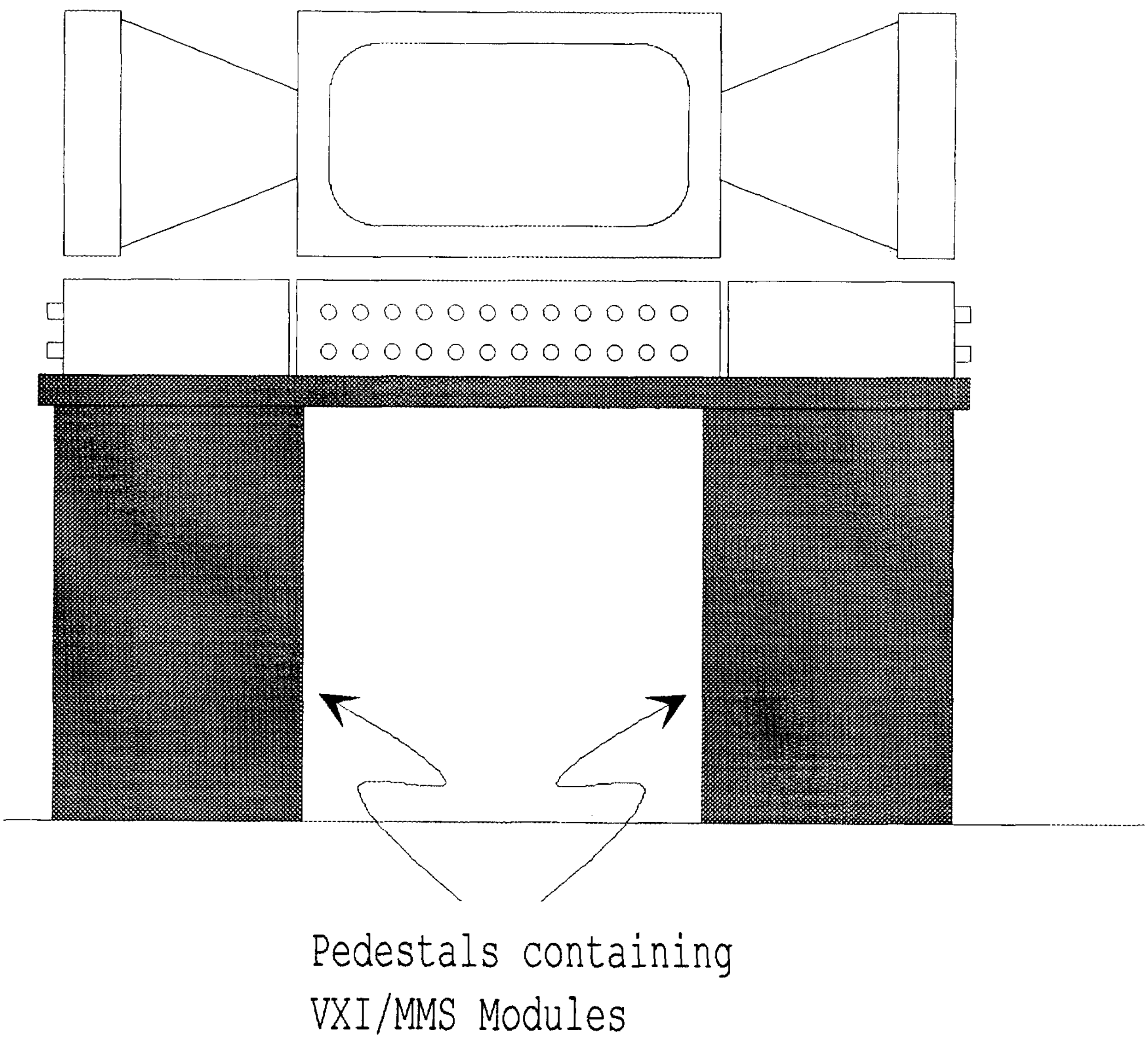

Fig. 11. Possible design of CALSETS 2000 test bed workstations.

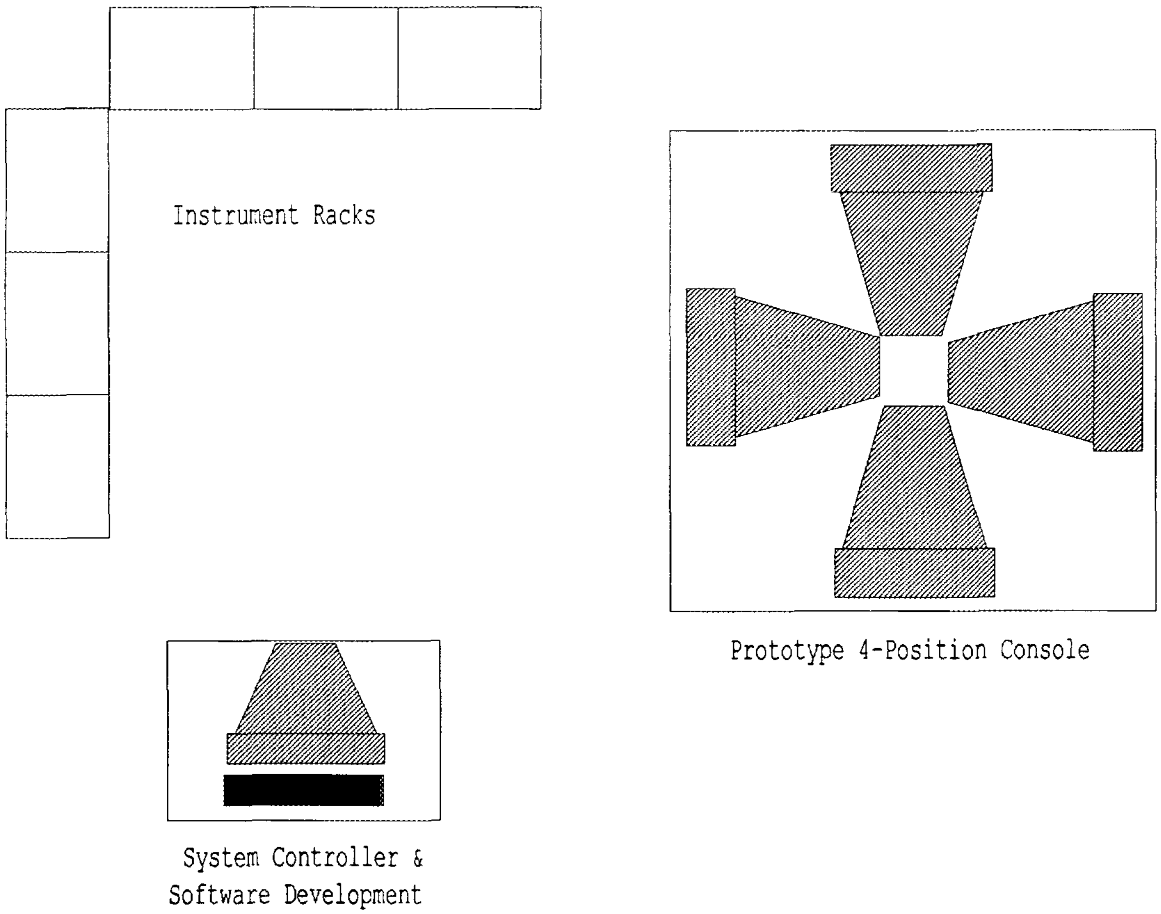

Fig. 12. A proposed layout of the test bed for demonstrating CALSETS 2000 principles.

10.3 DESCRIPTION OF THE PROPOSED CALSETS 2000 CONCEPTUAL DESIGN

CALSETS 2000 is divided into four device-independent modules linked by software, data buses, and signal lines. A more comprehensive understanding of the conceptual design can be gained from Fig. 13.

10.3.1 User Interface

The graphical user interfaces (GUIs) are presented on color displays at each workstation. For the purposes of prototyping, these displays may be large-screen CRT monitors. If color flat-panel displays are available at a reasonable cost when the test bed is implemented, these may be used instead.*

The GUI can be designed to resemble the front panel(s) of familiar instruments or be entirely customized for the calibration procedure being performed. Data or commands are entered

*IBM has just announced a new notepad computer, "Thinkpad 700T," that employs a color flat-panel display that was developed jointly with Toshiba. It is described in the November 1992 issue of Byte on pp. 50 and 51.

by the operator on flat-screen displays with handwriting recognition—using such new technology as the Apple "Newton," PDA (personal digital assistant).

10.3.2 Virtual Instrument Interface

Currently, the most advanced software system that provides the graphical user interface and a virtual instrument interface is LabView, which is available for both the Macintosh and for Windows 3.0. LabView will be installed on the system controller to provide the graphical user interface and the virtual instrument interface.

The interface system will use the hardware in the core module (see Sect. 10.3.3) to simulate virtual instruments. Because the controller must provide different virtual instruments to different users at nominally the same time, it must also control a time-sharing multiplexer that will distribute the virtual instrument's physical outputs and inputs to the different workstations on a time-sharing basis so that it is transparent to the user. In other words, more than one user may use an instrument at the "same" time. The system controller will synchronize the switching of all input and output signals. Multitasking is not currently a feature of LabView; so it may have to be simulated as well.

10.3.3 Calibration Instrumentation—Core Hardware Module

The hardware module may be a mixture of (1) individual, stand-alone instruments and (2) VXI or MMS IOC modules. Instrument modules can be mixed and matched to provide any desired measurement or signal generation function. An assembly of functional modules can be configured and reconfigured through software into any of several instruments or instrument functions. Simulating this on a single controller may not be feasible, in which case each workstation would have a separate controller, and a system controller would act as a master controller to coordinate these individual controllers. Since only one set of measuring instruments and calibration standards is needed for four to six workstations, considerable savings in weight and volume will be obtained.

10.3.4 Multiplexer

The multiplexer takes all of the input and output lines from the core module and distributes them to the appropriate I/O panel at each workstation. Again, it may not be feasible to carry this out with a single unit. Instead, it may be necessary to parallel the signal leads from the core module to each of four individual multiplexers, one for each workstation.

10.3.5 Analog Input/Output Panels

Each workstation will be equipped with a generalized analog input/output (I/O) panel where signals to the core module are available for the units under test. Both input and output signal lines are multiplexed. The local controller synchronizes the multiplexers to the analog I/O panel. Connections are made from the panel to the instrument or transducer under test. Some high-powered signal sources may be connected directly to one of the output/input panels but would still be controlled by the system controller.

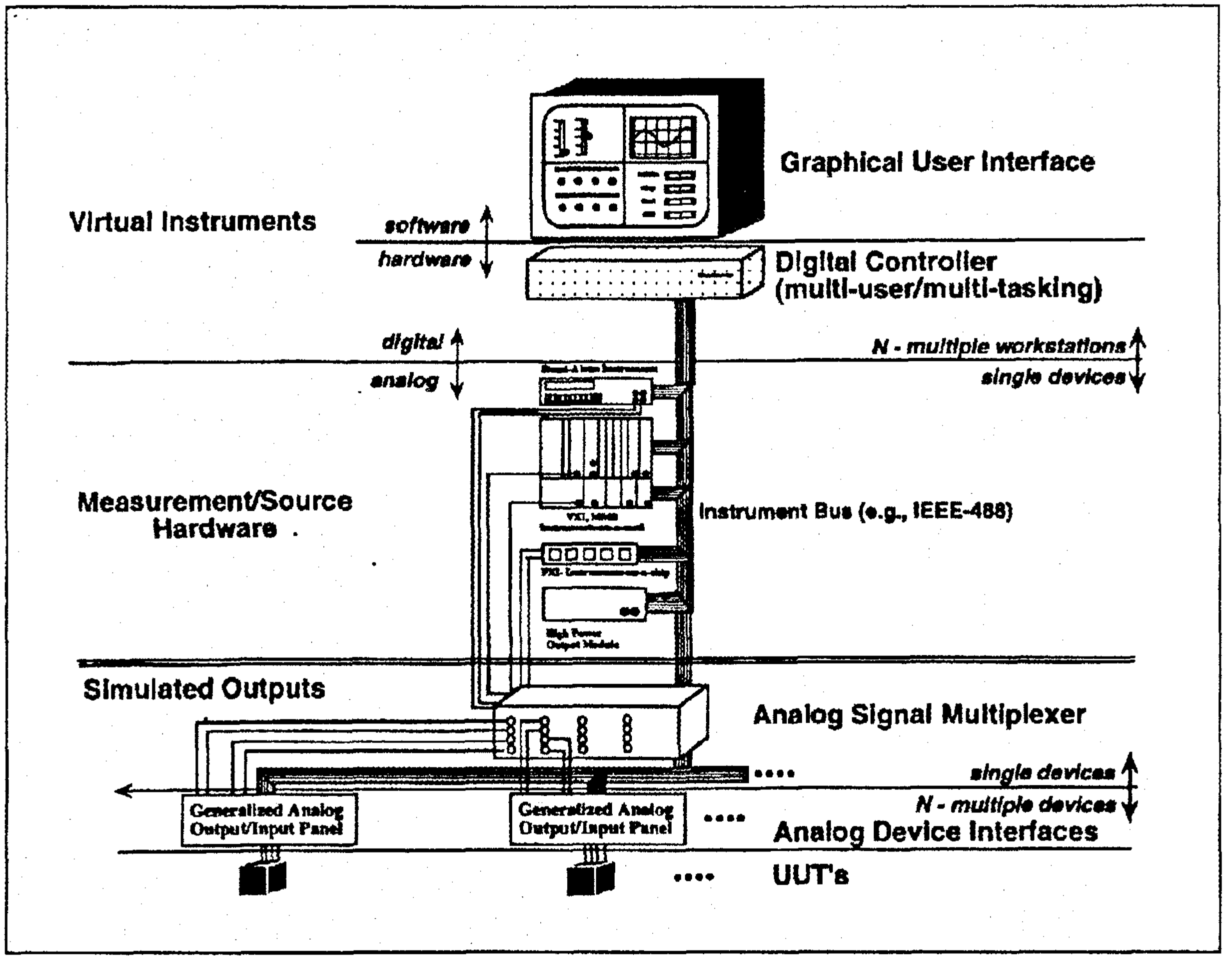

Fig. 13. A more detailed diagram of the proposed CALSETS 2000 test bed.

10.3.6 Units Under Test

The units under test (UUT) may be past or present generation. (The Army is required to support old equipment that has been supplied to the National Guard for several years after it is no longer in the active Army inventory.)

The virtual instrument interface in Module I can be designed to present the operator with the most useful interface. It is not limited by existing hardware since it exists entirely in software. Virtual instruments can include control knobs and switches, strip-chart recorders, scopes, meters, etc. Internally the virtual instruments may include signal processing modules. The user interface and local control in Module I can present the UUT with input and read the output. If the UUT can be digitally controlled, the local controller can do this also.

Again, the four workstations are physically and logically independent. They are linked to the core module hardware by software through the virtual instrument interface. This independence means that one module can be changed or upgraded without the need for altering any of the other modules (within the limits of the convention for the interface between modules). This is equally valid for hardware as well as software modifications.

11. REFERENCES

1. R. Dove et. al., *21st Century Manufacturing Enterprise Strategy,* Lehigh University, Pa., 1991.

2. Richard Dove, from presentation at Oak Ridge Y-12 Plant on Nov. 30, 1992. Dove was co-chairman of the Core Team that produced the *21st Century Manufacturing Enterprise Strategy,* conducted at Lehigh University in 1991.

3. The Art of Forecasting, A brief introduction to thinking about the future, World Future Society, 1992.

4. Arthur C. Clarke, *Technology and the Future*, 1967.

5. J. M. Connell, "Forecasting a New Generation of Electronic Components," p. 14 in *Proceedings, IEEE Compcon 1981*, San Francisco, 1981.

6. James P. Womack, Daniel T. Jones, and Daniel Roos, *The Machine That Changed the World*, Rawson Associates, New York, 1990, pp. 20–21.

7. H. Pothier et. al., *Single-Electron Pump Based on Charging Effects*, Service de Physique de l'Entat Condes'e, Centre d'Etudes de Saclay, 91191 Gif-sur-Yvette, France, Jan. 14, 1992.

8. U.S. Army TMDE Support Group, The CARES Book, U.S. Army Calibration and Repair Evaluation System (CARES), AMXTM-OA, Redstone Arsenal, Ala., June 1, 1990.

9. U.S. Army TMDE Support Group, The CARES Book, U.S. Army Calibration and Repair Evaluation System (CARES), AMXTM-OA, Redstone Arsenal, Ala., June 1, 1990.

10. R.L. Anderson and G.N. Miller, "Reduction of Storage Related Instrumentation Failures," presented at Instrument Society of America Conference, 1989.

11. R. P. Feynman, "There's Plenty of Room at the Bottom," Miniaturization, Reinhold, 1961.

12. E. Clayton Teague, "Nanotechnology—What's Happening in the U.S.," *Proceedings of Institute of Physics Conference on Nanotechnology*, London, UK, May 23, 1990.

13. A. Franks, "Nanotechnology," *Journal of Physics E, Scientific Instrumentation* **20,** 1442-1451 (1987).

14. "EE's Tools & Toys," *IEEE Spectrum*, p. 59 (July 1992).

15. J. Kohlmann, P. Gutmann, and J. Niemeyer, "Upscaling DC Resistance Using a Josephson Junction Array," *IEEE Transactions on Instrumentation and Measurement* **41**(1) (August 1992).

16. S. S. Osofsky and S. E. Schwarz, "Design and Performance of a Non-Contacting Probe for Measurements on High-Frequency Planar Circuits," *IEEE MTT* **40**(8), 1701–1708 1992.

17. "EE's Tools & Toys," *IEEE Spectrum* p. 59 (July 1992).

18. J. Marczewski, M. Zachau, A. Asenov, F. Koch, and D. Gruetzmacher, "A Diode Device Combining Lateral Field-Effect Transport and Vertical Tunneling in a Multi-Quantum-Well Heterostructure," *IEEE Electron Device Letters* **13**(6) (June 1992).

19. D. Jaeggi and H. Bates, "Thermoelectric AC Power Sensor by CMOS Technology," *IEEE Electron Device Letters* **13**(7) (July 1992).

20. D. Rossi, J. Song, E. Fossum, P. Kirchner, G. Pettit, and J. Woodall, "A Resistive-Gate In0.53Ga0.47As/InP Heterostructure CCD," *IEEE Electron Device Letters* **12**(12) (December 1991).

21. W. Peatman, T. Crowe, and M. Shur, "A Novel Schottky/2-DEG Diode for Millimeter- and Submillimeter-Wave Multiplier Applications," *IEEE Electron Device Letters* **13**(1) (January 1992).

22. D. Yang, Y. Chen, T. Brock, and P. Bhattacharya, "DC and Microwave Performance of a 0.1-um Gate InAs/In0.52 Al0.48 As MODFET," *IEEE Electron Device Letters* **13**(6) (June 1992).

23. J. Hong, N. Shin, T. Jen, S. Ning, and C. Chang, "Graded-Gap a-SiC:H p-i-n Thin Film Light-Emitting Diodes," *IEEE Electron Device Letters* **13**(7) (July 1992).

24. Y. Jun, S. Rha, S. Kim, J. Roh, W. Kim, and H. Lee, "The Fabrication and Electrical Properties of Modulated Stacked Capacitor for Advanced DRAM Applications," *IEEE Electron Device Letters* **13**(8) (August 1992).

25. H. Liu, A. Steele, M. Buchanan, and Z. Wasilewski, "Long-Wavelength Infrared Photoinduced Switching of a Resonant Tunneling Diode Using the Intersubband Transition," *IEEE Electron Device Letters* **13**(7) (July 1992).

26. S. Ito, D. Kwong, V. Mathews, and P. Fazan, "Highly Reliable SiO_2/Si_3N_4 Stacked Dielectric on Rapid-Thermal Nitride Rugged Polisilicon for High-Density DRAM's," *IEEE Electron Device Letters* **13**(7) (July 1992).

27. R. Woolnough, "Credit Card PC Developed," *Electronic Engineering Times*, Issue 684, p. 20 (Mar. 16, 1992).

28. "An Open Supercomputer Emerges," *Military & Aerospace Electronics*, **3**(1), 13 (January/February 1992).

29. "PCXI Challenges VXI in Growing Modular ATE Arena," *Military & Aerospace Electronics*, p. 14 (November 1991).

30. D. Zandusky and J. Pichler, "Virtual Instrument for Instantaneous Power Measurements," *IEEE Trans. Instru. Meas.* **41**(4), 528–534 (August 1992).

31. M. A. Weiss and D. W. Allan, "An NBS Calibration Procedure for Providing Time and Frequency at a Remote Site by Weighting and Smoothing of GPS Common View Data," *IEEE Trans Instru. Meas.* **IM-36**(2), 572–578 (June 1987).

32. D. M. Lyons et al., "VXI Evaluation Test Bed," *IEEE Trans. Instru. Meas.* **41**(1), 144–146 (February 1992).

33. D. P. Morgan, *Surface-Wave Devices for Signal Processing*, Elsevier Science Publishers B.V., 1985.

34. P. J. Edmonson et al., "Injection Locking Techniques for a 1-GHz Digital Receiver Using Acoustic-Wave Devices," *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.* **39**(5), 631–637 (September 1992).

35. S. N. Ivanov, "The Use of Yttrium-Rare Earth Aluminium Garnet Solid Solutions for Bulk-Acoustic-Wave (BAW) Devices," *IEEE Trans. Ultrason., Ferroelec., Freq. Contr.* **39**(5), 653–656, (September 1992).

36. R. W. Ralston et al., "Cooperating on Superconductivity," *IEEE Spectrum*, pp. 50–55, (August 1992).

37. P. L. Richards et al., "Superconductor-Insulator-Superconductor Quasiparticle Junctions as Microwave Photon Detectors," *Appl. Phys. Lett.* **36,** 480-482 (Mar. 15, 1980).

38. R. P. Robertazzi et al., "$Y_1Ba_2Cu_3O_7$/MgO/$Y_1Ba_2Cu_3O_7$ Edge Josephson Junctions," *Appl. Phys. Lett.* **61** 711–713 (Aug. 10, 1992).

39. K. K. Agarwal, "Superconductors and MMICs in Microwave Systems—A Special Report," *Applied Microwave Magazine*, pp. 72–81 (Spring 1992).

40. R. C. Booton and H. R. Fetterman, "Advanced Millimeter-Wave Solid-State-Device Research," *Microwave Sys. News* **18**(12), 68–73 (December 1988).

41. G. Gao, H. Morkoc, M. F. Chang, "Heterojunction Bipolar Transistor Design for Power Applications," *IEEE Trans. Electron Devices* **39**(9), 1987–1997 (1992).

42. D. C. Scott et al., "60 GHz Sources Using Optically Driven Heterojunction Bipolar Transistors," *Appl. Phys. Lett.* **61,** 1–3 (July 6, 1992).

43. M. B. Das, "Millimeter-Wave Performance of Ultrasubmicrometer-Gate Field-Effect Transistors: A Comparison of MODFET, MESFET, and PBT Structures," *IEEE Trans. Elec. Dev.* **ED-34**(7), 1429–1440 (July 1987).

44. R. C. Booton and H. R. Fetterman, "Advanced Millimeter-Wave Solid-State-Device Research," *Microwave Sys. News* **18**(12), 68–73 (December 1988).

45. F. Ali et al., *Microwave and Millimeter-Wave Heterostructure Transistors and Their Applications*, Artech House, Norwood, Mass. (1989).

46. R. C. Booton and H. R. Fetterman, "Advanced Millimeter-Wave Solid-State-Device Research," *Microwave Sys. News* **18**(12), 68–73 (December 1988).

47. J. T. Glass et al., "Diamond, Silicon Carbide and Related Wide Bandgap Semiconductors," Materials Research Society, Pittsburgh, Pa., 1990.

48. R. C. Booton and H. R. Fetterman, "Advanced Millimeter-Wave Solid-State-Device Research," *Microwave Sys. News* **18**(12), 68–73 (December 1988).

49. T. J. Drummond et al., "Quantum-Tailored Solid-State Devices," *IEEE Spec.*, pp. 33–37 (June 1988).

50. R. C. Booton and H. R. Fetterman, "Advanced Millimeter-Wave Solid-State-Device Research," *Microwave Sys. News* **18**(12), 68–73 (December 1988).

51. M. Feng et al., "Ultra Low-Noise Performance of 0.15 Micron Gate GaAs MESFET's Made by Direct Ion Implantation for Low-Cost MMIC's Applications," *IEEE Microwave & Guided Wave Letter* **2**(5), 194–195 (May 1992).

52. L. Raffaelli and E. Stewart, "A Standard Monolithic Transmitter for 38 GHz PCN Applications," *Microwave Journal* **35**(10), 24–30 (October 1992).

53. R. Basset et al., "10 Watt, MBE GaAs FET Power Amplifier," *Applied Microwave Magazine,* pp. 62–74 (Summer 1992).

54. A. Platzker et al., "Development of Highly Dense Four-Stage Flat-Gain 1-W 6-18-GHz MMIC Power Amplifier Chip," *IEEE J. Solid-State Circ.* **27**(10), 1405–1411 (October 1992).

55. T. Apel and S. Ludvik, "A Compact High-Gain, 2-20-GHz MMIC Amplifier," *IEEE, Solid-State Circuits* **27**(10), 1463–1469 (October 1992).

56. G. Hegazi et al., "A 0.5-Watt 47-GHz Power Amplifier Using GaAs Monolithic Circuits," *IEEE Microwave & Guided Wave Letter* **2**(2), 61–62 (February 1992).

57. T. N. Ton et al., "A W-Band, High-Gain, Low-Noise Amplifier Using PHEMT MMIC," *IEEE Microwave & Guided Wave Letter* **2**(2), 63–64 (February 1992).

58. M. N. Solomon et al., "A Monolithic Six-Port Module," *IEEE Microwave & Guided Wave Letter* **2**(8), 334–336 (August 1992).

59. S. S. Osofsky and S. E. Schwarz, "Design and Performance of a Non-Contacting Probe for Measurements on High-Frequency Planar Circuits," *IEEE MTT* **40**(8), 1701–1708 (1992).

60. R. Basset et al., "10 Watt, MBE GaAs FET Power Amplifier," *Applied Microwave Magazine*, pp. 62–74 (Summer 1992).

61. Frank J Bartos, "Configurable Transmitter Bridges Digital and Analog Worlds," *Control Engineering*, pp. 40–41 (November 1990).

62. George J. Blickley, "Electronics, Materials Advance Pressure Measurement," *Control Engineering*, pp. 57–59 (May 1992).

63. Robert B Stockdale, "New Digital Control Systems Need Better Temperature Sensors," *Control Engineering*, pp. 63–67 (November 1991).

64. Romel Bhullar, Flour Advanced Controls , "DP Transmitters Revisited," *Control Engineering*, pp. 38–41 (September 1992).

65. Tom McCusker, "Neural Networks and Fuzzy Logic, Tools of Promise for Controls," *Control Engineering*, pp. 84–85 (May 1990).

66. Henry M. Morris, "Microsensors Enhance Process Variable Transmitters' Abilities," *Control Engineering*, pp. 122-125 (October 1991).

67. C.C. Collins, "Miniature Passive Pressure Transensor for Implanting in the Eye," *IEEE Trans. Biomed. Eng.* **BME-14**(2), 74–83 (1967) .

68. Ylva Backlund et al., "Passive Silicon Transensor for Biomedical Remote Pressure Monitoring," pp. 58–61 in *Proc. 5th Int. Conf. on Solid-State Sensors and Actuators*, Vol. A21–A23, 1990.

69. Brian L. Evans, Monolithic Sensors Inc., "Pressure Sensor Application Specific Integrated Circuits," *Proceedings—Sensor Expo—Chicago, Ill., October 1992.*

70. Seldon Crary et al. Solid State Electronics Laboratory, Univ. of Michigan, "Digital Compensation of High Performance Silicon Pressure Transducers," pp.70–72 in *Proc. 5th Int. Conf. on Solid-State Sensors and Actuators*, Vol. A21–A23, 1990.

71. Paul B. DuPuis, Honeywell Military Avionics, "A Matchbook-Sized Smart Pressure Transducer for Critical Applications," *Proceedings—Sensor Expo—Chicago, Ill., October 1992.*

72. M. Madou, Teknekron Sensor Development Corp. and F. Maseeh, Intellisense Corp., "Feasibility and Practicality of Monolithic Sensors," *Sensors, the Journal of Machine Perception* (September 1992).

73. F. Maseeh and F. Pourahmadi, "Computer-aided Development of Silicon Sensors and Microstructures," *Proc. Sensor Expo, Chicago, Ill., October 1992.*

74. H. Newton, "Imaging Systems We'd Like On Our Desks," *Imaging Magazine,* pp. 41–53 (December 1992).

75. C. M. Horak, J. A. Jefferies, and A. G. Roberts, Instrumentation and Controls Division, "Knowledge Based Assistant for Troubleshooting Industrial Equipment," Authoring Manual, personal communication, June 1991.

76. Larry Carlson, *VXIbus Overview*, Hewlett-Packard Company, VXIbus Compendium of Papers, February 1991.

77. "mms—The RF and Microwave Standard," pamphlet prepared by MMS Consortium Member Companies, September 1991.

78. Modular Measurement System, HP7000 Family Catalog, April 1991, Hewlett-Packard Company, Catalog # 5952-217 EUS.

79. Modular Measurement System, HP7000 Family Catalog, April 1991, Hewlett-Packard Company, Catalog # 5952-217 EUS.

80. Fred Bode, "Microwave Wars: VXIbus vs. MMS," *Evaluation Engineering*, pp.44–49 (May 1990).

81. R. Colin Johnson, "Europe Gets into Fuzzy Logic," *Electronic Engineering Times,* pp. 31, 33 (Nov. 11, 1991).

82. Roger Woolnough, "SGS-Thompson to Make Fuzzy ICs," *Electronic Engineering Times*, pp. 31, 33 (Nov. 11, 1991).

83. Linda Bernier and David Lieberman, "Pixel Grabs Lead in FED Display Race," *Electronic Engineering Times,* Issue 715, pp. 1, 8 (Oct. 19, 1992).

84. E. Betzig et al., "Near-Field Magneto-Optics and High Density Data Storage," *Appl. Phys. Lett.* **61**, 142–144 (July 13, 1992).

85. T. E. Bell, "Innovations," *IEEE Spectrum* **29**(10), 11, 17 (October 1992).

86. Henry M. Morris, "Microsensors Enhance Process Variable Transmitters' Abilities," *Control Engineering,* pp. 122–125 (October 1991).

87. George J. Blickley, "Electronics, Materials Advance Pressure Measurement," *Control Engineering,* pp. 57–59 (May 1992).

88. Tom McCusker, "Neural Networks and Fuzzy Logic, Tools of Promise for Controls," *Control Engineering,* pp. 84–85 (May 1990).

89. J. L. Riner, AMS Corp, "In-Situ Testing of Industrial Sensors," *Control Engineering,* pp. 175–176 (October 1991).

90. Henry M. Morris, "Microsensors Enhance Process Variable Transmitters' Abilities," *Control Engineering,* pp. 122–125 (October 1991).

91. M. Madou, Teknekron Sensor Development Corp., and F. Maseeh, Intellisense Corp., "Feasibility and Practicality of Monolithic Sensors," *Sensors, the Journal of Machine Perception* (September 1992).

92. F. Maseeh and F. Pourahmadi, "Computer-Aided Development of Silicon Sensors and Microstructures," *Proc. Sensor Expo, Chicago, Ill., October 1992.*

93. J.B.D. Soole et al., "Fast High-Efficiency Integrated Waveguide Photodetectors Using Novel Hybrid Vertical/Butt Coupling Geometry," *Appl. Phys. Lett.* **61,** 13–15, (July 1992).

94. Z. Z. Ho et al., "Electro-Optic Phenomena in Gelatin-Based Polymer," *Appl. Phys. Lett.* **61,** 4–6 (July 1992).

95. T. L. Cheeks et al., "Magnetic and Magneto-Optic Properties of Epitaxial FerroMagnetic MnAl/(Al/Ga)As Heterostructures," *Appl. Phys. Lett.* **60,** 1393–1395 (March 1992).

Appendix A

LIMITED DEPLOY CAPABILITY

Army Calibration System Transfer Limited Deploy Capability Available To Army Area TMDE Support Teams (ATST) TMDE Support Operation (TSO) or TMDE Support Center (TSC)

Parameter	Equipment	Range	Frequency	Error Limits
Power RF Source	Signal Generator NARDA 18500-19A	5 kW (peak)	0.92 to 1.25 GHZ	± 0.7 dB
RF Peak Power Measurement	Peak Power Calibrator Boonton HP 8900B	200 mw	50 MHz to 2.0 GHz	± 0.6 dB
	w/NARDA 2936 Atten	5kW	0.92 to 1.25 GHz	± 0.7 dB
Azimuth Measurement	Fixture Azimuth Test (7691596)	0 to 6400 mils		± 0. 15 mil
Pressure Measurement (Hydraulic)	Hydraulic Pressure Standard (MIS-35941)	0 to 10,000 psig Hydraulic		± 0.05% Reading from 1,000 to 10,000 psig; ± 0.07% reading from 500 to 1000 psig; ± 0.1% reading from 200 to 500 psig; and ± 0.2% reading from 0 to 200 psig.
*Pressure Manometer	Manometer (APN 7915892)	0-2500 Pa		± 0.1% full scale
	High Pressue Gauge (APN 7916290)	0-20,000 psi		± 0.1% full scale
	High Pressure Gauge (APN 7916291)	0-40,000 psi		± 0.1% full scale
Air Speed	(MIS-30859/1)	0 to 400 knots		± 0.1 knot from 120 to 400 knots ± 0.2 knot from 0 to 120 knots.
Differential Pressure	(MIS-30859/1)	0 - 120 in.-$H_2$0		± 0.05% reading from 10% full scale to full scale
Flow Measurement	Flow Rate Meter Kit Shutte & Koerting,18200	0.6 cm^3/min to 41 gallon/min of water		± 2% full scale
		2.2 cm^3/min to 110 ft^3/min of air		± 2% full scale
	Flow Transfer Kit MIS-10391A	1.0 to 50.0 gallon/min		± 0.35% R
	Positive Displacement Flowmeter MIS-10418	0.01 to 2.0 gallon/min		± .20% R
	Gaseous Flowmeter Assembly, Size 10 (APN 7913480)	1.0 to 10.0 gallon/min		± 0.5% full scale
	Gaseous Flowmeter Assembly, Size 30 (APN 7913481)	3.0 - 30.0 ft^3/min		± 0.5% full scale
	Gas Flowrate Calibrator 450 CC Capacity - 1055	0 - 450 cm^3		± 0.2% of indicated volume
Force Measurement	Load Cells and indicator	400 - 60,000 lb		± 0.1% Reading
Specific Gravity Measurement	Hydrometer Kit FIB 11-582	0.07 to 2.0		± 0.2% of Reading
	ASTM 82H-62	0.65 to 0.71		± 0.2% of Reading
Torque Measurement	Torque Cell, Lebow and Indicator	0 - 20,000 ft-lb		±0.5% applied torque above 20% full scale.
Ionizing Radiation Measurement	Calibrator Set (RADIAC) AN/UDM-2	0 - 600 R		± 20%
		0 - 1000 R		±30%
	Calibrator (RADIAC) AN/UDM-7C	0 - 10^6 counts/min		±20%
	Calibrator Set (RADIAC) AN/UDM-6	0 - 2,000,000 counts/min		± 5%

Appendix B

AN/GSM-287 CAPABILITY

Army Calibration System Transfer AN/GSM-287 Capability Available To Army Area TMDE Support Teams (ATST) TMDE Support Operation (TSO) or TMDE Support Center (TSC)

Parameter	Equipment	Range	Frequency	Error Limits
Current, AC Source and Measurement	Ammeter Calibrator Holt 250 (APN 7912648), AC Driving Source KH410OA/7500A (APN 7915950-1)	0.010- 0.100 A	50 Hz-20 kHz	± 0.03-0.05%
		0.100- 1 A		± 0.05-0.15%
		1 - 10 A		± 0.05-0.15%
		10 100 A		± 0.05-0.20%
	Range Extender Holt 90254	100 - 500 A Source	50 - 400 Hz	±0.25% IR
Voltage, AC Measurement	Thermal Transfer Voltmeter JF 54OB/AB	0.5 - 500 V	5 Hz - 50 kHz	± 0.03% IR
		500 - 1000 V	5 - 50 kHz	± 0.05% IR
		0.5 - 50 V	50 - 100 kHz	± 0.15% IR
		100 - 500 V	50 - 100 kHz	± 0.30% IR
		0.5 - 10 V	100 KHz-1 MHz	± 0.30% IR
		20 - 50 V	100 kHz-500 kHz	± 0.30% IR
	Differential Voltmeter JF 887AB/AN	0.001-1100 V	5-10 Hz	±(1% IR + 25 uv)
			10-20 Hz	±(0.3% IR + 25 uv)
			20 Hz -5 kHz	±(0.1% IR + 25 uv)
			5 kHz -10 kHz	±(0.15% IR + 25 uv)
		0.1 - 1100 V	10 - 20 kHz	±0.3% IR
		0.1 - 110 V	20 - 50 kHz	±0.5% IR
			50 - 100 kHz	± 1% IR
	Electrostatic Kilovoltmeter ESV	0.0 - 6000 V	DC to 750 kHz	± 0.5% FS
	Digital Voltmeter HP 3490A with K25 - 3490A Probe	0.1 - 1000 V	20 -50 Hz	± (0.40% IR + 0.06% FS)
			50 Hz - 100 kHz	± (0.10% IR + 0.03% FS)
		1 - 10 V	100 - 250 kHz	
		1000 V - 7.5 kV	20 - 100 Hz	± (0.75% IR + 0.07% FS)
			100 - 400 Hz	
				± 0.5% of input
				±5% of input

True RMS Voltmeter JF 8922A/AA	0.002 Volt Range	2 - 20 Hz	± 5% IR
		20 - 50 Hz	± 3% IR
		50 Hz - 10 kHz	± 2% IR
		10 kHz - 2MHz	± 4% IR
		2 - 10 MHz	± 5% IR
	0.020 Volt Range	2 - 10 Hz	± 3% IR
		10 - 20 Hz	± 5% IR
		20- 50 Hz	± 2% IR
		50 Hz - 200 kHz	± 1% IR
		200 kHz - 1 MHz	● 2% IR
		1 - 2 MHz	± 4% IR
		2 - 10 MHz	± 5% IR
	0.200 Volt - 700 Volt Range	2 - 10 Hz	± 3% IR
		10 - 20 Hz	± 5% IR
		20- 50 Hz	± 1% IR
		50 Hz - 200 kHz	± 0.5% IR
		200 kHz - 1 MHz	± 0.7% IR
		1 - 2 MHz	± 3% IR*
		2 - 10 MHz	± 5% IR*
*Unit not specified above 20 V between 2-10 MHz, and Unit not specified above 200 V between 1-10 mHz			
Voltmeter Electronic HP 410C (APN 7910902)	0.5 - 300 V	20 - 100 Hz	±10% FS
		100 Hz - 50 MHz	±2% FS
		50 - 100 MHz	0 to -4% FS
		100 - 700 MHz	±10% FS
Coaxial Thermal Converter BAL 13940 and 1395	0.25 - 20 V root mean square	50 Hz - 50 kHz	● 0.10% of AC-DC Difference w/Test Report
		50 kHz - 1 MHz	± 0.2% of AC-DC Difference w/Test Report
		1.0 - 10 MHz	± 0.4% of AC-DC Difference /Test Report
		10 - 30 MHz	± 1.0% of AC-DC Difference w/Test Report
		30 - 100 MHz	± 4.0% of AC-DC Difference w/Test Report

	Multimeter, Digital TEK DM 501A	0 - 100 mV and 100 - 1000 V	20 - 50 Hz 50 Hz - 2 kHz 2 - 20 kHz 20 - 100 KHZ	±(0.08% IR + 0.01% FS) ±(O.03 IR + 0.015% FS) ±(0.10% IR + 0.025% FS) ±(0.20% IR + 0.05% FS)
		100 mV - 1 V, 1 - 10 V, and 10 - 100 V	20 - 50 HZ 50 Hz - 2 kHz 2 - 20 kHz 20 - 100 kHz	±(0.08% IR + 0.004% FS) ±(0.02% IR + 0.01% FS) ±(0.045% IR + 0.02% FS) ±(0.16% IR + 0.04% FS)
Current, DC Measurement and Source	DC Current Shunt GUF 9711 with DC Power Sply SOA QRE3-3OO-M3 and Differential Voltmeter JF 887AB/AN	10 microamps - 10 A		± 0.016% IR
		100 A		± 0.056% IR
		300 A		± 0.011% IR
	Voltmeter, Electronic HP 410C (APN 7910902)	± 1.5 micro A- ± 150 milli A		± 3% FS
Voltage, DC Measurement	Differential Voltmeter JF 887AB/AN	50 milli V -1100 V		±(0.005% + 5 Micro V)
	High Voltage Divider JF 80E-10AR/AN with Differential Voltmeter JF 887AB/AN	1000 - 10,000 V		± 0.03%
	Multimeter, Digital TEK DM 501A	0 - 200 mV 0.20 - 200 V 200 V - 1000 V		±(0.05% IR + 0.015% FS) ±(0.05% IR + 0.01% FS) ±(0.05% IR + 0.02% FS)
	Digital Voltmeter HP 3490A W/K25-3490A Probe	0.1 - 1 Volt		±(0.015% of IR + 0.005% of FS)
		10 - 1000 V		±(0.01% of IR + 0.002% of FS)
		1000 - 10,000 V		±0.25% of IR
Voltage, DC Source	DC Voltage Standard JF 332B/AF	0 milli V - 10 V		±(0.003% + 10 micro V)
		10 - 100 V		±(0.003% + 20 micro V)
		100 - 1000 V		±(0.003% + 40 micro V)
	Voltage Reference JF 730A	1 Volt 10 V 1.018 - V (mean output)		0.001% of calibrated value for 90 days
	H.V. Power Supply JF 410B	0.0 - 10,000 V		± 0.25% or 250 micro V
Ratio, DC Measurement and Source	Voltage Divider RV722	0 - 1.000000		± 0.0001% of input voltage
Voltage, AC Source	AC Power Source KH410OA/7500	0 - 125 V	10 Hz - 1 MHz	±0.05% resolution (External monitoring system required)
	Oscilloscope Calibrator BAL 6126M	0.1 mV - 200 V	10,000 1K & 10KHz	± (0. 25% IR + 1)zv)
	Test Oscillator HP 652A	1 millivolt - 3.16 V into 50 ohms	10 - 100 Hz	± 3%
			100 Hz - 1 MHz	± 2
			1 - 10 MHz	± 3%%

	AC Precision Calibration System HP 745A/7456A	0.0001 - 109.9999 V	10 - 20 Hz	±(0.2% IR + 0.005% FS+50 micro V)
			20 - 30 Hz	±(0.1% IR + 0.005% FS+50 micro V)
			30 - 50 Hz	±(0.05% IR + 0.005% FS+50 micro V)
			50 Hz - 20KHz	±(0.02% IR + 0.002% FS+50 micro V)
			20 - 100 kHz	±(0.05% IR + 0.005% FS+50 micro V)
		100 - 1099.999 V	10 - 20 Hz	±(0.2% IR + 0.005% FS)
			20 - 50 Hz	±(0.08% IR)
			50 Hz - 20 kHz	±(0.04% IR)
			20 - 50 kHz	±(0.08% IR)
			50 - 110 kHz	±(0.15% IR)
Frequency Measurement	Counter HP 5345A, VLF Receiver Tracor 599K, Omega Gating Unit Tracor 543		5X10 - 5 Hz -500 MHz	± (((2 X 10^{-9})/(Gate Time))+Trigger Error+Time Base Error + (2 x 10^{-11})]
	Frequency Difference Meter Tracor 527E	10^{7} - 10^{11}	100 kHz, 1 MHz, 2.5 MHz, 5.0 MHz and 10 MHz	± 5% FS
Frequency measurement and Source	Counter HP 5345A, Sig Gen HP 864OB-H66		1 Hz - 550 MHz	±1X10^{-7}
	Crystal Oscillator HP 105A		100 kHz, 1 MHz, 5 MHz	± 2 ppm
Time Interval Measurement	Counter HP 5345A	10 nanoseconds-20,000 seconds		± (2 nB + Time Base Error + Trigger Error)
RF modulation Source	Sig Gen HP 864OB-H66 or HP 8642M	0-100% AM	0.5 - 512 MHz	±(5.5% IR+1.5% FS)
		0-5120 kHz FM	0.5 - 512 MHz	±(7% IR+1.5% FS)
RF modulation Measurement	Modulation Analyzer HP 8901	0-99% AM	10 - 1300 MHz	± (1% IR + 1 digit)
		0-400 kHz FM	10 - 1300 MHz	± (1% IR + 1 digit)
Resistance,DC Measurement	Res Bridge ESI 230B (APN 7912150-2)	10 milliohms-12,000 megohms		± 0.01% or+1 dial division, whichever is greater
	Multimeter, Digital TEK DM 501A	1ohm - 10 megohms		0.01% IR
Resistance,DC Source	Resistor Decade Biddle 601147-1	0.01 ohm-1.11111110 megohm		± (0.03% + 0.001 ohm/decade)
	Resistor Standard 11 C CR 10M	100 kilohm - 10 megohm		±+0.02%
	Resistor Standard 11 C CR 100M	1 megohm - 100 megohm		± 0.05%
	Resistor Standard 11 C CR 1000M	10 megohm - 1000 megohm		± 0.25%
	Resistor Decade Biddle 71-650	1 milliohm - 1 ohm		± 1 milliohm
		1 ohm 10 - ohm		± 0.01%
		10 ohm 1.1 megohm		± 0.0025%
	Resistor Set PEN 9A-5120	1 x 106, 1 x 10^{7} megohm		± 1% w/Test Report

Resistance,AC Measurement	Impedance Measuring System SP 2280, ESI 230B (MOD) Resistance Bridge	10 ohm - 100 Kilohm	1 kHz	± (0-05% + 1 dial division)
		100 milliohm-10 megohm	1 kHz	± (1% + 1 dial division)
		1 milliohm - 1000 megohm	1 kHz	± (0.1% + 1 dial division)
	ESI 865A Generator Detector		DC - 1 kHz	± 1%
Capacitance Measurement	Impedance Measuring System SP 2280, ESI 1290B Impedance Bridge	10 - 1200 picofarad	1 kHz	±(0.2% + 1 dial division + 1% x D x F_{kc})
		1200 picofarad -120 microfarad	1 kHz	± (0.1% + 1 dial division + 0.5% x D x F_{kc})
		120 microfarad -1200 microfarad	1 kHz	± (0.2% + 1 dial division+O.l% x D x F_{kc})
Inductance Measurement	Impedance Measureing System SP 2280, ESI 290B Impedance Bridge	10 - 1200 microhenry	1 kHz	± (.2% + 1 dial division + .7% x F_{kc})
		1200 microhenry - 120 henry	1 kHz	±(.1% + 1 dial division + .7% x F_{kc})
		120 henry - 1200 henry	1 kHz	± (.2% + 1 dial division + 1.2% x F_{kc})
Attenuation Source	Attenuator HP 350D	*0.0 - 10 dB	DC to 100 kHz	± 0.125 dB into 600 ohms
		10 - 70 dB	DC to 100 kHz	± 0.25 dB into 600 ohms
		70 - 110 dB	DC to 100 kHz	±0.5 dB into 600 ohms
	Attenuator HP 355C	0.0 - 12 dB	DC to 1 MHz	± 0.1 dB into 50 ohms
			DC to 500 MHz	±0.25 dB into 50 ohms
			DC to 1 GHz	± 0.35 dB into 50 ohms
	Attenuator RLC A2648B	*0 - 120 dB	DC to 10 MHz	± 0.15 dB from 0 to 6O dB and + 0.3 dB from 60 to 120 dB
			10 to 100 MHz	± 0.35 db from 0 to 6O db and + 0.7 dB from 60 to 120 dB
			100 MHz to 1 GHz	± 3 dB from 0 to 120 dB
	Attenuator HP 355D	0 - 120 dB	DC - 1 GHz	±(1.5 dB to 90 dB) ±(3 dB to 120 dB) at 1 GHz
AC Ratio Measurement and Source	Ratio Transformer ESI DT 72A (A-DN 7915908)	0 - 1.000000 (Accuracy derated to 0.001%)	1 - 50 Hz	Multiply 50 Hz - 1 kHz accuracy by 50/frequency
			50 Hz - 1 kHz	±(0.5 ppm of input) for 0.1 - 1.0 settings ± (0.5 (10 X Setting) 1/2 + 0.01) ppm for 0-0.1 settings
			1 - 10 kHz	Multiply accuracy for 50 Hz - 1 kHz by $(F_{KHz})2$
Capacitance Source	Capacitance Set ARCO SS-32 (APN 7907233)	0.0001 - 0.0004 microfarad	1 kHz	± 0.5 picofarad
		0.0005 - 0.5 microfarad	1 kHz	± (0.1% + 0.5 picofarad)
	Variable Capacitance GR 1422-D (APN 8579475)	35 - 115 picofarads	1 kHz	± 0.03% or 0.1 picofarad
		100 1150 picofarads	1 kHz	± 0.03% or 0.6 picofarad

Distortion Measurement	Distortion Analyzer HP C41-334A (APN 7911957)	Any Fundamental Frequency between 5 Hz - 600 kHz with min input of 0.3 V		
		Input less than 30 V, distortion 0.3% - 100%	10 Hz - 1 MHz	± 3%
			10 Hz - 3 MHz	± 6%
		Input less than 30 V, distortion 0.1%	30 Hz - 300 kHz	± 3%
			30 Hz - 500 kHz	± 6%
			10 Hz - 1.2 MHz	± 12%
		Input greater than 30 V, distortion 0.3% - 100%	10 Hz - 300 kHz	± 3%
			10 Hz - 500 kHz	± 6%
			10 Hz - 3 MHz	±12%
		Input greater than 30 V, distortion 0.1%	30 Hz - 300 kHz	± 3%
			20 Hz - 500 kHz	± 6%
			10 Hz - 1.2 MHz	± 12%
Rise Time Source	Pulse Generator HP 1-105A/1106A	35 picoseconds rise time		± 5 picoseconds -7 picoseconds
Rise Time Measurement	Oscilloscope, TEK 5440 with Plug-in 5S14N	350 picoseconds rise time		
RF Power Measurement	Power Meter HP E12-432A w/Thermistor Mount HP H75-478A	10 microwatts- 10 milliwatts (-20 dBm to + 10 dBm)	1 MHz - 1 GHz	±1% FS + VSWR error+calibration factor error)
			10 MHz - 10 GHz	± 3%
	Standing Wave Indicator HP 415E (APN 7910160-2)	0.0 - 70 dB	W/1 kHz square wave modulation, adjustable 7%	±0.05 dB/10 dB step
RPM (Source)	Ignition Simulator Electronics, SK-D- 4850-15 (APN 7916123), Frequency Counter, HP 5345A, Oscillator Wavetek 145A (APN 7915944)	60 - 8000 RPM	1 - 1000 Hz	± 0.5%
Dwell (Source)	Ignition Simulator (APN 7916623) SK-D-4850-15, Electronics, Freq Counter HP 5345A, Scope, TEK 5440, Square Wave Gen, Wavetek 145	50% of full-scale on any Dwell range	10 80 Hz	± 0.5%
Signal Source (Sine Wave, Square Waves, & Pulses)	Function Generator wavetek 145 w/Rack Mount Option (APN 7915944)	1 Hz - 20 MHz	1 Hz - 1 MHz	± 3% of full range
			1 - 20 MHz	± 5% of full range
	Synthesizer/Function Generator HP3325B	1 microhertz - 21 MHz	1 microhertz 21 MHz (sine) 1 microhertz 11 MHz (square) 1 microhertz- 11 kHz (ramp)	± 5 x 10-6 of selected frequency value for square
Frequency Source	Signal Source W-E 4310 AK-16P w/W-E 4311B-EIP351D or HP 8642M w/HP8673M	0.1 to 18 GHz 20 @ 15mW	10 MHz to 18 GHz	$\pm 1 \times 10^{-6}$
Frequency Measurement	Electronic Frequency Counter, EIP-351D Frequency meters (7910718, 7910310), HP 5352B	+ 5 to -20 dBm	0 to 18 GHz 1 to 18 GHz 0 to 40 GHz	$\pm(1 \times 10^{-6})$
Standing Wave Ratio Measurement	HP 415E System (APN 7910160-2)	1.02 to 6.0	500 MHz to 18 GHz	± 0.015 (Reflection Coefficient)
	VSWR Bridge (7916686)		10 to 2000 MHz	± [0.01 + 0.009 (Reflection Coefficient))
	VSWR Bridge (7916685)		2 to 18 GHz	± (0.011 + 0.31 (Reflection Coefficient)]

Attenuation Measurement and Source	Receiver System W-E VM4-A Calibrator Attenuator/ Signal Generator	0 to 100 dB	10 MHz to 18 GHz	± 0.02 to + 0.7 dB depending on VSMR and value of UUT
RF Power CW	HP E12-432A System	0.01 milliwatt to 10 milliwatt	10 MHz to 18 GHz	± 3% rss
Calibration Factor Measurement (RF Power)	HP E12-432A System	Up to 100%	1 to 18 GHz	± 5%
Power RF Source	Wattmeter Calibration System MCL 15122 w/Plug-ins	50 watts (CW)	10 MHz to 1 GHz	± 6%
Angular Speed Source	Tachometer Calibrator Stewart Warner, ST165OH-1	0-5000 RPM		± 2% FS
Angular Speed Measurement	HP 5345A Counter; Motional Pickup, HP 506A or Power Instruments (APN 7913463) -	0-12,000 RPM		± 1 count
Pressure Source and Measurement	Pressure Gauge Tester, Mansfield and Green 10-10525 (APN 8598963) (or hydraulic pressure standard from limited deploy listing)	5 to 10,000 PSIG Hydraulic		± 0.15% Reading
	Pressure Gauge Tester, Mansfield and Green, 10-10525 (Fluid Separator MIS-26326 Pneumatic)	5-1,000 PSI Pneumatic 5-1,000 PSI Pneumatic (completely fill fluid separator pneumatic side with $H_2$0)		
	Contains Pressure Gauges	0-160 PSI, 0-600 PSI, 0-5000 PSI and 0-10,000 PSI		each ± 0.25% FS
Pressure Measurement	Pressure Gauge Test Set, (APN 7907754)	0 to 10,000 PSIG		
	APN 7907647 (US Gauge # 133076)	0 To 160 PSI		0.5% FS
	APN 7907648 (US Gauge #133080)	0 to 600 PSI		0.5% FS
	APN 7907649 (US Gauge # 132085)	0 to 5,000 PSI		0.5% FS
	APN 7907650 (US Gauge # 132274)	0 to 10,000 PSI		0.5% FS
Pressure Absolute Measurement	Pnuematic Pressure Standard (MIS-30859)	0 to 250 psia		0 to 2 psia:+(0.25% - 0.1% reading/psia) 2 to 20 psia: ±0.05% reading 2 to 25 psia: ±(0-05%- 0.1% reading /psia) 25 to 250 psia: ± 0.05% reading
Altitude	(MIS-30859)	-1000 to 60,000 feet		Convert altitude reading to absolute pressure (psia) and use error limits of pneumatic pressure standard above.
Rate of Climb	(MIS-30859)	0 to ± 6000 feet/min		Error is equivalent to the worst pressure error (of pneumatic pressure standard above) encountered during climb/descent.
Length Source	Gauge Blocks, Grade 3, Class 1	0.05 to 1 inch		± 0.000020 inch
		1 to 20 inches		± 0.000020 per inch
Length Measurement	Federal Products Dial Indicator Calibrator, MIS-10327	up to 1 inch		within 0.000050 inch from mean value
Mass Source	Weight Set, Class C	1 to 500 Grams		Class C
	Weight Set, Class C	1/128 to 8 ounces		Class C
	Weight Sets, Class T	1 to 190 pounds		Class T
Temperature Measurement	Thermometer, Resistance Digital	Dual Range -75 to 6000F and -60 to 3000C		± (0.20F + 0.1% of reading)

Torque Measurement	Torque Cells, Lebow and Indicator	0-60 in lb 0-20 ft lb 0-100 ft lb 0-500 ft lb 0-1000 ft lb 0-3000 ft lb	± 0.5% applied torque above 20% full scale
Viscosity Measurement	Kinematic Viscometer Set, Emil Grenier, ASTM 25, 50, 100, 150, 200	0.4 to 80 centistokes	± 1%
	Viscometer Set (APN 7913076)	0-80 centistokes	

INTERNAL DISTRIBUTION

1–5. J. A. McEvers
6–10. R. L. Anderson
11–12. J. O. Hylton
13. T. J. McIntyre
14. M. R. Moore
15. H. R. Brashear
16. R. M. Davis
17. B. G. Eads
18. D. N. Fry
19. R. A. Hess
20. D. W. McDonald
21. D. R. Miller
22. G. N. Miller
23. R. E. Uhrig
24. J. O. Stiegler
25. D. F. Craig
26–27. Central Research Library
28. Y-12 Technical Reference Section
29–30. Laboratory Records
31. Laboratory Records–Record Copy
32. ORNL Patent Section
33. I&C Division Publications Office

EXTERNAL DISTRIBUTION

34. R. K. Dubois, U.S. Army TMDE Activity, Attn.: AMXTM (R. Dubois), Redstone Arsenal, AL 35898-5400
35. Col. S. Dasher, U.S. Army TMDE Activity, Attn.: AMCPM (S. Dasher), Redstone Arsenal, AL 35898-5400
36–110. M. L. Fecteau, U.S. Army TMDE Activity, Attn.: AMXTM-S-D (M. Fecteau), Redstone Arsenal, AL 35898-5400
111. J. Ball, U.S. Army TMDE Activity, Attn.: AMXTM-E-D (J. Ball), Redstone Arsenal, AL 35898-5400
112. Assistant Manager for Energy Research and Development, DOE-ORO, P.O. Box 2001, Oak Ridge, TN 37831-8600
113. B. Chexal, Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94303
114. V. Radeka, Brookhaven National Laboratory, Instrumentation Division, 535-B, Upton, NY 11973
115. M. M. Sevik, Carderock Division, Naval Surface Warfare Center, Code 1900, Bethesda, MD 20084-5000
116. R. M. Taylor, Leeds and Northup, Sunneytown Pike, North Wales, PA 19454
117–118. Office of Scientific and Technical Information, U.S. Department of Energy, P.O. Box 62, Oak Ridge, TN 37831