INTEGRATED CIRCUIT FABRICATION FACILITIES

An Evaluation of Their Use, Size and Installation Requirements

prepared by

INTEGRATED CIRCUIT ENGINEERING CORPORATION

November, 1967

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I INTEGRATED CIRCUIT FACILITIES?

The question of "whether" and "how much" to invest in integrated circuit fabrication facilities is confronting all electronic system and equipment manufacturing companies. The extent of the decisions range from a small piece of test equipment for incoming inspection or other QC efforts at several hundred dollars to complete fabrication facilities involving cost in excess of $4 to $5 million dollars. The critical nature of this decision usually transcends the cost involved. Generally, every major company which wishes to become or remain in a position of importance in the electronic industry has decided to make a facilities investment and is now in the process of planning or implementing that decision. Whereas the question several years ago was "whether-or-not?", it now is "to what extent?" In most cases, the facilities they are developing may be divided into three broad classifications, the simplest of which is a laboratory facility solely for R&D and prototype development work. Others are installing facilities capable of producing custom or proprietary circuits to satisfy their specific requirements while the third group is preparing for virtually complete self-supply. The last group is limited to a number of the giants of the industry, many of which also are already involved or planning to become commercial suppliers of integrated circuits.

This article reviews the many faceted problems involving the purposes, types and installations of integrated circuit facilities. Divided into three parts, the first part reviews the background, purposes and goals for having in-house integrated circuit fabrication facilities together with potentially offsetting drawbacks. The second section considers the cost of facilities including the many additional economic considerations in addition to the original equipment purchase price. The final part of this article reviews some of the practical problems involved with the actual installation.

The technological revolution in the electronics industry wrought by integrated circuitry continues unabated. The impact of this technology is spreading throughout all facets of the industry. It has already usurped the role of discrete components in many areas and is disrupting conventional industry design and marketing patterns. Advances in the technology creating engineering design and systems adjustments, are also continuing unabated as production levels increase rapidly and prices tumble. In most field applications, the promise of high reliability is being realized. Conversely, quality control and testing problems are mounting in intensity.

Electronic companies presently involved with the fabrication of components, modules, instruments, equipment and systems are all feeling the impact of integrated circuits, either by directly participating in the development of their use or indirectly through competition. Because of major shifts in labor costs as well as material costs, many companies have decided to participate by assembly or complete fabrication of integrated circuits. Only through the process of making integrated circuits, either on a laboratory, pilot line or production basis, can a firm retain the design "know-how" and engineering control required to assure a stable equity in contributed value.

Facilities to design and fabricate integrated circuits are being recognized as a minimum requisite to the R&D functions of the entire equipment producing industry. The past year has seen a substantial number of electronic equipment manufacturers establish their own facilities. The coming years will see additional activity in this area.

The facility established by ICE in Phoenix will be reviewed as a typical example of the considerations which must be weighed in such an undertaking. Many of the practical problems of facility implementation do not actually become apparent until a company is well advanced in their establishment. However, ignoring these considerations can either cause long delays in making the facility functional or even the inability to enter into production

Advantages of In-House Production

There are many advantages that accrue as a result of having an in-house production capability. A qualitative examination of them proves most revealing since specific corporate goals must be identified because the optimum facility implementation program is dependent upon these specific requirements of each equipment manufacturer.

Many of these advantages have potentially offsetting disadvantages Figure I-1 figuratively shows some of them weighed against one another. The importance of each consideration will vary depending upon the charter of the organization making the evaluation. Each organization must assign its own weighting factor to each item

Optimization of Design

More economic designs can be created with a thorough knowledge of the circuit system relationship available within the company. Impractical and impossible requirements can be recognized early so that alternate approaches may be explored Over-specification, with its attendant high cost, can be avoided

The range of parameters and characteristics that can be readily achieved with integrated circuit fabrication are different from those with which the discrete component designer has become familiar. He must also work with different types of parasitics and tolerance ranges. Some of the better designs now available take advantage of inherent parasitics and use them for the improved performance of the circuit, for example, lateral and substrate PNP transistors. Similarly, broader tolerance ranges can be accommodated by modified design techniques.

INTEGRATED CIRCUIT IN-HOUSE FABRICATION

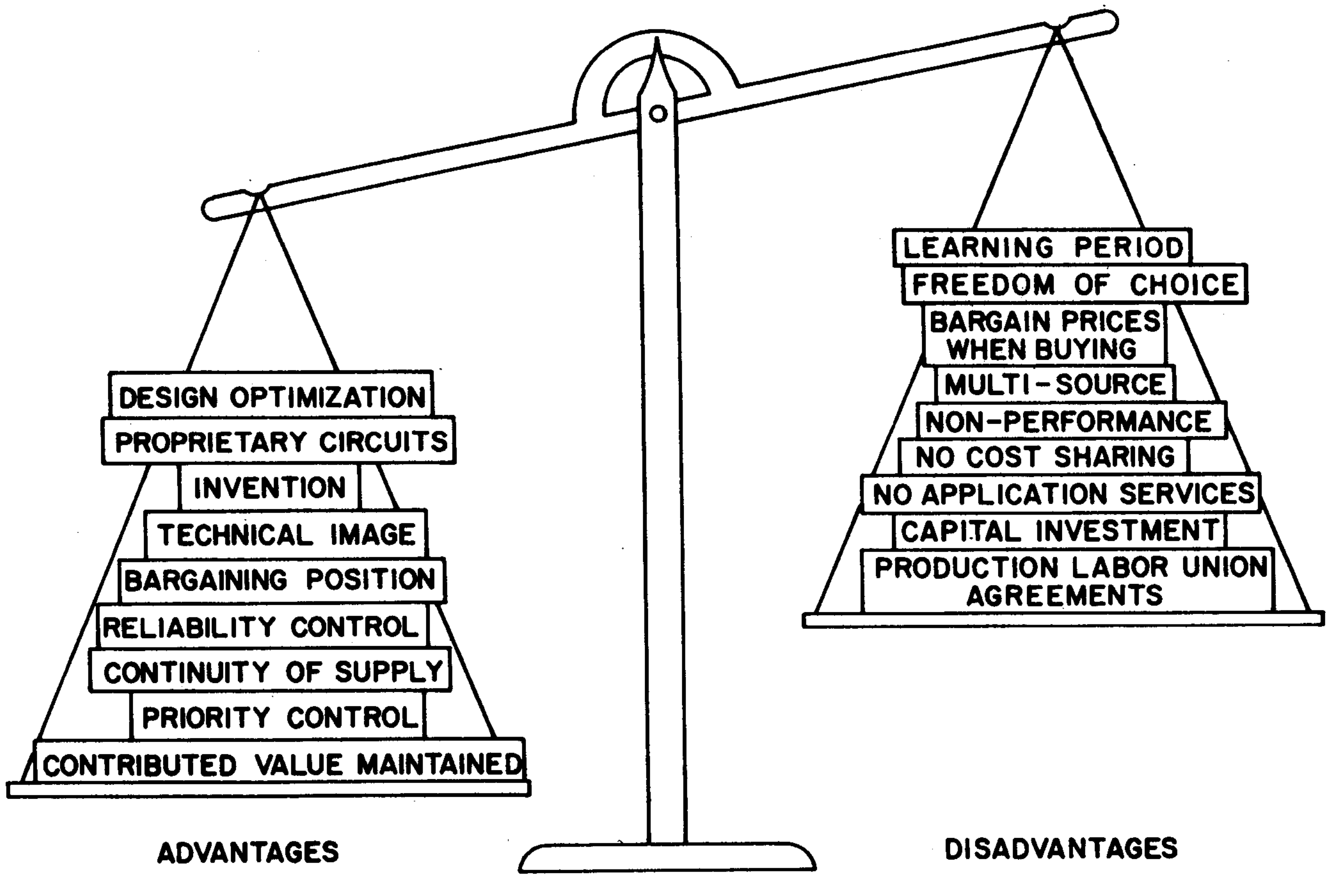

Figure I-1

Component economics are also vastly different. For instance, in integrated circuit form, additional transistors are considerably cheaper than resistors and capacitors. Similarly, resistors are cheaper than capacitors. It is frequently desirable, therefore, to replace a capacitor with a series of transistors or a large value of resistance or capacitor with a combination of a smaller value of that component operating in conjunction with a transistor. Many other advantages accrue readily to the integrated circuit form which are limited in discrete component designs, e.g., matched components which track closely over wide operating temperature ranges. These types of design considerations can best be appreciated by those who have experienced the translation of a theoretical design into production. This type of association and experience is seldom available to the designer who is limited solely to negotiation with outside suppliers.

Secrecy

The possibility of disclosure of production plans to competition is reduced with in-house integrated circuit production. This is especially important in view of information exchange frequently practiced within multidivision corporations or with vendors who also act as suppliers to competitive accounts.

Development of Proprietary Circuits and Inventions

Specialized proprietary engineering skill can be developed over the years by practical experience. This can result in providing improved performance at no increase in circuit cost for specialized equipments or systems. The opportunity for invention is also greatly enhanced by the in-house effort. New product developments also can be generated as a result of internal facilities. Desirable patent positions that would be impossible to obtain otherwise can be established and maintained.

Establishing a Desirable Technical Image

The technical image of competence is greatly enhanced with an in-house capability to manufacture integrated circuits. Some government procurement activities require that the successful bidder have an in-house integrated circuit facility. The importance of "timing" should not be overlooked. Often being first in the market causes development of the desired technical image. The second or third announcements of product innovation such as the use of the integrated circuit reinforces the first announcer's claims to technical leadership and may generate a "me-too" image for the others.

The capability of attracting top technical and managerial personnel is increased with an in-house facility. Recruiting top technical talent is a highly competitive business in today's supply-limited engineer shortage. The educational and experience opportunities are broadened while image and stature are improved. These things appeal to the ambitious new graduate as well as seasoned veterans. Engineers more than most other professional groups fear stagnation and obsolescence.

Bargaining Position

A complete knowledge of integrated circuit fabrication costs permits a user to develop the best possible bargaining position in purchasing integrated circuits from outside alternate sources. It is usually desirable for the internal facility to carry the development through pilot production from a costing standpoint, if for no other reason. This is a most important consideration since almost all integrated circuit fabricators contemplate extensive outside supplementary purchases. Those with smaller facilities generally intend only the most limited self supply. First hand knowledge, however, permits obtaining the most favorable supply position.

Reliability Control

Control of system reliability (system MTBF's) will be better if based on internal supply since manufacturing process changes will be dominated by thinking oriented toward the lowest system costs without immediate economic benefits resulting from lower costs alone. Changes in basic reliability of integrated circuits frequently take some time to appear in the data supplied by integrated circuit production facilities. Any change in process can be more carefully evaluated on this basis, whereas with outside suppliers, details of the change may or may not be given to the user.

Continuity of Supply

Continuity of supply on a long term basis for a specific integrated circuit can be assured. This may be especially important for the manufacturer of large systems tooling for a system life approaching twenty years. An equipment manufacturer may sometimes be frustrated by having much of his preliminary design work done with early commercial samples which the supplier may change or decide not to produce in large quantity. Internal supply partially solves this problem because of the inherent liaison required. Bankruptcy, merger and abandonment of the field also increase the problem of maintaining continuity of supply.

Production Priority Control

The ability to control production priorities in a rapidly growing market is of considerable importance to an equipment manufacturer. Delivery dates for equipment may be missed with serious consequences if an integrated circuit supplier fails to deliver or alters his production schedule. Large orders from preferred customers may take precedence. A crash program in another area might cause the supplier's delivery schedule to slip.

With internal supply, positive control over these schedule delays and priorities can be exercised.

Contributed Value

As indicated in the Introduction to this section, maintaining "contributed value" has proven to be one of the strongest incentives toward in-house facilities. Figure I-2 shows in bar chart form the significance of self supply on total equipment cost.

Whereas this figure shows that each added increment is of equal size and importance, specific situations can increase the importance of any of the individual considerations. Normally, however, materials for most state-of-the art production integrated circuits are of the smallest consequence. Contrasted with this, with today's technology, the assembly areas represent a significantly large proportion of the labor necessary to produce integrated circuits. This is shown most dramatically in the shift of contributed value between integrated circuits and discrete component circuits as shown in Figure I-3.

A cold analytical approach to the problem of contributed value may be made when one is approaching the problem from a purely abstract point of view. Normally, however, there are real peripheral considerations that can be of overwhelming importance. For instance, the maintenance of contributed value may mean the continued employment of a substantial portion of the work force which might be eliminated by the purchase of all of the components outside. This would result in the layoff of the staff, shut down of factory facilities and write-off or abandonment of their attendant investment. This might also have a substantial impact on the community in which the company is located.

Disadvantages of In-House Production

There are, of course, disadvantages arising from having an in-house production facility. The most basic may be the higher unit cost of obtaining the necessary circuit functions. The cost factors will be discussed in detail. The following lists the more qualitative disadvantages.

Start-up Time or Learning Curve

The decision to establish in-house facilities does not provide instantaneous availability of the desired integrated circuits. Rather, the decision to establish the facilities is followed by the expenditure of time and money in the planning, organizing, ordering and installation of the facilities themselves. Obtaining, organizing and training adequate personnel to staff the facility also represent substantial investments in time and money prior to production.

"MAKE OR BUY" CONTRIBUTION TO FINAL EQUIPMENT

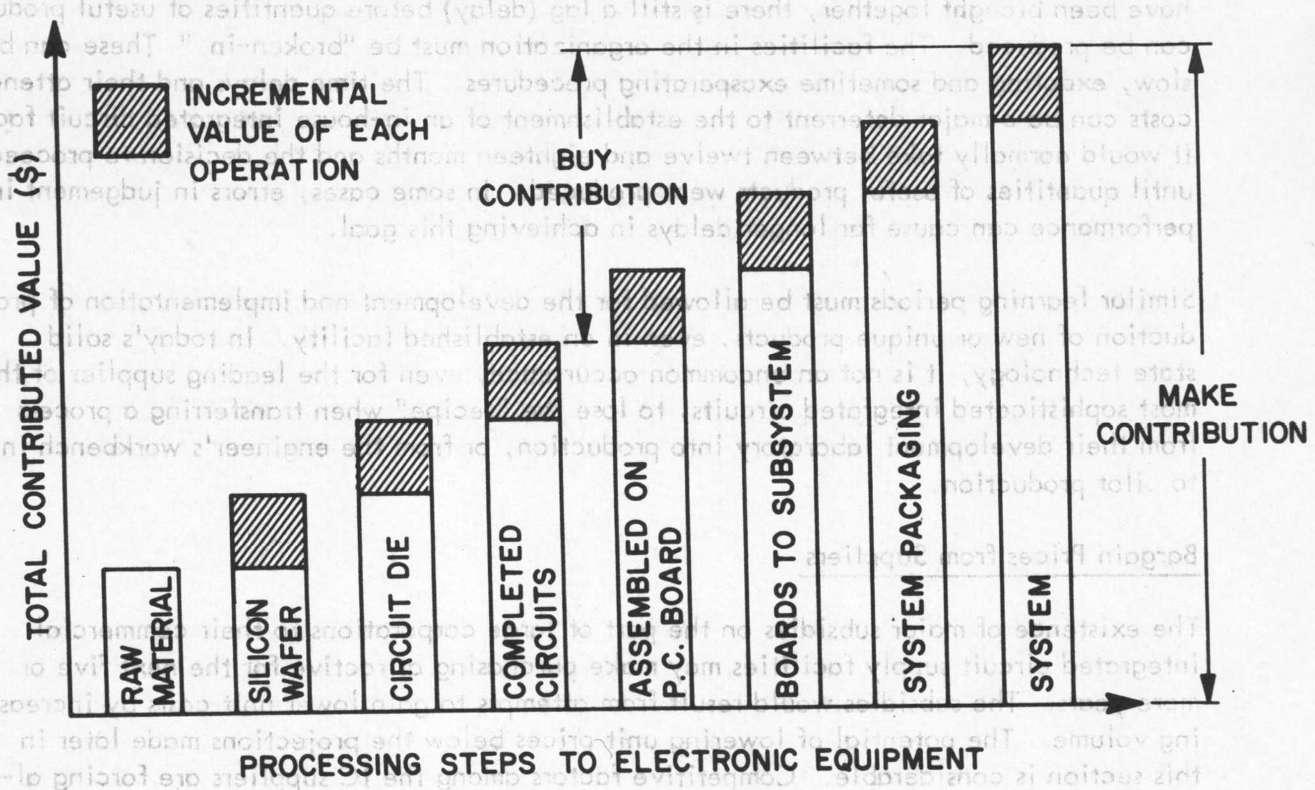

Figure 1-2

SHIFT IN CONTRIBUTED VALUE INTEGRATED CIRCUIT vs DISCRETE

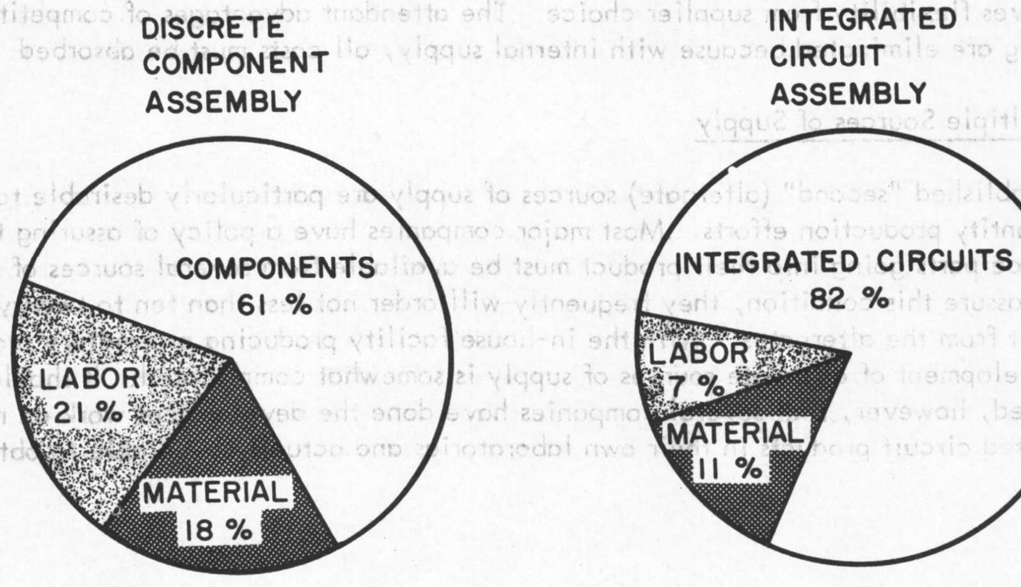

Figure 1-3

Invariably, even when all the elements necessary for the production of integrated circuits have been brought together, there is still a lag (delay) before quantities of useful products can be produced. The facilities in the organization must be "broken-in." These can be slow, exacting and sometime exasperating procedures. The time delays and their attendant costs can be a major deterrent to the establishment of an in-house integrated circuit facility. It would normally take between twelve and eighteen months and the decision to proceed until quantities of useful products were produced. In some cases, errors in judgement in performance can cause far longer delays in achieving this goal.

Similar learning periods must be allowed for the development and implementation of production of new or unique products, even in an established facility. In today's solid state technology, it is not an uncommon occurrence, even for the leading supplier of the most sophisticated integrated circuits, to lose the "recipe" when transferring a process from their development laboratory into production, or from the engineer's workbench into pilot production.

Bargain Prices from Suppliers

The existence of major subsidies on the part of large corporations to their commercial integrated circuit supply facilities may make purchasing attractive for the next five or more years. The subsidies would result from attempts to gain lower unit costs by increasing volume. The potential of lowering unit prices below the projections made later in this section is considerable. Competitive factors among the IC suppliers are forcing almost all suppliers to operate at a loss or greatly reduced profit margins.

Changing Sources of Supply

A change to another vendor may be made if one vendor proves ineffective. However, an ineffective in-house facility may be kept running for years because of the necessity to consider capital cost, personnel, community and other factors. Internal supply removes flexibility from supplier choice. The attendant advantages of competitive bidding are eliminated because with internal supply, all costs must be absorbed.

Multiple Sources of Supply

Established "second" (alternate) sources of supply are particularly desirable to support quantity production efforts. Most major companies have a policy of assuring that any piece parts going into their product must be available from several sources of supply. To assure this condition, they frequently will order not less than ten to twenty-five percent from the alternates. With the in-house facility producing proprietary products, development of alternate sources of supply is somewhat complicated. It should be noted, however, that several companies have done the development work on new integrated circuit products in their own laboratories and actually been able to obtain production from several sources of supply, maintaining only in-house prototype capability (Computer Control Division of Honeywell, Inc., Framingham, Massachusetts).

Non-Performance

There is considerable risk that the in-house facility will not perform on schedule over a short-term period because of the complexity of the problem with attendant possibilities of major "goofs." Improperly managed, the in-house production facility can represent a sink for many millions of dollars as several major operations have already proved.

Commercial suppliers, although they have the same potential difficulties, generally have sufficient inventory as well as production capability so that no one customer will hurt too badly. Except in the case in which a commercial supplier is exclusively supplying a related equipment division, any one customer rarely takes more than 10 percent of a supplier's output. Further, if one commercial supplier fails to supply, there are others perhaps who are both capable and willing to supply.

Sharing Costs

There are several major expenses in addition to product development that cannot be spread among several customers or over several related product lines. In the case of internal supply, reliability certification costs cannot be shared with other users. The costs for testing and evaluation range from over $50,000 per year for a 0.01% per thousand hour failure rate to over $500,000 per year to certify a failure rate less than 0.001% per thousand hours (90% confidence level). Needless to say, reliability must be certified for each product facility. Similarly, the costs attendant to either an unsatisfactory or abandoned developmental effort must be fully borne by the internal supplier.

Commercial Suppliers Services

The engineering skills of the integrated circuit supplier become less available with in-house facility. Their importance can be realized when one considers that research and development costs are currently $3 million per year for leadership positions and approximately $6 million per year for marketing and application assistance. These costs are, of course, included in the selling price of the supplier with the skills and service indirectly available to customers.

Labor Problems

The establishment of integrated circuit production capability as an integral part of an electronic equipment manufacturers organization sometimes has attendant labor problems. Physiologically, females are much more adept at doing the fine work and working with microscopes that are required with microelectronic production. These rates, attendant with this kind of work, can be different from those associated with normal equipment assembly. In addition, among engineers and management skilled in semiconductor technology, the wage scales are generally higher than the norms in the electronic industry. This has occurred because of the rapid development of the newer technology and the shortage of trained personnel capable of working with the newer techniques. These pay scale premiums can cause major upsets in the organization and destroy morale when newer employees are brought in to work for a company at substantially higher pay rates than the existing loyal staff members. In some areas of the company, jurisdictional disputes with organized labor unions have been attendant to the establishment of integrated circuit production facilities.

Summary

The importance of making the proper "make or buy" decision is crucial. It is not, however, black or white in terms of absolutes. Rather, it now appears that to maintain a leadership position, some degree of "make" must be implemented. However, this may be limited to only an advanced development laboratory. Some of the alternatives that are available will be reviewed in the remainder of this text.

In evaluating the considerations, pro and con, for the development or installation of an integrated circuit production facility, economics plays an extremely important part. Only a few of the factors included in Figure I-1 are capable of direct economic evaluation. When a direct dollar factor is applied to them, the advantage invariably results in favor of "buying" rather than "making" the circuits in-house. Engineering and management responsibility, however, carries the responsibility of establishing their importance. Many of these considerations are emotionally involved, therefore extremely difficult to put a dollar value upon. Who is to say what is the value of a new invention?

A number of companies have made attempts at building sophisticated products and have lost substantial quantities of money. Many others barely obtained profitable return of their investment. A few have achieved the "pot of gold" from their efforts. The opportunity is still there and is enhanced by having the in-house facility. The situation may best be summarized by the specific statement of a predominant equipment manufacturer which has made the decision to produce its own integrated circuits in-house. Hewlett-Packard summarized their decision to build integrated circuits designed in-house in the following three reasons.

1. Designers could anticipate components that are beyond the state of the art at the present time.
2. They were limited to whatever devices the semiconductor industry deigned to produce.

3. The company could merchandise the proprietary features of their circuits which were developed on an exclusive basis.

Hewlett-Packard contends that its investment in integrated circuit facilities at each of its major operating divisions represents several millions of dollars, not only in facilities, but also in training and the development of the capability to operate such facilities. They have, they said, customized the facilities to satisfy the needs of each of their operating divisions which vary from one another, thus providing them with greater flexibility.

II FACILITIES FOR INTEGRATED CIRCUIT FABRICATION

General Considerations

During the past several years of development of integrated circuit technology, increasing numbers of the major electronic equipment manufacturers sensed a compelling need to build integrated circuit fabrication facilities despite their natural trepidation because of the many technical problems. These manufacturers are aware of the large amounts of time and money invested by many of the semiconductor companies to develop and construct integrated circuit facilities and are generally hesitant or unable to make the same investment. They find themselves on the horns of a dilemma - faced with the full impact of integrated circuits on the one side and the investment demand and their own technological shortcomings on the other.

In this section, the problems and economic factors that should be considered in establishing a fabrication facility will be reviewed. Techniques of avoiding the large lump sum investment in a complete integrated circuit production facility are being employed by many equipment manufacturers. They are entering the field initially by setting up laboratory or pilot production facilities. These facilities are normally being laid out to provide for expeditious expansion to full production capability as the company's needs grow. Facilities of this type are emphasized in this discussion.

It should be evident that it is impossible to prepare a universal set of rules which will fully govern every requirement. Corporate technological, economic and traditional patterns and positions must be fully evaluated and factored into the implementation of the proper facilities.

One of the first considerations involved in establishing an integrated circuit production facility is the determination of the equipment and personnel requirements based on the needs and their schedules. These requirements are based on the number usable tested circuits, the type of construction and specific circuit performance functions. Thus, in order to establish a practical facility economically, the potential manufacturer must be familiar with his circuit yields, be knowledgeable of the various available equipments for the types of processes to be used and be aware of the suitability of these equipments for the types of circuit assemblies he requires.

Other factors such as factory area, facilities and room layout must also be considered. In general, because of the newness of the field, few of the potential users are acquainted with all of the requirements of such assembly facilities. Little authenticated information has been published on this subject.

Several years ago, it became apparent that almost every major electronic manufacturer would require integrated circuit processing information and capabilities. These requirements included personnel, equipment and "know-how." The growing requirement for trained personnel apportioned between these electronic system and equipment companies and the expanding number of major semiconductor manufacturers is creating an increasing critical shortage - particularly of engineers.

The ICE laboratory in Phoenix has been arranged to facilitate processing experiments and permit prototype production. The basic design concept utilized for this laboratory is of great interest since it is representative of the type of facility required by every electronics company that intends to maintain its technical position in the industry. Its establishment exemplifies the resolution of the aforementioned considerations and provides an example for this review.

Types of Requirements

The initial decision to be made must establish the emphasis among the many different facility requirements which must or could be included. Basic divisions may be made by process techniques. The major process divisions are:

1. Silicon Bipolar Monolithic
2. MOS - Metal Oxide Semiconductor
3. Multichip Assembly
4. Thin-film
5. Thick-film

Other major specifications for facilities include the volume and number of different type of circuits to be produced. The employment of different types of closures also causes a considerable range of variations in equipment requirements. Considering only silicon monolithic structures, the facility has been equipped for both MOS and bipolar construction. Table II-1 is a list of typical laboratory equipment used to produce silicon monolithic circuits. These particular types and arrays of equipment are listed with their approximate prices with the intent of being used for preliminary budgeting considerations only. They represent a composite (average) of many similar-size facilities designed for a wide range of specific requirements. Further study would be required to determine the optimum combinations for satisfying a company's particular requirements in view of schedules and economic circumstances.

To properly illustrate the range of facilities that are possible, three basic types can be considered. These are:

1. A laboratory facility, producing 500 circuits per week, emphasizing flexibility over production economy. The ICE laboratory would be within this classification.

2. A typical in-house facility producing 5000 circuits per week.

3. A large manufacturing facility producing 50,000 circuits per week.

EQUIPMENT LIST
(MAJOR CAPITAL EQUIPMENT)

I.	**DESIGN AND EVALUATION**	
1.	Digital counter	$2,000.00
2.	Q-meter	1,000.00
3.	Power supplies (3)	400.00
4.	Signal generator	100.00
5.	Audio oscillator	300.00
6.	Vacuum tube voltmeter	400.00
7.	Oscilloscope	700.00
8.	High current power supply	200.00
9.	Frequency meter	200.00
10.	Deviation meter	500.00
11.	Communications receiver	200 00
12.	DC power supply, high voltage	200.00
13.	High frequency oscillator	350.00
14.	Oscillator power supply	100.00
15.	Pulse generator	1,300.00
16	DC differential voltmeter	900.00
17.	Oscilloscope camera	500.00
18	Oscilloscope with sampling plug-in and amplifier plug-in	2,700.00
19.	High frequency oscilloscope with amplifier plug-in	2,400.00
20.	Transistor curve tracer	1,400 00
21.	DC vacuum tube voltmeter	400.00
22.	RF voltmeter	800.00
23.	Impedance bridge	1,300.00
24.	Test ovens	650.00
II.	**MATERIALS**	
1.	Epitaxial reactor	12,000.00
2.	RF generator	6,000 00
3	Metallurgical microscope	2,700 00
III.	**PHOTOMASKING AREA**	
1.	Clean room	5,000 00
2.	Photo lab chemical sink	500 00
3.	Multiaperture camera	12,000.00

Table II-1