6

New Fab Criteria and Cost Modeling

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In recent years, many IC manufacturers including Motorola and Toshiba have announced plans to cut the cost of building and equipping fabs by as much as one half. In addition, as the cost of constructing cleanrooms has risen to $3,000 per square foot, manufacturers are exploring a variety of innovative fab designs to reduce the footprint of cleanrooms, while maintaining the flexibility needed to meet a variety of upcoming requirements. The push to design fabs to last multiple generations of product is extremely strong today, as the cost of building and equipping new fabs continues on its logarithmic growth to several billion dollars per facility by the year 2000.

A variety of cost-reduction strategies are being used to control the spiraling cost of new fabs. New fabs are being designed with a focus on time-to-market, improved management of yield and factory control information, and early development phases for new equipment so that systems are production-worthy when installed. Lessons learned from existing manufacturing facilities regarding spare parts management, yield improvement, and organizational structure are being effectively implemented in the new fabs.

This section begins by explaining the differences between hypothetical fab costs and the actual cost of new fabs. It then presents new approaches to equipment acquisition and proliferation into fabs, as well as the advantages to leasing equipment. One of the most important determinants of new fab success is the ease with which companies bring new technologies into the fab. A section covering hot topics in the industry discusses the future of optical lithography, the obstacles to 300mm wafer processing, advanced yield management, chemical-mechanical polishing, and computer integrated manufacturing (CIM). Fab output, directly tied to return on investment, can be increased using effective CIM systems. Issues regarding equipment and cell control, simulation, and factory control are addressed. Finally, a few new strategies for fab construction are reviewed, clean-build protocol and using simulation to improve the fab layout.

Fabs Today

ICE estimates that between 1995 and the year 2000, approximately 127 new fabs will be constructed (or upgraded) to meet the demand for memory, microprocessor, and ASIC families of devices (Figure 6-1). These numbers of leading-edge (sub-0.5mm) fabs will support a projected $100 billion increase in worldwide semiconductor sales over this period. Last year's equipment sales, estimated by SEMI to be $14.7 billion, were up 42 percent over 1993, demonstrating the strength of the new fab equipment market. A sampling of new fabs and the years they are scheduled to start full-scale production are shown in Figure 6-2. These fabs are estimated by the semiconductor manufacturers to cost between $700 million and $1.3 billion each. It may be useful, at this point, to compare these cost figures to ones generated for ideal fabs to gain an understanding of the areas needing improvement.

New Fab Costs: Theory and Reality

A number of studies have been performed in recent years to try to understand the reasons why new fabs construction and tooling costs amount to roughly a billion dollars, and cleanrooms cost between $2,000 and $3,000 a square foot. As discussed in chapter 1, one of the most important findings from Texas Instruments' MMST program were the surprisingly low utilization of traditional semiconductor processing equipment (typically 35 percent), and the very negative impacts batch-to-single-wafer transitions and poor "shop floor control" have on fab productivity. TI's $30-50 million minifab (5,000 ft^2) was able to produce a 0.35mm, double level metal device (Figure 6-3) with a three-day cycle time! This was accomplished using all-single-wafer processing, vacuum-based minienvironment enclosures, and all-RTP furnace operations. Real-time sensing and process control were instrumental in this success. Figure 6-4 projects this minifactory concept into the year 2000, where smart, embedded real-time sensors are used in the equipment, all equipment is single wafer, and utilization of the equipment is 70 to 80 percent. The traditional downtime for testing chambers (monitor wafers) and downtime for scheduled and unscheduled maintenance are significantly reduced.

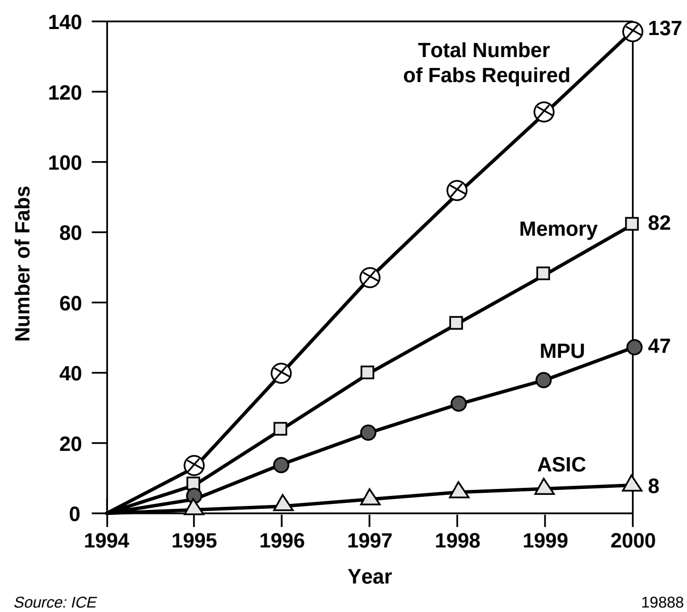

Figure 6-1. Number of New Fabs Needed Through the Year 2000

1995	1996	1997 or 1998
AMD, Austin TX	AMD, Dresden, Germany	Chartered SC, Singapore (Fab III)
Chartered SC, Singapore (Fab II)	Hualon Microelectronics, Taiwan	China Huaging, China
Cypress SC, Bloomington, MN (Fab IV)	IBM-Philips, Stuttgart, Germany	Fujitsu-AMD, Japan
Fujitsu-AMD, Aizawakamatsu, Japan	IDT, Hillsboro, OR	Intel, Hillsboro, OR
Holtek Microelectronics, Hsinchu, Taiwan	Motorola, Chandler, AZ (MOS 12)	Intel, Chandler, AZ (Fab 12)
Hyundai, Ichon, S. Korea (E3)	Motorola, Austin, TX (MOS 13)	Macronix International, Hsinchu, Taiwan
IBM-Cirrus Logic, E. Fishkill, NY	Nanya Tech, Taoyuan, Taiwan (Formosa Plastics is parent co.)	Micron, Lehi, UT
Intel, Albuquerque, NM (Fab II)	NEC, Livingston, Scotland	Mitsubishi, Kumamoto, Japan
Intel, Aloha, OR (DI)	Powerchip SC**, Hsinchu, Taiwan	Mosel-Vitelic, Hsinchu, Taiwan
Matsushita, Tonomi, Japan	Rockwell, Newport Beach, CA	Motorola, Tianjin, China
Mosel-Vitelic, Hsinchu, Taiwan	Samsung, Kiheung, Korea	NEC, Kumamoto, Kyushu Island, Japan
Motorola, Austin, TX UAPRLD (R&D) line	SGS Thomson, Phoenix, AZ	Texas Instruments, Dallas, TX, (R&D and prod. fab)
Motorola-Toshiba (Tohoku SC)	Siemens, Dresden, Germany	TSMC, Hsinchu, Taiwan (Fab IV)
Oki Electric, Miyagi, Japan	Submicron Technology Co. (SMT, formerly Alphatec), Bangkok, Thailand	Winbond Electronics, Taiwan
Shougang-NEC, Beijing, China	Texas Instruments, Avezzano, Italy	
SGS-Thomson, Phoenix, AZ	TI-Hitachi, Richardson, TX	
TI-Acer, Taipei, Taiwan	Toshiba, Mie Prefecture, Japan	
UMC, Hsinchu, Taiwan	TSMC, Hsunchu, Taiwan (Fab III)	

*Based on date of full-scale production starting some time in the the year shown.
** Venture between Mitsubishi, Kanematsu, Taiwan UMAX group.

Source: ICE

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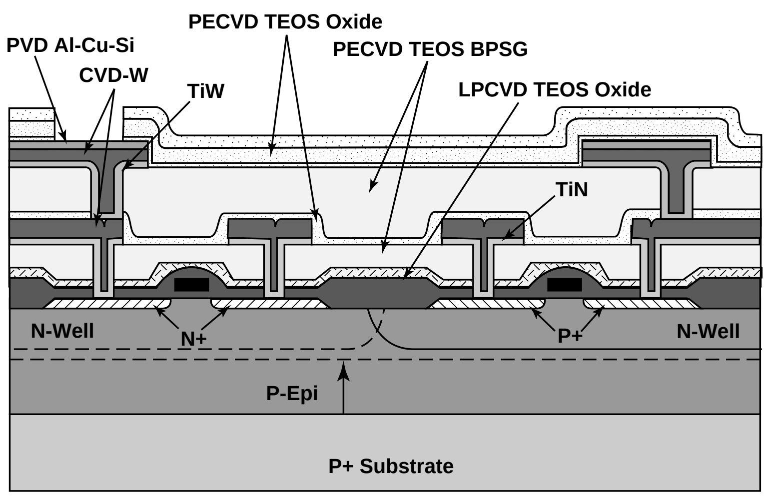
*Figure 6-2. Schedule of New Fabs**



Source: Solid State Technology

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Figure 6-3. 0.35µm CMOS Device Developed and Produced in the MMST Minifactory

Attribute	1990 Factory	Gigabit Factory circa 2000
Factory Automation	20%	>90%
Equipment Utilization	25% - 45%*	70% - 80%
Wafer (fab) Yield	70% - 90%*	>98%
Chip Yield	60% - 80%	85% - 95%
Cycle Time	30 - 90 days	3 - 20 days
Manufacturing Equipment	Mixed, diverse, lot-processing oriented	Cluster tools, single-wafer processing
Process Control	SPC, charting	Supervisory, real time
Pilot Wafers	200 + per month	Each wafer its own pilot
Sensors	Off-line measurements	Smart, embedded, real time

*Yields and utilization would be higher in single-product, high-volume fabs (i.e, - DRAMs, microprocessors)

Source: *Solid State Technology* 19891

Figure 6-4. Comparison of Present and Future Semiconductor Manufacturing Technologies

Shortly after the MMST program results were made public, Fluor Daniel, a cleanroom construction firm, organized a group of 23 companies to perform a "Fab of the Future" study[1], modeled after the MMST program, yet designed to use commercially-available equipment including cluster tools, chemical mechanical polishing systems, and minienvironments with "smart-tag" material tracking. The most critical findings from this study were the significant impact fast fab ramp-up, factory simulation, and rapid yield learning could have on return-on-investment (ROI). The study compared four "virtual factories" — three using Class 1 minienvironments in Class 10,000 fabs and a fourth using a conventional Class 1 ballroom design with tools in a bay-and-chase layout. The most cost-effective and profitable fab uses minienvironments, integrated processing tools, advanced yield management, and factory simulation to enable:

- A reduction of cycle time from 60 days to 7 days,
- A reduction in yield learning time from 2 years to 1 year, and
- A reduction of ROI time from 3 years to 18 months.

The use of cluster tools was projected to allow a significant reduction in processing steps, while also reducing the probability of wafer contamination and potentially reducing cycle time. Calculated product cost is $1,100 per 200 mm wafer, or $3.51 per square centimeter of silicon. Construction costs were estimated to be between $1,250 and $2,000 per square foot of fab area.

In reality, semiconductor companies around the world claim that wafer processing costs average around $5 or more per square centimeter of silicon and the estimated cost per square foot of fab space is as high as $3,000. The immediate question here must be — "where do the lines between theory and reality meet?"

One critical factor that the Fluor Daniel study did not consider was the time a new fab needs to spend to bring new equipment and processes into the fab. Typically, new equipment and processes may require up to a year to bring to production-worthy condition. There is much room for improving the quality of delivered equipment, especially of new products. In addition, many times the new fab is being constructed to process larger wafers than the company's previous fabs, thereby requiring changes in each and every process step in the fab.

Furthermore, there remains a large gap between the performance expectations of integrated processing (cluster tools) and the actual amount of clustering that is successfully performed in fabs to reduce the total number of process steps. Most often, as discussed in Chapter 2, cluster tools consist of like process chambers (i.e., PVD and PVD), which are run in parallel, to speed the throughput of the overall system. Finally, determining the most cost-effective layout and most cost-effective design of utilities (i.e., DI water, gases, and chemical distribution systems) is becoming much more difficult as leading-edge fabs must be painstakingly designed for ultimate cleanliness and ultimate performance.

Breakdown of Fab Costs

New fab manufacturing costs, including facility and equipment costs, are determined early-on by decisions made regarding:

- Fab design concept (ballroom, slab-on-grade, etc.),
- Fab capacity (wafer starts per week),
- Factory layout,
- Products to be fabricated (linewidths, device complexity, number of different products),
- Fab location,
- Equipment selection,
- Equipment acquisition method (buying or leasing),

and several other factors. In addition, fab facility design must not only be optimized to reduce costs, but to fully support the manufacturing operations throughout the facility's lifetime, at the lowest cost possible. In facility design, many trade-offs must be considered. For instance, a very flexible fab design would have piping, air circulation, and all utilities provided throughout the building, allowing equipment to be located anywhere, thereby optimizing equipment layout. However, very high expense prohibits this approach. Therefore, cost-reduction strategies must target approaches that minimally impact manufacturing operations.

Another example is the selection of materials for the fab. While ultrapure gases and chemicals may be needed for some processes, lower-grade materials may be acceptable for others. However, the high cost of purchasing different grades may be offset by the waste and complexity associated with using them, making the use of strictly ultrapure gases and chemicals possibly more cost-effective in the long run. Facility cost evaluations must consider such trade-offs.

Sematech's Cost-reduction Strategies

A recent SEMATECH study[2] used the results of four submicron facilities that were constructed by different contractors for different owners in different geographic regions to identify the most important cost factors in factory design and to determine cost-reduction strategies for new fabs. The study identified ten assemblies that contributed more than 90 percent of facility costs, including:

- Process equipment
- Structural/building
- Electrical system

- Mechanical wet side
- Mechanical dry side
- Interior architectural finishes
- Cleanroom
- Site development
- Instrumentation and control
- Life safety systems

Targeting these key categories, Sematech identified several cost-reduction strategies (Figure 6-5) including the use of minienvironments (for potential yield impact), reducing the amount of process exhaust, reducing the distance of roof spans, selective reduction of vibration criteria, leasing equipment (ultra-pure water distribution system as well as gas distribution system and process equipment), choosing site location for low cost, and reduced consumption of process materials. A combined cost savings of 5-15 percent is anticipated when these cost-reduction strategies are implemented.[2]

New Fab Site Selection Criteria

A major consideration in contemplating a new fab is where the fab should be located. If an existing location has become saturated and a new site is required, many factors must be carefully evaluated. The following tabulation illustrates some of the criteria.

- Tax Incentives
- Availability of land and location
- Available infra-structure
- Regulatory Restrictions including Zoning and Covenants
- Availability of qualified workers for all skill levels
- State and Local Incentives
- Transportation considerations
- Cost of Living and associated considerations
- Utilities
- Educational Facilities

Fundamentally, establishing of a modern semiconductor facilities requires a good business climate, a world-class workforce and a modern infrastructure.

The financial impact to build a semiconductor facility must be structured very carefully. For example, property tax incentives have been a very influential factor in the site selection process. This is shown in the following situations:

- Intel saved $114 million in taxes to locate its new fab in Rio Rancho, NM
- Siemens saved $80 million in taxes to locate its new fab in Newcastle, U.K.
- IBM and Toshiba saved $165 million in taxes to locate its new fab in Virginia
- Motorola saved $48 million to locate its new fab in Virginia
- Both LSI Logic and Fujitsu are negotiating tax breaks in Oregon for their new fabs

During the past seven years the Pacific Northwest and the Southwest have been the more successful areas to attract new semiconductor factories. Oregon in the Pacific Northwest and New Mexico, Arizona, and Texas in the Southwest have been the more preferred sites.

Top 23 Cost Categories	Reduce Roof Spans	Selective Reduction Vibration Criteria	Lease Equipment	Reduce Exhaust	Use Mini-environments	Choose Location	Limit Flexibility	Reduce Consumption
1 Concrete	✔	✔				✔	✔	
2 Ultrapure Water Equipment			✔					✔
3 Structural Steel	✔	✔				✔		
4 Recirculation Air Handling					✔		✔	
5 FMS/Control System				✔	✔	✔	✔	
6 Cleanroom Ceiling/Grid					✔		✔	
7 HVAC Piping				✔	✔	✔	✔	✔
8 Scrubbed Exhaust				✔	✔		✔	✔
9 Secondary Electrical Distribution				✓	✔	✔	✔	✔
10 Exterior Skin						✔		
11 UPW Piping			✔				✔	✔
12 Air Supply Distribution				✔	✔	✔	✔	
13 Metal Studs and Drywall								
14 Substation				✔	✔	✔		✔
15 Cleanroom Wall System					✔		✔	
16 Fab Electric				✔	✔	✔	✔	
17 Fire Protection								
18 Cleanroom Raised Floor							✔	
19 Earthwork						✔		
20 Make-Up Air Handler				✔	✔	✔	✔	✔
21 Ultrapure Water Building			✔	✔	✔		✔	✔
22 Process Chemicals							✔	✔
23 Chillers				✔	✔	✔	✔	✔

Source: Sematech/IEEE/SEMI 19892

Figure 6-5. Cost-Reduction Strategies for New Fabs

Leasing Equipment

Leasing is a fairly new approach to financing semiconductor equipment acquisitions that has been gaining popularity over the last several years. IC manufacturers lease equipment to reduce the amount of up-front capital needed for new fabs. Leasing may make equipment changes easier, thereby enabling the IC manufacturer to more easily adjust its operations to changes in fab capacity, product mix, and technology. Leasing plans can also simplify the disposal of equipment as it is being retired. It a fab needs equipment very quickly, and used equipment is being considered, some asset management companies maintain inventories of equipment and can provide systems with a shorter lead-time. Used equipment may also be available through a variety of sources including the OEM, equipment brokers, other semiconductor manufacturers, etc. (Note: used equipment purchasing is discussed in Chapter 2). As mentioned previously, leasing the ultrapure water system can also help limit up-front capital requirements.

Leasing is most attractive to companies that turn over equipment rapidly, and expect the pattern to continue. In many cases, the processing equipment reaches the end of its useful life in a fab before it is fully depreciated. The company might store the system in its inventory, or attempt to extend the life of the equipment by upgrading it, sometimes at significant cost. Selling the system is risky because a "blue-book" value for semiconductor equipment does not exist, and the systems may be sold below market value. Some of the larger IC houses with diverse product lines such as Samsung, Toshiba, and Motorola will make the equipment available throughout their organizations. However, many of the smaller and less diversified companies do not have that luxury. The financial impact can be very significant for companies retiring numerous systems over the course of several years.

In leasing, the benefits that can be gained by the IC manufacturer include:

- Economics — cash flow improvement, less capital required up-front, and the option to spread expenditures over 3-, 5- or 7-year periods,
- Fab flexibility — the ability to change capacity, product mix (i.e., DRAMs to ASICs), and technology (1.0 to 0.8mm), and
- Simplified equipment disposal — obsolete equipment can be removed by the leasing company on a designated date, relieving the burden of having to resell the equipment or store the equipment until it is fully depreciated.

Determining whether or not a fab is a good candidate for leasing is a straightforward process, which essentially depends on the answers to five important questions, including:

- What is the expected life of the tool being purchased?
- What level or corporate financial risk does the purchase of the equipment represent?
- Does the company wish to acquire the equipment locally, regardless of the fab location?
- How do the tax benefits of purchasing versus leasing compare?
- Does the retirement of old equipment interfere with the company's business?

The benefits to the equipment manufacturer include:

- Control of vendor's reputation — the asset management company will contact the OEM to facilitate service contracts, or to have the systems upgraded or refurbished, possibly improving the OEM's business and assuring proper service of the system,
- Improved logistics of new equipment sales — often the fab will have to dispose of equipment prior to acceptance of new systems. The leasing company removes the equipment on a designated date, expediting the purchase of the new equipment, and
- Facilitates equipment exchanges — leasing companies will often trade pre-owned equipment for new when the new equipment is leased.

Equipment companies typically prefer to deal only in new equipment sales, because profit margins are highest for new systems. For this reason, leasing fills an important need in the industry. The asset management (or other) company prolongs the use of existing equipment (by making it available to more users) and makes pre-owned systems sales the business of companies other than the OEM. This allows the equipment manufacturer to protect the company's name (by supplying maintenance and refurbishing services), without requiring that the OEM get into the used equipment business.

Companies offering leasing services in the semiconductor industry include asset management companies, such as Comdisco and Integrated Solutions Inc. (ISI), brokers such as Bid & Brokerage and EASE, and leasing companies, such as GE Capital. (note: ISI and GE Capital work together to provide overall asset management). Depending on the company, services can include:

- Design of the lease based on the fab's requirements
- Refurbishing the equipment if it is pre-owned
- Facilitating the interface with the OEM,
- Purchasing the equipment from the OEM that is then leased, or
- Purchasing the equipment from the fab after the semiconductor manufacturer has purchased it, and then leasing it to the manufacturer (buy-back lease)
- Removing the equipment at the end of the lease period
- Maintaining an inventory of pre-owned equipment
- Tracking the availability of new and pre-owned equipment

Fast-track Construction

Today, an aggressive project schedule, referred to as fast-track construction, allows equipment to be installed and brought-up while the fab facility is being constructed. The advantage to fast-track construction is that it can reduce the time needed to construct and tool a fab from the conventional period of 20-23 months to as short as 12-16 months. In addition, since time to market and ROI have become so critical to fab profitability, savings of even one to two months can be extremely significant.

Figure 6-6 shows a typical fast-track construction schedule where tool design overlaps with the final stages of fab construction. A very aggressive schedule for an IC fab facility can involve the simultaneous design of the process tools and fab construction, so that design of the process tools does not impact the schedule at all. This is the type of schedule today's new fabs are following to reduce new fab construction time to about 12 months. Some industry experts believe that the use of minienvironments, tool and cassette enclosures with standard mechanical interfaces (SMIF) that minimize contamination to the wafer, can further shorten this period (Figure 6-7). Minienvironments may allow a manufacturer to bring up one of each type of tool first, so that engineering and qualification lots can be run while construction is being completed and new equipment is still being brought into the fab. At NCR's Colorado Springs facility (now Symbios Logic, owned and operated by Hyundai), the company estimated that it reduced overall fab construction time by two to three months by using minienvironments.

New Strategies in Equipment Acquisition

Digital Equipment Corp. recently used cross-functional teams to select the equipment needed for its new 200mm fab in Hudson, Mass.[3] Most importantly, the team-based approach enabled cost-effective equipment selections in a timely manner with full commitment from both process development and manufacturing process engineers. In addition, by developing a more informed purchasing staff, the company improved its bargaining power with suppliers and improved the communication of users' needs to the suppliers. Furthermore, by transferring the budgetary and time constraints to the teams, management was able to dramatically improve the selection process. The company's six- step approach included:

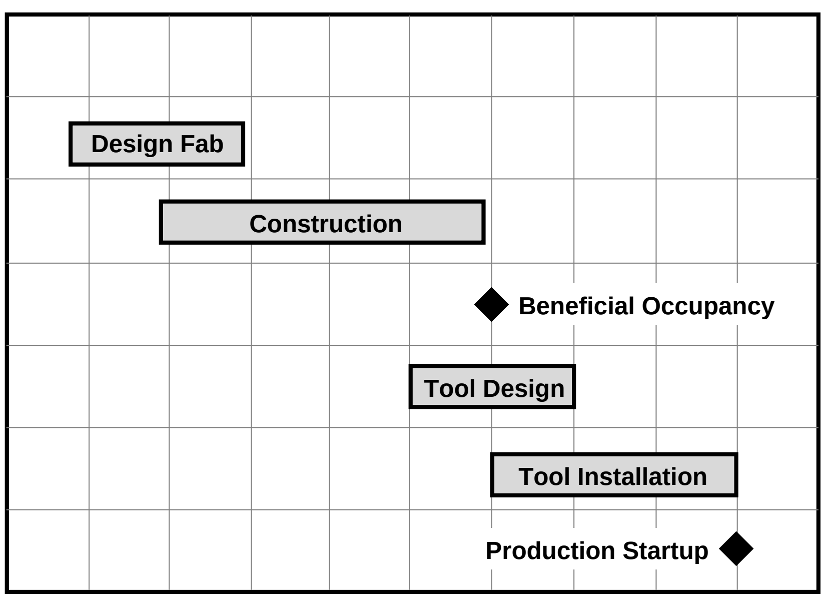
- The formation of cross-functional teams (8-10 members each) for each major equipment set — steppers, coat/develop tracks, dielectric deposition, ion implant, chemical-mechanical polishing, etc.,
- Development of objectives and constraints — financial, technical, and schedule-based,
- Development of selection criteria and a decision-making process,
- Monitoring team progress (through monthly meeting where cost budgets were discussed), and
- Making final selections and ordering equipment.

Each team included members from process development, manufacturing, CIM, safety, contamination control, industrial engineering, and purchasing, to ensure that all needs were being addressed. Management determined significant technical constraints such as minimum wafer throughput rates, minimum safety requirements, process flow and feature size, maximum edge exclusion, and minimum system uptime requirements. Each tool assessment was weighed using the following criteria.

Process capability	(33%)
Manufacturability	(33%)
Schedule manageability	(20%)
Supplier support	(14%)

Technical criteria (such as etch rate uniformity, particle levels, etc.) were assigned in each of the equipment categories. The selection process flow involved the following steps.

- Develop and weigh criteria
- Review all potential suppliers
- Eliminate those that do not meet the "must" criteria



Source: Microcontamination Conference Proceedings 19920A

Figure 6-6. Typical Fast-Track Construction Schedule

• Further evaluate remaining suppliers (via proposals, RFQs)
• Generate "short" lists
• Conduct in-depth evaluations
• Calculate technical scores
• Complete cost analysis (capital cost, cost of ownership)
• Complete risk analysis
• Make selection
• If selection exceeds budget, petition management for over-run approval
• Inform selected and other suppliers

Importantly, the selection process preceded the customer evaluations of commercially-available products, thereby eliminating partiality towards certain vendors. A key aspect of the team-based approach to equipment selection was the role of integrators on each team. These individuals managed interactions between teams, identified possible cost savings opportunities (e.g., spare parts, basic order agreements), and resolved team-to-team issues. The cross-functional teams further smoothed the transition to manufacturing due the improved role each member played in the selection process.

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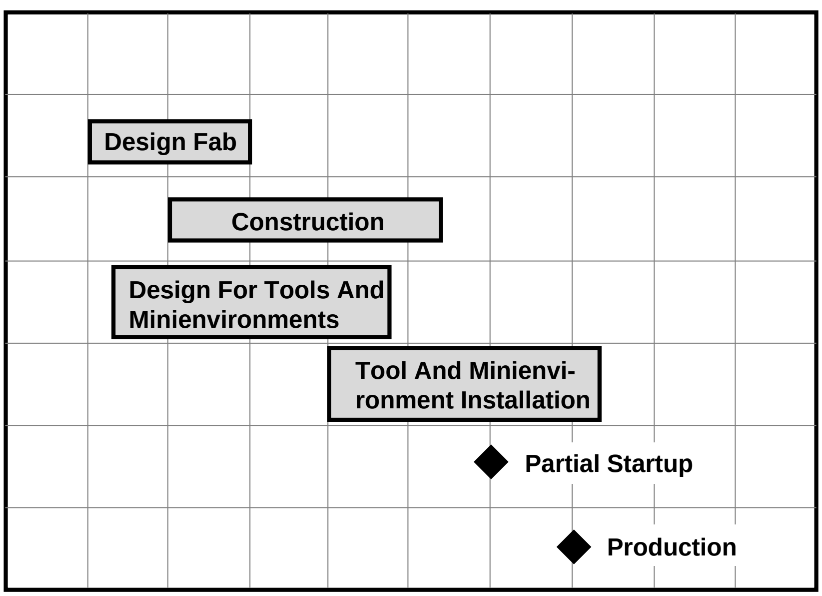

Source: Microcontamination Conference Proceedings 19921A

Figure 6-7. Fast-Track Construction Schedule With Minienvironments