RAND

Technology Access from the FS-X Radar Program

Lessons for Technology Transfer and U.S. Acquisition Policy

Ike Y. Chang, Jr.

Project AIR FORCE

The research reported here was sponsored by the United States Air Force under Contract F49620-91-C-0003. Further information may be obtained from the Strategic Planning Division, Directorate of Plans, Hq USAF.

Library of Congress Cataloging in Publication Data

Chang, Ike Yi.
Technology access from the FS-X radar program / lessons for technology transfer and U.S. acquisition policy / Ike Y. Chang, Jr.
p. cm.
"Prepared for the U.S. Air Force."
"MR-432-AF."
Includes bibliographical references.
ISBN 0-8330-1533-8
1. Radar—United States—Military applications. 2. Technology transfer—United States. 3. Technology transfer—Japan. 4. FSX (Jet fighter plane). 5. United States. Dept. of Defense— Procurement. I. United States. Air Force. II. Title.
UG612.3.C49 1994
338.97306—dc20 94-10799
CIP

Published 1994 by RAND
1700 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
To obtain information about RAND studies or to order documents,
call Distribution Services, (310) 451-7002

RAND

Technology Access from the FS-X Radar Program

Lessons for Technology Transfer and U.S. Acquisition Policy

Ike Y. Chang, Jr.

Prepared for the
United States Air Force

Project AIR FORCE

Preface

Launched in 1989, the FS-X is a U.S.–Japan program to develop cooperatively a new fighter for the Japan Air Self-Defence Forces. The program involves an intricate process entitling the United States to sufficient access to Japanese indigenously developed FS-X technology to determine the merits of procurement not inconsistent with the Military Technology Transfer Framework.

This report discusses the issues surrounding U.S. access and options to license technology from the Japanese active phased array radar under development for the FS-X. This report also examines the military importance of this type of radar technology, past efforts to realize the technology in U.S. programs, and the potential benefits to be gained from technology transfer.

This report should be of interest to analysts and policymakers concerned with relevant issues of international defense cooperation and technology transfer.

The sponsor for this research is the Deputy Assistant Secretary of the Air Force for Acquisition (Management, Policy, and Program Integration). Research at RAND was performed under a project entitled *Fighter Codevelopment on the Pacific Rim: Issues and Problems of Technology Transfer* in the Acquisition Project of the Project AIR FORCE Division.

Contents

Preface iii

Figures vii

Tables ix

Summary xi

Acknowledgments xiii

List of Abbreviations xv

1. INTRODUCTION 1
   - Technology Access in the FS-X Program 1
   - Current Status of Technology Transfer 4
   - Organization of the Report 5

2. ADVANTAGES OF APAR 6
   - Differences from Current Technology 6
   - Advantages over Mechanical Scan 8
     - Agile Beam Steering 8
     - Mode Interleaving 9
     - Flexible Beam Shapes 9
     - Compatibility with Stealth 10
     - Reliability 11
   - Advantages over Passive Phased Arrays 11
     - Reliability 11
     - Elimination of Waveguides 12
     - Wide Bandwidth 13
     - Phase Shifting with Time Delay 13
     - Module Amplitude Control 14

3. TECHNICAL CHALLENGES 15
   - Transmit/Receive Module Requirements 15
     - Design and Development 15
     - Active Device Requirements 16
     - Automation Requirements 18
   - Affordability Issues 20
     - Process Costs 20
     - Materials Costs: Limitations of MMIC 22
     - Other Materials 26
   - Antenna Array Issues 26

4. FS-X RADAR ASSESSMENT 29
   - System Assessment 29
   - Emphasis on Cost Containment 31
     - Selective, Incremental Improvement 33
     - Frequent Prototyping 35

Industrial Base Motives 37
Implications of the FS-X Radar 38

5. CANDIDATES FOR TECHNOLOGY TRANSFER 42
T/R Module Manufacturing 42
Chip/Subassembly Pick and Place 44
Chip Attachment with Epoxy 45
Automated Wirebonding 45
Quality Control/Test Strategies 46
Materials Fabrication 46
GaAs MMIC 46
Packaging Structures 47
Systems Integration 47
Component Design 49
Summary 49

6. PROBLEMS OF TECHNOLOGY TRANSFER 51
Lack of Knowledge and Access 51
Procedures and Restrictions 52
Proprietary Interests 54
Different Program Requirements 55
Nontransferable Industrial Factors 58

7. BROADER INDUSTRIAL FACTORS IN JAPANESE APAR 61
MELCO's Dual-Use Industry 61
Dual-Use Resource Sharing 61
Japan's Commercial Lower-Tier Network 63
Benefits of Dual-Use 64
Scale/Scope Economies 64
Learning Economies 66
Automation and Flexibility 68
Clearing the Hurdle: The U.S. Low-Volume Problem 69
Labor-Intensive Assembly 69
Low Capacity Utilization 70
Implications of Japan's Commercial Strategy 72

8. CONCLUSIONS 76
Indications of a Sound Technical Capability 76
Valuable Capabilities, but Questionable Transfer 78
Japanese Strengths: R&D and Industrial Philosophy 79
Implications of Japan's Commercial Strategy 82

9. POLICY RECOMMENDATIONS 85
Reducing Barriers to Technology Transfer 85
Further Study into Japanese Acquisition and Industry 87
Incremental R&D 87
Promoting Dual-Use 88
Spin-On More Effective Than Spin-Off 89

Bibliography 93

Figures

2.1. F-22 Radar T/R Module 7
2.2. F-22 Antenna 8
3.1. Labor Dominates Production Cost 21
3.2. Quality Check and Test Dominate Process Costs 21
3.3. Diminishing Returns from Increased Integration 23
7.1. Japan Dominates Market Share for GaAs FET Discretes 74

Tables

3.1. Module Complexity Evolution 23
3.2. Some Reasons for High GaAs MMIC Costs 25
5.1. Promising Technologies for Transfer 43

Summary

The FS-X is a cooperative aircraft development program launched in 1989 between the United States and Japan. The FS-X program entitles the U.S. government and U.S. industry access to Japanese FS-X technology. This report explores the issue of U.S. access and possible licensed transfer of Japanese FS-X radar technology for use by the U.S. government and industry.

The FS-X radar program is significant in that it may be the first program to develop an operational active phased array radar (APAR) for airborne fire control. APAR technology has the benefits of superior performance, reliability, and maintainability. Nevertheless, because of stringent U.S. program requirements and high production costs, APAR has not yet become an operational reality in the United States. The FS-X is, therefore, important in that it may signify growing strengths of Japan in a technical area historically dominated by U.S. firms.

The FS-X radar is a very conservative attempt at developing APAR. Its performance will be much lower than that of the APAR system planned for the F-22 radar, primarily because of the far lower mission and program requirement of the FS-X and an emphasis on cost containment in design. However, the FS-X radar will probably be developed several years sooner and at a much lower cost than the F-22 radar.

Despite the conservative design of the FS-X radar, several technologies from Japan, if successfully transferred, could benefit U.S. industry. One area is high volume, low-cost manufacturing technology for transmit/receive (T/R) modules. Other FS-X radar technologies that might benefit U.S. defense programs include the built-in-test algorithm and composite materials technology for the FS-X antenna.

Despite the high *potential* for benefits, the practical implementation of technology transfer faces several obstacles, such as the lack of knowledge and access of Japanese FS-X technology by U.S. industry, complex technology transfer procedures, conflicts with proprietary interests, differing program needs, and the difficulties of transferring industrial assets. These obstacles narrow the scope of what can be feasibly transferred from the FS-X radar program.

Rather than technology *per se*, U.S. industry and government could benefit most from learning about Japanese practices in industrial research and development (R&D) and defense acquisition. Most of the strengths of the FS-X radar contractor, Mitsubishi Electric Company (MELCO), can be attributed to an efficient dual-use industrial structure and dominance over related civilian markets rather than leadership in particular technology areas.

The acquisition approaches of the Japan Defence Agency (JDA) also offer promising alternatives for the Department of Defense (DoD) to adapt to the lean post-Cold War budget environment. In particular, DoD may consider adopting the Japanese practices of rapid system prototyping and incremental improvement to maintain improvements in the state of the art under diminishing resources. Whether or not DoD consciously adopts Japanese acquisition approaches in the near future, however, eventually continued downsizings in the U.S. defense budget could force DoD to take a more conservative, incremental improvement system acquisition approach similar to that of Japan's in the FS-X radar program.

Acknowledgments

I extend thanks to all of the officers and employees of the U.S. Air Force who supported the research for this report. Special thanks go to Colonel Lee Witbracht, Major Craig Mallory, Mrs. Charline Gormly, Captain Sid Perkins, and Captain Rick Lilley. William Denk of the Department of Commerce also provided a useful review.

At RAND, George Donohue, former director of Project AIR FORCE, had the early insight to study the FS-X as a case of international defense collaboration and technology transfer. As project leaders, Mark Lorell and Dennis Smallwood provided invaluable guidance and moral support for my research. Hyman Shulman, Jeffrey Drezner, and, in particular, Joel Kvitky and Charles A. Goldman contributed insightful reviews and comments.

I also thank individuals from various organizations who contributed their time and expertise to this research. These organizations include:

- Anadigics
- AT&T Bell Laboratories
- Advanced Research Projects Agency
- General Dynamics (now part of Lockheed Corporation)
- Hughes Radar Systems
- Lockheed Sanders
- Mitsubishi Electric
- Motorola
- Raytheon
- Texas Instruments
- U.S. Air Force Systems Command, Aeronautical Systems Division:
  - Wright Laboratories
  - F-16 System Program Office
- Westinghouse Corporation

Responsibility for all errors or omissions in this report lies solely with the author.

List of Abbreviations

APAR	active phased array radar
ARPA	Advanced Research Projects Agency
ATF	Advanced Tactical Fighter
BIT	built-in-test
CAD	computer-aided design
CD	compact disc
CIM	computer integrated manufacturing
DARPA	Defense Advanced Research Projects Agency
DBS	direct broadcast satellite
Dem/Val	Demonstration/Validation
DoC	Department of Commerce
DoD	Department of Defense
DRAM	dynamic random-access memory
ECM	electronic counter-measures
EIA	Electronics Industry Association
EM	engineering model
EMD	Engineering Manufacturing Development
FET	Field-effect transistor
FM	flight model
GaAs	gallium arsenide
GNP	gross national product
HARM	High-Speed Anti-Radiation Missile
HEMT	high-electron mobility transistor
IC	integrated circuit
IR&D	Independent Research and Development

JDA	Japan Defence Agency
JIAWG	Joint Integrated Avionics Working Group
JMTC	Joint Military Transfer Committee
JSTARS	Joint Surveillance Target Attack Radar System
LRU	line-replaceable unit
MANTECH	Manufacturing Technology
MBE	molecular beam epitaxy
MELCO	Mitsubishi Electric Company
MERA	Molecular Electronics for Radar Applications
MIC	microwave integrated circuit
MIMIC	ARPA program to develop MMIC technology
MITI	Ministry of International Trade and Industry
MMIC	monolithic microwave integrated circuits
MTBF	mean time between failures
NEC	Nippon Electric Company
NRL	Naval Research Laboratory
PPAR	passive phased array radar
RASSR	Reliable Advanced Solid-State Radar
R&D	research and development
RDT&E	research, development, testing, and evaluation
RF	radio frequency
SAR	synthetic aperture radar
SSPA	Solid-State Phased Array
T/R module	transmit/receive module
TSC	Technical Steering Committee
TWT	travelling wave tube
WSC	Working Subcommittee

1. Introduction

Technology Access in the FS-X Program

The goal of this study is to devise strategies for U.S. collaboration with international allies to enhance benefits to the DoD and U.S. industry. To ascertain these strategies, this report discusses the case of the FS-X program and issues behind U.S. efforts to gain access to Japanese active phased array radar technology.

The FS-X, a U.S.-Japan program to codevelop a new fighter-support aircraft, provides unique opportunities for the United States to gain access to Japanese military technology. FS-X agreements and subsequent bilateral negotiations entitle the United States to the "free and automatic flowback" of all Japanese "derived technology," defined as "anything essentially developed as a result of the use of U.S. technical data."[1] The FS-X also entitles the United States to gain access to technical data regarding "nonderived technology," defined as anything solely developed by Japan. Access to technical data on nonderived technology is intended to allow the United States to assess whether or not to procure the technology from Japan for a fee negotiated at a later date.[2,3]

DoD is currently assessing several FS-X technologies to determine whether or not to negotiate a procurement agreement with Japan. So far, DoD focused on one technology in particular because of its advanced stage in development: the active phased array radar (APAR).[4,5] This approach involves technical innovations that DoD considers may be applicable to U.S. defense needs.

The FS-X radar is significant as possibly the world's first APAR to be operationalized on a tactical aircraft. DoD is particularly interested in the radar

---

[1] *Technology Transfer and Technology Flowback with Japan: U.S. Industry Approaches to the FS-X Co-Development Project*, White Paper, U.S. Departments of Commerce, Defense, and Air Force, May 1991.

[2] Ibid.

[3] Free and automatic flowback of derived technology has precedent in licensed production programs with Japan, including the F-15 and Patriot. However, the licensed access to solely Japanese-developed technology is unprecedented in the history of U.S.-Japan collaborative programs.

[4] Japanese R&D in APAR predates the FS-X program by more than a decade. Correspondence in 1993 with Captain Sid Perkins, USAF, FS-X Liaison Officer stationed at MHI, Nagoya, Japan.

[5] DoD has conducted visits to Japan to gain information about the FS-X mission computer, integrated electronic warfare system, and inertial reference system. Ibid.

because it is developing the same kind of radar for the F-22 program.[6] APAR differs from conventional radar technology in that it contains numerous radar emitting and receiving elements called transmit/receive (T/R) modules. This approach enables APAR to combine the advantages of electronic beam steering with the high reliability and maintainability of highly redundant, parallel systems. The biggest problem with APAR, however, is module cost. DoD considers T/R modules to be too expensive under current production processes. For example, while DoD has set a goal of $500 per module, it currently costs several thousand dollars per module.[7] With up to 2,000 T/R modules required per system, modules alone would cost more than $5 million per system at current costs.

DoD believes that Japan may enjoy superior manufacturing capabilities that would allow it to reduce module costs below that of U.S. producers.[8] Although module costs quoted by Japan were comparable to U.S. modules, Japan expressed confidence in meeting DoD goals if demand increased to 1,000 modules per day.[9] According to Japanese claims, if fully automated manufacturing were justified with higher demand, module cost would fall to below $1,000. Nevertheless, Japan expects module production in the FS-X program to peak at about 100 modules per day. Evidently, Japan is quoting costs based on the assumption that demand will increase beyond that of the FS-X program, probably from U.S. purchases of modules from Japan.[10]

DoD is also considering Japanese manufacturing capabilities to help U.S. contractors meet high volume capacity requirements from F-22 radar procurement. Radar procurement of up to ten systems per month might involve several hundred modules per day, a production rate much higher than the current peak capacity of U.S. producers. DoD is considering the transfer of Japanese mass production technology to the United States to help defense contractors meet the cost and volume demands of APAR procurement.[11]

Despite DoD interest, controversy arose over whether military technology from the FS-X would have much benefit for U.S. industry. In Congressional hearings in 1989, critics of the FS-X program charged that Japanese capabilities in military

---

[6]Keller, J., "Advanced Avionics: Technology Meets Tight Budgets," *Military & Aerospace Electronics*, February 15, 1993, p. 13.

[7]GAO Report, 1990, op. cit.

[8]Ibid.

[9]*FS-X Active Phased Array Radar, U.S. Team Report*, 28–31 May 1991.

[10]U.S. producers have also claimed that they could meet DoD cost goals if demand increased to 1,000 per day. Some DoD managers were skeptical of these claims, since current U.S. capacity is far below 1,000 per day. Interview with engineers at Air Force Wright Laboratory.

[11]Ibid.

technology are overestimated and that neither Japan nor the United States could produce T/R modules economically at the time.[12] This position was supported by a 1990 GAO report, which questioned the value of Japanese FS-X technology. The report asserted that the approach taken by Japan to make the wing is very high risk. The report also described the FS-X radar as embodying "soldering iron vintage" technology. The report concluded that since Japanese technology was either behind or redundant with U.S. research and development (R&D) efforts, it offered little value to U.S. interests.[13]

Nevertheless, Congress approved of the FS-X program. Soon after, a DoD technical team that visited Mitsubishi Electric Company (MELCO), the prime contractor developing the FS-X radar, judged its radar facilities to be as "modern and well equipped as anything found in the U.S." The team was particularly impressed with manufacturing operations observed at MELCO and noted that access to MELCO manufacturing technology might help in improving the cost and automation of module production in the United States.[14]

After lengthy bilateral negotiations and political debate, the FS-X agreements gave the United States the right to gain access to all the technology that Japan had indigenously developed in the FS-X. An FS-X Technical Steering Committee (TSC) and Working Subcommittees (WSC), comprised of U.S. and Japanese government representatives, were set up to manage and oversee, among other things, implementation of access and licensed transfer of Japanese technology in the FS-X. DoD representatives in the WSC are responsible for providing Japanese indigenous technology documentation to interested U.S. companies. DoD representatives may take the initiative to seek out documentation of Japanese indigenous technologies that the DoD deems potentially useful to U.S. industry. DoD representatives on the TSC and the Department of Commerce (DoC) are charged with assisting U.S. companies in seeking additional information on Japanese indigenous technology and supporting company-to-company negotiations over licensed transfer of the indigenous technology.[15]

[12] Griffin, T., *The Debate over International Armament Programs: Integrating Current Knowledge and the FS-X Case*, Masters Thesis, Air Force Institute of Technology, September 1989.

[13] GAO Report, 1990, op. cit.

[14] *FS-X Active Phased Array Radar, U.S. Team Report*, op. cit.

[15] "Transfer of Japanese Indigenous Technologies During the FS-X Development Program," *FS-X Technical Steering Committee Pamphlet 1*, June 8, 1992, pp. 13–14.

Current Status of Technology Transfer

As part of their assigned roles, the DoD and DoC have been working to facilitate technology transfer from the FS-X program to U.S. industry. DoD has been collecting data and information on the FS-X radar to assess whether Japanese technology could benefit U.S. industry. DoD had sent two teams of technical experts to visit facilities at MELCO and the Japan Defence Agency (JDA), once in 1990 and again in 1991. Through these visits, DoD was able to receive technical documentation from Japan outlining the radar system and its components. DoD also has obtained general information on some of the process technologies used by Japan to develop and manufacture the system and its components. Language is not a barrier to the transfer process. The FS-X agreements have required that the Japanese contractors be responsible for translating documents into English and providing them to the DoD. MELCO has already handed over several documents on the FS-X radar to the DoD.[16]

At the time of this writing, no radar technology has yet been transferred to U.S. industry. The USAF, after a one-year negotiation with Japan, had received five sample T/R modules from a MELCO production run of the FS-X flight model (FM) radar in October 1993. The Air Force Aeronautical Center's Wright Laboratory has completed evaluating and testing the sample modules. Although the Air Force has no specific application in mind, it will distribute test results to other U.S. government agencies and to U.S. industry. These results are intended to allow U.S. recipients to determine whether to pursue a licensing agreement with MELCO regarding its module technology.[17]

The DoC is charged with informing U.S. industry of the opportunities for technology access in the FS-X program. In May 1992, DoC sponsored the one-day FS-X Radar Symposium. The symposium started off with DoC and DoD officials, who gave presentations describing the technology access mechanism within the FS-X program. In the second half, MELCO engineers gave technical presentations describing the radar technology. The audience consisted of approximately 200 representatives from the U.S. government and defense industry. A few months after the conference, at least two defense contractors attending the symposium reportedly had private meetings with MELCO to discuss the possible use of FS-X radar technologies for commercial purposes.[18]

---

[16] Discussions with Major Craig Mallory, USAF, 1992.

[17] "U.S. Air Force Take Delivery of Japanese FS-X Transmit/Receive Modules," *Electronic Warfare Digest*, October 1993, p. 4.

[18] In 1992, Hughes Aircraft Company and Westinghouse Electric separately expressed interest in obtaining MELCO FS-X radar technology. Both companies have expressed interest in using MELCO FS-X monolithic microwave integrated circuit (MMIC) technology for civilian products such as

These meetings were not organized by any U.S. government agencies but reportedly were made voluntarily among the corporate parties. At the time of this writing, there are no indications that any technology transfer had taken place as a result of these meetings. Technical managers of the relevant parties denied that technology transfer had taken place as a result of these private meetings.[19]

Organization of the Report

This report examines the case study of the FS-X APAR to provide background on the technology and to assess whether a potential exists for U.S. benefits from the FS-X radar program. Section 2 is an introduction to APAR technology and discusses the operational advantages of APAR. Section 3 discusses U.S. challenges in realizing APAR technology. Section 4 contrasts the FS-X and F-22 radar systems and examines how these differences reflect acquisition approaches of the two countries.

Section 5 discusses specific technical areas that could benefit U.S. interests. Section 6 describes potential problems and obstacles hindering the transfer of FS-X technology to the United States. Section 7 describes how broader industrial factors rather than technology might determine some Japanese advantages over the United States in APAR. Section 8 contains conclusions and Section 9 offers policy recommendations.

---

automobile collision avoidance systems. "Mitsubishi Electric Considering Exporting FSX Radar Technology," *Nikkei Sangyo Shimbun*, October 8, 1992, translated into English by JPRS: *Japan Science & Technology*, October 29, 1992.

[19]Discussions with Robert Dunn, U.S. Department of Commerce.

2. Advantages of APAR

Differences from Current Technology

To appreciate the technical advances embodied in the FS-X radar, one must first acknowledge advances of APAR technology over the conventional types of radar currently installed in modern fighters. APAR utilizes an antenna composed of numerous active[1] T/R modules. Beams are synthesized when the radiation emitted by all the modules combine in space as they propagate outward. The shapes of synthesized beams are determined by the distribution of phase shifts and amplitudes applied at each T/R module. Thus, beams of varying shapes can be generated simply by controlling the phase shift and amplitude instructions sent to each module in the antenna. Extremely high beam agility is, therefore, possible. Figures 2.1 and 2.2 show T/R modules and an APAR antenna being developed for the F-22 program.[2]

Technically, APAR differs from most airborne fire control radar systems in two major respects. First, most systems in U.S. fighters manipulate beams through mechanical controls that rotate the antenna. This type of radar is called a mechanical-scan system. APAR, on the other hand, is classified as an electronic-scan system because beams are manipulated through purely electronic controls (e.g., phase shift instructions are sent from the radar computer to the modules).[3]

APAR differs from another type of electronic-scan system that contains passive phase-shift modules to control beams.[4] Such systems, called passive phased array radar (PPAR), do not house amplification circuits within their modules. Instead, amplification is typically performed in centralized sources such as vacuum tubes that are separated from the modules.

---

[1]The term *active* refers to circuitry that amplify more radio frequency (RF) power than they dissipate.

[2]Cheston, T. and J. Frank, "Phased Array Radar Antennas," from Merrill Skolnik, *Radar Handbook*, Second Edition, 1990.

[3]*Jane's Radar and EW Systems*, 1990–91.

[4]The term *passive* refers to the lack of amplification function. Phase-shift modules are "passive" because they do not amplify RF energy but dissipate it through circuit losses.

RAND#249-2.1-0993

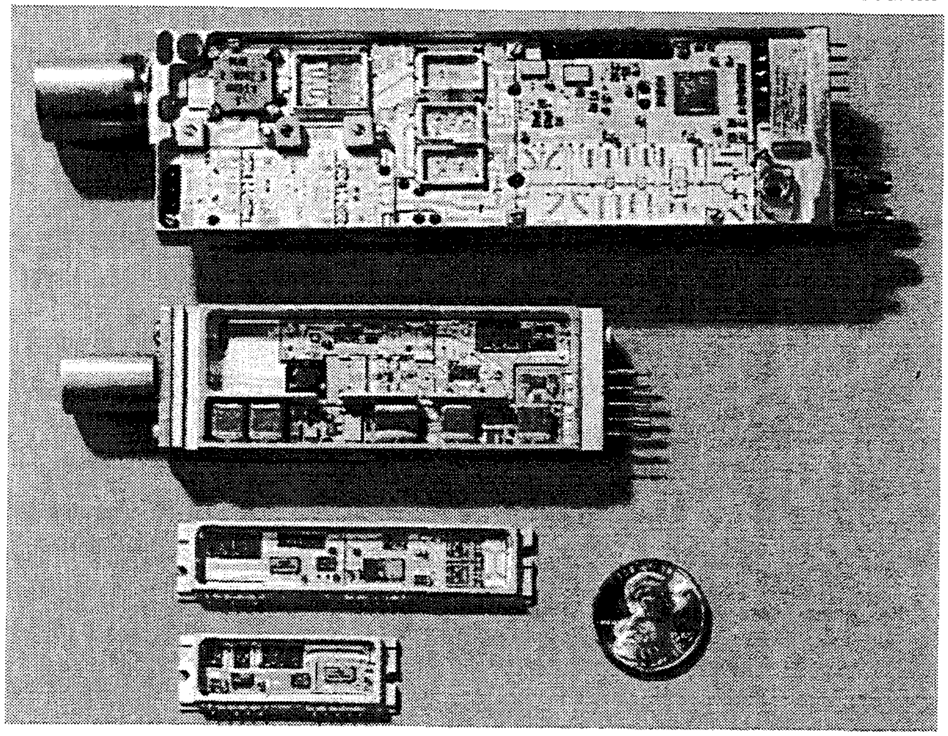


Figure 2.1—F-22 Radar T/R Module

Some radar systems have characteristics of both phased array and mechanical-scan systems.[5] For instance, the Joint Surveillance Target Attack Radar System (JSTARS) can be considered a hybrid between mechanical-scan and PPAR in that it contains a linear array of phase shifters that electronically steer the beam in the horizontal direction. However, the linear array is connected to an actuator that mechanically steers the entire array antenna in the vertical direction.[6] In another example, the ground-based PAVE PAWS fire control system can be considered a hybrid between active and passive phased array systems. PAVE PAWS contains one active amplifier connected to two apertures via a waveguide and passive phase shifter.[7] The F-22 and FS-X radar systems are pure active phased array

[5]Interviews with Bernard Schweitzer, RAND.

[6]Sweetman, W., "The U.S. Airborne Radar Scene," *Interavia*, May 1989.

[7]Hoft, D., "Solid-State Transmit/Receive Module for the PAVE PAWS Phased Array Radar," *Microwave Journal*, October 1978.

RAND#249-2.2-0993

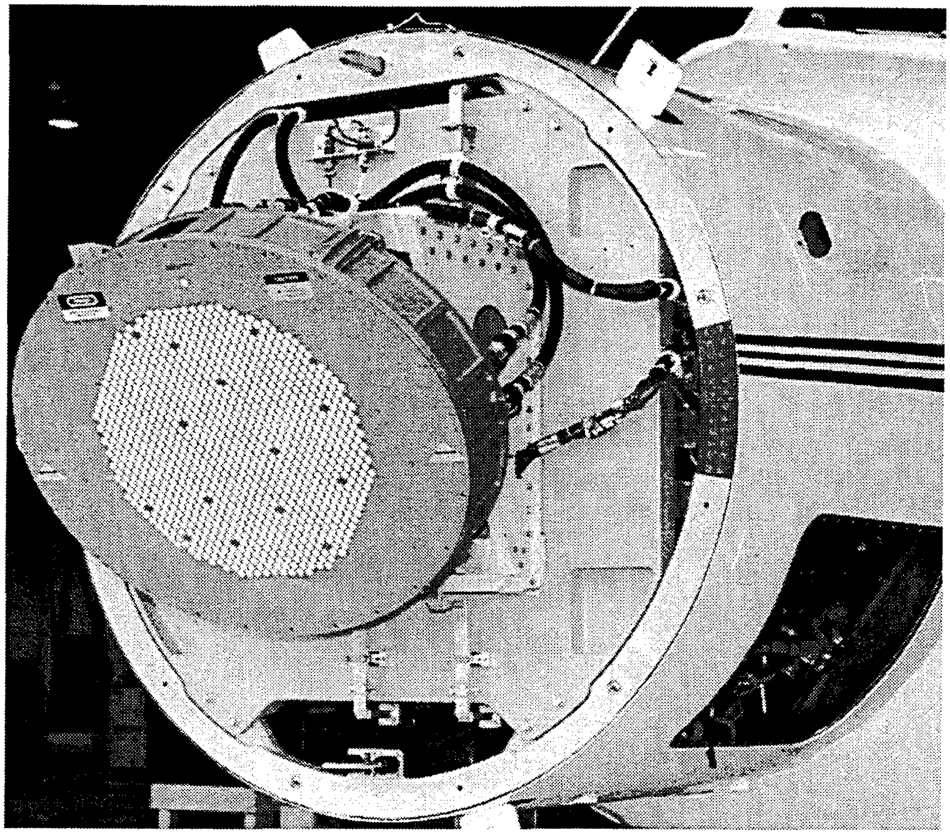


Figure 2.2—F-22 Antenna

systems; they scan electronically in both elevation and azimuth, and they have one active T/R module connected to every radiating aperture in the antenna.[8]

Advantages over Mechanical Scan

Agile Beam Steering

Both active and passive phased arrays enjoy many operational advantages over mechanical-scan technology. One advantage is electronic beam steering, which allows systems to emit consecutive beams in different directions almost instantly.

[8]*Jane's Radar and EW Systems*, op. cit.

While antenna inertia typically limits the beam-steering speed of mechanical-scan radar systems, electronic beam steering provides phased arrays with one or two orders of magnitude improvement over mechanical-scan systems in terms of scan speed and multiple-target tracking accuracy.[9,10]

Mode Interleaving

Modern radar systems have become more versatile because they can operate in an increasing number of modes. Since every mode performs a unique but important role, systems requirements have called for radar systems with greater capacity to timeshare among several modes simultaneously. This capacity, called mode interleaving, improves effectiveness by providing multiple perspectives simultaneously along with greater freedom of action to the pilot, leading to greater lethality, battlefield awareness, and survivability.[11]

Phased arrays generally have better mode interleaving capabilities than mechanical systems because of the high steering agility of electronic beam steering. Since mode transitions often require instant and unpredictable changes in beam direction, inertial mechanical-scan systems may have difficulties. Especially for complex, high-performance mode transitions, agile phased array systems are preferred.[12]

Flexible Beam Shapes

Another advantage over mechanical-scan systems is superior beam shaping adaptability and flexibility. Flexibility in generating various beam shapes can enable the optimization of system performance across more than one mode. Since mechanical-scan systems often have the problem of being optimized only for one beam shape, they are limited in their ability to perform a broad repertoire of modes. In many cases, mechanical-scan systems lack the flexibility to shape to different beam shapes. For instance, many fighter radar systems emit only pencil-shaped beams to optimize tracking accuracy and maximize gain. However, the inability to change to a fan-shaped beam reduces the search rate

---

[9] Antenna inertia has limited scan rates to 100 degrees per second for the fastest mechanical systems. Phased arrays can sweep 50 to 100 times faster than this rate. Beal, C., and W. Sweetman, "Fighter Radar in the 1990s: A Spectrum of Progress," *International Defense Review*, August 1992.

[10] According to Hughes Radar Systems, this feature can enable APAR to track 10 to 100 times more targets than possible with current mechanical-scan radars. Third Annual Monolithic Microwave Integrated Circuits (MMIC) Conference, 1991.

[11] Cheston, T. and J. Frank, op. cit.

[12] Sweetman, W. "The US Airborne Radar Scene," op. cit.

because numerous sweeps are required to cover the entire search cone of the system.[13]

On the other hand, because phased arrays modulate beam shapes, they can optimize the beam shape for one mode without sacrificing performance in another.[14] For example, phased arrays could emit a pencil beam in the track mode for higher accuracy and gain. When interleaving with search modes, however, the system can immediately switch to a fan beam without much difficulty to achieve faster search.[15]

Beam adaptability can provide other advantages such as jam resistance. For example, the system can generate a beam with nulls[16] placed in the direction of the jamming signals, thereby permitting high performance operation in environments with hostile electronic counter-measures (ECMs). Beam flexibility can also help improve clutter rejection. For example, if the system detects excessive clutter reflecting from terrain such as mountain ranges or urban areas, the system can place nulls into these sources while looking into other directions.[17]

Compatibility with Stealth

One important advantage of phased array technology is greater compatibility with stealth. The fitting of mechanical-scan systems into stealthy aircraft poses problems because of the extra space required to accommodate a rotating antenna. On the other hand, the fixed antennas within phased arrays can make for an easier fit within the tight constraints of stealthy aircraft. In addition, phased arrays can be shaped in ways that blend or conform with the unusual contours of stealthy airframes. Conformal shaping is difficult with rotating antennas, which tend to compromise stealth by presenting a highly reflective, orthogonal surface from many directions. Because of its many stealth advantages, phased arrays have been installed in the B-1B and B-2 bombers.[18] As stealth has grown in importance with next-generation platforms, phased arrays will likely be even more favored for installation in combat aircraft in the future.

---

[13] Discussions with Joel Kvitky, RAND.

[14] Jay, P., "Case Studies of Successful Production Applications of GaAs ICs," 1991 IEEE GaAs IC Symposium.

[15] Discussions with Joel Kvitky, RAND.

[16] Nulling is the means by which the antenna cancels out the reception of radar signals from a given direction by using destructive interference among apertures.

[17] Jay, P., "Case Studies of Successful Production Applications of GaAs ICs," op. cit.

[18] *Aerospace Daily*, p. 272, May 16, 1991.

Reliability

The reliability of mechanical-scan radars tends to be limited by the physical wear of moving parts. Passive and active phased arrays typically lack moving parts and, therefore, avoid the mechanical breakdown problems of mechanical-scan systems. Nevertheless, the reliability of phased arrays is still limited by such problems as transmitter burnout and electronic component overheating, problems that can also plague mechanical-scan systems.[19]

Advantages over Passive Phased Arrays

While the advantages of phased arrays over mechanical-scan systems is clear-cut, the trade-offs between active and passive phased array systems are less clear. The main advantage of PPAR over APAR is the use of an efficient and powerful centralized vacuum tube to power a radar system having the high beam agility of a phased array. PPAR systems typically use vacuum travelling wave tube (TWT) amplifiers that exceed the power levels and efficiency of the best solid-state amplifiers—the energy source for APAR systems.[20] Despite these advantages, other advantages give APAR technology an edge as the fighter radar technology of the future.[21]

Reliability

High reliability is one of the most widely touted advantages of APAR over PPAR technology. PPAR systems are often plagued by catastrophic failure caused by the burnout of vacuum tubes and their associated power supplies. APAR systems are far less susceptible to these failures because of two factors—the redundancy posed by numerous T/R modules within an APAR and the low operating voltages of solid-state T/R modules. Module redundancy provides the characteristic of graceful degradation, in which system performance degrades

[19]Lockerd, R. and G. Crain, "Airborne Active Element Array Radars Come of Age," *Microwave Journal*, January 1990.

[20]Existing airborne radar systems, including most mechanical-scan and PPAR systems, employ TWT amplifiers. See the chapter on U.S. airborne fire control radar in *Jane's Radar and EW Systems*, op. cit.

[21]Although no PPAR has been operationalized yet in any U.S. fighter, it is still a strong candidate for installation on future U.S. fighters. The only PPAR operationalized on a fighter is the "Flashdance," developed by the former Soviet Union and installed on the MiG-31. PPARs have also been installed on larger U.S. aircraft such as the B-1B bomber and JSTARS. Several development programs are aimed at operationalizing this technology. Westinghouse is developing PPAR prototypes for possible installation on the F-15 Block 50, and France is developing a new PPAR for the Rafale fighter. See Sweetman, W., "The U.S. Airborne Radar Scene," *Interavia*, op. cit., pp. 450–451.

gradually and predictably over time as T/R module circuits do. Aside from higher reliability, graceful degradation also has the advantage of providing greater operational flexibility and system robustness. Even after a substantial number of modules fail, the pilot often can continue to operate a partially degraded system until servicing is convenient.[22,23]

APAR reliability is enhanced further because of the use of low-voltage solid-state circuitry. Solid-state circuitry enables the system to be powered at a few volts, as opposed to the kilovolts required for high-performance tube amplifiers. Thus, APAR systems can be built using highly reliable low-voltage power supplies instead of unreliable high-voltage supplies of PPAR systems.[24,25]

APAR systems can also be easier to maintain than PPAR, as T/R modules can be designed for hand replacement during servicing. On the other hand, replacement of critical microwave components in mechanical-scan and PPAR systems may require complete removal and replacement of more substantial components such as transmitter tubes and other line-replaceable units (LRUs).

Elimination of Waveguides

To separate and combine the power travelling between the amplifier and passive modules, airborne PPAR systems typically contain a network of microwave waveguides and manifolds that incur high weight penalties and power losses to the system.[26] APAR systems avoid such problems because T/R modules contain amplifiers as well as phase shifters. Transmitter circuits, therefore, can be placed near the antenna surface, eliminating the need for complex microwave plumbing

---

[22]As many as ten T/R modules can fail without noticeable degradation in performance. "Case Studies of Successful Production Applications of GaAs ICs," op. cit.

[23]It is important to note, however, that module redundancy does not protect against array-level failures such as "hot spots" that affect a large group of modules simultaneously or power supply failures that affect all the modules at once. Interview with Hyman Shulman, RAND.

[24]High voltage power supplies tend to fail because of the high stress created by several kilowatts of microwave power generated in a small volume. Dornheim, M., "Gallium Arsenide Technology Replacing TWT Power Amplifiers," *Aviation Week & Space Technology*, October 19, 1992.

[25]In principle, the TWT used in most PPARs could be replaced by a unitary solid-state amplifier for increased reliability. However, doing so would compromise the major advantage of PPAR technology—the utilization of a compact, power-efficient TWT amplifier. The latest solid-state amplifiers still cannot match similar-sized TWTs in terms of their efficiencies and power levels. Discussions with Joel Kvitky, RAND.

[26]One possible exception is a space-fed PPAR that, instead of waveguides, may have an air chamber by which microwave energy is allowed to propagate between the phase shifting "lenses" and the TWT amplifier. However, no space-fed systems have been installed on any U.S. combat aircraft, apparently because of the large amount of volume and weight of the air chamber within a space-fed array. Thus space-fed arrays may be excessively bulky and large for fighter aircraft.

to connect amplifiers to the antenna apertures.[27] The lack of high-loss waveguide networks also helps to increase the overall power efficiency of APAR systems. According to some industry experts, such savings compensate for the lower power efficiency and power levels of solid-state transmitters compared to vacuum tubes.[28]

Wide Bandwidth

Another advantage offered by APAR is wider transmit and receive bandwidths. Solid-state technology has advanced to the point where T/R modules have been developed with wider bandwidths than even TWTs,[29] thereby providing advantages of superior jam resistance and electronic warfare capabilities.[30] Wide bandwidth can enable superior mapping resolutions when performing synthetic aperture radar (SAR) processing.[31] Wideband SAR in combination with beam shaping flexibility can provide for superior ground mapping quality if combined with image processing.[32]

Phase Shifting with Time Delay

PPAR systems such as the Patriot typically employ ferrite phase shifters that do not provide true time delays in their phase shifting operations. The resulting disadvantage is reduced coherence of emitted pulses directed away from boresight.[33] This problem can severely hamper beam performance and reduce the effective size of the search cone of the radar. With solid-state technology, APAR systems have been built with T/R modules using switched-line phase

---

[27]Waveguide and manifold networks have typically incurred almost 50 percent power losses in radars. Lockerd, R. and G. Crain, op. cit. and McQuiddy, D., et al., "Transmit/Receive Module Technology for X-Band Active Array Radar," Proceedings of the IEEE, Vol. 79, No. 3, March 1991.

[28]Ibid.

[29]Solid-State Phased Array (SSPA) prototypes developed in the late 1980s had 30 percent more bandwidth than the widest band TWT-based airborne radar. Interview with Dennis Mukai, USAF Wright Laboratories.

[30]For example, a wideband APAR could be more effective in a high-jam environment because it has a larger range of "hopping" frequencies to avoid the frequency of jammers. In addition, the wider bands on the receive side can allow APAR to act as a highly sensitive passive receiver to detect enemy microwave emissions without giving oneself up to the enemy by acting as a microwave beacon.

[31]SAR is a Doppler processing technique often used by radars to sharpen images of stationary objects by utilizing the forward motion of the aircraft to increase the resolution of the antenna. Stimson, G., *Introduction to Airborne Radar*, Hughes Aircraft Company, 1983, pp. 609.

[32]One problem with ground mapping from mechanical-scan, pencil-beam radars is the large number of "looks" required to cover the area of terrain under observation. On the other hand, because APAR can shape the beam to match the area under observation, the number of "looks" can be reduced for improved mapping quality, ibid., pp. 561.

[33]Boresight is the direction pointing perpendicular to the plane of the antenna surface.

shifters that employ time delays. Such systems do not suffer from off-boresight coherence problems characteristic of PPARs that use ferrite phase shifters.

Module Amplitude Control

One final advantage of APAR over PPAR is the former's ability to control the amplitude at each aperture when the T/R modules have variable gain. Amplitude control can provide APAR systems with additional degrees of freedom to achieve greater control over beams than PPAR systems of comparable size. In addition, amplitude control can also be leveraged for enhanced graceful degradation through adaptive array measures, in which the radar computer detects module errors and compensates them through a recalibration of both phase and amplitude instructions sent to the T/R modules. Because of the prohibitive cost of repairs in space, such adaptive measures are now commonly employed in space-based phased arrays to increase their system lifetimes.[34]

---

[34]Discussions with Joel Kvitky, RAND.

3. Technical Challenges

In pursuit of a fire control system of vastly improved performance, reliability, and maintainability, DoD has funded R&D and prototype development in APAR technology since the 1960s.[1] Despite the long history of R&D in APAR, technical bottlenecks and high development and procurement costs have prevented their installation into operational fighters.[2] To understand potential payoffs for the United States in technology transfer, it is first necessary to discuss the technical obstacles and difficulties that have prevented the realization of tactical airborne APAR technology.

Transmit/Receive Module Requirements

Design and Development

One of the most demanding aspects of APAR technology is the design and development of high-quality X-band[3] T/R modules. Functional requirements for T/R modules are very stringent—each module must perform such electronic functions as transmit amplification, receive amplification, T/R switching, and phase shifting, all at very high performance and uniformity. Such requirements have represented bottlenecks because of limitations in contemporary solid-state technology. For instance, current module requirements call for advanced circuits made of gallium arsenide (GaAs)[4] monolithic microwave integrated circuits (MMICs). The integration of multiple microwave and logic functions into a single module involves highly sophisticated packaging with significant miniaturization, airtightness, and complexity.[5]

---

[1]The USAF began exploratory development into X-band APAR in 1964. McQuiddy, D., et al., op. cit.

[2]Sweetman, W., "Active array for ATF," *Interavia*, August 1988.

[3]X-band, covering 8–12 GHz, is the operating frequency of most tactical airborne fire control systems. Skolnik, M., "An Introduction to Radar," *Radar Handbook*.

[4]GaAs is an expensive semiconductor that operates several times faster than silicon. In the United States, GaAs circuits have been used primarily for military applications because of their high-speed operations and inherent radiation-hardness. GaAs's high speed makes it the preferred solid-state material for both military and commercial higher-frequency microwave applications.

[5]Military requirements have driven module designs into considerable complexity. A recent module prototype involves several hundred wire interconnections and several microwave integrated circuits, capacitors, resistors, multiple-layer substrates, and complex feedthroughs. T/R modules also must be hermetically sealed to protect module circuitry from damage caused by moisture and atmospheric contaminants. The housings are only a fraction of an inch in width and height and a few inches in length, since several hundred or thousand modules must fit on an array inside the nose of a tactical aircraft. McQuiddy, D., et al., March 1991, op. cit.

Thermal requirements introduce further complexities into the module design. Because modules generate heat, they require extensive thermal sinks and paths to prevent burnout of their active circuits. Thermal considerations also dictate the study and use of various exotic materials that not only must dissipate heat well but also expand at similar rates as adjacent materials when heated.[6]

T/R module design also poses a significant modeling challenge. Because these modules contain high frequency analog functions, the development of accurate models to predict electrical behavior is difficult. This kind of modeling is more difficult than that of digital circuits, since analog circuits operate in a continuum of states instead of a discrete set of binary states. Consequently, discrete analog models may have to incorporate an exponentially increasing number of states to model and calculate as the number of circuit stages increase. As a result, problems could occur when trying to evaluate and predict the behavior of conceptual designs.[7]

Active Device Requirements

Microwave performance specifications have also led to stringent requirements for T/R module active devices. In the past, such requirements posed as bottlenecks with respect to available solid-state technology. Historically, the feasibility of prototype technology has been contingent mostly on new developments in solid-state technology. For example, system requirements have dictated T/R modules capable of several watts of peak output power at power-added efficiencies of almost 20 percent. Throughout the 1960s and early 70s, however, performance limitations of contemporary solid-state technology had forestalled prospects of meeting these requirements for airborne radar.[8]

X-band APAR prototypes developed before the late 1970s could not satisfy contemporary requirements because the latest solid-state devices could not amplify signals efficiently at X-band. These latest devices were made of silicon, which as a material inherently limits the switching speed of the device. Consequently, T/R modules developed during this time had suffered from very

[6]Mechanical stress caused by a high mismatch in expansion rates can be severe enough to damage modules. Ibid.

[7]Interview with radar engineers at Westinghouse Electric.

[8]McQuiddy, D., et al., op. cit.

low efficiency and duty cycles. Array prototypes containing such devices could not generate the requisite power levels without overheating.[9,10]

Higher transmit power and efficiency became a possibility with the development of GaAs transistor technology. GaAs is an expensive semiconductor with switching speeds six times faster than silicon.[11] Because GaAs is fast enough to amplify X-band signals directly, GaAs amplifiers have enabled the development of microwave circuits for T/R modules that met the stringent power and efficiency requirements of contemporary airborne fire control applications.[12] In 1980, GaAs single-transistor chips integrated within a hybrid circuit were used to amplify and phase shift signals within X-band T/R modules developed at the Naval Research Laboratory (NRL). By 1985, the NRL program completed 45 X-band T/R modules, which demonstrated feasible performance levels in terms of transmit power, power-added efficiency, noise figure, and bandwidth.

After the NRL program, the Air Force began funding the Solid-State Phased Array (SSPA) program to develop two radar prototypes containing T/R modules with GaAs microwave integrated circuit (MIC) amplifiers. SSPA was able to demonstrate simple radar functions at feasible performance levels. The success of SSPA in ground tests led to the DoD decision to develop an X-band APAR for the Demonstration/Validation (Dem/Val) phase of the Advanced Tactical Fighter (ATF) program,[13] later to become the F-22 program.

Although GaAs technology was developed to improve circuit performance, recent R&D has focused on miniaturizing circuits by integrating more microwave functions into GaAs circuits. The problem with SSPA and earlier programs was that their hybrid MICs[14] occupied much of the space and drove up the weight of

---

[9]During the 1960s and 1970s, Molecular Electronics for Radar Applications (MERA) and Reliable Advanced Solid-State Radar (RASSR) programs aimed to circumvent limitations of silicon. Module amplifiers were operating at a frequency lower than X-band, and the outputs to these amplifiers were connected to frequency multipliers converting the output signal to X-band. Nevertheless, the power losses from frequency conversion reduced module efficiencies to 1 or 2 percent, far below what is considered acceptable for airborne radar. McQuiddy, D., et al., op. cit.

[10]Although limited in X-band performance, silicon devices are capable of direct RF amplification at frequencies lower than X-band. Thus, APAR using silicon-based T/R modules had been developed for larger, surface-based systems that can support lower wavelength radiation. Two examples include the SPY-1 Aegis fire control system and the PAVE PAWS early warning missile detection system. Sweetman, W., "Active Array for ATF," op. cit.

[11]Abe, M., "Present Status and Future Prospects of Compound Semiconductor LSI Technology," *Handotai Shuseki Kairo Gijutsu*, June 27, 1991, pp. 73–78, translated into English by *JPRS Japan Science & Technology*, April 15, 1992, p. 15.

[12]McQuiddy, D., "Solid-State Radar's Path to GaAs," *IEEE Microwave Theory & Techniques: Symposium Digest*, 1982.

[13]McQuiddy, D., et al., op. cit.

[14]Hybrid MICs tended to be among the bulkiest circuits within T/R modules because each consisted of several single-device GaAs chips (also called discretes) mounted and wired on a thick carrier. Ibid., p. 71.

T/R modules. To reduce module size, U.S. industry developed GaAs MMICs in the mid-1980s as functional replacements of hybrid MICs. MMICs, which involves the integration of several microwave devices on a single chip, have replaced hybrid MICs several times their size and have allowed for dramatic reductions in module size, part count, and assembly costs.[15] MMIC technology is very costly, however. The utilization of MMIC within modules has introduced additional complications to module assembly. The impact of MMIC technology insertion on the costs of T/R modules is addressed later in this section.

Automation Requirements

Module technology also raises unique challenges for production. Stringent production requirements result from the process complexities of module assembly along with the high production demands of radar system procurement. Because of stringent requirements on cost, quality, and production rates, U.S. contractors have focused on automating three major processes of the T/R module assembly: component placement, component attachment, and wire interconnection.[16] Module electrical performance is highly sensitive to process variability in all three process areas.

In component placement, highly accurate dimension control is required to ensure that the desired electrical performance is met. Deviations of as little as one-twentieth of a millimeter in placement can cause 10 percent deviations in electrical design values.[17] MMICs are also highly fragile and require the utmost care in handling. Although GaAs material is very brittle (twice as brittle as silicon), the material cannot dissipate heat well and must, therefore, be thinned to allow enough heat to escape. Thinned chips not only exacerbate the problem of chip breakage in handling[18] but also require extensive modifications of assembly equipment, most of which are designed to handle thicker, more rugged silicon chips.[19]

T/R module assembly must also meet stringent thermal and environmental requirements for component attachment. Higher power MMICs require solder

[15]U.S. MMIC efforts have taken a broader scope than just T/R modules with the MIMIC program sponsored by Defense Advanced Research Projects Agency (ARPA). Launched in 1987, the tri-service program aims to develop and validate MMIC technology for possible use in a variety of military microwave applications, including communications, seekers, and sensors. Cohen, E., "MIMIC from the Department of Defense Perspective," *IEEE-Microwave Theory & Techniques Transactions*, Vol. 38, No. 9, September 1990.

[16]McQuiddy, D., et al., op. cit.

[17]Ibid.

[18]*Strategic Industrial Initiative: Phased Array Radar*, op. cit.

[19]Interview with Westinghouse Electric engineers.

attachments for adequate thermal and electrical grounding, while lower power MMICs may use epoxy for better control and repeatability. Even the most minute imperfections in the adhesive bond of components can cause noticeable degradation of electrical performance and limit thermal dissipation. Costly, automatic adhesive dispensers and furnaces are required to ensure that such requirements are met.[20]

Finally, T/R module assembly requires stringent control in making wire interconnections between components, particularly in bonding the MMICs to thin films. Given the sensitivity of electrical performance to minute changes in the placement, force, power, and inductance of wirebonds, automatic equipment with very high mechanical control and throughput is required.[21]

Increased automation is particularly critical to the production capacity of the assembly line. Capacity is currently a limiting factor in module assembly. For the F-22 program, a typical procurement of ten airborne radar systems per month would require a production rate of almost 1,000 T/R modules per day.[22] The U.S. defense industry has recently demonstrated peak capacity of several hundred X-band T/R modules per month, indicating the need for further automation to increase throughput rates.[23]

Module throughput of APAR procurement is much higher than what U.S. contractors have handled in past programs. Defense contractors typically have produced electronic components at much lower rates than the high T/R module per day requirement of APAR procurement. Instead, radar programs, for instance, have involved mostly mechanical-scan technology requiring the production of only a handful of active radio frequency (RF) components per system.[24] Although some missile programs have involved somewhat higher production rates than mechanical-scan radar, even the former does not match the volumes involved in APAR procurement. For instance, production of the High-Speed Anti-Radiation Missile (HARM) relies on two-shift operations with volume production of about 1,000 microwave modules per month. A ground-based theater missile defense program produces 300 X-band T/R modules per day in two separate production facilities. T/R module production for APAR

---

[20] McQuiddy, D., et al., op. cit.
[21] Ibid.
[22] *USAF Manufacturing Technology,* U.S. Government Printing Office, 1991.
[23] "Case Studies of Successful Production Applications of GaAs ICs," op. cit.
[24] Interview with David McQuiddy, Texas Instruments.

may involve a higher production load than any other solid-state microwave production run by U.S. defense contractors.[25]

Affordability Issues

Cost is considered the highest risk facing the F-22 radar program, and the DoD believes that T/R modules could be the costliest subsystem in APAR. Modules are costly because of a combination of high unit costs and the large number required per system. With current manufacturing processes, each module costs about $2,400. Thus, modules per F-22 radar would cost more than $5 million.[26] Module costs must fall an additional order of magnitude for APAR technology to become cost competitive with mechanical-scan or passive phased array technologies.[27] Two considerations drive the production cost for T/R modules: process and materials.

Process Costs

For X-band T/R module production in the United States, labor accounts for two-thirds of module production costs, as shown in Figure 3.1. Furthermore, assembly automation is especially crucial to reduce the costs, as indicated by Figure 3.2. The challenge of testing is not only to automate but also to devise efficient testing strategies that screen subcomponents thoroughly within reasonable time and cost constraints. The problem of module testing lies with the large number of measurements and test structures required for thorough testing across wide ranges of operating frequencies and states. The number of test structures can increase exponentially with the number of electrical measurements and state changes. Thus, the test process can typically cost more than all the module assembly processes combined.[28]

---

[25]Ibid.

[26]Westinghouse reports a module cost of $8,291 in 1985 dollars during a 1991 production run. "Case Studies of Successful Production Applications of GaAs ICs," op. cit.

[27]McQuiddy, D., et al., op cit.

[28]Discussion with Motorola engineers.

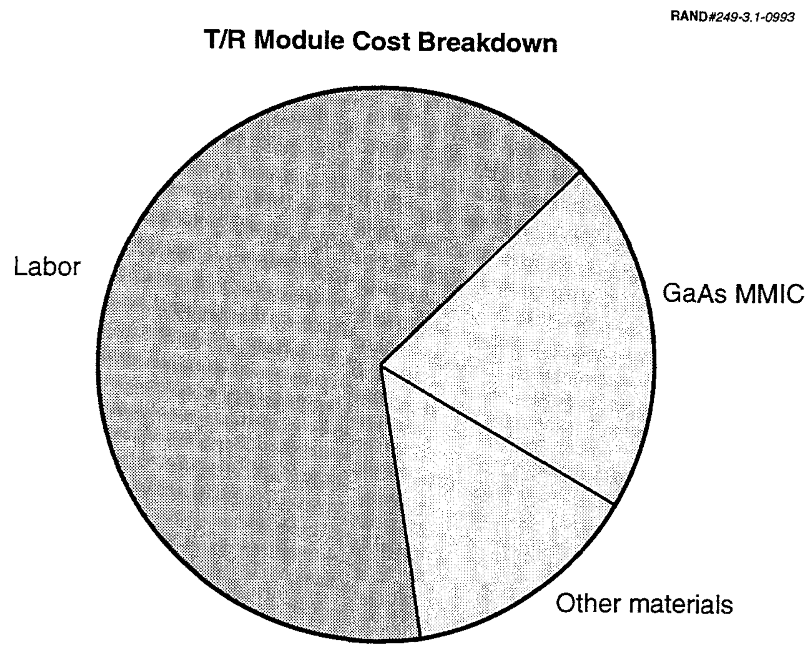


Figure 3.1—Labor Dominates Production Cost

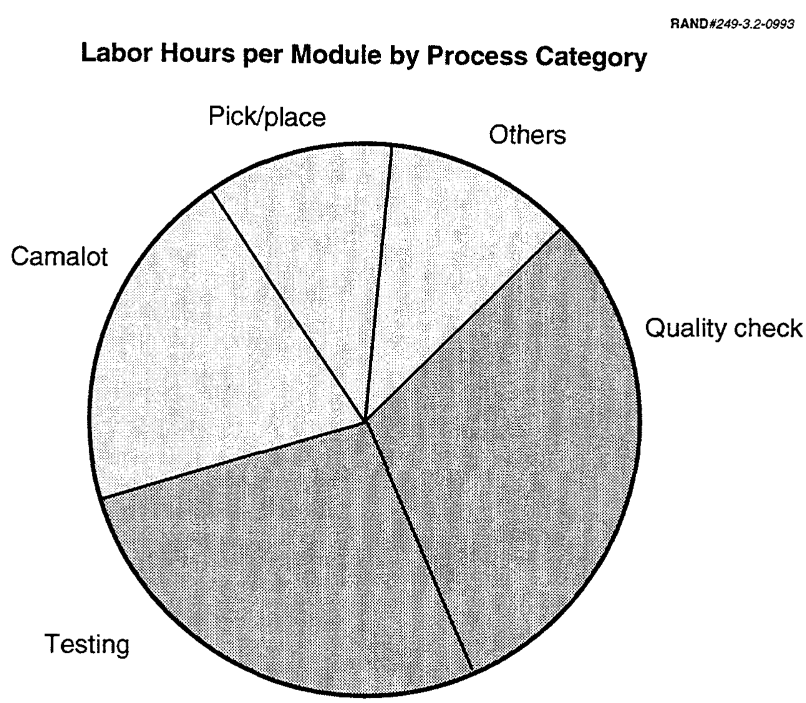


Figure 3.2—Quality Check and Test Dominate Process Costs

Since the early 1980s, U.S. contractors have made considerable progress in automation. In addition to funding from DoD Manufacturing Technology (MANTECH) programs, contractors invested several million dollars to set up automated wire-bonding, pick and placement of chips, and module testing processes. Still, some processes are labor-intensive, particularly the placement of subassemblies onto carriers. Despite such progress so far, process costs alone are still higher than DoD cost goals.[29]

Apart from automation, U.S. industry is trying to reduce module costs by integrating more T/R module functions into MMIC. MMIC integration reduces assembly labor because the number of parts and interconnects can be reduced. Table 3.1 shows three programs in which increased MMIC integration lead to reductions in part and interconnect count for T/R modules.[30] In 1985, SSPA modules cost $10,000 in 1985 dollars. By the late-1980s, module cost fell to about $3,000. Furthermore, MMICs also lead to modules of higher reliability by reducing the number of wire interconnections required.[31]

Materials Costs: Limitations of MMIC

Despite the advantages of reducing part count, MMICs can also increase material costs for T/R modules. Any kind of GaAs circuit is expensive to fabricate and test. A finished GaAs MMIC die can cost several dollars per square millimeter,[32] and MMIC costs currently comprise one-third the total costs for U.S. T/R modules.[33] High MMIC chip costs could also indicate diminishing benefits of designing MMICs at high levels of integration. As Figure 3.3 illustrates (the graph does not represent actual numbers but is included for illustration purposes only), MMIC integration may at some point increase module costs, as reductions in assembly costs are overwhelmed by increases in MMIC chip costs. MMIC chip costs could grow more than linearly as integration levels are increased because larger chip areas may be required to accommodate the increased number of devices and elements packed on the chips. Larger chips incur higher fabrication

[29] *MANTECH for T/R Modules: Industry Review*, Manufacturing Technology Directorate, Wright Research and Development Center, Contract No. F33615-C-5705, 23–24 October 1991.

[30] *USAF Manufacturing Technology*, op. cit.

[31] Wire interconnects are among the most frequent causes of failure within complex hybrid microcircuits and modules. Interview with AT&T engineers.

[32] McQuiddy, D., et al., op. cit.

[33] Cohen, E., op. cit.

Table 3.1

Module Complexity Evolution

Item	Program A	Program B	Program C
Components	181	127	26
Solder Connections	49	0	0
Wire/Strap Interconnects	606	802	207
Process Steps	242	76	17
Assembly Labor Hours	90	55	5

SOURCE: McQuiddy, et al., "Transmit/Receive Module Technology for X-band Active Phased Array Radar," *Proceedings of the IEEE*, Vol. 79, No. 3, March 1991.

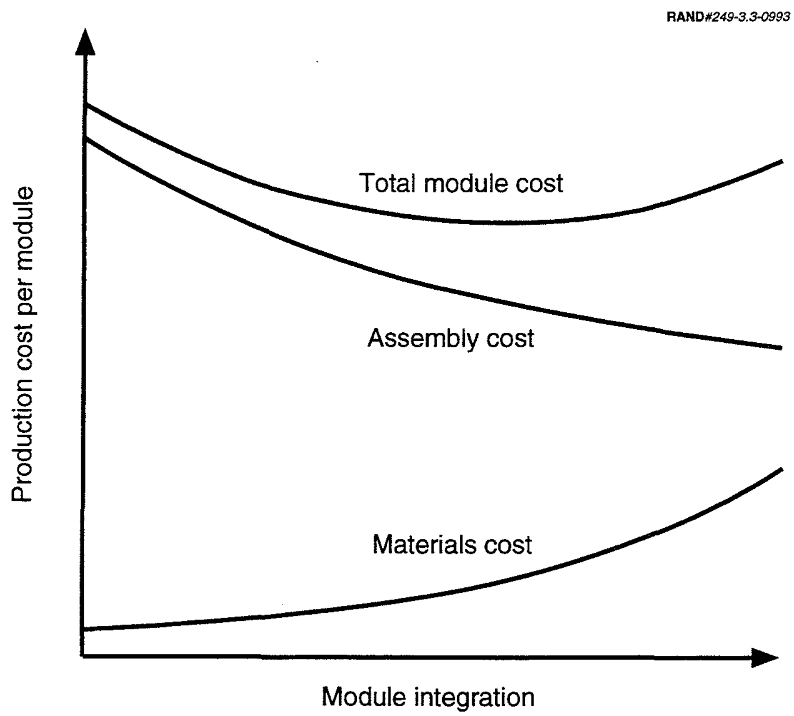


Figure 3.3—Diminishing Returns from Increased Integration

costs because labor and materials usage is roughly proportional to chip area. Yield[34] can also fall as the chip area is increased because of increases in the likelihood of defects on any given chip.[35]

---

[34]Yield is the proportion of chips that pass specifications in relation to all chips produced.

[35]Skinner, R., "What GaAs Chips Should Cost," *Technical Digest, IEEE Gallium Arsenide Integrated Circuit Symposium*, 1991, pp. 273–276.

U.S. industry is working to counteract rising integration costs by increasing packing densities through closer spacing between devices. However, these efforts often run against the need to provide enough spacing to prevent shorting. Another obstacle preventing GaAs chips from achieving the high packing densities of silicon is the relatively large spacing required between devices on GaAs chips, largely because GaAs lacks a native oxide. The existence of a native oxide in silicon enables higher packing densities and integration levels as seen in the latest silicon dynamic random-access memory (DRAM) devices.[36]

Even if GaAs could achieve the same densities as silicon, GaAs would still cost several times more than silicon devices of the same area. One reason is fabrication costs. GaAs integrated circuits (IC) fabrication requires extra process steps to etch ditches and deposit insulating materials between adjacent electronic elements. With silicon, these steps can be avoided because silicon material forms a native oxide with heating that acts as good insulation between tightly spaced circuits.[37]

Second, costly stringent safety precautions are required to handle volatile and toxic arsenic gas when growing GaAs starting material. On the other hand, silicon is a pure element, and its growth processes are well understood. Therefore, silicon starting material is far easier to make, is far purer, and is less costly than GaAs material.[38]

Third, GaAs is a less mature materials technology with fewer applications than silicon. Consequently, GaAs materials have far lower purity levels than silicon materials, leading to lower GaAs yields and high costs.[39] In addition, because of the limited applicability of GaAs technology, factory production levels of GaAs represent only a small fraction of that of silicon. The lower production volumes result in higher unit costs resulting from steep economies of scale.[40] The factors that increase GaAs MMIC costs are summarized in Table 3.2.

Because of the new challenges GaAs poses for circuit designers, R&D funded by the DARPA Monolithic Microwave Integrated Circuits (MMIC) Program in the mid-1980s worked to develop models and databases for statistical MMIC design and yield analysis. Program contractors were required to produce large databases for inputs into models used to predict the impact of process

---

[36] Sze, S., *Semiconductor Devices: Physics and Technology*, 1985, p. 342.
[37] Ibid.
[38] Interview with Westinghouse Electric engineers.
[39] Ibid.
[40] Skinner, R., op. cit.

Table 3.2

Some Reasons for High GaAs MMIC Costs

Cost Factor	Causes
Fabrication Yield	• Impure starting materials • Process variations • Wafer breakage • Contamination at fabrication
Handling Yield	• Chip breakage • Improper placement and attach • Contamination at assembly
Materials Cost	• Costly starting materials • Larger chip areas (lower integration)
Fabrication Cost	• Extra process steps (insulation, safety) • Higher unit overhead (lower volumes)

parameters on chip performance.[41] However, these efforts are costly. DARPA has spent more than $500 million on the MIMIC program, with a large portion of program funds dedicated to developing a domestic design and procurement industry for MMIC technology.[42]

One goal in the MIMIC program is to increase parametric yields of MMICs. Parametric yields, the percentage of product output whose parameters pass specifications, tend to fall as integration levels of chips are increased because the performance of highly integrated chips tends to be more sensitive to process variations. In a highly integrated chip, off-center electrical performance from process variability at an early stage in the circuit can become amplified as signals pass through to subsequent stages. As a result, final output can deviate significantly from expected performance.[43] Lower chip yield increases the costs of finished chips because the cost of discarded chips must be recovered through the high price of the final product.

With hybrid MICs, such problems of parametric yield can be mitigated through tuning or adjustment of passive elements. Such tuning can help to counteract the impact of process variations on circuit performance. However, tuning is not an option within MMICs because of the microscopic feature sizes of the tuned

[41] Cohen, E., op. cit.
[42] Interview with Michael Driver, Westinghouse Electric.
[43] Ibid.

elements. MMIC producers must, therefore, settle for lower parametric yields and lower electrical performance than tuned hybrid MICs.[44]

Other Materials

Other factors contributing to high module costs include nonactive materials used for passive functions or used for structural protection of the module. The cost of materials such as the module housings, lid, and interconnect comprise about one-fourth of the costs of recent module prototypes. Including such passive components as capacitors and logic circuits, the cost of all nonactive parts exceeds the DoD cost goal for entire modules.[45]

Stringent requirements on module properties and the desire to simplify assembly may dictate materials even more expensive than those identified above. Texas Instruments and Westinghouse have developed T/R modules made of metal matrix composites, and Hughes has developed modules made of low-temperature co-fired ceramics. Currently, both materials are not as mature as conventional alloy materials and, therefore, will require additional investments in nonrecurring engineering and capital equipment before they can be widely utilized in defense products.[46] Furthermore, at current levels of production, these newer materials will probably cost several times more than materials currently used.[47]

Antenna Array Issues

The APAR antenna also poses engineering challenges. One challenge is the design of an interconnection scheme for the various parts of the array. Antennas for both the F-22 and FS-X antennas are connected to a feed system that must supply power and communications to and from the modules. Such a system may involve complex striplines[48] and cables converging in several places in the antenna, power supply, exciter,[49] and signal processor.[50] Interconnection design

---

[44]Ibid.

[45]Manufacturing Technology for Radar Transmit Receive Modules, *Phase 3 Industry/Government Review*, US Air Force MANTECH Directorate, February 1992.

[46]*Strategic Industrial Initiative: Phased Array Radar*, op. cit.

[47]Course on hybrid microcircuit and multichip module packaging, UCLA Extension, May 24–26, 1993.

[48]A stripline is typically a miniature flat strip of metal mounted or encased within an insulating substrate that can act as a microwave waveguide, antenna, or connection.

[49]An exciter is an LRU that supplies a weak, input signal to provide timing to the transmitters within each T/R module.

[50]*Strategic Industrial Initiative: Phased Array Radar*, op. cit.

must reconcile the problems of electromagnetic interference, impedance matching, signal losses, and thermal effects in the antenna.[51]

One of the most challenging problems in antenna engineering involves thermal management. Active array antennas involve complex issues in which circuit performance and reliability must be maintained through exacting mechanical design, thermodynamic engineering, and machining. With many modules packed into a small array, heating inside the modules can adversely impact system performance and reliability. A liquid flow cooling system covering the face of the array is required to transport heat out the antenna.[52] Antenna designers must be careful to develop a cooling system that transports heat uniformly across the array face. Thermal irregularities, such as "hot spots," in the antenna can severely degrade radar performance by introducing phase and gain errors into a cluster of T/R modules in the antenna. Hot spots can also accelerate failures of components within the system.[53]

The production of the array also raises problems of cost. One potential affordability problem with the antenna is the microwave coaxial cables to connect signals between the numerous nodes within an APAR system. Although far less expensive and cumbersome than the microwave tubing in corporate-fed PPAR systems, current connector technology involves costly coaxial copper cables. Some DoD-funded Independent Research and Development (IR&D) programs have developed fiber optic connectors lighter and more resistant to electromagnetic effects than metal cable. However, electro-optics technology needs further development before fiber optics become practical for APAR interconnections.[54] Finally, the construction of the rack holding the modules requires highly precise machining, as the slightest deviations in the placement of modules can adversely impact radar performance. Highly accurate fabrication of the array structure at an affordable cost will require the latest in multifunctional, high-speed multiple-axis machine tools.[55]

Probably the most challenging task is the development of a scheme to characterize and screen T/R modules running off the assembly line. Such a scheme is necessary to ensure that the modules inserted into the array are of high performance and reliability. APAR applications have required a different approach in the screening of components from what defense electronics contractors have utilized in the past. Past electronic systems have not contained

---

[51]Interview with Dennis Mukai, USAF Wright Laboratory.
[52]Ibid.
[53]Discussion with Dennis Mukai, USAF Wright Laboratories.
[54]Ibid.
[55]Ibid.

as many active components as APAR. Consequently, in production, contractors could afford the high reject or rework rates associated with stringent screening levels, as each system contained only a few of these components. However, as T/R module cost has become a principal determinant of the successful adoption of APAR technology, the DoD can less afford high module costs caused by high reject rates and rework typical of screening processes.

The development of new, economical screening processes for modules can be a problem because of the difficult trade-offs between quality assurance and cost. If screening limits are set too loosely, system performance will be degraded because of process-induced variations among the T/R modules. On the other hand, if the screening regime is too rigorous, then test costs may skyrocket, even under automated testing. One challenge of screening is to develop models that can predict the impact of process variations within a population of finished modules based on the performance of the system and yielded cost of modules. Another problem is to devise quality assurance strategies that ensure the highest system performance without incurring exorbitant testing costs.[56]

The T/R module cost problem has forced DoD contractors to consider different quality methods from the past. Instead of heavy screening, high rejection rates, and extensive rework, contractors will need to emphasize process control to assure the quality of modules that will go into an APAR system. Contractor incentives to move in this direction will likely grow because of lean post–Cold War budgets. If APAR is to become widely adopted by the U.S. military, DoD contractors will have to learn new methods of quality assurance procedures, based on process control widely embraced by commercial firms. Contractors will need to rely more on good processes rather than rejection and rework to assure quality of product.

However, contractors may face some handicaps in their ability to apply commercial quality-control methods. These handicaps include sharply declining businesses in defense and the lack of experience with continuous, high-volume production. Continuous, high-volume production is crucial in allowing firms to refine and tightly control their processes. These factors, among others, are believed to have contributed to the unsurpassed quality achieved among commercial firms in Japan today.

---

[56]Ibid.

4. FS-X Radar Assessment

This report has argued that although APAR enables many operational advantages, it is difficult and costly to develop and produce. One clear indication of these difficulties is the lack of any APAR that is operational in a tactical fighter. In light of its enabling capabilities, both the United States and Japan continue to invest considerable resources to overcome these difficulties and to reduce production costs over time.

The approaches taken by both countries to realize APAR differ in several respects. To shed light on these differences, this section briefly compares the APAR system developed by Japan for FS-X with the fighter radar systems recently developed in the United States in addition to the APAR currently under development for the F-22 program. Then the implications of such a comparison are discussed.

System Assessment

Along most conventional measures, the FS-X radar is not the highest performance system by U.S. standards. Although the FS-X is based on APAR technology, the operating modes of the FS-X engineering model (EM)[1] are similar to those within existing U.S. radar systems based on mechanical-scan technology. The FS-X modes, for instance, include typical functions found in most U.S. fighter radars, including track-while-scan,[2] target illumination,[3] range-while-search,[4] and ground mapping and imaging.[5] U.S. fighter radars developed over the past 20 years have similar capabilities. For instance, all

[1]The engineering model is the preliminary prototype used to test and prove the system concept being developed. Engineering models can be considered analogous to prototypes developed in U.S. Demonstration/Validation (Dem/Val) programs.

[2]In track-while-scan, the radar system tracks the bearing of one or more detected targets while searching for new ones at the same time without interrupting the search sequence.

[3]In target illumination, the radar fixes a strong beam to a target to lead homing missiles to the target.

[4]In range-while-search, the radar scans for targets and simultaneously calculates their ranges, typically by imposing frequency modulation on a coherent burst of pulses.

[5]The imaging mode generates maps that can discern roughly the shape and other physical characteristics of detected objects using SAR techniques.

modes mentioned above are also programmed within the F-15/APG-70 and F-16/APG-68.[6]

In addition, along some measures, the FS-X EM radar can be considered lower than the U.S. state-of-art. In particular, flight test results of the EM supplied by the JDA indicate considerably lower detection range, sidelobe suppression, and resolution than the U.S. F-16/APG-68—one of the most advanced U.S. systems compatible with F-16 or FS-X–sized aircraft.[7] In addition, the operating ranges of the FS-X EM radar are several times worse than the APG-68 in track-while-scan and range-while-scan modes. FS-X imaging resolution specs were also several times worse than the APG-68 and APG-70. Because DoD is aiming for a system of far higher performance than existing radar systems with the F-22 radar, it is safe to say that the performance specs of the FS-X EM are far lower than those of the F-22 radar.[8]

Despite the modest test results of the FS-X EM prototype, it contains several features that make it a significant development even by U.S. standards. One important feature is a mode interleaving and multi-target acquisition capability far better than most existing U.S. fighter radar systems. Because the FS-X EM is an electronic scanning radar, it can perform highly sophisticated mode interleaving such as interleaved air-to-air and air-to-ground modes. Interleaving should give the FS-X advanced capability of timesharing a broad range of modes. Although DoD has attempted equally complex mode transition logic in fighter radar systems of the past, such efforts have generally failed because of the limitations inherent with mechanical-scan type radar systems.[9]

Another operational advance of the FS-X radar is its ability to generate and interleave beams of differing shapes. For example, the FS-X in the track-while-scan mode will be able to switch very easily between wide, fan-shaped beams and thin, pencil-shaped beams. This ability would enable the system to capture the advantages of both fast searching for new targets and precise tracking of multiple-acquired targets simultaneously.[10]

Finally, the FS-X radar system could be one of the most reliable and maintainable multimode fighter radar systems ever built. Its reliability, as measured by mean time between failures, is several times better than the APG-68 and an order of

---

[6] *Jane's Radar and EW Systems*, op. cit., pp. 260–261.

[7] This report compares the FS-X with the APG-68 because of comparable aperture sizes and overall system dimensions. Also, both are designed to fit in F-16–sized aircraft.

[8] Interview with David McQuiddy, Texas Instruments.

[9] *FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[10] MELCO video tape on FS-X APAR technology, FS-X Radar Technology Symposium, Department of Commerce, May 1992.

magnitude better than the F-15/APG-70.[11] System reliability and maintainability are also vastly improved by its unique and unprecedented array built-in-test (BIT) and self-calibration features.[12] The FS-X will also be highly maintainable because the system is designed with self-diagnostics that obviate a maintenance shop on the runway. The FS-X array and modules are designed for the replacement of defective modules by hand. BIT features and the ability to hand replace defective modules should help reduce life-cycle costs substantially.[13]

Emphasis on Cost Containment

The FS-X radar reveals some broader philosophical differences between Japan and the United States regarding objectives in systems acquisition. For instance, a close examination of Japan's R&D strategy in APAR reveals a higher priority on costs than is typically the case with the United States. If one assumes that Japan's objective is to develop its own independent, indigenous defense technology capability, such objectives would probably be served best by going for a conservative radar system with the FS-X.

Japan's priority on cost can be seen in the relatively low number of T/R modules in their FS-X array design. The FS-X array contains only 800 active T/R modules, less than half of the U.S. F-22[14] and SSPA prototypes.[15] Since T/R modules are a major engineering driver for APAR, a system design with fewer modules not only reduces procurement costs but also can simplify system engineering and integration.

Design for low cost is also apparent in the low performance specifications of the EM and FM T/R modules. A notable U.S. expert in solid-state technology had judged the FS-X EM modules to be about three to four generations behind the United States in performance and compactness. The expert found the FS-X T/R modules as more conservative than U.S. modules developed as far back as 1987 in the ATF Dem/Val program, particularly in transmit peak power and bandwidth.

---

[11]The FS-X EM radar has a mean time between failure (MTBF) of more than 300 hours, compared to about 100 hours for the APG-68. Interview with Hyman Shulman, RAND.

[12]BIT allows the radar system to perform an end-to-end test of every active module in the array. Each module is fired one at a time to determine errors in gain and phase-shift. The radar computer uses the test information to recalibrate the antenna through adjustments in phase shift commands that compensate for the module errors detected. Through such compensation, antenna performance is reoptimized, leading to increased system reliability and enhancing graceful degradation. MELCO briefings at the FS-X Radar Technology Symposium, Department of Commerce, May 1992.

[13]MELCO briefings, op. cit.

[14]*Jane's Radar and Electronic Warfare Systems*, op. cit.

[15]McQuiddy, D., et al., op. cit.

By going for lower power, for example, Japan could ensure that the FS-X would be far less expensive and lower risk than the F-22. In addition, Japan would not have to deal with the plethora of technical challenges caused by excessive heating in the array and high load on the power supply. Such problems are best alleviated with a radar designed to utilize lower transmit power in the modules. Such a design would also reduce cost and risk as lower power could enable the use of a far simpler design, resulting in lower fabrication and assembly costs.[16]

Japan has apparently compromised system performance for the sake of lower cost. For example, by utilizing fewer modules in the antenna, Japan had limited the ability of the final system to transmit at the higher power levels necessary to increase detection ranges and to sharpen beams. Because the FS-X will not only have fewer modules but lower performance modules, the F-22 radar, if completed, will enjoy a considerable performance edge over the FS-X.[17]

One could explain the design conservatism in the FS-X as simply arising from constraints posed by FS-X platform requirements. The FS-X is designed to be a relatively small, lightweight fighter similar in size to the F-16, with especially limited space and payload available for avionics. Such constraints pose limits on the size, power utilization, and cooling for the FS-X radar. Since the F-22 is much larger than the FS-X, the former can accommodate and support a far larger radar system and associated cooling and power supply apparatus.[18]

Nevertheless, some aspects of the FS-X system indicate a clear decision by Japan to develop a system somewhat below the maximum capability obtainable. For example, Japanese engineers had apparently decided to keep the FS-X T/R modules simple by not designing any variable gain into them, although they clearly have the capability to do so. Without variable gain, the FS-X array would not be able to utilize amplitude modulation to achieve even better beam control than PPARs. However, many of the technical difficulties caused by variable gain errors in T/R modules could be avoided.

The use of array thinning to amplitude taper[19] the FS-X antenna reflects another example of Japan's pragmatic decision to compromise potential performance for the sake of reducing costs. Some of the elements away from the array center are fitted with lower power and nonactive modules to taper the array[20] so that

[16]Interview with David McQuiddy, Texas Instruments.

[17]Cheston, T., and J. Frank, "Phased Array Radar Antennas," op. cit.

[18]A larger APAR emitting at higher power levels requires a platform capable of accommodating not only a larger antenna but also larger power supplies, greater power generation, and a more complex cooling system. Interview with a MELCO engineer.

[19]Amplitude tapering is necessary to reduce sidelobes for phased array antennas.

[20]*FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

variable gain would not be necessary. While this approach saved considerable engineering effort and costs, it also represented a performance compromise from an array utilizing variable gain modules.

Japan's cost emphasis can be further revealed by the kinds of improvements made in their FM[21] T/R modules over the EM modules. Most improvements were in producibility and cost rather than performance. The most notable change is the substantial increase in MMIC integration, resulting in a new module prototype that contained only half the number of parts and chips as the EM.[22] The MMIC fabrication processes were also significantly upgraded for improved manufacturability. Improvements in quality control also enabled a new module that did not require timing adjustments after assembly.[23]

Despite the dramatic improvements in producibility, the FM performance hardly changed from the EM. Despite an entirely new active circuitry, module size and transmit power of the FM were identical to the EM. The internal circuitry was not revamped to shrink the module and increase its power. Instead, it was done to improve on module cost and producibility.

Selective, Incremental Improvement

Consistent with their cost focus, Japanese contractors appear to rely on incremental rather than revolutionary improvements with respect to their APAR systems technology. One engineer at USAF Wright Laboratories recalled a meeting in which MELCO engineers mentioned that software for the final FS-X radar was already completed in an earlier prototype development effort. Any improvements made with the EM over the previous generation prototype had to be incremental because old software could be transferred. This strategy might explain how Japan could develop successive prototypes in such short cycle times.[24]

Incrementalism can also be seen in numerous similarities between the FM and EM modules. Despite slight differences in bandwidth, receive gain, and noise figure specs, the size and transmit power specs were identical.[25] Thus, the FM

[21]The flight model is presumably analogous to the full-scale development prototype; the final prototype reflects the system that will go into production.

[22]FS-X Radar Technology Symposium, June 22 1992, U.S. Department of Commerce.

[23]Ibid.

[24]Software development is one of the most time-consuming and difficult tasks for new military systems. System software now consumes almost half the total development costs for avionics.

[25]FS-X Radar Technology Symposium, op. cit.

modules could be a form-fit with the array already developed from the EM development effort to conserve considerable time and cost.

The desire for a form-fit between the FM modules and EM system may be the rationale behind Japan's highly incremental improvement strategy for its module R&D. Since complex systems must be fine-tuned so that their parts operate harmoniously, a change in the characteristics of one part could require a substantial redesign in other parts of the system. If one is not careful in choosing areas for improvement, then the entire design of the system might have to be overhauled at significant expense.

For example, if Japan had decided to increase module transmit power, the cooling system would have to be redesigned because of the extra heat generated. In addition, the power supply design would require further changes to meet the higher electrical loads caused by a more powerful cooling system and module transmit function. A similar situation exists with module size. If module size were reduced, a new antenna layout would be needed to ensure a tight fit between the modules and feed system. In turn, the signal distribution network and cooling system might have to be modified to accommodate these changes. By changing one attribute in the T/R modules such as transmit power or module size, the entire antenna design may have to be changed.

Japan had probably elected to focus primarily on improvements in receive characteristics of the FM module to avoid redesigning the entire antenna system. The primary areas in which the FM module had a notable improvement over the EM were receive characteristics such as bandwidth, noise figure, and gain.[26] Unlike transmit parameters, these parameters could be improved to enhance system performance while preserving a functional form-fit with the antenna to control costs.

By confining improvements to module receive performance, Japanese contractors found a way to improve system performance at minimal cost. This choice was made because improved module receive performance of the module would not necessarily change the thermal characteristics of the antenna, since only a small fraction of the total power is dissipated by the receive side. In addition, the mechanical and electrical interconnections of the antenna system would not be affected, because the receive side draws very small amounts of power compared to the transmit side. In this way, the improved FM modules would still make a form-fit with the antenna and line replaceable units (LRU) EM prototypes.

---

[26]Ibid.

Frequent Prototyping

The incremental improvement strategy as outlined above is part of a long-term Japanese strategy of rapid prototyping of APAR systems technology. Since 1967, Japan has followed such a strategy to advance its state of the art.[27] Development timelines indicate that MELCO had completed the development of five APAR prototypes successively from 1967 to 1975.[28] In the same time period, the United States had barely completed four.[29] The rapid prototyping strategy is also visible in recent efforts. For example, timelines show that the FS-X EM prototype was developed in only three or four years, and the FM, if completed on schedule, in only two to three years.

Probably Japan's ability to complete new prototypes frequently has been possible because of the highly incremental improvement approach discussed above. Since design conservatism and incrementalism make the system integration easier, new system prototypes can be developed quicker. Japan may view the rapid prototyping as a way to make up for the small improvements made per prototype. Consequently, Japan can make rapid progress overall in its state-of-the-art technology.

Through rapid prototyping, Japan has accumulated decades of design and systems integration experience. Rapid prototyping, supported by incremental improvement, has provided valuable opportunities for Japan to gain critical flight testing data and to practice in designing and integrating new military systems. Japan had commenced flight testing of an X-band APAR system prototype as early as 1986,[30] four years before the first U.S. flight tests of the ATF Dem/Val radar. Such experience would give Japan the advantage of early feedback that could guide them to make the most cost-effective improvements for later prototypes.

As a result, Japan may acquire an initial operational capability in APAR several years before the United States. Completion of full-scale development (FSD) of the FM radar is scheduled for 1994, three years before completion of FSD of the F-22 radar. This time lead could grow if the U.S. program experiences more stretchouts as a result of the lean budget environment. Stretchouts have already plagued the F-22 program, causing a slip in F-22 FSD from 1992 to 1994.[31] If

---

[27]Ibid.

[28]Ibid.

[29]McQuiddy, D., et al.

[30]"Defense Agency to Enter Detailed Design Phase of APAR Radar," *Comline Transportation*, August 3, 1987, p. 6.

[31]Since the beginning of ATF Dem/Val, EMD for the radar already has been moved back from 1992 to 1994. Interview with Westinghouse Electric engineers.

technical and budget problems persist on the F-22, further delays can be expected as well as extreme difficulty in the completion of an operational U.S. airborne APAR by the end of the decade.

Japan may also be ahead of the United States in terms of demonstrating manufacturability of critical radar components such as LRUs and T/R modules.[32] Their readiness was clearly revealed in their announcement that initial production of FM modules would begin by mid-1993. At the time of this writing, U.S. contractors are still building and refining their automated factory module[33] and have not completed the production setup for the radar system and LRUs.[34] Unlike their Japanese parallels, U.S. APAR contractors have striven for much higher improvements over previous prototypes rather than incremental improvements. F-22 program requirements have called for a radar system of substantially higher capability than any other radar developed. Consequently, instead of incrementally building on the F-22 Dem/Val, U.S. contractors have had to develop an entirely new radar for FSD.[35] This happened despite the fact that the ATF Dem/Val system was judged as highly successful in demonstrating radar operations during flight tests. Nevertheless, the Dem/Val prototype was not viewed as adequate because it did not reach the stringent performance requirements of the F-22 program.[36]

To meet such performance requirements, U.S. contractors have been racing to develop T/R module prototypes in which a new version often appears radically different from the previous one.[37] While pushing U.S. module technology to the forefront, such large improvements have incurred very high engineering costs as well as long development times to U.S. APAR development. For example, U.S. contractors have been developing innovative but risky technologies such as composite parts and high power MMICs for their T/R modules. However, such technologies involve less mature designs, materials, and components whose producibility has yet to be demonstrated.[38] In addition, with the emphasis on improving module performance over the years, relatively less attention has been given to other important aspects of the system, such as the electrical

---

[32]MELCO showed a videotape of what appeared as automated production of LRUs and other components of the EM radar. FS-X Radar Technology Symposium, op. cit.

[33]T/R module MANTECH program, Phase 4, is scheduled for completion in late 1993. "Manufacturing Technology for Radar Transmit Receive Modules," op. cit.

[34]Interview with Westinghouse Electric engineers.

[35]Beal, C., and W. Sweetman, op. cit., p. 745.

[36]The ATF Dem/Val modules did not have as much peak power as the 10 W requisite in the F-22 radar program. *FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[37]Over the past decade, a T/R module generation is superseded by a new one almost every two to three years. Every generation has resulted in dramatic reductions in module dimensions and increases in output peak power. Interview with David McQuiddy, Texas Instruments, Inc.

[38]Interview with an engineer on the F-22 program.

interconnection system among modules, the signal processor, and the radar computer. These factors may have placed the United States behind Japan in system maturation and producibility. Stringent requirements may have already served to lengthen the expected time of development for the F-22 radar. One U.S. radar engineer commented that had the F-22 requirements been as low as the FS-X, the United States would have had an F-22 radar flying today.[39]

Rapid prototyping has enabled Japan to advance its systems technology rapidly but probably at much lower risk and cost. One advantage of rapid prototyping is that the latest technology can get inserted into systems without high costs. A strategy of frequent product iterations is reportedly employed by many successful commercial Japanese firms in the automotive and machine tool sectors.[40] Such a strategy is widely credited as one of the secrets of Japanese business success throughout the 1980s.[41,42] The FS-X radar program may indicate that a similar strategy can be used successfully in the defense area as well.[43]

Industrial Base Motives

Japan may be driven in the FS-X radar program by a long-term motive to advance its indigenous military capabilities. Rather than pursue the highest performance radar system in the short run, Japan has instead chosen to advance its technological capabilities over the long run through rapid prototyping and incremental improvement.

One indication of this motive was Japan's decision to develop APAR for the FS-X in the first place. The mission requirements of the FS-X could have been met with the purchase of one of several conventional, off-the-shelf mechanical-scan radar systems developed in the United States.[44] The mission requirements also did not dictate the need for many of the novel capabilities enabled by APAR technology such as mode interleaving and accurate multiple target engagement.

---

[39]Interview with Captain Sid Perkins, FS-X Technical Liaison Officer, USAF.

[40]In the automobile industry, U.S. and European product development projects use about twice as many engineering resources and take 12 to 13 months longer than Japanese projects when controlling for body size, number of body types, and price. Also, a comparison of flexible manufacturing systems showed that U.S. development times were 1.25 to 2.25 years longer than Japan's. See Alexander, A., *Comparative Innovation in Japan and in the United States*, RAND, R-3924-CUSJR, August 1990, pp. 18, 41.

[41]Ibid.

[42]See Clark, K., et al.,"Product Development in the World Auto Industry," *Brookings Papers on Economic Activities*, 1987, and Jaikumar, R., "Japanese Flexible Manufcturing Systems: Impact on the United States," *Japan and the World Economy*, No. 1, 1989.

[43]Texas Instruments and Westinghouse Electric 1991 documents show FSD for the F-22 radar scheduled to begin by 1994 and end by 1996. The FM is scheduled for completion by 1994.

[44]*FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

Rather, these capabilities seem to be additional features made possible by electronic-scan technology.[45]

Unlike the U.S. objective of fielding the highest performance radar, Japan appears motivated by the desire to demonstrate a conservative, baseline APAR system as early as possible. Japan seems to be successful in this objective. As of 1989, Japan had completed the development of a conservative, baseline FS-X radar system, the EM prototype, and had conducted numerous flight tests on this system. By 1992, EM flight tests were considered successful in demonstrating that the EM met all requirements set by JDA. Japan has announced that it is ready to roll out a flight-worthy APAR system by 1994.

Japan may also be motivated by a desire to develop a military system that also helps Japanese industry commercialize advanced dual-use technology. Because APAR draws on so many dual-use technologies, such as solid-state devices and microwave circuits, Japan might also be using the program to help Japanese industry commercialize advanced technologies based on microwave device, materials, and tooling technologies.[46] The issue of dual-use technologies as relevant to APAR is discussed in greater depth in Section 7.

Implications of the FS-X Radar

Both the United States and Japan recognize the immense military utility of APAR technology, as reflected in the long-term efforts by both countries to develop this technology.[47] DoD has identified phased array technology as critical to the nation's security, as APAR technology is a leading candidate to satisfy myriad defense needs over the next decade.[48] If cost and performance bottlenecks can be resolved, APAR technology can be expected to proliferate through the weapons arsenals of the United States, Europe, and Japan.

---

[45]Ibid.

[46]A U.S. avionics expert familiar with the FS-X program is quoted as saying, "The Japanese target [defense] technology that is applicable to commercial applications, whereas U.S. companies will target only military technology." Keller, J., op. cit., p. 14.

[47]Japan has three other military programs to develop APAR for ground-based, ship-borne, and air reconnaissance applications, FS-X Radar Technology Symposium. On the U.S. side, APAR is being developed not only for airborne fire control but also for the Ground-Based Radar program for theater missile defense. The U.S. Navy is also developing APAR for ship defense and fire control applications. Interview with David McQuiddy, Texas Instruments Defense Electronics.

[48]Of the 22 technologies identified on a DoD list of critical technology, three technologies—sensitive radars, passive sensors, and phased arrays—could be realized with APAR. In addition, five other technologies on the list—preparation of GaAs semiconductors, parallel computer architectures, fiber optics, data fusion, and pulsed power—could see their largest applications coming from the production of APAR systems. See *The Department of Defense Critical Technologies Plan*, For the Committees on Armed Services, U.S. Congress, 5 May 1989.

It is, therefore, no surprise to see Japan emphasize the demonstration of a baseline APAR system as early as possible. Such a demonstration would set the stage for Japan as a world-class developer of a highly critical technology for defense electronics. A successful APAR product could give Japan a big boost in the highly lucrative defense export business, of which Japan currently is a minor player in comparison to U.S. and European producers.

Should the United States be interested, given current Japanese technical capabilities in APAR? The numerous APAR flight tests already conducted in Japan indicate a more than rudimentary technical capability in military systems integration. Although the FS-X performance is lower than the U.S. F-22 and the APG-68, the EM prototype has been judged to be better than the F-16/APG-66,[49] a defense system with strong export sales. The DoD team charged with evaluating the FS-X radar had judged Japan to be only "three years behind in realizing APAR of improved RF performance." With Japan nearing completion of the FM radar, a system that should be considerably improved over the EM,[50] the FS-X radar could be the first break for Japan in advanced military radar systems.[51]

This assessment runs contrary to the conventional wisdom among U.S. policymakers that Japan is hopelessly behind the United States in defense electronics. Throughout the post–World War II period, Japan has been seen as lagging far behind the U.S. military technology. How has Japan managed to develop a competitive radar system in the FS-X given their comparatively small defense budget?[52]

The answer probably lies with long-term rapid prototyping R&D. One advantage of rapid prototyping is that it provides contractors with the engineering experience necessary to improve design and integration capabilities for defense subsystems. Frequent experience with prototyping allows contractors to gain an understanding of high-level trade-offs and relationships among design features and system performance, cost, and reliability. The rapid

---

[49] *FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[50] The FM module specification shows solid improvements over the EM in noise figure, receive gain, and bandwidth. Consequently, the FM should be a more capable system than the EM, which has already been judged to be more advanced than the F-16/APG-66. Ibid.

[51] In receive performance, the FM is competitive with U.S. module prototypes developed as recently as 1990. The FS-X Radar Technology Symposium and *Manufacturing Technology for Radar Transmit Receive Modules*, op. cit.

[52] While data are lacking on total Japanese and U.S. spending on X-band APAR R&D over the past decades, U.S. spending levels on defense technology in general have dwarfed Japan's by two orders of magnitude by any measure. Publicly, Japan acknowledges defense spending at roughly 1 percent of gross national product (GNP) throughout the post–World War II period. Friedman, D., and R. Samuels, *How to Succeed Without Really Flying: The Japanese Aircraft Industry and Japan's Technology Ideology*, MIT-Japan Program, 1992.

prototyping approach can allow for long-term advancement of technical capability at lower cost. Risk is also reduced because contractors are improving only gradually and are developing new prototypes within proven capabilities.

The Japanese approach contrasts with the U.S. approach of aiming for radical performance improvements over fewer design iterations. Admittedly, one could argue that the United States did follow an incremental strategy with the several APAR technology demonstration programs during the 1960s and 1970s. With the ATF and F-22 programs, however, DoD has been striving for systems of drastically superior capability over the previous generation.[53]

The U.S. tendency for radical improvements with each new system presents two problems. First, a large improvement introduces technical risks to the program because contractors develop systems of far greater sophistication and complexity than what they have accomplished in the past. Second, the development of a radically improved system also can increase the time required by contractors to bring the system to operational status. The extended time delay between development iterations not only increases development costs through the phenomenon of the "check-writing machine"[54] but could also reduce organizational competency of the contractor because of a loss of "institutional memory."[55]

Such a tendency can be attributed to historically high defense spending levels of the United States. Throughout the Cold War, the United States outspent any of its allies by orders of magnitude. Thus, the United States could more easily afford making large, costly improvements from one prototype to another. As defense budgets undergo a steep decline, the United States may find itself forced to apply a more incremental approach in research, development, testing, and evaluation (RDT&E) programs. Several U.S. policymakers have already begun to discuss strategies that stress incrementalism and prototyping. Several members of the Congressional Armed Services Committees have put forward proposals to emphasize fieldable and, in particular, producible prototypes as a new lean

---

[53]The SSPA and ATF Dem/Val APAR systems are not prototypes for the final F-22 FSD radar. Rather, the final F-22 radar will be an entirely different system. Beal, D. and W. Sweetman, August 1992, op. cit.

[54]The "check-writing machine" refers to the phenomenon by which projects, even while in a dormant state or on hold, can still incur overhead and administrative costs that pile up over time.

[55]Through worker attrition or degradation of skills, design organizations can lose capabilities acquired from the previous design and integration experience if the organization has not undertaken integration activity for a long time. One former executive of Lockheed Corporation attributed the extreme difficulties of finding experienced development program managers for ATF Dem/Val to loss of institutional memory caused by a 20-year gap since Lockheed had its last system development activity.

acquisition strategy.[56] DoD program managers have already edged closer to incrementalism in the F-22 aircraft program. Program managers have reportedly backed off of several performance requirements to ease the cost burden of F-22 system development and integration.[57]

---

[56]Among four acquisition approaches iterated by then-House Armed Services Chairman Les Aspin, one was to "prove out" a series of fully operational and producible prototypes before entering production. Capaccio, T., "USAF Must Align Acquisition Strategy with Aspin's Views: Loh," *Defense Week*, February 8, 1993, p.12.

[57]Budget cuts have already induced the Air Force to emphasize design refinements, lower-cost materials, and increased manufacturing efficiencies in the F-22 program. Possible alterations in the near future include reductions in computer processing ability, reduced electrical power, and deferral of plans for advanced radars. Opall, B.,"USAF Braces to Deflect Possible F-22 Cuts," *Defense News*, March 29, 1993, p. 3.

5. Candidates for Technology Transfer

This section presents a discussion of candidate FS-X radar technologies from which the United States may derive benefits for the DoD and the industrial base. The FS-X agreements give the United States the option to procure by license any FS-X technology indigenously developed in Japan. The agreements also entitle the United States access to technical data on Japanese FS-X technology to allow the United States to ascertain whether or not it wishes to exercise its option of procuring technology from Japan. As the FS-X radar is classified as indigenous, the United States will have the right to obtain technical data on the radar.

Table 5.1 summarizes several process, component, and systems technologies in the FS-X radar program that U.S. experts have identified as possible candidates for technology transfer. A technology is considered a candidate if Japanese firms are believed to enjoy a comparative advantage over U.S. firms in the particular technology area, or if the Japanese level of competency in the particular technology area might serve U.S. defense or commercial interests. This discussion, however, does not address whether the transfer of these technologies is feasible, practical, or even possible. These latter issues are discussed in Section 6.

T/R Module Manufacturing

DoD has officially identified manufacturing technology for T/R modules as one of the technical areas offering the greatest opportunity for U.S. benefit. DoD recognizes the unparalleled capability of Japanese electronics manufacturers such as MELCO renowned for low-cost, high-volume production. Since DoD expects to produce T/R modules in high volume if cost can be reduced,[1] DoD believes that Japanese module manufacturing technology holds the greatest promise for benefiting U.S. industry.[2]

MELCO officials have reinforced this belief by commenting that production costs would be reduced substantially if demand increased to about 1,000 T/R modules per day. According to MELCO officials, if demand increased so that fully automated manufacturing were justified, costs could fall below $1,000 per

[1]*Strategic Industrial Initiative: Phased Array Radar*, op. cit.
[2]GAO Report, 1990, op. cit.

Table 5.1

Promising Technologies for Transfer

Technologies	Subtechnologies
T/R Module Manufacturing	• Chip/subassembly pick and place • Chip attachment with epoxy • Automated wire bonding • Quality control and testing
Materials Fabrication	• GaAs MMIC • Packaging structures
Systems Integration	• Built-in-test
Component Design	• Miniaturized packaging

module. MELCO officials have also stated that demand from the FS-X program is insufficient to justify full-scale automation. Thus, for the three EM prototype antennas, MELCO admitted using semiautomated processes to produce 10 to 20 modules per day at about $3,300 per module. In FS-X procurement, MELCO expects daily module production to peak at 100 to 200 per day.[3]

Nevertheless, DoD believes that MELCO may be more effective than U.S. firms in moving into high-rate, low-cost manufacturing. A team of DoD radar specialists assigned to assess MELCO technology witnessed high-volume, high-performance production processes used for commercial components. The team noted that many of these processes were nearly identical to those used for T/R module production in the United States. However, the production rates were typically three to ten times higher than those of U.S. producers.

The team witnessed, for example, automated gold wire-bonding, GaAs die-bonding, and epoxy dispensing, all of which are also used for U.S. module production. However, these processes were operating at rates unprecedented in U.S. firms. Many of these processes were being used to build high-demand commercial products such as satellite dish receivers and facsimile thermal heads. The team also witnessed a broad array of company-modified automated equipment supporting the manufacture of a wide variety of defense and consumer electronics products.[4,5]

---

[3]*Strategic Industrial Initiative: Phased Array Radar*, op. cit.
[4]Ibid.
[5]Interviews with USAF engineers.

Although U.S. contractors claim that they could bring module costs below $500 if T/R module demand increased to 1,000 per day, such claims have not been substantiated. Furthermore, several DoD teams that visited Japan to assess their technology have indicated in written reports of a strong comparative advantage over U.S. producers in high volume electronics manufacturing. The team concluded that MELCO advantages in mass production could provide benefits to U.S. defense industrial needs including module production.[6] Such observations are consistent with other reports comparing Japanese and U.S. electronics manufacturing.[7,8]

On the basis of interviews and technical literature, several manufacturing processes might be enhanced if the United States could gain access to Japanese technology. These processes are described below.

Chip/Subassembly Pick and Place

One important area of U.S. interest is Japanese robotics technology for the pick and placement of GaAs MMICs into module parts. This process can be particularly troublesome because of the high fragility of finished GaAs MMICs. Thus, the most careful robotics handling equipment is required.[9] Pick and place equipment must have high dimensional precision, since imprecise placement can induce changes in the electrical performance. Robotics equipment utilizing the latest in visual sensor and pattern recognition technology may be required.[10] U.S. contractors do have access to highly advanced pick-and-place equipment, but Japanese firms are believed to have access to the best pick-and-place

[6] *U.S.-Japan Codevelopment: Update of the FS-X Program,* GAO Report, June 1992.

[7] "[The Japanese] produce at quality levels essentially unknown in most U.S. manufacturing . . . If the [U.S.] Defense Industrial Base could produce as efficiently as Japanese industry, the U.S. could have the defense systems it requires early enough to allow its technical superiority to convey a decisive operational advantage . . ." *Findings of the U.S. Department of Defense Technology Assessment Team on Japanese Manufacturing Technology,* Draft, November 1988.

[8] "The Japanese have equaled or surpassed all world competition in many types of capital equipment, materials, and services important to the semiconductor industry . . . including packaging, automated assembly equipment, various ultra-pure materials, and some categories of fabrication equipment. . .," from Dertouzos, M., et al., *Made in America: Regaining the Productive Edge,* MIT Press, 1990, p. 250.

[9] MMICs break easily not only because of their inherent brittleness but also because of thinning required to dissipate heat from power generating chips. *Strategic Industrial Initiative: Phased Array Radar,* op. cit.

[10] McQuiddy, D., et al.

equipment in the world, particularly those capable of meeting the more stringent handling requirements of GaAs.[11,12]

U.S. producers may benefit by gaining access to MELCO flexible manufacturing systems used for handling variable-sized components. MELCO revealed their utilization of advanced pick-and-place robots capable of handling different sized components.[13] While U.S. producers do have automated pick-and-place equipment for GaAs, most equipment available in the United States lacks the capability to handle subcomponents of vastly differing sizes and shapes, from tiny MMICs to relatively large hybrid MIC subassemblies.[14]

Chip Attachment with Epoxy

MELCO is also reportedly using a conducting epoxy to attach chips to carriers. The epoxy provides a bond of high reliability and tight control in addition to useful thermal and electrical conducting properties. Such an epoxy, if transferred to U.S. companies, might help producers lower defects, increase controllability in chip attachment, and provide electrical and thermal grounding to circuits.[15]

Automated Wirebonding

Wirebonds, the electrical connections between different subcomponents in T/R modules, are a critical reliability, yield, and throughput driver for T/R modules. Currently, the roughly 200 wirebonds inside T/R modules are the primary limiting factor for module reliability and yield.[16] The DoD team visiting MELCO facilities in Japan witnessed what appeared to be superior high-speed wirebonding equipment used in the mass production of facsimile thermal heads. Such wirebonding processes could be highly applicable to high throughput T/R module production needs.[17] If transferred, such technology might be useful in

---

[11] Because of the prevalence of silicon integrated circuits, most materials handling equipment available on the merchant markets has been designed to handle silicon instead of GaAs. Consequently, U.S. producers of GaAs circuits often have had to modify equipment designed to handle silicon to work effectively with GaAs. Interview with Westinghouse Electric engineer.

[12] The Japanese leadership in GaAs pick-and-place equipment is widely believed to have become apparent sometime in the 1980s when Japanese firms had begun to gain their foothold in GaAs circuit technology for satellite dish receivers. Interview with Westinghouse Electric engineer.

[13] Such technology was revealed to U.S. producers in a videotape shown at the FS-X Radar Technology Symposium.

[14] *Manufacturing Technology for Radar Transmit Receive Modules,* op. cit.

[15] Interview with USAF engineers.

[16] *Manufacturing Technology for Radar Transmit Receive Modules,* op. cit.

[17] Each thermal head, although similar in size, contains about four times as many wirebonds as U.S. T/R modules. In addition, MELCO is producing thermal heads at 7,000 per day, 7 times the

helping U.S. producers increase throughput and yield in their module production process.

Quality Control/Test Strategies

MELCO has also developed a quality control regime that allows more extensive RF testing of chips before they go into the modules.[18] By screening active devices before their insertion into modules, this test regime might help to increase yields and reduce rework. If transferred, the successful utilization of this regime might help U.S. factories increase yield and reduce module costs.

Materials Fabrication

GaAs MMIC

High cost materials are the second largest cost factor of T/R modules, especially the active MMICs. During the FS-X Radar Technology Symposium, MELCO described some of their GaAs MMIC products and revealed several that they were producing at high volume by GaAs analog device standards. An area of interest for U.S. industry may be fabrication process technologies for MMICs.

MELCO has also developed a solid capability in GaAs MMIC design and fabrication. It has developed highly integrated active circuits and switch circuits for the FM modules, enabling a module design with only three chips. MELCO has also developed MMIC technology and has inserted high performance circuits in a variety of commercial and military applications. These applications, in addition, have helped to make MELCO a world leader in GaAs MMIC fabrication and handling.[19]

U.S. industry could also benefit from access to MELCO quality control procedures in IC fabrication. Process control is a paramount issue not only in performance but also affordability. The fabrication of X-band active devices to operate at higher pulsed power levels requires extremely tight control tolerance over feature size and doping levels. The slightest variability along these

---

maximum projected throughput levels expected for T/R modules during procurement. In terms of wirebonding throughput, MELCO has already achieved about thirtyfold of what U.S. producers hope to achieve with high-rate T/R module production. *FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[18] FS-X Radar Technology Symposium, op. cit.

[19] Interviews with U.S. attendees at the FS-X Radar Technology Symposium.

processes can radically degrade performance and manufacturing yield, especially with X-band microwave circuits.[20]

The fabrication of GaAs IC with active layers is one area where MELCO may be particularly strong. The power-MMICs contained in the FS-X EM and FM modules contain molecular active layers fabricated with highly advanced molecular beam epitaxy (MBE) processes. The difficulty in achieving predictable and repeatable results with active layers is an obstacle for more widespread utilization of active layer MMIC technology.[21] Although U.S. industry has developed many advanced devices using active-layers, many firms lack the high-volume production experience necessary to gain confidence with their fabrication processes. High volume production is necessary to learn and demonstrate tight control over the dimension and purity of active layers. The vast commercial experience of Japanese firms in epitaxy-based circuits has likely given firms such as MELCO a quality advantage in this process.[22]

MELCO is also strong in backside processes for GaAs as well as silicon ICs. Backside processes include polishing, etching, drilling, and metallization of the side of the chip opposite to the integrated circuit. Such processes are required to clean the surface of the chip and to provide thermal and/or electrical grounding. The transfer of these processes might help U.S. industry develop MMICs and MMIC-based modules with improved reliability and electrical performance.[23]

Packaging Structures

At the DoC Symposium, MELCO had mentioned its use of carbon-based composite materials for the array structure and module housing. The United States may wish to pursue more information in this area. Knowledge of how to run a well controlled process for strong, lightweight composite structures could benefit programs aimed at solid-state communications and sensor applications.[24]

Systems Integration

It is difficult to judge the benefits that Japan can provide U.S. industry in system design and integration. Few within the United States are knowledgeable about Japanese system integration capabilities. According to the conventional wisdom,

---

[20]Ibid.
[21]Interview with engineers at Texas Instruments.
[22]Ibid.
[23]Interview with MELCO engineers.
[24]Interview with USAF engineers.

Japan is far behind the United States in systems integration because it lacks the depth and breadth of experience in this area. With regard to radar systems, one can point to a dearth of systems design and integration experience in Japan. Most notably, since World War II, no Japanese-developed radars have been fielded. Nevertheless, if Japan is successful with the FS-X, then it may be closing the technological gap with the United States. APAR technology can represent a technology that would leapfrog decades of U.S. dominance in radar technology, especially since nearly all radars in the U.S. fighter inventory are mechanically scanned. Thus, the FS-X radar could mark a new beginning for Japan as a world-class developer of tactical airborne radar.

The success of the 1989 flight tests of the FS-X radar may be an indication that Japan has finally developed a system integration capability in military radar. Japan has also displayed strong managerial skills in handling acquisition programs, with the on-schedule completion of the EM prototype and the satisfaction of all requirements in flight tests. Although these requirements were conservative by U.S. standards, they do include rather sophisticated systems operations such as end-to-end BIT and roughly 20 stand-alone modes, submodes, and interleaved modes.[25]

Of all the aspects of the FS-X radar, the one feature generating the most interest from U.S. industry appears to be the BIT scheme. The FS-X BIT performs not only fault detection but also array calibration and other diagnostics without the use of an intermediate avionics maintenance shop.[26] While BIT has been implemented in most U.S. systems, the U.S. record with BIT has been mixed.[27] While Japan seems to have matured the BIT concept within the FM prototype, U.S. industry has yet to operationalize a fully functional, self-contained BIT algorithm for an APAR system. Also, an APAR calibration scheme proposed by a U.S. contractor in the F-22 program had involved measuring equipment outside the radar system entirely.[28] However, the BIT within the FS-X radar will not require outside equipment and is conducted by assets within the radar itself. U.S. access and license of such a capability plausibly could provide tremendous insight for U.S. contractors hoping to develop BIT features for new U.S. systems such as the F-22 radar.[29]

---

[25]Ibid.

[26]During the FS-X Radar Technology Symposium question and answer session, most of the audience questions regarding the FS-X radar concerned the BIT.

[27]Gebman, J., et al., *A New View of Weapon System Reliability and Maintainability*, RAND, R-3604/2-AF, January 1989. One-third of the time when the BIT on the F-15 C/D radar indicates a fault, there is none.

[28]McQuiddy, D., et al., op. cit.

[29]Interview with USAF engineers.

Component Design

The design methodology used by MELCO to package the FS-X radar into compact, reliable, and low-cost LRUs is another area of potential interest to U.S. industry.[30] Japanese electronics firms are renowned for strong electronic packaging and design capabilities for consumer electronics, especially in miniaturizing components. One U.S. engineer pointed out the compactness and low weight of the FS-X LRUs as an indication of MELCO's highly advanced packaging capabilities. The engineer especially singled out the radar signal processor as weighing only half of that produced by his company.

The advanced construction of the FS-X T/R modules also reflects MELCO's good packaging capability. Despite conservative transmit performance by U.S. standards, the receive performance of the FM module is comparable to U.S. specifications in terms of noise figure, gain, and dynamic range.[31] Histograms from production runs of the FM modules also show better process control than that achieved by U.S. production runs. The FS-X T/R modules are also highly advanced in construction and utilize state-of-art design and materials technologies. MELCO has also shown a solid MMIC design capability, as indicated by the wide variety of MMIC devices that they developed—from multiple function MMICs to simple, low-noise discrete chips.[32]

By gaining access to MELCO packaging capabilities, U.S. industry could improve their design tools and methodologies used to analyze mechanical-stress, thermal management, and sealing of microwave components. Methodologies for incorporating robustness and process control into design would also be highly beneficial to cut development times, reduce costs, and improve product reliability.

Summary

In summary, DoD and U.S. industry see the greatest potential benefits in gaining access to Japanese module process and materials technologies and the FS-X BIT regime. In the T/R module assembly area, MELCO may have some automation technologies in pick-and-place, chip attachment, wirebonding, and testing that

[30]LRUs are the separate parts that compose a radar system. The FS-X radar consists of four LRUs: radar processor, power supply, antenna, and exciter/receiver. FS-X Radar Technology Symposium, op. cit.

[31]This assessment is based on a comparison of specifications of the EM module and Texas Instruments/Westinghouse MANTECH modules. *Manufacturing Technology for Radar Transmit Receive Modules*, op. cit.

[32]FS-X Radar Technology Symposium, op. cit.

are of interest to U.S. industry. Some U.S. industry experts also expressed interest in MELCO MMIC fabrication processes, composite materials for array structure and T/R module housings, and component design tools and methodologies.

Except for the BIT regime, most U.S. experts seemed least impressed with Japanese capabilities in software and integration. Many of the modes programmed into the FS-X are conventional and have already been programmed within U.S. mechanical-scan radar systems. In addition, the number of modes programmed into the FS-X radar did not seem unusual for modern airborne multi-mode radar systems. While mode interleaving and ground moving target indication modes within the FS-X have been recently incorporated into U.S. radar systems, several U.S. firms have already demonstrated superior capabilities in airborne reconnaissance or ground-based fire control systems. Overall, however, interviews with U.S. experts seemed to reveal a widening U.S. appreciation for advanced, high performance military technology from Japan.

6. Problems of Technology Transfer

Section 5 identified Japanese FS-X radar technologies that could benefit U.S. interests if transferred easily and costlessly. However, it did not address the potential problems and costs associated with the real-world implementation of technology transfer. This section discusses the various obstacles facing technology transfer. Such obstacles, it is argued, limit the scope and degree by which technology transfer from the FS-X radar program can actually benefit U.S. interests.

Lack of Knowledge and Access

Despite DoD and U.S. industry interest in several aspects of Japanese technologies, technology transfer faces several problems. One of the most important is the lack of U.S. industry knowledge of the technologies at hand. One reason for this lack is the minimal access to technical information on the radar. Although DoD and DoC take the position that U.S. industry should be the primary recipient of technology transfer,[1] nearly all U.S. industry experts interviewed expressed very little familiarity with not only the FS-X technology but also the process by which technology is accessed through the program.[2]

In particular, technical managers have remarked that much more technical information on the FS-X radar is needed to assess whether or not benefits might accrue from acquiring Japanese radar technology. Before the FS-X Radar Technology Symposium in 1992, U.S. industry virtually had no access to technical information about the FS-X radar or MELCO engineering and manufacturing capabilities. Only DoD personnel visited MELCO facilities in 1990 and 1991. No industry representatives were included.[3] In addition, the transfer of documentation on FS-X technology to U.S. industry encountered

[1]The U.S. government takes the position that industry has a greater capacity and incentive to absorb technology than the government itself. *FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[2]During interviews with dozens of U.S. radar program managers, none revealed detailed knowledge of FS-X technology or the bureaucratic process through which U.S. industry would gain access to FS-X technology.

[3]Before 1992, the FS-X agreements prohibited U.S. industry participation in the "technology visits" to Japan. After negotiations in February 1992, this prohibition was lifted so that all subsequent technology visits could contain U.S. industry representation. Indeed, U.S. industry representatives were part of a U.S. team visiting Japan in 1993 to examine the FS-X mission computer. Correspondence from Captain Sid Perkins, USAF, July 1993.

delays because of the bureaucratic review and approval processes set up between the two countries.[4]

In addition, while the symposium was unprecedented in providing official exposure to Japanese military technology, the information from the symposium did not reach many small firms whose business is highly related to some of the technologies used for the FS-X radar. Although the attendees' list contained a group of defense firms and government organizations, numerous lower-tier U.S. suppliers with strong market positions in relevant technology areas did not attend, including several developers and suppliers of MMIC technology. In phone interviews conducted a few months after the symposium, most high-level managers within these firms indicated ignorance regarding the FS-X radar and technology transfer process. Since Japan's industrial strengths are closely related to the capabilities of these lower-tier suppliers, such firms may have been the best of candidates for receiving licensed technology from Japan.[5]

Procedures and Restrictions

Another obstacle to technology transfer is posed by the complex bureaucratic rules and procedures that govern the transfer of military items between the two countries. Some procedures might appear to block outright the transfer of useful technologies to the United States. One of the most restrictive procedures comes from an official policy of Japan's powerful Ministry of International Trade and Industry (MITI) requiring that all overseas sales of military items developed and produced be subject to review and approval. During the review, MITI will determine whether an item falls in the category of "military item." If it is determined that less than 5 percent of sales of that exact item are used for non-military applications, the item under review is classified as "military," and its export can be banned. If it is determined that 5 percent or more are for nonmilitary uses, then the item is classified as "dual-use," and its export is not prohibited.[6] Much FS-X hardware, especially custom-built parts, very easily

[4]Although the first technology visit for the FS-X radar was conducted as early as 1990, the trip report for the visit was restricted to government use only, and a significantly abridged version was not released to U.S. industry until 1992. The FS-X agreements require that reports compiled by U.S. teams that conduct the technology visits to Japan be subject to review and approval by the JDA and all private Japanese contractors involved before its release to U.S. industry. Such a review process contributed to the roughly six-month delay between the completion of the FS-X radar report and its dissemination to U.S. industry during the FS-X Radar Symposium. Ibid.

[5]In telephone conversations with high-level managers at several specialized MMIC suppliers, nearly all admitted ignorance about the FS-X radar program and the technology transfer opportunities it presented. Many were not even aware that MMIC technology was being used for the radar, although most were not surprised. When told that Japan is developing MMICs for defense purposes, almost all indicated an interest in learning more about the FS-X radar.

[6]Interview with Major Craig Mallory, USAF.

would fall under the definition of a military item, and their transfer would be subject to intense MITI scrutiny.[7]

These procedures have obstructed technology transfer efforts in the past by creating burdensome paperwork for the Japanese exporter. Because of the lengthy MITI review process, requests for transfer could encounter significant delays; all parties involved might have to incur high paperwork costs, especially the prospective technology exporter. Without banning the transfer of items, such burdens have acted to discourage would-be exporters of military items and technology to the United States.[8]

Procedures can also present obstacles for U.S. firms hoping to receive military technology. For instance, interviewed U.S. industry managers admitted utter confusion over the regulations and transfer process in the FS-X. The confusion centered on the 12 categories of technologies and the unique bureaucratic processes and paperwork involved with each.[9] The managers also noted that some of the rules seem based on highly arbitrary and subjective definitions. For example, for nonderived military items from Japan, MITI has allowed an exception to the export ban if the item "facilitates technology transfer to the US." Under this rule, MITI has allowed MELCO to sell sample T/R modules to DoD for test purposes only, presumably under the justification that DoD testing would "facilitate technology transfer to the US."[10] Documents issued by DoD and DoC on guidelines of FS-X technology access do not define exactly what "facilitating technology transfer" means.[11]

Finally, fears of political repercussions can pose a significant deterrent for Japanese companies that hope to sell military or even dual-use technologies overseas. Even as the Cold War recedes, weapons proliferation to the Third World has remained as one of the largest political concerns of developed nations. Given the affiliation of large defense contractors with divisions in the consumer and industrial areas and the strong pacifist sentiment of the Japanese public, contractors in Japan fear a public backlash to any perceived profiteering from any arms sales abroad.[12] Japanese contractors are using the FS-X program as the

---

[7]Japan's restrictions block the export of all military "end items" only. So-called military "technology," including process technology, manufacturing know-how, and blueprints, also can be transferred overseas subject to MITI approval. Correspondence from Captain Sid Perkins, USAF, July 1993.

[8]Ibid.

[9]Ibid.

[10]The 1985 Detailed Arrangements for the Transfer of Military Technologies allowed for the single exception to Japan's military export ban—sample articles of hardware sold to the United States for "facilitating technology transfer." Ibid.

[11]Interview with Major Craig Mallory, USAF.

[12]Interview with high-level official at MELCO Radar Group.

test case on public reaction to the export of Japanese military technology and items.[13]

Proprietary Interests

Access to contractor-owned technology also poses problems with proprietary interests and intellectual property. The FS-X agreements recognize indigenous technology as either JDA-owned or contractor-owned. For JDA-owned technology, terms of access are negotiated between governments. If the technology is contractor-owned—the case for most process and design technologies—the U.S. company or government organization wishing access must negotiate commercial arrangements with the Japanese contractor.[14] Most Japanese technologies of interest to U.S. industry would fall within the category of contractor-owned technology. JDA-owned technology typically is comprised of systems-level technologies, such as the entire radar system and separate LRUs. However, the lower-tier design, process, and component technologies of considerable interest to the United States are likely classified as contractor-owned.

In gaining access to contractor-owned technology, tension naturally arises between the contractor's proprietary interests and bilateral political interests to promote transfers of technology for U.S. benefit. This tension arises given the competition-sensitive nature of process and design technologies, many of which have been developed for use in the commercial sector. MELCO is known to be applying commercial technology and expertise to the FS-X radar. Given the high commercial value of some of these technologies, it is understandable that MELCO officials would be reluctant to release technical information to potential U.S. competitors.[15]

U.S. firms hoping to receive technology can also face conflicts with their own interests. By receiving indigenous Japanese FS-X technology, U.S. firms may be obligating themselves to provide free flowback to Japan of any modifications they make on the technology. One U.S. manager expressed discomfort with this provision, as ambiguity might arise as to whether a technology improvement

---

[13]"Defense Industry Watching Issue as Test Case," *Nikkan Kogyo Shimbun*, October 10, 1992, p. 7, translated to English by *JPRS, Japan Science and Technology*, October 29, 1992.

[14]*Technology Transfer and Technology Flowback with Japan: U.S. Industry Approaches to the FS-X Co-Development Project*, op. cit.

[15]DoD teams visiting MELCO in Japan have reported that MELCO officials often refused to answer many technical questions posed by the team. One of the most frequent reasons stated by the officials was that the answer was "proprietary." *FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

belongs to the Japanese company or the U.S. recipient. This provision was included in the FS-X agreements to mirror image the provision for the guarantee of flowback to the United States of Japanese-derived technology.[16]

Another disincentive for U.S. firms to receive FS-X indigenous technology comes from the rule that technology acquired from FS-X be used only for defense purposes.[17] This rule could prevent the United States from applying these technologies for dual-use applications. In many cases, particularly process technologies with high fixed costs, commercialization is indispensable to the achievement of economically efficient production volumes.[18]

The key factor that can make conflicts of proprietary interests a serious obstacle to technology transfer is the necessity for extensive cooperation between the giver and recipient of technology. In particular, transfers of process technology will require many intricate details of day-to-day operations and maintainence of the processes in question. Many such details cannot be recorded and transmitted in written form but rather must be transferred via a close working relationship or even apprenticeship between technology giver and technology recipient. Unless full cooperation and complete mutual trust exist between the giver and receiver, nearly any attempt at technology transfer, especially process technology, will be doomed to failure.

Different Program Requirements

Another barrier to technology transfer is the inapplicability of Japanese technology to U.S. program needs. Despite many commonalities, FS-X mission requirements diverge far from those of U.S. programs, particularly the F-22. As argued below, the F-22 mission requirements call for a system of far higher performance than that required for the FS-X.

This report has argued that Japan intentionally developed a conservative system for the FS-X radar. A conservative design is entirely consistent with the primary FS-X mission. Such a mission, which was derived from the role assigned by the Japan Self-Defence Forces,[19] does not require a radar system of highest performance. The FS-X is assigned the role of interdicting hostile shipping in the

---

[16]"FS-X Technology Transfer Process," briefing by Captain Sid Perkins, USAF, during the FS-X Radar Technology Symposium, June 1992.

[17]Ibid.

[18]Interview with Texas Instruments engineers.

[19]In a 1981 communiqué by Prime Minister Suzuki, Japan is committed to defend the air space around Japan out to several hundred miles from the shoreline and the sea-lanes out to 1,000 nautical miles. "U.S.-Japan Burden Sharing: Japan Has Increased Its Contributions but Could Do More," *GAO Report*, op. cit.

sea-lanes surrounding Japan. Because ships are large, slow-moving targets, a radar of the highest mapping resolution would not be required. Very low sidelobes also would not be as critical with the FS-X as U.S. fighter missions, since the radar would be operating in a relatively low-clutter, sea environment. Moderate detection ranges also would be adequate for the FS-X to operate in the sea-lanes surrounding Japan. The limited geographical area of the intended FS-X missions does not extend far from home airfields.[20]

In contrast, U.S. combat aircraft must typically perform often highly ambitious missions requiring the highest level of performance. Modern U.S. fighters must detect, acquire, and defeat fast-moving, moderately stealthy unfriendly aircraft over hostile territory. Operation over hostile territory requires very low sidelobes to reduce the likelihood of detection by enemy sensors and to provide immunity from jamming. It also requires longer radar detection ranges to gain the combat initiative over unfriendly interceptors. Attack or support missions require low sidelobes and sharp beam and map resolutions to interdict smaller vehicles in a very high clutter, land environment. High clutter rejection is also needed to conduct look-down, shoot-down engagements over land against moderately or highly stealthy aircraft.[21]

The F-22 will have a more stringent mission requirement than any other in the history of U.S. fighter acquisition. The primary mission is to interdict high performance interceptors over hostile territory with very heavy air defenses.[22] To gain combat initiative over interceptors, which are small, fast targets, the radar systems must have very long detection ranges and excellent beam control to evade detection in a heavy air defense environment. The F-22 mission, therefore, will require a radar that meets the highest standards of beam control, mapping resolution, and detection ranges.

The highly divergent mission requirements between the FS-X and F-22 may make FS-X system technology inapplicable to U.S. needs. For example, DoD is pursuing the Joint Integrated Avionics Working Group (JIAWG) architecture for the F-22 as part of a follow-on to the conventional MILSTD-1750A architecture designed in existing front-line aircraft. JIAWG is also planned for the Army LHX helicopter and Navy AX bomber programs. The data architecture used by FS-X, on the other hand, will use the conventional MILSTD-1750A avionics standard.[23]

---

[20] *FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[21] Discussion with Joel Kvitky, RAND.

[22] Discussion with Donald Stevens, RAND.

[23] Keller, J., "New Avionics Group Targets Upgrades," *Military & Aerospace Electronics*, Vol. 3, No. 8, October 15, 1992.

The F-22 program may likely need more advanced software algorithms and data architecture than the FS-X. Given the longer ranges at which the F-22 must operate, the F-22 radar will also need to process at much higher data loads. To stay compatible with software innovations, DoD is also considering a highly advanced and costly processor architecture, perhaps based on parallel microprocessors. These new architectures may be deemed necessary to meet the stringent processing required for high speed analog/digital conversion and phase shift calculation posed by 2,000 T/R modules operating at fast update rates.[24] If parallel processors are used for processing and signal control, entirely different software languages and algorithms may be required.[25] Thus, even highly effective software algorithms and architectures developed for the FS-X may not be applicable to F-22 needs.

Mission requirements may also dictate entirely different hardware specifications. For example, the F-22 radar will likely require a far larger, more powerful cooling system than the FS-X. The range requirements for the F-22 have driven requirements for T/R module peak power that is several times greater than the FS-X. Range requirements also drive the need for a larger aperture. Consequently, the F-22 antenna contains two and half times as many modules as the FS-X. In turn, the F-22 will require a cooling system dissipating an order of magnitude more heat.

To achieve superior beam control, the F-22 T/R modules also may contain functions of variable gain,[26] which the FS-X modules lack.[27] Requirements on mapping resolutions also appear to drive wider module bandwidths than the FS-X. MELCO engineers have noted their capability to develop modules of higher peak power and wider bandwidths[28] but have apparently found such improvements unnecessary to meet FS-X requirements.[29]
Although differences in *systems* requirements, i.e., LRU size, avionics architecture, and circuit design, have been noted, differences in *process* requirements between the United States and Japan may also lead to incompatibilities as well. Although many of Japan's military process standards are derived from U.S. standards, differences in the standards of the two countries

[24] *Strategic Industrial Initiative: Phased Array Radar*, op. cit.

[25] Ibid.

[26] Sweetman, W., Active Array for ATF, op. cit.

[27] The FS-X module does not contain variable attenuators, indicating a lack of gain control. *FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[28] During the FS-X Radar Symposium, MELCO had revealed some active-circuit GaAs MMIC technology of comparable performance to those developed in the United States.

[29] *FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

could forestall the application of Japanese process and manufacturing technology to U.S. military programs. In one specific case, MELCO is noted to be using an organic-based epoxy as a hermetic sealant for T/R modules. The use of organic materials in hermetic military components is prohibited by U.S. military standards.[30]

Nontransferable Industrial Factors

Furthermore, the applicability of Japanese process or manufacturing capability may be limited by industrial factors that are inseparable from the firm. One example is customer-supplier networks, which play a critical role in controlling quality in manufacturing both in the United States and Japan. Large Japanese conglomerates in particular rely on long-standing relationships inside a vast network of subcontractors to provide tooling and other process inputs. Customer-supplier relationships are highly critical in quality assurance within Japanese industrial networks.[31]

These relationships, however, are not transferable across national boundaries as easily as data packages or pieces of equipment. Networks typically cut across the boundaries of many firms and can involve hundreds of tightly interacting firms that provide technical support, equipment, and parts for each other. Networked firms are often bound within a common inventory and accounting system so as to improve the overall efficiency of the network. Networked firms also swap technologies and personnel with each other and provide two-way technical and financial support.[32] The integral role that these networks play in supporting industrial processes in Japan could forestall even the effective transfer of process technology to the United States.

The transfer of certain process technologies to the United States could be especially difficult given the close customer-supplier interactions required to support MELCO processes. For example, an important process step required before fabricating power MMICs is the growth of active layers with MBE.[33] This process requires a multimillion dollar tool developed by a Japanese supplier;

---

[30]Ibid.

[31]"Rather than design and manufacture their own goods, they [giant Japanese manufacturers] actually coordinate a complex design and manufacturing process that involves thousands of smaller companies," from Sakai, K., "The Feudal World of Japanese Manufacturing," *Harvard Business Review*, November–December 1990, pp. 38–43.

[32]Ferguson, C., "Computers and the Coming of the U.S. Keiretsu," *Harvard Business Review*, July–August 1990, p. 63.

[33]MBE involves high precision growth of active layers by ejecting molecules on to pure GaAs wafers through heating in a near vacuum environment. Sze, S., op. cit., p. 333.

however, the complexity of operating the tool requires close interaction between the supplier and customer to ensure the quality of its output. Because of a lack of technical service infrastructure in the United States, this supplier does not sell its molecular beam product to any U.S. customers. Without this critical tool, U.S. production of active-layer MMICs based on a MELCO process would be difficult.[34] For industrial reasons, this process technology is not transferable.

Industrial factors could also present barriers by reducing the incentives for U.S. firms to receive Japanese technology. Some U.S. technical managers have expressed doubts about acquiring an unfamiliar process technology from Japan. They were often not sure of the advantages of the Japanese process technologies if they were transferred into their own corporate environment. Others had doubts about whether technology acquired from another country could be effectively exploited in the United States.

These doubts are understandable given that most U.S. defense firms do not have the same lines of business as MELCO. Lines of business play a strong role in determining the industrial capability of firms. Also, operating procedures are often optimized within the unique set of products and services offered by the firm. Consequently, process or industrial capability from one firm may not be easily transferable to another. For example, MELCO has a wide portfolio of electronics products ranging from consumer to defense applications. MELCO has optimized its technology and management procedures to support the operation of these businesses. Consequently, Japanese firms such as MELCO are known to invest heavily in flexible, high-volume production to meet customer demands in the consumer electronics sector. U.S. defense firms without high-volume consumer electronics business may not find enough demand from the defense sector to justify investment and operation of high-volume production technology.

Finally, the adoption of a new technology can involve very high switching costs that could deter would-be technology recipients. For example, one U.S. manager noted the high cost of adopting a new MMIC fabrication process from Japan. Implementation of such a process would require very costly investments in production infrastructure. Acquisition of a new GaAs process technology would cost several tens of millions of dollars in plant and equipment. Even if the technology were free, high set-up costs could discourage U.S. firms from making the necessary investments needed to exploit it.[35]

---

[34]Interview with Richard Pedersen, AT&T Bell Laboratories.

[35]Discussions with Chiao Hsieh, Norden Systems.

How about firms that already have a production infrastructure? Although such firms would not have to invest in an entirely new infrastructure, they would still have to incur some switching costs to adapt a new process into their current operations. Also, the addition of a new process and a supporting infrastructure probably would require some sunk investments to be lost. For firms that already have an in-house process, the cost of switching to another may be greater than the benefits, even if the new process is superior.[36]

Not only would adoption of a new process incur additional expenditures for new equipment, but it might add considerable risk to the smooth functioning of the firm's production process because of requisite changes in operating procedures. Such changes always incur the risks of side effects such as temporary losses of quality control and extended downtime and servicing. When such side effects do occur, the ensuing degradation in quality can often take months to fix.[37]

Such an argument is reinforced by the existence of steep learning curves in the electronics manufacturing industry, implying high opportunity costs to switch to a new process. Successful manufacturing processes typically result from many years of streamlining a process using a unique combination of capital and personnel. The efficiency improvements gained over years of process refinement are risked whenever a new, unfamiliar process is introduced. Thus, because of the risks of lower yields and frequent downtime as well as consumed labor and floor space, firms may be discouraged from taking chances for marginal gains by acquiring a foreign process.[38]

---

[36]Ibid.

[37]Tyre, M., "Managing Innovation on the Factory Floor," *Technology Review*, October 1991, pp. 59–65.

[38]Ibid.

7. Broader Industrial Factors in Japanese APAR

Broader industrial factors, including industrial networks, lines of business, and R&D philosophy determine many of the industrial capabilities that support technology. It will be argued that the APAR cost problems of U.S. contractors, especially in producing T/R modules, are a result of the industrial factors prevailing in the U.S. defense business. MELCO advantages in low-cost manufacturing may be more an issue of industrial structure and management rather than superior technology. The conclusion drawn from this section is that the most important areas to learn from the FS-X case study are not only technology but also the Japanese acquisition approach and industrial structure.

MELCO's Dual-Use Industry

Dual-Use Resource Sharing

MELCO's solid business base in commercial microwave and wireless communications products has allowed it to develop a strong technical capability in APAR. MELCO has committed R&D resources into developing GaAs processes for components inserted into commercial products such as cellular phones, satellite television receivers, and global positioning systems.[1] MELCO also hopes to apply T/R module technology to build highway and automobile sensors and telecommunications for cellular radios and vehicles.[2] The revenues and technical experience gained from involvement in these areas may have laid the groundwork for APAR.

Through success in its commercial businesses, MELCO has developed world-class electronic design and manufacturing capabilities, which it is applying to military products. MELCO has unique opportunities to do this, since it is not only one of the world's largest consumer and industrial electronics firms but is also Japan's largest defense electronics contractor.[3] MELCO is the prime

---

[1]MELCO briefings at the FS-X Radar Technology Symposium.

[2]MELCO brochure on its Optoelectronic and Microwave Devices R&D Laboratory.

[3]In 1992, MELCO had the eleventh largest defense electronics sales in the world and ranked as the top defense electronics contractor in Japan. MELCO had a total of $2.250 billion in defense electronics sales, almost three times its biggest Japanese rival, Nippon Electric Company (NEC). However, unlike most U.S. defense electronics companies, MELCO's defense sales accounted for less

contractor for some of the biggest defense electronics programs in Japan, including licensed production programs for the Patriot air defense system and the F-15/APG-63 radar.[4]

In addition, MELCO and other Japanese firms are known to embed defense R&D and production within their commercial infrastructures. One survey of Japanese defense firms found that more than 80 percent of equipment producing defense products were also used for nondefense products as well. A recent study noted that:

> "Unlike U.S. prime contractors that isolate defense from commercial production . . . Japan's prime contractors make no distinction between military and civilian products, except at final assembly. Components and sub-assemblies are designed by the same engineers and are produced by and tested on the same equipment, regardless of the project for which the equipment was initially obtained or the ministry from which subsidies may have been initially derived."[5]

Furthermore, Japanese firms appear to place considerable emphasis on "spin-on" rather than "spin-off."[6] These firms have focused on applying commercial production capital and component technologies for use in military systems.[7] There are several instances where this occurs. In one example, a manager at the MELCO radar group noted commercial assembly machines building FS-X T/R modules.[8] MELCO custom-modified equipment that pick-and-place GaAs integrated circuits into receivers for home use of direct broadcast satellite (DBS) television can perform the pick-and-placement of MMICs into T/R modules.[9] Commercially available computer-aided-design (CAD) software at MELCO is also being used to design various ICs such as MMICs for military uses.[10]

MELCO is also applying commercially developed proprietary materials technologies for sealing and bonding T/R module parts. For example, MELCO

---

than 10 percent of total electronics sales. Tapscott, M., "Defense Electronics' Top 100 Companies," *Defense Electronics 1993 Buyer's Guide*, p. 8.

[4]*FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[5]Friedman, D. and R. Samuels, op. cit., p. 11.

[6]"There are many cases of Japanese corporations developing advanced defense technology based on [their civilian technology]. Little technology has been developed fundamentally for weapons themselves. In Europe and the U.S., in contrast, there are many cases of technology that the [defense departments] and corporations developed from the start as weapons being transferred to civilian technology." "Defense Industry Watching Issue as Test Case," *Nikkan Kogyo Shimbun*, op. cit.

[7]*FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[8]Friedman, D. and R. Samuels, op. cit.

[9]Comments from briefing, "Case Studies of Successful Production Applications of GaAs ICs," at the 1991 IEEE GaAs IC Symposium.

[10]Interview with a manager at MELCO radar group.

has noted its use of conductive adhesive to attach highly fragile GaAs chips to module carriers. Reportedly offering higher reliability and repeatability than solder, the adhesive was developed to attach fragile GaAs chips into DBS circuits. Japanese electronics firms have been continually producing GaAs for DBS equipment since the mid-1980s.[11] A proprietary adhesive is also used for hermetic sealing lids and feedthroughs in the FS-X T/R modules. There is good reason to believe that Japanese commercial process technologies are applied to T/R modules and other APAR components.

Japan's Commercial Lower-Tier Network

Commercial/military sharing is even more pronounced in the lower-tier network of suppliers in Japan. Market dominance in consumer electronics end-products has coincided with the market strengths in lower-tier sectors that feed both civilian and military production in the United States. These sectors also supply components that are inserted within APAR prototypes in the United States.

For instance, U.S. APAR technology draws on a long "food chain" of critical component, tooling, and process technologies. Products in the "solid-state RF food chain" include GaAs starting material, epitaxy, MMICs, and T/R modules. These lower-tier products are clearly dual-use in that the same products are being employed for both defense and commercial applications. Usually, the lower the tier of a technology or product, the greater are the commonalities between military and civilian usage.[12]

Most of these lower-tier "food chain" products are produced by networks of small and large commercial companies in Japan.[13] Japanese electronics giants typically belong to a vast network of customers and suppliers to support their highly diverse consumer electronics product lines. These networks design and produce the components, tools, and processes that feed the fabrication and assembly of U.S. and Japanese military systems.[14]

---

[11] Interview with engineers at Westinghouse Electric.

[12] Lower-tier products contain fewer system-specific features and thus exhibit greater commonalities for different end uses. For example, defense contractors typically buy the same GaAs wafers as commercial firms. On the other hand, products in the higher tiers, such as T/R modules, exhibit more system specific characteristics. Consequently, these products will exhibit fewer commonalities among different end uses. Thus, a fire control T/R module will exhibit considerable differences from a cruise control T/R module for automobiles.

[13] Japanese firms are the principal suppliers for "food-chain" products for even U.S. defense contractors. This phenomenon has raised U.S. concerns over foreign dependency in critical materials and tooling technologies. The issue of foreign dependency is discussed later in this report.

[14] Sakai, K., op. cit., p. 39.

It is highly probable that the commercial subsidiary and subcontractor base of MELCO is also supplying the food-chain products feeding the FS-X APAR program. For example, MELCO has commented that its own subsidiaries produce all microwave materials and components leading up to the FS-X APAR, including GaAs wafers, MMICs, and T/R modules. MELCO is also using the same or similar products for non-military telecommunications and broadcasting applications, including phased arrays for space communications and GaAs MMICs for cellular telephones and DBS dishes.[15] These products are going into mass markets in the United States, Japan, and Europe.

Benefits of Dual-Use

This section has described ways in which MELCO applies commercial sector resources to military needs. The capability to integrate dual-use production gives MELCO certain advantages over those U.S. defense firms that lack a market base in consumer and industrial electronics. A dual-use integrated firm with strong market positions in civilian markets can pool demand together to gain various benefits such as scale/scope economies, learning economies, automation, and flexible production.

Scale/Scope Economies

With its many high-volume product lines in the consumer sector, Japanese dual-use firms typically can achieve greater scale economies than many U.S. defense electronics contractors. Unit demand for components such as integrated circuits or multichip modules from the commercial sector often outnumber military demand by orders of magnitude. In 1988, the total military demand for integrated circuits was only one-twentieth that of nonmilitary sales.

By pooling commercial demand with military, MELCO can achieve the volumes necessary to generate cost advantages through economies of scale. Even in GaAs, a technology considered highly specialized for military use, commercial production demand is approaching that of the military. Although currently most of the revenues in the U.S. GaAs industry come from the military budget, it will be changed by the end of the decade by an ongoing explosion in cellular communications and home television reception of DBS.

---

[15]*FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

Commercial broadcast has already provided U.S. and Japanese firms with higher production volumes in chip areas than demand from the U.S. government.[16] MELCO in particular is deriving most of its production workload in GaAs from cellular phones and broadcast dishes. If global cellular phone service continues to boom at current rates, civilian markets will easily dominate the global revenue for GaAs production. In Japan alone, global cellular telephone subscribership should exceed 20 million by 1994, with a continuation of rapid growth projected throughout the rest of the decade.[17]

Japanese strengths in GaAs technology arose through an effort at controlling the DBS equipment markets during the 1980s. This market, which has already sustained high growth in subscribership in Japan and Europe for several years, is providing most of the demand for commercial analog GaAs firms. In Japan, the state-owned broadcast company NHK has already acquired 4.5 million DBS subscribers, with an additional 1.2 million subscribers acquired by a semiprivate consortium.[18]

Commercial-military "resource sharing" implies scope economies because most of the scale economies are with inputs rather than end products themselves. For instance, MELCO has an impressive high volume GaAs hybrid IC fabrication line that feeds both commercial and military production facilities.[19] Even when end products are produced in different facilities, enormous scale economies can still be gained through sharing subcomponents. Scope economies can be particularly important if such inputs drive the cost, performance, or quality of the end products, as T/R modules do for APAR.

In addition, human capital or technology can be considered a critical input shared across civilian and military applications. Scope economies are generated if the same expertise and infrastructure contribute to the realization of both commercial and military products. MELCO is applying its phased array antenna design and integration expertise not only to military fire control but also to satellite broadcasting and remote sensing applications as well.[20]

Expertise can also be dual-use. Commercial experience with microwave component assembly and GaAs MMIC fabrication is providing the human

[16]Two small U.S. companies have each reported production of more than 200 3-inch GaAs wafer starts per week, compared to about 200 wafer starts for all MIMIC contractors for all of 1989. Interviews with industry representatives and DoD Project MIMIC managers.

[17]Interview with engineers at Motorola, Inc.

[18]"Japanese satellite TV," *The Economist*, January 23, 1993.

[19]*FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[20]*Strategic Industrial Initiative: Phased Array Radar*, op. cit.

capital needed for military applications. A MELCO technical manager noted that manufacturing technicians from the commercial division had taught radar engineers how to use semiautomated commercial equipment to build T/R modules.[21] In another example, MELCO used rapid wirebonding capabilities to mass produce thermal heads for facsimile machines. The type of wirebond is similar to that used to assemble T/R modules in the United States.[22]

A GM Hughes and Delco Electronics joint venture is taking advantage of synergies between military and commercial sectors. The venture is developing a system to alert school bus drivers as to whether any children are in front, on the side, or underneath the bus after it has stopped. The system detects moving objects using X-band T/R modules with GaAs MMICs developed from the DARPA MIMIC program. Although the system has a purely commercial application, GaAs MMICs for the system are being produced at a defense facility operated by Hughes Aircraft Company. A managing director of the joint venture said, "We have a strategy . . . to satisfy military and commercial products and customers using most of the same processes, same line, and same people."[23]

Learning Economies

Sustained, high-volume commercial production provides a steady flow of manufacturing experience for firms to learn and improve their own processes and productivity. Manufacturing processes can be improved through "learning cycles,"[24] in which output from a production run is measured and analyzed. Data from production runs can be used to ascertain sources of quality problems and consider ways to solve them. Lessons learned from the analysis then can be used to fine-tune the production process for the next production run. The learning cycle can be applied over and over, resulting in incremental improvements in process control and yield. Over time, the application of several learning cycles can lead to dramatic improvements in cost as well as product quality.[25] Such efforts may have been responsible for well documented learning curves in the semiconductor industry, in which unit costs for a particular product

---

[21]Interview with a manager at MELCO Radar Group.

[22]Interview with engineers at USAF Wright Laboratories.

[23]Keller, J., "Delco, Hughes Leveraging Military Radar," *Military & Aerospace Electronics*, April 19, 1993, p. 1.

[24]A term used by Motorola engineers.

[25]Interview with David Lutz, Motorola, Inc. The learning cycle is a process undertaken within the quality circles concept in design and production organizations. See Deming, W., *Quality, Productivity, and Competitive Position*, MIT Center for Advanced Engineering Study, 1982.

typically fall 30 to 40 percent every time cumulative output for the product doubles.[26]

While learning is facilitated with statistical methods, a high-volume production facility provides the best environment to apply them. Experience from numerous, high-volume production runs enables the generation of huge data samples that can be used to identify problems and limitations of production processes. A well known process improvement method, full-factorial design of experiments,[27] works best with datasets containing millions of data points, each coming from a sample taken from a process employed in a high-volume production run.[28] Effective analysis of large data sets can enable a manufacturer to achieve dramatic improvements in efficiency and productivity. Such improvements often take the form of simplified material flows—reduced process variations, downtime, and defects—and the introduction of new manufacturing technologies on the factory floor.[29]

Learning curve economies reinforce the market position and profitability of market leading firms. Firms first to market with high-volume products have the opportunity to gain a dominant market share early in the game based on a strategy of moving first down the learning curve. Rapid movement down the learning curve, in turn, helps to lower cost and raise quality over competitors. Learning economies, therefore, can provide positive feedback for high volume producers.[30]

In theory, firms successfully targeting high-volume consumer electronics markets could eventually gain monopoly positions in dual-use industries or technologies in the long run by outrunning competitors down the learning curve. Early market dominance is not only sustained by learning but can also be increased and reinforced over time until monopoly positions are obtained.[31] This market

---

[26]Moxson, R., "The Chip War," Case Study for the Graduate School of Business, University of Washington, 1987.

[27]Design-of-experiments involves the experimental variations of factors that may impact the product quality and characteristics. These factors are varied in all combinations, and the resulting product characteristics are measured. A mathematical fit is performed on the data to develop a model for predicting the impact of the factor values on product characteristics. This fit then is used to calculate values for factors that will yield the greatest process uniformity and repeatability. Juran, J. M. and F. M. Gryna, *Juran's Quality Control Handbook*, McGraw-Hill, 1988, pp. 26–29.

[28]Interview with David Lutz, Motorola, Inc.

[29]*Findings of the U.S. Department of Defense Technology Assessment Team on Japanese Manufacturing Technology*, op. cit., p. 43.

[30]Arthur, B., "Self-Reinforcing Mechanisms in Economics," in Anderson, P., et al., *The Economy as an Evolving Complex System, Proceedings of the Evolutionary Paths of the Global Economy Workshop*, 1987.

[31]Learning-by-doing tends to provide self-reinforcement of market position by the market leader. See Arrow, K., "The Economic Implications of Learning-by-Doing," *Review of Economic Studies*, Vol. 29, 1962, pp. 155–173.

phenomenon could explain how commercial Japanese firms have come to dominate global production of many solid-state materials and components feeding both the civilian and military sectors in the United States.[32]

Automation and Flexibility

Japanese dual-use electronics manufacturers typically enjoy higher production automation than do many U.S. contractors because consumer electronics firms are under considerable competitive pressures to automate. The advantages of automation arise not only because of reduced labor costs but also because of higher process control and yields. These cost advantages, however, must be weighed against the added fixed and sunk costs of introducing automation to the factory floor. The high-volume demand and increased cost sensitivity of consumers provide large incentives for Japanese firms to bear these costs. Firms catering only to the low-volume defense market in the United States will have much lower incentives. Lack of incentives could explain why U.S. defense firms generally employ more labor-intensive processes for production than Japanese consumer electronics firms.

One common drawback of highly automated production systems is the high adjustment costs incurred when changing either the production rate of the system or adapting the system for different product models. Flexibility is, therefore, necessary for commercial sector firms to compete in a market based on short product lifetimes and high product turnover rates. To address this problem, Japanese consumer electronics firms have developed assembly lines capable of mixed-flow production of multiple product models. In mixed-flow production, line operations can be changed to match the particular model moving on the line. Once production capital is flexible enough to produce more than one product at variable production rates, manufacturers lower their equipment costs and increase their ability to cope with demand fluctuations and the rapid introduction of new models.[33]

To enable and support flexible production, Japanese firms began development of computer integrated manufacturing (CIM) systems to integrate all activities of a

---

[32]Japanese giant Sumitomo Electric sells more than half of all GaAs wafers consumed in the world. Kyocera sells about 90 percent of all microwave ceramic packages consumed by U.S. defense contractors. Furukuwa Electric supplies more than 90 percent of all GaAs slugs consumed in MBE machines in the United States. Interview with several U.S. industry experts.

[33]English translation of "Developments in Assembly Line Automation," *Nikkei Mechanical*, June 29, 1992; from *JPRS: Japan Science & Technology*.

business from raw materials to final end use.[34,35] By the late 1980s, Japanese firms gained a several-year lead over U.S. firms in CIM systems for electronics manufacture. Such capabilities may have enabled MELCO to demonstrate automated manufacturing of the FS-X radar and subcomponents.[36]

Clearing the Hurdle: The U.S. Low-Volume Problem

Since most U.S. defense firms have not commercialized dual-use technologies to the extent that MELCO has, they may be at a disadvantage in achieving scale economies, learning economies, automation, and production flexibility. Low production volumes in U.S. defense procurement and low entry of U.S. defense firms into high volume commercial product sectors may have imposed some handicaps in competing with MELCO in producibility and cost.

Labor-Intensive Assembly

One impact of low-volume defense production in the United States is the use of labor-intensive processes. A 1989 report noted that U.S. contractors were employing several manual processes to assemble T/R modules. One process was the construction of module housings by machining aluminum stock and brazing parts together. With this process, module housings cost $400 each. Another labor-intensive process was the drilling of holes in the housing to allow electrical connections to the rest of the antenna. Holes also had to be individually soldered to provide hermetic protection from exposure to moisture.[37] Labor-intensive processes have contributed to the high cost of T/R modules, with labor costs exceeding $1,000 per module.[38]

Since the report, F-22 radar contractors have made considerable progress in increasing automation. Under programs such as the Air Force T/R Module MANTECH, U.S. contractors have reduced labor content by increasing automation and designing producibility into modules. Testing has also been made more efficient. In an early phase of the MANTECH program, testing accounted for more than half the labor devoted to module production. By the

---

[34]*JTECH (Japanese Technology Evaluation Report) on CIM/CAD.*

[35]*Manufacturing 21 Report: The Future of Japanese Manufacturing,* National Center for Manufacturing Sciences, 1991, p. 10.

[36]Ibid.

[37]*Strategic Industrial Initiative: Phased Array Radar Study,* op. cit.

[38]*Manufacturing Technology for Radar Transmit/Receive Modules,* op. cit.

latter part of the program phase, the contractor managed to reduce testing by a factor of eight, thereby cutting total labor costs in half.[39]

Nevertheless, more progress is needed to meet the cost and throughput goals for T/R modules. Costs of direct labor still exceed the DoD cost goal for entire modules by severalfold. Also, some labor-intensive tasks remain, such as the placement of subassemblies on module carriers. As of 1990, U.S. contractors have demonstrated production capacity of about 300 modules per month, while DoD estimates that peak F-22 demand could require the production of several hundred modules per day.[40] More automation may be needed to reduce costs by improving process quality and yields and to increase peak production rates with higher process throughputs.

Low Capacity Utilization

Low volume demand in defense contracting has also contributed to the high materials cost of T/R modules. As active materials, GaAs MMICs are the critical performance and cost drivers for T/R modules. However, MMIC costs are very high; a chip set for a T/R module can cost from several hundred to several thousand dollars.[41] MMIC costs are high partly because of the low utilization rates of most U.S. producers. GaAs MMIC production exhibits very large economies-of-scale because of the prevalence of large fixed costs. IC fabrication typically involves hundreds of interlinked process steps, each requiring equipment costing in the millions of dollars. The operation of these steps requires that firms employ a "critical mass" of technical personnel to operate even the lowest volume factory. Because these costs are incurred regardless of production volumes, unit costs are lowest when factories are producing at approximately their full utilization rates.[42]

Unfortunately, defense demand is currently too low to justify operation at high production rates. In 1991, total production output of the roughly 15 contractors in the DARPA Project MIMIC program totaled about 50 wafer starts.[43] Project MIMIC, while providing more than $500 million in funding for contractors over the program's 8-year period, assigned 15 producers the same level output over

[39]Ibid.
[40]Interview with USAF engineers.
[41]McQuiddy, D., et al., op. cit.
[42]Interview with David Lutz, Motorola, Inc.
[43]*Third Annual MIMIC Conference Proceedings*, DARPA, 1991.

1 year that a single fully utilized foundry could perform in 2 days.[44] Low demand has resulted in producers operating at less than 10 percent of capacity utilization. Most MMIC contractors in the United States are producing at less than 40 wafer starts per week, although a low volume GaAs fabrication facility can handle 400 wafer starts per week. The cost penalty of low utilization is severe; a factory operating at 50 percent utilization will have 70 percent higher unit costs than the same factory operating at 100 percent utilization.[45]

The defense sector has not generated a higher volume because programs have not produced systems that use MMICs in large quantities. The ARPA MIMIC program is a technology development program rather than procurement; thus it involves very low quantities of MMICs produced for demonstration and evaluation. Current systems procurement programs for MMICs fail to provide adequate volumes for efficient utilization. One program that is expected to use MMICs heavily, the F-22, still remains in development and has years to go before production.[46]

Many MMIC defense producers without high-volume commercial customers will face extinction over the long run if defense demand continues to stay low.[47] Although the F-22 may be the largest program user of MMIC in the near future, F-22 procurement will still support only one or two fully utilized foundries, even in an optimistic procurement scenario.[48] At the same time, a few civilian applications have already generated higher volumes than total DoD procurement for MMIC. For example, total MMIC throughput in wafers per week currently going into the cellular phone assembly line at MELCO alone has already surpassed the projected demand by the F-22 radar procurement.[49]

Projections show that the civilian wireless applications will soon dwarf the demand by the U.S. military for microwave solid-state technology and components by the late 1990s. Over the past few years, the communications industry has expanded at two to four times the rate of the general economy, with

---

[44]Maximum capacities for MMIC fabrication plants are reported to be about 400 wafer starts per week or more than 50 wafer starts per day. Cohen, E., op. cit.

[45]Skinner, R.,"What GaAs Chips Should Cost," op. cit.

[46]Interview with Westinghouse Electric engineers.

[47]In early 1993, AT&T left the GaAs business. During 1992, several other small GaAs producers had already been liquidated or sold by their investors. Interview with a U.S. GaAs manager.

[48]Typical fighter radar production runs during the Cold War have supported rates of about ten radar systems per month. McQuiddy, D., et al., op. cit.

[49]MELCO alone is producing 30,000 MMICs per month in cellular phone amplifiers. MELCO briefings at FS-X Radar Technology Symposium.

the wireless portion growing even faster throughout the rest of the 1990s.[50] Companies worldwide have already begun to design-in systems and components for digital cellular telephone services in Europe, the United States, and Japan in the 1994 to 1996 timeframe. On the other hand, flat or moderate growth in military spending is forecasted for the rest of the 1990s.[51,52] Furthermore, more military spending in this area will go toward commercial, off-the-shelf products, reinforcing the expectation of a rapidly expanding civilian presence in the technology frontier.[53]

Implications of Japan's Commercial Strategy

As a result of the loss of the consumer electronics industry to Japan during the 1980s, U.S. producers have depended on Japanese suppliers of critical solid-state technologies. The technologies that are feeding APAR production also feed production of the high-volume commercial markets described above. Japanese market dominance in these commercial end products has coincided with the global dependence on Japanese supplies of lower-tier tools, materials, and components that enable APAR. This cause-effect relationship is to be expected, since civilian products generate the greatest demand for these lower-tier technologies. Also, commonalities between commercial and military products are greater.

In particular, Japanese firms have managed to capture dominant market shares for several "RF food-chain" items that are critical to the cost and quality of APAR systems. Such products include GaAs starting wafers, GaAs discrete circuits, fabrication tools, and microwave ceramic packages. Not only are RF food-chain products important cost and performance drivers for APAR, but they also enable other military systems such as electronic warfare sensors, communications equipment, and microwave missile seekers.[54] Several U.S. radar companies interviewed admitted purchasing solid-state materials from Japanese sources to build these types of systems.

The phenomenon of Japanese market domination, however, should not be viewed as a problem of defense dependency. Rather, this issue is one of

---

[50] According to a Motorola company statement, high growth rates for wireless should remain steady throughout the rest of the 1990s. "Industry Again Looks for Wireless Boost," *Electronic News*, January 4, 1993.

[51] "EIA [Electronics Industry Association] Forecasts DoD opportunities," *Defense & Aerospace Electronics*, October 26, 1992.

[52] "Growth in DoD electronics market by 1995," *Defense & Aerospace Electronics*, July 15, 1991.

[53] "NATO C3 Must Use Commercial Equipment," *Defense & Aerospace Electronics*, July 15, 1991.

[54] Interviews with engineers from several U.S. defense electronics contractors.

commercial dependency. The dependence by U.S. defense contractors on Japanese lower-tier suppliers is actually a result of broader market realities where Japan controls the supply of materials, components, and production technologies for nearly all applications, both military and civilian. Take for example solid-state materials. Most of the world's supplies for GaAs wafers are controlled by a handful of Japanese firms.[55] In MBE, Japanese firms also dominate global production and tooling sales and purchases. Although the United States pioneered MBE research in the 1970s, a Japanese supplier dominates the global market for production-worthy, MBE machines. Japanese electronics firms are also the biggest purchasers of MBE machines and are the dominant producers of MBE-grown transistors. Fujitsu, NEC, and MELCO are the world's top producers of the high-electron mobility transistor (HEMT), a product responsible for most of the world's MBE production.[56]

Many U.S. experts believe that Japan is behind the U.S. in GaAs MMICs, especially in modeling and design of circuits. For the simpler GaAs discrete devices, however, Japanese firms have dominated global market share since the early 1980s and are strong in all aspects of this technology. In 1989, just three Japanese commercial companies, one of them MELCO, had controlled about half the global market for GaAs discrete field-effect transistor (FET) devices. The market shares of all U.S. makers combined amounted to less than 20 percent (see Figure 7.1).[57] Japanese firms also hold a large market share of higher performance discrete HEMT devices. Fabricated from MBE wafers, Japanese HEMT devices are now high volume products inserted into DBS home receivers in Europe and Japan.[58]

Dominance in discretes certainly would give Japanese firms an edge with MMIC. GaAs discretes are often thought of as the precursor technology to MMIC. While discretes contain only one device, MMICs contain several. By being dominant producers in discretes, Japanese firms may have an edge in device design, fabrication, and handling of GaAs MMICs.[59]

---

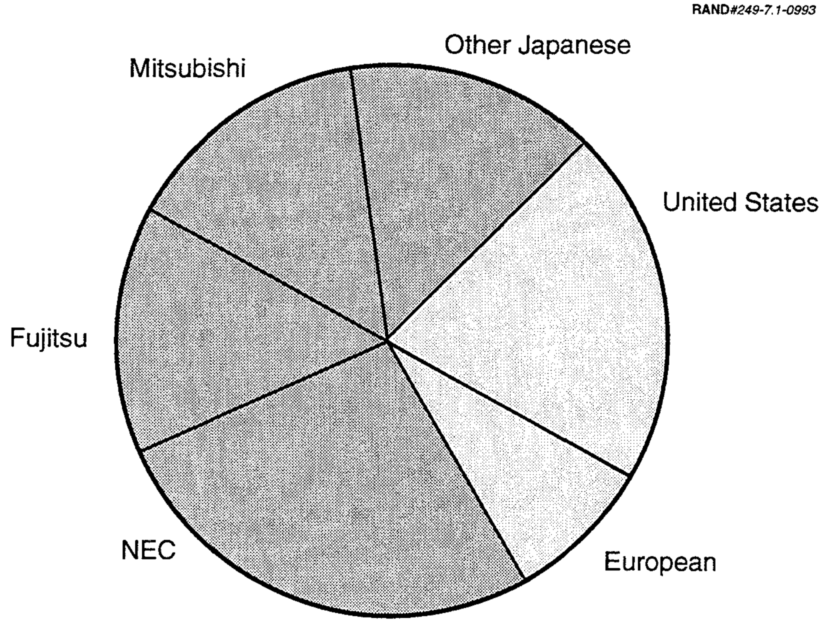
[55]Several engineers interviewed within U.S. defense contractors noted their company's dependence on Japanese suppliers for starting wafers.

[56]Interviews with Philip Sullivan, VG Instruments. Fujitsu is a dominant global supplier of HEMTs.

[57]"Japan—Gallium Arsenide I.C. (GaAs IC)—Industry Analysis," *Industry Subsector Analyses*, Foreign Commercial Service, U.S. Department of Commerce, October 1990. The generally higher prices charged for military procurement will bias the market share upward for U.S. firms, whose sales are more heavily dominated by military work than Japanese firms.

[58]Ibid.

[59]Interview with AT&T engineers.



SOURCE: "Japan—Gallium Aresenide I.C. (GaAs IC)—Industry Analysis," op. cit.

Figure 7.1—Japan Dominates Market Share for GaAs FET Discretes

How did Japan come to dominate the discrete markets? One could attribute their successes to a strategy of early usage of incrementally improved process and component technologies for high volume, commercial applications.[60] For example, in the late 1970s, Japanese consumer electronics firms began inserting simple but high-performance discrete GaAs devices into "traditional" consumer electronics products lines whose production they controlled, such as televisions, video cassette recorders,[61] and compact disc (CD) players.[62] In the same period, U.S. firms were applying similar technology mostly for low-volume defense needs.[63]

Because of early commercialization, Japanese firms became leaders in GaAs discrete FET production by the mid-1980s.[64] The early 1980s also witnessed growing Japanese strengths in high-quality, low-noise microwave GaAs

[60]Ibid.

[61]Interview with Bert Berson, Berson & Associates.

[62]CD players contain GaAs laser devices made from similar fabrication processes as those used for transistors. Nakajima, H., "Dreams and expectations of III-V semiconductors," *International Symposium GaAs and Related Compounds*, 1989.

[63]Interview with AT&T engineers.

[64]Ibid.

technology for space applications, based on sophisticated GaAs epitaxy-based processes.[65] By 1991, the United States had an almost complete dependence on Japanese-made GaAs HEMT devices for microwave receive equipment for communications and electronic warfare during the 1991 Persian Gulf War against Iraq. U.S. industry, on the other hand, applied similar technology mostly for low volume needs of the DoD, which had funded relatively low production quantities for R&D and limited procurement.[66]

In many cases, Japanese firms inserted GaAs devices into products even though they provided only marginal benefits over more mature technology.[67] The early use of GaAs did provide Japanese firms with the early engineering and production experience needed to master processing and handling. By leaping on the experience curve before the U.S. firms, Japanese firms nearly assured their dominance of the GaAs discrete markets by the mid-1980s.

Beyond discretes, Japanese electronics firms went further and began inserting increasingly sophisticated GaAs circuits into high-volume, commercial products. As part of an incremental improvement strategy, these firms built on their base in discrete GaAs circuits and expanded their presence into more sophisticated hybrid integrated circuits for new high-volume "wireless" applications. From the late 1980s to early 1990s, the Japanese have developed and are now producing highly integrated GaAs MMICs for cellular telephones, automobile and traffic control sensors, and satellite navigation. By the late 1980s, Japanese industry had gained a dominant position in packaging and assembling of hybrid MICs and subassemblies as well as multichip modules. The strategy of early entry into high-volume, commercial markets has enabled Japanese firms to master many critical process and product technologies that drive cost and performance of APAR systems.[68]

[65]Interview with an engineer at Hughes Aircraft Company.
[66]Interview with AT&T engineers.
[67]Interview with Bert Berson, Berson & Associates.
[68]Interview with engineers at Westinghouse Electric.

8. Conclusions

Indications of a Sound Technical Capability

The allied victory in the Persian Gulf War had demonstrated the decisive role of sensors in modern warfare. The development and operation of sensors based on active phased array radar constitutes a critical milestone in the quest for military security and superiority into the 21st century. Because of its many inherent advantages over mechanical-scan technology, APAR is recognized as providing the capability to steer beams extremely rapidly, engage multiple targets, maintain some degree of stealth, generate high quality terrain maps, and change beam shapes. Compared to PPAR systems, APAR systems also enjoy higher reliability and maintainability as well as superior beam control and off-boresight performance.

Japan's timely completion of the FS-X radar may be an early sign of Japanese competencies in defense electronics. While the FS-X radar performs at a lower level than front-line U.S. systems such as the F-15 along several measures, the FS-X radar still represents a significant achievement as the world's first APAR operational in a tactical fighter.

Despite this achievement, many U.S. observers cling to the conventional wisdom discounting Japan's ability to develop world-class weapon systems on her own. This wisdom follows the reasoning that because Japan has limited experience developing and integrating its own weapon systems, it is far behind the U.S. and Western Europe in military technology. A closer examination of Japanese accomplishments in systems integration may reveal that the West has severely underestimated Japan's technological prowess in developing its own defense systems. For instance, by the end of the 1980s, MELCO had completed several EM prototypes on its own that, according to the JDA, had passed all flight tests and had demonstrated 20 stand-alone modes, submodes, interleaved modes, and BIT. Furthermore, experts on Japanese technology can also point to the extensive experience by Japanese primes in the integration of complex systems such as

nuclear power plants, ships, satellites, and the most elaborate railway network in the world.[1,2]

Japanese system integration capabilities were not developed overnight, however. In the case of APAR, Japanese technical capabilities can be attributed to a more than 20-year acquisition relationship.[3] Throughout this period, JDA had spent an undisclosed sum to develop and nurture APAR technology at MELCO through continuous RDT&E funding. JDA funding also does not include a reported 100 billion yen of internal funds spent by MELCO on T/R module technology throughout this period.[4] This acquisition relationship has led to four successive X-band APAR prototype systems since 1975. By 1994, MELCO is scheduled to complete its fifth successive X-band APAR prototype, the FS-X FM radar. Clearly, Japan has had a consistent long-standing desire to develop X-band APAR technology using a rapid prototyping, incremental improvement approach.[5]

Apart from government-funded R&D, MELCO has benefited from process capabilities it developed through its civilian divisions because MELCO has managed to integrate its commercial and military industrial activities. For instance, not only has commercial know-how been applied to the design and production of components such as T/R modules, but commercial production lines, tooling, and expertise are being utilized to make components for the FS-X radar.

A record of successful commercialization of high technology appears to have provided MELCO with some advantages over U.S. contractors in realizing APAR. MELCO's rise to dominance in the DBS equipment market for home television allowed the company to gain an edge in process technologies applicable to APAR, including solid-state circuit fabrication and handling and assembly of such circuits into packaged parts.

Furthermore, MELCO's defense efforts may have also benefitted from commercial investments in flexible manufacturing systems. High product

---

[1]Friedman, D. and R. Samuels, op. cit., p. 22.

[2]Yet another indication of Japan's emerging systems integration skills is an imaging SAR developed by MELCO, which reportedly has the highest resolution of any civilian satellite radar in the world. Proctor, P., "Japan Plans New Generation of Remote Sensing Satellites," *Aviation Week & Space Technology*, July 13, 1992, p. 67.

[3]MELCO officials have noted that JDA has continuously funded APAR R&D at MELCO since 1964. *FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

[4]"FS-X Radar Technology Transfer," *Nihon Keizai Shimbun*, January, 26, 1993, p. 1.

[5]Quick product turnaround is a strategy commonly used by commercial enterprises in Japan, including the automobile or electronics industries. Curiously, one finds that MELCO takes a similar strategy in its R&D and prototyping of military APAR.

turnover and fluctuating demand in the consumer electronics industry gave Japanese electronics firms the incentives to develop flexible systems. The application of this infrastructure to defense needs likely enabled MELCO to demonstrate automated assembly of FS-X radar components quickly after its development. Because MELCO has been applying GaAs and solid-state microwave technology for high-volume production in civilian products, MELCO can also enjoy scale economies, learning economies, automation, and flexibility in some of its defense production as well.

Although the performance of the FS-X EM prototype is regarded as conservative by U.S. standards, Japan may be using the FS-X as the groundwork for advancing Japanese defense capabilities over the long run. Through a strategy of incremental, but continual and rapid improvements, Japan may soon be poised to become a serious contender as a developer of first-rate defense technology. Especially as many national governments consider cost-effectiveness as well as performance, Japan may be poised to leverage its technical prowess in electronics manufacturing to become a low-cost exporter of defense products.

Futhermore, Japan may be in a position to enter new high value-added markets for complex electronics systems. Currently the Japanese government has several programs in place to exploit APAR technology for a variety of defense and civilian system applications such as ground-based air-defense, weather monitoring, and civilian air traffic control and surveillance.[6]

Valuable Capabilities, but Questionable Transfer

The transfer of Japanese FS-X radar technology to the United States, if successful, could prove valuable to U.S. interests. In particular, DoD believes that access to Japanese manufacturing capabilities could help U.S. contractors reduce costs and increase production capacity for T/R modules. T/R module production poses one of the most difficult challenges for the U.S. defense electronics industry, and some studies indicate that Japan is ahead of the United States in low-cost, high-quality manufacturing. Consequently, some within DoD are considering adopting Japan's manufacturing technologies to improve defense manufacturing in the United States.

Other Japanese capabilities that might benefit U.S. interests include the BIT algorithms in the FS-X radar, composite materials for the array structure and module, and electronic packaging design methodologies and tools. To ascertain

[6]Interview with engineers at MELCO Radar Systems Group.

benefits, however, the United States will have to obtain more details and data on MELCO technology.

Although several Japanese technologies may appear highly promising, several factors appear to reduce the prospects for successful transfer to the United States. One factor, diverging systems requirements, may cause the United States to develop systems of higher design complexity, rendering Japanese hardware designs inapplicable. For example, requirements on detection ranges in the F-22 may call for a more powerful radar antenna, which in turn may call for a different power supply and cooling system design than that of the FS-X.

Another obstacle to technology transfer is a lack of knowledge by U.S. industry. Lack of knowledge of Japanese technology had been a significant problem during the first few years of the FS-X program. Before the FS-X Symposium, U.S. industry knew little about the FS-X radar as well as MELCO design and process capabilities. Until the Symposium, only a few U.S. government officials, part of teams that conducted periodic visits to Japan, had knowledge of the FS-X radar.

Other problems hindering technology transfer are the complex procedures and regulations governing the technology transfer process. These procedures are often based on highly subjective definitions of technology and can involve elaborate approval requirements by both the U.S. and Japanese governments.

Stark differences in program requirements could render FS-X hardware and software technologies inapplicable to U.S. needs. Japan may be employing processes or designs that violate standards and practices in the United States. Thus, applications of Japanese processes for U.S. programs might require an extensive reevaluation of U.S. and Japanese military requirements.

Finally, Japanese industrial capabilities may not be transferable because of the integral role of broader industrial factors in processes. Production processes are often interlinked within a broader corporate context of firms. Often, a process technology can operate smoothly only within the context of a single firm because of its dependence on a unique customer-supplier network or internal operating procedures of a corporation. Consequently, a good process from one firm may not perform so well when transplanted to a different firm.

Japanese Strengths: R&D and Industrial Philosophy

Japanese manufacturing strengths can be attributed more to industrial management and philosophy rather than superior technology. The impressive Japanese manufacturing capabilities witnessed by DoD can be seen largely as a

result of MELCO sucesseses in their consumer electronics division, whose business generates the highest volume of demand for component production. Given the traditionally low volumes of DoD production, U.S. defense contractors typically lack the high-volume business base to apply Japanese manufacturing methods.

High-volume consumer products have given Japanese dual-use companies the ability to apply flexible automated lines to defense needs. In addition, JDA program managers have shown considerable flexibility in their willingness to relax requirements from the outset so that commercial components can be used inside defense systems. Perhaps what the United States can learn most from the FS-X experience is not so much technology *per se* but the method by which Japan manages and integrates technology for commercial and military use.

Another interesting aspect of the FS-X radar is the overall R&D strategy to advance technology. The Japanese government has followed an incremental improvement strategy, in which new systems are developed incrementally improved above a conservative baseline design. Prototyping is done rapidly to ensure the state of the art advances very quickly. While ensuring rapid progress over the long run, this approach also appears to have the advantage of lower risks. Most of all, this approach may have enabled Japan to develop the world's first tactical airborne APAR. Projecting past accomplishments into the future, Japan could, by 1997, complete an FS-X radar follow-on that might be more competitive with the latest U.S. technology.

Another interesting feature of the Japanese acquisition approach is the strong emphasis on cost and process improvements. For example, improvements from the EM to FM were focused largely on cost and process improvements, almost to the exclusion of performance improvements. Chip integration of the FM T/R module was substantially increased, and the fabrication processes used to make the chips were substantially upgraded. Meanwhile, key performance specifications such as peak output power were not changed at all.

This approach reveals a cost-reduction strategy based on selective improvement. Contractors agree on values for the critical system specifications early in the design, and then "freeze" these specification values throughout one or more development iterations. Contractors then focus on high leverage areas where performance can be improved at minimal additional redesign cost.

In contrast, the United States has tended to pursue systems of unparalleled performance and has often found itself changing critical design specifications in the middle of development cycles. While inducing dramatic improvements in the performance of successive module prototypes in the United States, this

overall approach may contribute to delays and cost overruns in completing the F-22 radar.

Japanese motivation in the FS-X radar program seems driven by a desire to develop a world-class industrial base over the long run rather than to build the highest performance system over the short run. The FS-X radar program can almost be considered a demonstration program in which the Japanese government is proving the systems integration capabilities of its contractors.

Some knowledgeable FS-X observers in the United States note that MELCO appears to understand APAR technology well enough to have developed a system of much higher capability. These observers feel that the FS-X radar could be an "engineering exercise" or "technology driver" to improve the state of the art of Japanese military technology. In addition, the specifications set by JDA for the FS-X were so conservative that they were judged as not to dictate the need for an APAR. If the primary goal of Japan is to maintain or improve indigenous military design or production capabilities,[7] then the development of a system of unmatched performance at the present may not only be unnecessary but counterproductive.

Rather than to develop the highest performance system immediately, Japan may be using the FS-X as an opportunity to advance indigenous systems integration skills quickly without incurring high costs. The FS-X could give contractors the necessary experience base and feedback to hone design and integration skills. The performance data gathered from flight tests could give the feedback necessary for engineers to develop a truly superior system in the near future.

As contractors learn more and as the state-of-art technology improves, Japan could then develop a much higher performance system after the FS-X, perhaps at lower cost and risk than that for the F-22 radar program. Once a conservative, baseline operational system is completed for the FS-X, development of a higher performance follow-on radar system would not be so difficult because of the scalability of APAR technology. By completing an operational, albeit conservative, baseline system as soon as 1994, Japan may be setting the stage for a highly advanced follow-on radar program to be completed by the late 1990s. Once a low-level baseline system is built, a significantly improved version could be built quickly by increasing the array size, the number of modules per array, or module performance.

---

[7]Friedman and Samuels have argued that "Japan has embraced a vision of national security that elevates local control, national learning and substained development over [short-term] procurement criteria." Op. cit.

Implications of Japan's Commercial Strategy

APAR provides a visible case study of the linkages between a nation's civilian electronics industry and military technology base. Strengths of MELCO and other Japanese electronics firms in consumer electronics have provided a vast technical infrastructure capable of manufacturing both civilian and military components at high quality and low cost. Such an infrastructure has also helped Japan to meet production for their military systems sooner than U.S. contractors. For instance, MELCO's rapid demonstration of automated production of T/R modules may have been possible because of knowledge gained from commercial experiences with flexible production and CIM.

A focus on commercial applications has enabled Japanese firms to dominate the market for various lower-tier process, tooling, and materials technologies that drive APAR cost and performance. Not only have U.S. civilian firms depended on these Japanese suppliers for process inputs, but U.S. defense firms have also found themselves heavily dependent on them for critical components such as microwave ceramic packages and discrete GaAs transistors.

On the other hand, the paucity of commercial applications of APAR-related technologies by U.S. defense firms has resulted in a captive industry that has relied on the public sector for financial support. The failure of U.S. defense firms to commercialize dual-use technologies on a large scale has contributed to low assembly automation and underutilized fabrication, as well as a heavy dependence on foreign sources for some critical materials and tooling technologies.

Dual-use production sharing with high volume commercial applications is crucial for reducing the cost and improving the process quality of military APAR production. Because of higher volumes and revenue in the commercial sector, commercialization of cost-driving components such as MMIC and T/R modules is necessary to reduce costs and improve quality. With deep reductions in national defense budgets and a rapidly growing civilian technology base, commercialization of dual-use technology will become increasingly critical for the maintenance of a healthy military technology base.

Studies increasingly note that commercial processes and components are surpassing those developed in the defense sector in terms of cost, performance,[8]

[8]In four classes of silicon ICs—microprocessors, digital signal processors, static random-access memories, and programmable read-only memories—"commercial markets . . . equal or lead military markets in the introduction of technologically advanced products" and that "government R&D funding intended to skip product generations does not produce advanced ICs faster than commercial

reliability, and sophistication.[9] Several factors can explain this trend. One factor is faster turnover rates of commercial products and processes, inducing more rapid innovations within commercial firms.[10] A second factor is the explosion of the size of the commercial high-tech sector relative to the military. Especially in many component technologies, the commercial sector sales, production volume, and profit margins have begun to dwarf that of the military sector. Consequently, commercial firms can better afford to spend more on R&D and capital investment than many defense firms in dual-use component and process technology. A third factor is the broadening competition in high technology induced by the commoditization of components and systems, particularly such well-known items as personal computers, workstations, and micro devices. With competition intensifying, market forces have imposed strict discipline on firms with regard to their delivery, cost, and performance. Such discipline has forced firms to remain flexible, low-cost, and innovative.[11] On the other hand, the government contracting system has tended to reward firms based on short-term system performance with only secondary emphasis on process efficiency, cost, and delivery. As the global commercial sector takes over as the primary driving force for technical innovations, "spin-on" will become the dominant paradigm for military-commercial technology flows, while "spin-off" will likely wane.[12]

Some commentators have observed that Soviet deficiencies in military technologies, i.e., their inability to keep up with U.S. weapons in electronic miniaturization and information processing, can be attributed to their severe weakness vis-à-vis the United States in their civilian semiconductor and computer industries. These observations about dual-use linkages are nothing new. Writers throughout the 20th century from Fredrick List in the early 1900s, Joseph Schumpeter in the mid-1900s, to Paul Kennedy in the 1980s have written about the centrality of commercial industry and technology to a nation's military security. The central role of Japan's commercial sector in the development of Japanese APAR only confirms what industrial economists and historians have

---

evolutionary development." Slomovic, A., *An Analysis of Military and Commercial Microelectronics: Has DoD's R&D Funding Had the Desired Effect?*, RAND Graduate School Dissertation, 1991.

[9]Even in terms of reliability and durability, two factors strongly stressed by the military, the commercial sector has essentially caught up or surpassed the military in many areas. Commercially available computers, radios, and displays were found to be as durable in harsh environments, several times cheaper, five times easier to acquire, and more reliable than their counterparts in the military. *The Use of Commercial Components in Military Equipment*, Defense Science Board, 1986.

[10]Commercial producers in the United States and Japan introduce a new generation of devices every two to three years. On the other hand, military systems typically evolve over a 5- to 20-year cycle. Vogel, S., "The Power Behind 'Spin-ons': The Military Implications of Japan's Commercial Technology," *Berkeley Roundtable on the International Economy*, April 1991, p. 7. Will appear in Sandholtz, Borrus, Stowsky, Vogel, and Zysman, *The Highest Stakes: Technology, Economy and Security Policy*, Oxford University Press, forthcoming.

[11]Ibid.

[12]Ibid.

known for more than a century. Perhaps the almost singular success of U.S. civilian industries in foreign trade after World War II allowed many U.S. policymakers to take for granted the role of U.S. civilian technology in the advancement of defense systems technology. Only very recently, as foreign competition in civilian high technology has intensified, U.S. policymakers have become more attuned to the importance of the commercial industrial base to U.S. national security.

9. Policy Recommendations

Reducing Barriers to Technology Transfer

Despite seemingly promising areas, several factors hinder the transfer of Japanese FS-X radar technology to the United States. One difficulty arises from imperfect information flows. Technical managers within some subtier suppliers were not aware of FS-X technology transfer opportunities in their areas of business, although these areas are enabling technologies for APAR. Although the symposium was widely advertised, many subtier suppliers did not attend.

One area where U.S. policy can help is to expand information flows deeper into relevant, lower-tier subsectors of U.S. industry. While the DoC should be commended for its vigorous advertising for the FS-X Symposium and the high turnout by large defense firms, greater focus is now needed toward firms specializing in such relevant fields as microwave components, electronic packaging, assembly tools, and solid-state materials. If the FS-X is advertised only as a military radar instead of as a complex system drawing on many state-of-the-art technologies, many potential beneficiaries will be missed.

To address this problem, the DoC and DoD need to continue to work together in expanding communication about the FS-X deeper into the more specialized subtiers. DoC should take the broadest possible view of the technologies that may be accessible in the program and then disseminate such information throughout as many subtiers as possible. DoD could greatly assist DoC by recruiting technical expertise residing at the defense laboratories. Such expertise can play a critical role in composing a comprehensive list of all technologies, both products and processes, that could be related to that used by MELCO to design, develop, and produce APAR. With such a list, DoC could better identify new subtiers that may be relevant to the FS-X. It could also inform these subtiers on how the FS-X can be relevant to their businesses.

Over time, the DoC should set up meetings and notices with more of the specialized industry and trade associations. For example, in addition to the EIA, the DoC should also send notices to even more specialized associations within the EIA, such as the U.S. GaAs Manufacturing Technology Association or the Multi-Chip Module and Packaging Association. In this way, a maximum

number of industrial sectors can be informed of the FS-X, and its relevance to their specific fields of business can be conveyed.

Another problem of technology transfer was revealed by the widespread confusion expressed by U.S. managers over the procedures and mechanisms for receiving technology through the FS-X program. Furthermore, these managers typically come from technical backgrounds and lack the knowledge, experience, and interest in the complex legalities of U.S.-Japan acquisition agreements and bureaucratic rules governing technology transfer. Such confusion points to the need for further clarification and, if possible, simplification of the technology transfer process.

One option is for the United States to bargain with the Japanese delegation in the Joint Military Transfer Committee (JMTC)[1] to clarify the procedures. This option, however, may be limited because many of the procedures have been set in writing by the FS-X agreements. In addition, the JMTC lacks the jurisdiction to change these agreements.[2] Another option is to mitigate the complexities of the procedures by making the transfer process more "transparent" to U.S. industry. A single office could be established to handle most of the bureaucratic hassle and paperwork on behalf of all the U.S. companies requesting access to the FS-X. For instance, instead of having government officials delve into the different technology categories and procedures when dealing directly with interested U.S. companies, a single, authoritative source of contact should be established to simplify the process of U.S. company inquiries. This source should be operated by people experienced with all the technology transfer procedures and regulating bodies that can provide support to U.S. companies.

This agency should act on behalf of individual U.S. companies by consulting with and gaining approvals from all agencies involved in the technology transfer process. This agency should also be required to provide timely feedback to all inquiring U.S. companies about the likelihood of approval of their request, modifications needed for approval, and the amount of time expected before approval.

---

[1]The JMTC is the bilateral body of U.S. and Japanese military officials that was set up to manage and monitor technology transfers in the FS-X.

[2]The technology transfer procedures were written in the FS-X agreements and are not subject to change by the JMTC. Correspondence with Captain Sid Perkins, USAF.

Further Study into Japanese Acquisition and Industry

The policy environment for U.S. defense acquisition has reached a crossroads. The Cold War imperative to develop systems of the highest performance has run into conflict with a post–Cold War emphasis on budget savings. Despite the many operational performance benefits of APAR, an austere budget environment has raised new concerns over procurement costs of the technology. In the F-22 radar program, DoD views T/R module cost as the biggest risk facing the program, and the desire to resolve the affordability issue is a primary motive behind DoD's interest in Japanese manufacturing technology.

Nevertheless, high requirements are an important factor driving up T/R modules costs. DoD has set very stringent performance specifications for the F-22 T/R modules to ensure that the radar's performance will be superior to existing radar systems. While successful in inducing contractors to improve performance of module prototypes in a very short time, it may have imposed difficulties in maturing the system design and production technology to operational status.[3]

Consequently, the United States should study not only Japanese technology in the FS-X program but also its own acquisition management strategy. The United States may even want to consider Japan's long-term acquisition approach as a possible alternative to the current system as U.S. defense budgets downsize. The Japanese approach emphasizes cost and schedule reduction through design maturation, parallel engineering, and process improvement. Such an approach could inject greater cost-responsiveness into the acquisition process during system design and integration phases. The U.S. Air Force is funding a program that will send U.S. scientists, engineers, and managers to Japan to learn about Japanese technology and management practices. The government may wish to include acquisition management as a target field of study for such courses as well.

Incremental R&D

In considering Japanese acquisition practices, DoD may consider further easing of systems requirements for programs such as the F-22 to control costs and schedule better. While programs that improve the defense manufacturing base, such as MANTECH and Industrial Modernization Initiatives Programs are highly commendable, the DoD may wish to consider other reforms based on

---

[3]Interview with a technical manager for a U.S. radar contractor.

Japanese practice that better internalize costs in the requirements setting process. Further study by such agencies as the Defense Management College on the iterative, incremental improvement acquisition approach employed for Japan's APAR R&D is recommended.

Another pattern emerging in the discussion of Japanese acquisition is an explicit long-term relationship between MELCO and the JDA. In this arrangement, financial incentives for innovation could be provided by linking financial rewards to improvements over a baseline in system cost, process, and/or performance. Such a baseline could be set by the cost and performance of the previous prototype iteration. One benefit of this approach is internalizing costs into the requirements and specifications setting process while also providing incentives for continual improvements in the state of the art.

Yet another difference in Japanese approaches toward acquisition is apparent in the reliance on fewer sources for development and procurement for APAR. Throughout its history, the JDA has relied almost exclusively on MELCO for APAR technology. In current times of tight budgets, the United States can less afford the redundancy and duplication of effort of multiple sourcing, although the likely reduction in rivalry among firms could introduce other problems.[4] With U.S. contractors using labor-intensive processes and under-utilized factories, DoD may consider awards to joint ventures and teaming of firms rather than dual-sourcing to several competing firms. This approach might help to foster longer-term relationships among fewer sources for a particular technology.[5] Also, DoD should not interfere with the waves of industrial consolidation overtaking the U.S. defense industry. While creating turmoil and economic hardship in the short run, the costs may be outweighed by the benefits of creating a more efficient and capable defense industry over the long run.

Promoting Dual-Use

The case of MELCO has highlighted the critical importance of commercializing dual-use technologies whenever feasible. The active role of the Adminstration and Congress in helping domestic industries commercialize dual-use technology

---

[4]A move toward single-sourcing raises a difficult dilemma in which the benefits of scale economies through single-sourcing runs against the potential risks of supply interruption or price gouging caused by a single-source arrangement. Many would also note that a move away from fair, competitive, multiple source contracting might open a Pandora's box of corruption and inefficiency if the government had to rely on a monopolistic, single-source for the supply of a crucial technology or system.

[5]Teaming is an approach that can help diffuse R&D-generated knowledge through the industry and eliminate duplication of multiple-sourcing while avoiding potential antitrust problems.

is, therefore, justified on national security grounds. As this report has argued, commercialization will likely become the primary source of technology innovation for the U.S. military services in the foreseeable future. Perhaps as importantly in the long run, however, commercialization would also help to generate the domestic jobs and corporate profits necessary to ease the economic shock caused by downsizing defense budgets.[6]

The case study of the FS-X radar reveals the importance of unsurpassed technical prowess in the commercial sector and spin-on to military strength in the post–Cold War era. As defense spending declines, the erosion of the U.S. defense industrial base has become a primary concern for defense planners. Such erosion could be forestalled by a world-class commercial technology base and skillful application of commercial technology to military uses. The United States should continue steps to allow defense contractors to utilize more commercial resources in developing and producing military products. For example, with dual-use integrated firms, revenues from the commercial sector production could help maintain a "critical mass" of expertise applicable to the design, integration, and production of military systems.

The above argument assumes strong synergies between commercial and military sectors in R&D and production. The case of MELCO and the FS-X radar sheds light on the forms of these synergies. For example, not only is MELCO applying similar assembly processes for defense and commercial products, but it is also using the same production lines.[7]

Spin-On More Effective Than Spin-Off

The case study also reveals that, for the most part, commercial-military synergies tend to be one-way, that spin-on predominates spin-off. This conclusion can be seen with the recent proliferation of commercial applications in civilian wireless communications and microwave sensing, which are operating in the same or higher frequency bands as military airborne fire control radar. MELCO, for example, has revealed its development of phased arrays for vehicular communications and air-traffic control operating at fire control frequencies.[8] Several other U.S. and Japanese companies are reportedly trying to develop T/R

---

[6]Gary Denman, director of ARPA, has reflected this viewpoint in the following quote: "A lot of technologies are so expensive that we can't afford to rely on purely military markets. We [also need to] use the commercial base to make military products more affordable." Scott, W., "ARPA Applies Dual-use to Affordable Defense," *Aviation Week & Space Technology*, April 12, 1993, p. 44.

[7]Interview with a U.S. engineer who worked on a joint venture with MELCO.

[8]*FS-X Active Phased Array Radar: U.S. Team Report*, op. cit.

modules for automobile collision avoidance and cruise control operating at X-band.

For example, Hughes Aircraft Company is investing in X-band module technology for automotive sensors for speedometers, cruise control, collision avoidance, and triggers for airbags.[9] Although the requirements will likely be far less demanding than in military applications, Hughes has claimed that many T/R module engineering concepts between military radar and civilian obstacle detection systems are similar. The entry of these products into the marketplace is highly auspicious for dual-use application of expensive capital equipment and specialized human talent in microwave, solid-state technology. Nevertheless, many industry observers note the difficulties facing Hughes in lowering the costs of the system to ensure wide acceptance in the civilian markets. Such difficulty highlights the inherent problems of spin-off.

Rather than focus on converting defense resources to commercial use, the FS-X radar case study calls for the advancement of commercial state-of-art itself, and the improvement of commercial-to-military technology flows.[10] The following lists some barriers to spin-on and policy recommendations drawn from the author's interviews and discussions with experts representing U.S. industry.

DoD accounting regulations pose entry barriers for successful commercial firms competing for defense contracts, especially R&D. Managers for commercial companies have long complained of the high cost of converting their accounting systems to comply with DoD contracting regulations. These regulations also raise barriers for defense contractors to enter commercial markets by giving defense firms excessively high overhead rates. Also, commercial industries often have to integrate their production and R&D together to ensure design for producibility. These regulations have not only made spin-off difficult but also illegal in some cases.

These barriers may seem formidable given the huge separation between commercial and defense sectors in the industry. Numerous examples tell of failures by defense firms in converting to commercial products.[11] Other examples tell of U.S. prime contractors that separate their commercial R&D and

---

[9]Interview with Charles Krumm, Hughes Radar Systems Group.

[10]Center for Strategic and International Studies, *Integrating Commercial and Military Technologies* discusses the benefits of dual-use integration and barriers impeding it in the United States. J. Gansler's *Affording Defense* lists 30 free market assumptions violated in defense contracting. J. Alic's *Beyond Spinoff: Military and Commercial Technologies in a Changing World*, describes the historical background, cases, and policy implications of dual-use segregation in U.S. industry.

[11]Friedman and Samuels note Grumman's failures in building canoes and school buses and Rockwell's failures in entering the aircraft overhaul business. Friedman and Samuels, op. cit. p. 46.

production operations from the military at both the plant and division level. A study on aerospace forging and casting firms showed U.S. subcontractors readily integrating civilian with military work but rarely venturing into nonaerospace work. Japanese aerospace companies such as MELCO focus on applying their commercial excellence to military needs and thus seem better able to perform aerospace along side of nonaerospace work.[12]

To faciliate spin-on, DoD may wish to review its contracting policies. For instance, DoD should consider allowing contractors to retain more of the intellectual property over the technologies it develops under contract. One widely noted disincentive against the participation of commercial firms in DoD contract work is the prospect of losing intellectual property over the technology developed under contract. Commercial firms have also noted lower profit margins and high risks of overruns in DoD contracting.

Further, DoD may also wish to rethink how it awards contracts. For example, most contract awards for MMIC have gone to large systems developers rather than lower-tier firms that specialize in high volume MMICs for the commercial sector. As a result, IC factories in large systems houses have suffered from low utilization rates and high cost. The DoD should consider ways to increase the involvement of lower-tier commercial suppliers into the defense contracting system.

To summarize, Japanese industry appears to have process and system technologies that are either superior to U.S. capabilities or that could serve the interests of U.S. companies, especially if they could be transferred costlessly. Nevertheless, numerous problems of lack of knowledge and access, conflicts of interest, incompatible requirements and needs, and nontransferrability of industrial assets severely hamper the chances for successful FS-X technology transfer. The case study of the FS-X radar, however, raises issues of industrial and acquisition management rather than technology as indicated by an examination of U.S. needs, Japanese strengths, and problems of access. This report has argued for closer examination of the broader acquisition and industrial issues of Japanese R&D and industrial management of high technology. Given the numerous difficulties that face technology transfer, perhaps the most valuable benefit of the FS-X program is the elucidation of successful Japanese approaches to government acquisition and industrial management of advanced, dual-use technology.

---

[12]Ibid. p. 46.

Bibliography

Abe, M., "Present Status and Future Prospects of Compound Semiconductor LSI Technology," *Handotai Shuseki Kairo Gijutsu*, June 27, 1991, pp. 73–78, translated into English by *JPRS: Japan Science & Technology*, April 15, 1992, pp. 15.

Aerospace Daily, May 16, 1991, p. 272.

Alexander, A., *Comparative Innovation in Japan and in the United States*, RAND, R-3924-CUSJR, August 1990, pp. 18, 41.

Alic, J., et al., *Beyond Spinoff: Military and Commercial Technologies in a Changing World*, Harvard Business School Press, 1992.

Arrow, K. "The Economic Implications of Learning-by-Doing," *Review of Economic Studies*, Vol. 29, 1962, pp. 155–173.

Arthur, B., "Self-Reinforcing Mechanisms in Economics" in P. Anderson, et al., *The Economy as an Evolving Complex System, Proceedings of the Evolutionary Paths of the Global Economy Workshop*, 1987.

Beal, C. and W. Sweetman, "Fighter Radar in the 1990s: A Spectrum of Progress," *International Defense Review*, August 1992.

Blake, B., *Jane's Radar and Electronic Warfare Systems*, 1990–1991.

Capaccio, T., "USAF Must Align Acquisition Strategy with Aspin's Views: Loh," *Defense Week*, February 8, 1993, p.12.

Cheston, T. and J. Frank, "Phased Array Radar Antennas," from Merrill Skolnik, *Radar Handbook*, Second Edition, 1990.

Clark, K., et al., "Product Development in the World Auto Industry," *Brookings Papers on Economic Activities*, 1987.

Cohen, E., "MIMIC from the Department of Defense Perspective," *IEEE-Microwave Theory & Techniques Transactions*, Vol. 38, No. 9, September 1990.

"Defense Agency to Enter Detailed Design Phase of APAR Radar," *Comline Transportation*, August 3, 1987, p. 6.

"Defense Industry Watching Issue as Test Case," *Nikkan Kogyo Shimbun*, October 10, 1992, p. 7, translated into English by *JPRS: Japan Science & Technology*, October 29, 1992.

Deming, W., *Quality, Productivity, and Competitive Position*, MIT Center for Advanced Engineering Study, 1982.

Department of Defense Critical Technologies Plan, Committees on Armed Services, U.S. Congress, 5 May 1989.

Dertouzos, M., et al., *Made in America: Regaining the Productive Edge*, MIT Press, 1990, p. 250.

"Developments in Assembly Line Automation," *Nikkei Mechanical*, June 29, 1992; from *JPRS: Japan Science & Technology.*

Dornheim, M., "Gallium Arsenide Technology Replacing TWT Power Amplifiers," *Aviation Week & Space Technology*, October 19, 1992.

"EIA [Electronics Industry Association] Forecasts DoD Opportunities," *Defense & Aerospace Electronics*, October 26, 1992.

Ferguson, C., "Computers and the Coming of the U.S. Keiretsu," *Harvard Business Review*, July–August 1990, pp. 55–70.

Findings of the U.S. Department of Defense Technology Assessment Team on Japanese Manufacturing Technology, Draft, November 1988.

Friedman, D. and R. Samuels, *How to Succeed Without Really Flying: The Japanese Aircraft Industry and Japan's Technology Ideology*, MIT-Japan Program, 1992.

FS-X Active Phased Array Radar, U.S. Team Report, Department of Defense, 28–31 May 1991.

FS-X Radar Technology Symposium, Briefings, U.S. Department of Commerce, June 22, 1992.

"FS-X Radar Technology Transfer," *Nihon Keizai Shimbun*, January 26, 1993, p. 1.

"FS-X Technology Transfer Process," briefing by Captain Sid Perkins, USAF, FS-X Radar Technology Symposium, June 1992.

Gansler, J., *Affording Defense*, MIT Press, 1986.

Gebman, J., et al., *A New View of Weapon System Reliability and Maintainability*, RAND, R-3604/2-AF, January 1989.

Griffin, T., *The Debate over International Armament Programs: Integrating Current Knowledge and the FS-X Case*, Masters Thesis, Air Force Institute of Technology, September 1989.

"Growth in DoD Electronics Market by 1995," *Defense & Aerospace Electronics*, July 15, 1991.

Hoft, D., "Solid-State Transmit/Receive Module for the PAVE PAWS Phased Array Radar," *Microwave Journal*, October 1978.

"Industry Again Looks for Wireless Boost," *Electronic News*, January 4, 1993.

Jaikumar, R., "Japanese Flexible Manufacturing Systems: Impact on the United States," *Japan and the World Economy*, No. 1, 1989.

"Japan—Gallium Arsenide I.C.—Industry Analysis," *Industry Subsector Analyses*, Foreign Commercial Service, U.S. Department of Commerce, October 1990.

"Japanese satellite TV," *The Economist*, January 23, 1993.

Jay, P., "Case Studies of Successful Production Applications of GaAs ICs," 1991 IEEE GaAs IC Symposium, Notes from 1991 IEEE GaAs IC Symposium.

JTECH (Japanese Technology Evaluation Report) on CIM/CAD. Science Applications International Corporation, 1989.

Juran, J. M. and F. M. Gryna, *Juran's Quality Control Handbook*, McGraw-Hill, 1988, pp. 26–29.

Keller, J., "New Avionics Group Targets Upgrades," *Military & Aerospace Electronics*, Vol. 3, No. 8, October 15, 1992.

Keller, J., "Advanced Avionics: Technology Meets Tight Budgets," *Military & Aerospace Electronics*, February 15, 1993, p. 13.

Keller, J., "Delco, Hughes Leveraging Military Radar," *Military & Aerospace Electronics*, April 19, 1993, p. 1.

Lockerd, R. and G. Crain, "Airborne Active Element Array Radars Come of Age," *Microwave Journal*, January 1990.

Manufacturing Technology for T/R Modules: Industry Review, Manufacturing Technology Directorate, Wright Research and Development Center, Contract No. F33615-C-5705, 23–24 October 1991.

Manufacturing 21 Report: The Future of Japanese Manufacturing, National Center for Manufacturing Sciences, 1991, p. 10.

Manufacturing Technology for Radar Transmit Receive Module: Phase 3 Industry/Government Review, U.S. Air Force MANTECH Directorate, February 1992.

McQuiddy, D., et al., "Transmit/Receive Module Technology for X-Band Active Array Radar," *Proceedings of the IEEE*, Vol. 79, No. 3, March 1991.

McQuiddy, D., "Solid-State Radar's Path to GaAs," *IEEE Microwave Theory & Techniques: Symposium Digest*, 1982.

MELCO briefings, FS-X Radar Technology Symposium, Department of Commerce, May 1992.

"Mitsubishi Electric Considering Exporting FS-X Radar Technology," *Nikkei Sangyo Shimbun*, October 8, 1992, translated into English by *JPRS: Japan Science & Technology*, October 29, 1992.

Moxson, R., "The Chip War," Case Study for the Graduate School of Business, University of Washington, 1987.

Nakajima, H., "Dreams and Expectations of III-V Semiconductors," *International Symposium GaAs and Related Compounds*, 1989.

"NATO C3 Must Use Commercial Equipment," *Defense & Aerospace Electronics*, July 15, 1991.

Opall, B., "USAF Braces to Deflect Possible F-22 Cuts," *Defense News*, March 29, 1993, p. 3.

Proctor, P., "Japan Plans New Generation of Remote Sensing Satellites," *Aviation Week & Space Technology*, July 13, 1992, p. 67.

Sakai, K., "The Feudal World of Japanese Manufacturing," *Harvard Business Review*, November–December 1990, pp. 38–49.

Scott, W., "ARPA Applies Dual-Use to Affordable Defense," *Aviation Week & Space Technology*, April 12, 1993, p. 44.

Skinner, R., "What GaAs Chips Should Cost," *Technical Digest, IEEE Gallium Arsenide Integrated Circuit Symposium*, 1991, pp. 273–276.

Skolnik, M., "An Introduction to Radar," *Radar Handbook*, Second Edition, McGraw-Hill, 1990.

Slomovic, A., *An Analysis of Military and Commercial Microelectronics: Has DoD's R&D Funding Had the Desired Effect?*, RAND Graduate School Dissertation, 1991.

Stimson, G., *Introduction to Airborne Radar*, Hughes Aircraft Company, 1983, p. 609.

Strategic Industrial Initiative: Phased Array Radar, Report to Wright-Pattersen AFB, General Research Corporation, June 1990.

Sweetman, W., "The US Airborne Radar Scene," *Interavia*, May 1989.

Sweetman, W., "Active Array for ATF," *Interavia*, August 1988.

Sze, S., *Semiconductor Devices: Physics and Technology*, 1985, p. 342.

Tapscott, M., "Defense Electronics' Top 100 Companies," *Defense Electronics 1993 Buyer's Guide*, Cardiff Publishing, 1993, p. 8.

Technology Transfer and Technology Flowback with Japan: U.S. Industry Approaches to the FS-X Co-Development Project, White Paper, U.S. Departments of Commerce, Defense, and Air Force, May 1991.

Third Annual MIMIC Conference Proceedings, DARPA, 1991.

"Transfer of Japanese Indigenous Technologies During the FS-X Development Program," *FS-X Technical Steering Committee Pamphlet 1*, USAF, June 8, 1992, pp. 13–14.

Tyre, M., "Managing Innovation on the Factory Floor," *Technology Review*, October 1991.

U.S.-Japan Codevelopment: Review of the FS-X Program, GAO Report, February 1990.

U.S.-Japan Codevelopment: Update of the FS-X Program, GAO Report, June 1992.

USAF Manufacturing Technology, U.S. Government Printing Office, 1991.

"U.S. Air Force Take Delivery of Japanese FS-X Transmit/Receive Modules," *Electronic Warfare Digest*, October 1993, p. 4.

Use of Commercial Components in Military Equipment, Defense Science Board, 1986.

Vogel, S., *The Power Behind "Spin-ons": The Military Implications of Japan's Commercial Technology*, Berkeley Roundtable on the International Economy, April 1991. Will appear in Sandholtz, Borrus, Stowsky, Vogel, and Zysman, *The Highest Stakes: Technology, Economy and Security Policy*, Oxford University Press, forthcoming.

MR-432-AF