

# ION BEAM TECHNOLOGY APPLICATIONS STUDY

## FINAL REPORT

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## 1. INTRODUCTION

This final report describes the findings of a study on the applications of Ion Beam Technology (IBT) to the processing of materials. This study was carried out by members of the Professional Staff of the Applied Technology Division of TRW Defense and Space Systems Group under contract sponsorship and the technical direction of the Lewis Research Center of NASA.

The report first describes the study methods and goals. The report then examines a series of factors which will influence the use of IBT in various applicational areas. Following this, the report advances a series of areas of assessment in the potential applicability of an IBT process and presents a list of IBT applications, rated against these assessment factors. The report concludes with a series of recommended areas of application for further technical pursuit.

During the study effort, an attempt was made to estimate the impact of IBT in various industries. For example, the semiconductor industry is estimated to have a marketplace measuring billions of dollars annually, while the semiconductor equipment industry is approximately \$200 million a year in size. The trend in semiconductors is definitely towards smaller scale devices, where IBT enjoys a number of processing advantages over alternate techniques. Even if IBT only affected 25% of the marketplace, its impact would be measured in hundreds of millions of dollars annually. Another example is in potential biomedical applications. There are approximately 10,000,000 cases of knee defects in the United States, ranging from partial to total incapacitation. At present, about 30,000 per year are being replaced. Clearly, there is a considerable gap between the present need and the surgical response to that need. Also, in the textile industry, polyesters account for \$15 billion annually. Surface treatment of even a small percentage of these fibers still represents a large total impact for new technology applications.

## 2. STUDY METHODS AND GOALS

The IBT Applications Study was carried out over an 8-month period and at a level of effort determined by the resources available to this program. The study was initiated by a technical conference at NASA, LeRC between TRW and personnel at LeRC currently active in IBT applications study and experiments. This technical conference provided the Study Group with a review of current LeRC sponsored research, both in-house and under various NASA grants, and allowed the Study Group to review the (then) known applicational areas of interest.

Following the technical conference, the Study Group initiated an assessment of the current status of IBT and applications. This assessment was carried out by both a literature search and individual consultation with workers in the field. Both the literature search and the individual consultation were selective in view of the very large body of literature and active research involving the interactions of ions with either the bulk or the surface properties of materials.

As a result of this assessment of IBT current status, the Study Group formulated a list of approximately 60 potential individual contacts. These individual contacts were selected as potential areas for the growth of IBT applications. In some instances, the individuals and institutions involved were along the leading edge of IBT development. In other instances, neither the institutions nor the individuals involved were aware of potential IBT use. In these latter cases, however, there were sufficient reasons to believe that potential IBT applicational growth could occur as a result of the planned individual contact. The individual contacts planned with presently active workers was for two reasons: (1) to broaden the perceptions of the present study effort as to current IBT status, and (2) to stimulate the conception and development of additional IBT applicational uses.

The initial list of potential individual contacts was reviewed by the Study Group's technical monitorship at NASA-LeRC and by an Advisory Group Board at TRW. The Advisory Group Board at TRW was composed of individuals with extensive previous experience in technology transfer. Following

these several reviews, the initial list was prioritized and the series of individual contact interviews was initiated.

The contact interviews between members of the Study Group and various institutions and individuals took place over a 5-month period and included 32 contact interviews, distributed broadly over the United States. These interviews were reported on a standardized interview form, submitted to NASA-LeRC at the close of the monthly reporting period in which the interview occurred. These interview forms constitute a separate submission under the program and will not be included in this report. Specific perceptions and possible IBT applications obtained as a result of these interviews are included in the reports findings, together with findings obtained in the literature search and in the consultations with various individuals, the Advisory Group Board, and with the technical monitorship at NASA-LeRC.

Following the contact interviews, the Study Group conducted an assessment of potential IBT applications. This assessment was then followed by the preparation of this final report.

### 3. FACTORS IN IBT APPLICATIONS

#### 3.1 GENERAL CONSIDERATIONS

The definition of Ion Beam Technology (IBT) required certain limiting assumptions in the study. For the purposes of this study, IBT applications are those derived from the use of electron bombardment ion sources. The electron bombardment ion source, sometimes described as a Kaufman ion source, is a low density gas discharge, whose ions are extracted and accelerated to form an ion beam. The major development of this ion source was for electric propulsion purposes (the ion engine). More recently, the same ion source has appeared in commercial manufacture under a variety of names. The presently available commercial sources typically operate on argon, create an external  $A^+$  ion beam at current densities of the order of 1 milliamperes/cm<sup>2</sup>, and have ion energies ranging from several hundred electron volts to several kiloelectron volts.

In accepting an IBT limitation to the electron bombardment ion source, operating through comparatively modest energy and current density ranges, some potential ion beam applications are excluded. For example, ion sources for (energetic) ion implantation will, because of the ion species required and the ion acceleration voltages required, generally lead to a different source configuration than the conventional electron bombardment source. Such energetic ion implantations will not be considered as a portion of IBT in its presently defined context. The discussions in this report indicate, however, alternative approaches to ion placement-in-bulk which does not require a high energy injection.

The problem of the exclusion or inclusion to the IBT definition of Neutral Beam Injection Systems (NBIS) for fusion applications illustrates the difficulty in setting limits to the IBT definition. In their development, the NBIS have moved from 1 ampere/cm<sup>2</sup>, 20 keV, beams of H<sup>+</sup> at total source current of approximately 10 amperes to total source currents more nearly 100 amperes at energies above 100 keV. The original source technology was strongly derivative of the electron bombardment ion source. Because of increasing sizes and acceleration energies, however, the NBIS has not been considered as remaining within the IBT boundary.

### 3.2 IBT GENERIC APPLICATIONS

Before beginning the discussion of IBT applications, it is worthwhile to present a generic approach to these applicational avenues. Figure 1 illustrates these various directions and areas.

Three applicational areas are not treated further in this report. These areas, indicated by the dashed lines in Figure 1, are ion beams for material injection in vacuo (the neutral beam injection systems for fusion applications), for environmental simulation (plasma wind tunnels, solar wind simulation), and for charge deposition (for example, neutralization of differentially charged spacecraft surfaces, electrical equilibration of electrically isolated bodies). While applications for ion beams exist in these areas and a variety of literature exists on such work, these subjects have remained outside of the boundaries of the study in order to focus the study into applicational areas with both growth potential and with emphasis on electron bombardment discharge ion sources.

The remaining areas of potential IBT applications may then be divided into three principal avenues: material deposition, material removal, and material alteration. The principal focus on IBT applications has been and may continue to be upon material removal. The material removal applications will involve the surface properties of the treated material and will consist, basically, of three actions: cleaning (which is defined here as the removal of comparatively small numbers of layers of surface contaminant materials), cutting (which is defined as the in-depth and uniform removal of material), and texturing (which is an in-depth process but will usually lead to an irregularly structured material surface). These major applicational sub-avenues may each be further subdivided into areas dealing with conducting materials and insulating materials.

A second applicational avenue for IBT is in material alteration. Emphasis here is directed toward the alteration of material bulk properties. Examples of possible applications here include cross-linking of polymers by ion impact upon the upper surface, stress relief in deposited material layers by simultaneous ion impact (at, perhaps, lower acceleration energies), and the deliberate creation of defect states within crystalline material by ion impact (at, perhaps, higher acceleration energies).

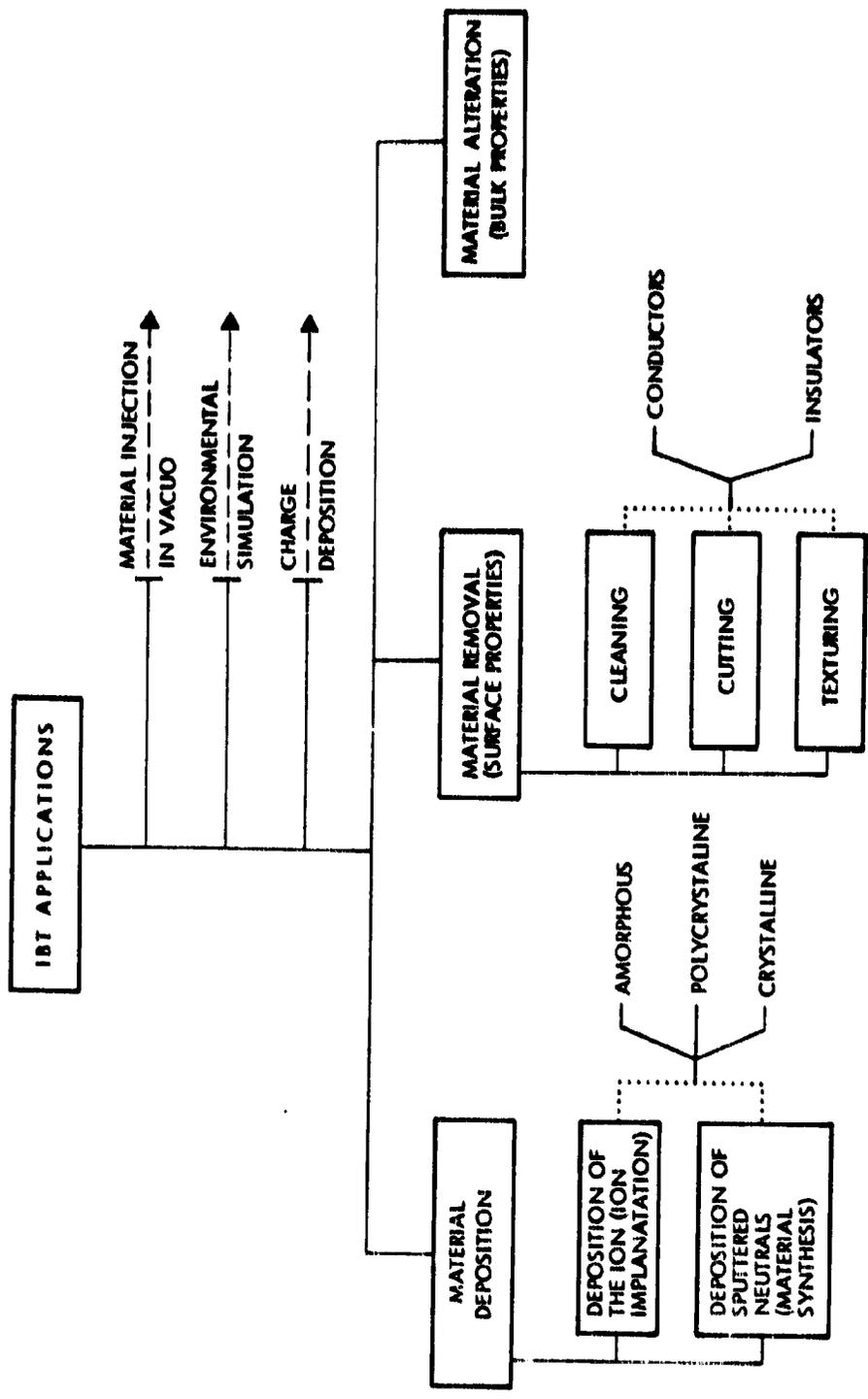


Figure 1. Generic Avenues for IBT Applications

The third applicational avenue for IBT is in material deposition. The emphasis here is upon material synthesis with two subavenues identified. These subavenues are the deposition of the ion only (for example, ion (implantation) deposition during epitaxial growth of crystalline materials) and the deposition of neutral materials sputtered by the ion beam. Applications in both subavenues may be seen in amorphous materials, polycrystalline materials, and crystalline materials. The subavenues are not totally distinct, one from the other, and it is possible to envision applications involving both ion deposition and simultaneous deposition of neutral material which has been sputtered from another location by ion impact.

### 3.3 BASIC CONSTRAINTS IN IBT APPLICATIONS

The many possible IBT applications illustrated in Figure 1 and described in Section 3.2 must be considered within specific constraints on scale size in the material treatment. For material removal applications, the order of magnitude rate using presently configured IBT sources is in angstroms per second, with dependences upon the material undergoing treatment, the ion mass in the beam, and ion acceleration energy. If it is postulated that the allowable process time for a material removal application will be of the order of 1 hour or less, than IBT applications must look to material removal requirements which will be, generally, in the range near and below  $10^{-4}$  centimeter ( $10^4$  Angstroms, 1 micron). This "micron" criterion marks an upper bound constraint, for the postulated upper bound allowable process time, for IBT applications in material removal.

The lower bound constraint for IBT material removal cannot, at present, be rigorously defined. Ordered surface material removals in the scale size range below  $100 \text{ \AA}$  have been carried out using ion beams. This scale size exceeds any presently known structural building requirement. It would appear, thus, that IBT applications in material removal should look to those processes requiring microns, or less, of removal with only an upper bound constraint in effect.

Material deposition rates for present IBT sources are somewhat reduced from the angstroms per second figure stated earlier for removal. This rate reduction occurs because of the more diffusely spreading material streams of ion sputtered materials. It is possible, nevertheless, to

invoke the same "micron criteria" for material deposition applications which was used earlier for material removal. Expected process times at these depths would range to hours. The lower bound constraint for material deposition applications may arise from many agglomeration phenomena in very thin deposited films and is probably of the order of  $100 \text{ \AA}$  (irrespective of the method of material deposition).

Material alteration in the bulk from ion impact on the surface is somewhat less precisely defined than either the removal or deposition processes. It is known that bulk alterations can occur to depths of the order of  $10^3 \text{ \AA}$  for the general range of ion energies used in IRI sources.

From the discussion above it may be tentatively advanced that IRI applications in material removal or material deposition should remain in a scale size range from a few  $\times 10^4 \text{ \AA}$  at the upper end to approximately  $10^1 \text{ \AA}$  at the lower end. An interesting question, then, is the possible number of applications falling within this scale size range. Because the response to this question is of such vital interest to national technology requirements, a separate section (3.4) addresses this question.

#### 3.4 SCALE SIZE AND TECHNICAL REVOLUTION

If technical activity during the past two decades is viewed in the context of the scale size of the material objects assembled by the technology, the most persistent images are in terms of large objects. Particle accelerators whose circumference or length become reasonable fractions of 1 mile, aircraft with gross weight at take-off in excess of 1 megapound, boost vehicles for spacecraft with thrust levels in the multi-megapound range, and supertankers, with carrying capacities in the hundreds of thousands of tons, all contribute (vividly) to these images. It becomes almost paradoxical, then, to advance the notion that the most pervasive revolution in this period has come, not in these large scale size areas, but in the area of small objects. The development of microelectronic circuits, and the alteration of societal processes to utilize these devices increasingly, affects the whole flow of commerce and, in many instances, may have permitted a genuine and continued growth in the national product.

The present "digital" revolution has occurred with devices whose basic scale size is in the range of tens of microns. At this point, technologies appear which hold the promise of another reduction in scale size by one order of magnitude. If this compression is carried out in a two-dimensional fashion, it offers the possibility of a component gain per area of 100. If the compression can be carried out in three dimensions, component number growth by three orders of magnitude can be obtained.

The technologies to provide this additional compression in the scale size of buildable objects are comprised of elements in many areas and include, as a backdrop, the large growth in recent years in the capability of diagnosis of material surfaces. IBI appears to be one of these contributing technology items. It should be emphasized that IBI is not the sole technology requirement for micron scale size building and below, but it may be a crucial contributor in terms of its capability to remove and or to deposit, in a precise fashion, minute quantities of material. The description of IBI as a possible contributor to these vital new areas is a conservative approach to the potential values of this technology. Section 3.5 examines the unique aspects and possible advantages and disadvantages of IBI which must be viewed in terms of the eventual role of this approach to the treatment of materials.

### 3.5 UNIQUE ASPECTS, ADVANTAGES, AND DISADVANTAGES OF IBI

There are five principal, and several unique, aspects to IBI for material removal applications. These aspects are:

- (1)\* The incident particle flow is a highly ordered (laminar) flow
- (2)\* The process can (and must) be carried out under high vacuum conditions
- (3) The cutting agent can be chosen to be chemically benign to the surface material (material removal is by the physical action of sputtering)
- (4) The cutting agent can be used against either conductors or insulators
- (5) The material removal rates are at small (and comparatively precise) levels (monolayers, or less, per second).

\*Unique.

The unique aspects of IBT are emphasized here in that these special qualities can serve to isolate IBT applications from the challenge of alternate technologies (see also Section 5.6). There are, clearly, many processes which can be used in material removal applications. Many of these methods do not have an ordered flow, which is crucial in the sharpness of masking operations and in the ability to cut precise patterns into the subject material. For example, even the ordered flow properties of visible wavelength photons lose precision at the level of wavelengths of the light in use. This has prompted that technology to consider the use of shorter wavelength photons (X-ray lithography), an approach that has many questions on feasibility remaining unanswered. For IBT, the ordered flow characteristics may allow precise cutting definition into the regime of 100 Å or less.

The high vacuum aspect of IBT, item (2) above, has both advantages and disadvantages. The disadvantage is in the requirement for vacuum pumping systems (with associated process time and attendance impacts). An advantage of the vacuum environment is in the (now reduced) rate of arrival at the subject material surface of unwanted gas species. These surface chemistry considerations are also present in item (3) above (possible choice of benign cutting agents), where, again, the chemical reactions of surface atoms and molecules may be "tailored" to the specific requirements of the material removal (or deposition or alteration) process.

Item (4) above (process use with either conductors or insulators), has been included to specifically point out a distinction between IBT material removal and dry plasma etch. The use of a negative bias potential on a conducting body in a plasma etch does produce an ordered ion flow across the sheath and onto the (negatively biased) body. This dry plasma etch process will not be possible, however, for an insulating material. IBT, through its use of a separate and controllable ion acceleration voltage, provides an ordered ion flow onto both conductors and insulators. The vacuum conditions of IBT are also at considerably lower pressures than for the plasma etching processes.

The final item, (5), above of very low rates of material removal (with comparatively precise control) is an advantage for those applications

moving into the very small scale size regime. For large scale size applications (above  $10^{-3}$  cm, for example) the process time for IBT may become too long and alternative methods should be considered. From the discussion in Section 3.4, however, it is now clearly apparent that an increased level of emphasis will be present in material fabrication at the level of microns or less, for which precise control at low rates of material removal will be a crucial requirement in the process technology.

It should be emphasized here that there are important questions yet to be answered on the precise control of IBT cutting. These questions include the variation of ion sputtering rate with angle of incidence, the disposition of secondary and tertiary materials from the cutting process, the development of "stops" (spectator gases with differential accommodation coefficients to various surface and substrate materials), low level in-beam ee contaminant materials, cutting uniformity for broad beam IBT sources, and substrate alteration as a result of surface generated shock waves under the ion impact. There remain, thus, considerable amounts of work to be done in the physics of ion sputtering. It is advanced here that this work will be carried out and that precise control on ion sputtering material removal processes will be developed as a natural and on-going portion of the total material treatment procedure.

In the areas of questions about ion sputtering given above, one area is of specific concern. This concern is in the growth of defect site density in crystalline material subjected to ion bombardment. The regions of defect site growth proceed sufficiently below the surface (say, of the order of  $10^3 \text{ \AA}$ ), so that direct deposition cannot be the process for the creation of the defect site. The more likely explanation is that the impacts of ions on the surface create shocks which propagate into the material and cause the defect site to appear at "susceptible" locations in the crystalline material. If this crystalline damage could not be overcome, and if crystalline damage were to persist for all levels of ion bombardment energy, then IBT material removal from crystalline matter would have a potentially serious disadvantage (for, at least, those applications in which the crystal depth is comparable to the damage depth). The recent work at the Namba Institute has indicated that defect site growth persists, albeit at a lowered rate, for lowered values of ion

bombardment energy. The Namba Institute research indicates, however, that these defect site effects can be removed by annealing at comparatively modest temperatures (less than 500°C) for comparatively modest periods. There is, thus, reason to believe that inadvertent substrate alteration by ion impact on the surface will not stand as a disadvantage to IBT material removal applications.

Turning now to material deposition processes, advantages and disadvantages are still present, but appear to present a smaller total advantage to IBT use than in the material removal cases. The advantage of IBT in material deposition is that it can be used for the deposition of nonconducting materials. The deposition of metals can be carried out at high rates by evaporation in vacuum (for example, vacuum deposited aluminum films), and by magnetron sputter guns. The former method does not permit an extension to insulating layer deposition, however. There are alternate technologies in chemical vapor deposition and sputter deposition for the build-up of thin insulating films, but these may have process control problems below a certain (as yet, undetermined) depth level. The potential areas of advantage for IBT in material deposition are, then, (1) a broad range of possible materials for insulating material deposition, and (2) precise control for very thin films of both insulating and conducting materials. The area of disadvantage, previously noted, is in the required process time for increased depth in the deposited film.

A final area to consider here is in surface material alteration by ion impact. In this application ordered flow is probably not crucial. The unique aspect of IBT is in the particle energy at impact with the surface. These particle energies can clearly exceed "oven generated" particles and, hence, can create surface restructuring, perhaps cause a more perfect crystalline epitaxial growth, and may have improved particle sticking coefficients because of incident particle energy. These latter applications ("ion beam epitaxy") lie in the realm of both material deposition and material alteration and hold out the possibility of a "bottoms-up" ion implantation (implantation during material growth rather than after a "tops-down" injection into previously formed material). The total field of applications here is seen, however, as an area of future research and development with no apparent present advantages or disadvantages to IBT.

### 3.6 COMPETITIVE ROLE OF ALTERNATE TECHNOLOGIES

One of the factors in the assessment of an application of a new technology is the possible roles which may be played by alternate, and competitive, technologies. In some instances there may be no alternate method and the pursuit and development of the new technology is governed only by the potential return from its application. In other instances, several alternate methods may exist and the (perhaps) protracted and (perhaps) expensive development of the new technology will not result in its predominant use in an applicational area. In some instances, even for acceptance of the new technology, returns may be comparatively short lived as the previously used technologies are either uprated or previously untapped reserves are discovered.

It is not possible to describe in detail all of the potential actions and counteractions of competing technologies as they contest for a given application, but the discussion here describes some possible examples. One of these examples, previously discussed, is the precision in cutting as the scale size diminishes. For the use of visible wavelength light to expose photo resist material, precision is limited to values of the order of the wavelength of the light. Alternate methods, using x-ray lithography, can improve on this precision. It does not appear likely, however, that modification of these previous technical approaches (in this instance by shortening the wavelength of light) can effectively compete against presently demonstrated exposure and cutting (using energetic electrons for exposure and ions for cutting) scale sizes of the order of  $100 \text{ \AA}$ . In this instance, IBT may have an unassailable position.

For material deposition applications it is not apparent that IBT can generate an unassailable position unless (perhaps) the scale size is sufficiently reduced. For example, material deposition by magnetron sputter guns can be at greatly elevated rates compared to IBT. It does not appear as a prudent course for IBT development to challenge the magnetron sputter gun in these (vacuum) deposition areas. On the other hand, the sputter gun is a source of neutrals only and cannot carry out cleaning operations so that it could develop that some material deposition

operations which require cleaning immediately before the deposition should be approached with a "hybrid" (sputter gun plus IBT source) facility. To further complicate such analyses are the possibilities of innovation in the previously utilized technology. Using electroplating as an example and recognizing the environmental problems of the disposal of these wet chemical residues, it would appear that the replacement technology of magnetron sputter guns would possess a secure position. The chemical electroplating approach, however, has responded with innovative measures (for example, in the reestablishment of the Cr VI population from the Cr III of depleted baths, and in the insoluble starch xanthate recovery of metals from the electroplating baths). With presently obscure balances between capital equipment and facility costs and environmental protection costs, it is not readily apparent at which point a previously used, and then replaced, technology may recover and may reassert itself in an applicational area.

A final example to consider here is in the applicational avenue of surface texturing. Many methods presently exist for generating structure above a given scale size in surfaces, and IBT may expect a hard competitive battle for applications in this area. If the application is in a biomedical area, and if there is a precedent for the use of technology methods in the specific (example) devices, the introduction of new technology will proceed with even more caution and review, particularly if the application is for clinical (and human) use. It has already been pointed out by other reviewers of technology, that the overall effect of these policies may be an unwanted one... i.e., the denial for human use of new and potentially beneficial technologies.

#### 4. AREAS OF ASSESSMENT IN IBT APPLICATIONS

The discussion of the preceding section described some of the many (complex) factors which determine the likelihood of success of a technically innovative application. It should be noted that many of the factors are only poorly understood and only a fraction of all contributing factors are under the direct control of the institution or individual attempting the development of the application. In the face of these many ambiguities and uncertainties, there is no rigorous, and absolute, assessment of the success or failure of a given application. Such an assessment will, however, be made of various IBT applications, noting that such an assessment may indicate, in relative terms, the most favorable areas for future IBT development.

The assessment criteria and scoring designations in a given criteria area are given in Table 1. The scoring technique is presented in Table 2.

Table 1. Assessment Factors

<u>Element</u>	<u>Designation</u>
Near-Term Market Size Projected Rate of Growth Future Potential Applications Market } Economic Factors	A1 C1
Systems Requirements	A2
Requirements for Acceptance by User	A3
Special Needs or Problems Further Technology Development Required } Anticipated Progress in the Advancement of IBT	A4 C2
Benefits of Application	B1

Table 2. Scoring Technique

A. REQUIREMENTS

A1. Market (Score: 0 to 10)

A2. Systems Requirements (Score: 0 to 10)

A3. Requirements for Acceptance by User (Score: 0 to 10)

A4. Special Needs or Problems  
Future Technology Development Required (Score: 0 to 10)

$$\text{Composite Score: } \frac{2(A1) + (A2) + 2(A3) + 5(A4)}{100}$$

B. BENEFITS

B1. Benefits of Application (Score: 0 to 10)

$$\text{Composite Score: } \frac{(B1)}{10}$$

C. IMPLEMENTATION

C1. Economic Factors (Score: 0 to 10)

C2. Anticipated Progress in IBT (Score: 0 to 10)

$$\text{Composite Score: } \frac{4(C1) + (C2)}{50}$$

D. ASSESSED VALUE

$$D = A \times B \times C$$

NOTE: 0 to 10 scoring scale ranges from least favorable to most favorable for each individual factor.

The high end of a relative score is given to the greatest benefit or greatest convenience. For example, an IBT application with only minimal systems requirements (maximum convenience) will score high in this category. An IBT application with many requirements for acceptance by a user will score low in this category. An application with many special needs or problems and requiring extensive further development will score low in this category.

The scoring system presented in Table 2 and to be used in the results of Section 5 yields a maximum possible assessed value of unity (1.0) and a minimum possible value of zero.

During the course of this study, 31 applications involving IBT (as defined earlier in this report) were investigated. On the basis of the limited work done, it is estimated that the total investment in IBT systems (hardware, materials, labor, etc.) is \$10 million annually. For this investment, the value of the parts produced where IBT is part of the production process would be in the vicinity of \$25 million, while the total value of the products containing such parts could range from \$250 million to \$2.5 billion annually. The growth potential of IBT over the next 10 years in the area of the existing and potential applications surveyed could be as high as a factor of 10.

## 5. ION BEAM TECHNOLOGY APPLICATIONS

A variety of IBT applications was investigated and assessed for probability of user acceptance and implementation. The assessment factors and scoring technique are shown in Tables 1 and 2. Table 3 presents the assessed values for each application, together with the scale ratings for each assessment factor. A brief description of each application is given below.

### Metallography

An ion source can be used to etch metallographic specimens and to remove surface contaminants from such specimens in a controlled, stress-free manner. Aluminum, low carbon steel, cast iron, and other soft materials are difficult to polish using conventional techniques. Electropolishing, for example, is neither very controllable nor reproducible. Chemical etching leads to rusting and staining of samples.

### Semiconductor Device Manufacturing

IBT is being extensively used for semiconductor device manufacturing, e.g., field-effect transistors and magnetic bubble memory devices. When used in conjunction with state-of-the-art lithographic techniques, IBT exhibits unparalleled resolution capabilities. The semiconductor industry is now extending these techniques to the development of new large scale integrated circuits, charge-coupled devices, etc.

### Surface Acoustic Wave Devices

Surface acoustic wave devices have found widest application as oscillators and resonators in communications electronics over the range from 50 MHz to about 2 GHz. The great advantage of surface acoustic wave delay lines is that a significant amount of delay can be obtained in a very small device. Ion beam etching is implemented in the manufacturing process to produce surface acoustic wave transducers.

### Gas Bearings

Ion beams are being used for etching grooves in gyroscope bearings. Military bearing manufacturing is a relatively high cost process. IBT processing is done under hard vacuum, leading to good groove definition

Table 3. Assessed Application Ratings for User Acceptance and Implementation

Application	● Near Term Market Size ● Perfect Rate of Growth ● Future Potential Markets	Economic Factors	Systems Requirements	Requirements for Acceptance by User	● Special Needs or Problems ● Further Technology Development Required	Anticipated Progress in IIT	Benefits of Application	Assessment
1. Metallurgy	8	9	9	9	9	5	9	2.72
<ul style="list-style-type: none"> <li>● Sample Preparation</li> <li>● Stress-line Polishing</li> </ul>								
2. Semiconductor Device Manufacturing	9	9	7	10	8	7	9	3.55
<ul style="list-style-type: none"> <li>● Field-effect transistors (FFT)</li> <li>● Large scale integrated circuits (LSI)</li> <li>● Charge-coupled devices (CCD)</li> <li>● Semiconductor diodes</li> <li>● Magnetic bubble memory devices</li> </ul>								
3. Surface Acoustic Wave Devices Manufacturing	6	5	9	10	5	7	9	3.83
4. Gas Bearings, Groove Etching	5	9	9	10	9	5	5	3.820
5. Optical Components	6	9	6	10	8	8	9	3.508
<ul style="list-style-type: none"> <li>● Gratings</li> <li>● Substrates (SiO<sub>2</sub> or Germanium)</li> <li>● Coatings of aspheric lens surfaces</li> <li>● Optical waveguides</li> </ul>								
6. Lubricating Coatings	4	9	7	9	8	8	8	3.51
7. Coatings for Solar Cells	5	7	7	5	7	7	8	3.38
<ul style="list-style-type: none"> <li>● Indium-tin-oxide (ITO)</li> </ul>								
8. Transmission Electron Microscope Sampling	2	9	9	10	9	5	5	3.32
9. Milling								

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Table 3. Assessed Application Ratings for User Acceptance and Implementation (Con't)

Application	● Near Term Market Size	● Projected Rate of Growth	● Future Potential Markets	Economic Factors	Systems Requirements	Requirements for User Acceptance by User	● Special Needs or Problems	● Further Technology Development Required	Anticipated Progress in IIT	Benefits of Application	Assessment
9. Structural Materials Texturing				7	7	2			5	10	0.30
<ul style="list-style-type: none"> <li>● Blown films</li> <li>● Piezoelectric devices</li> <li>● Piezoelectric connectors</li> <li>● Sensors, instruments</li> </ul>											
10. Abrasive Sanding	9	5	5	5	5	5			8	.9	0.25
<ul style="list-style-type: none"> <li>● Abrasive composites</li> <li>● Abrasive</li> <li>● Abrasive</li> <li>● Abrasive</li> <li>● Abrasive</li> </ul>											
11. In-flight cleaning of spacecraft surfaces	4	9	3	9	3	6			5	5	0.222
<ul style="list-style-type: none"> <li>● Thermophysical coatings</li> <li>● Laser crystal monitors (LCM)</li> </ul>											
12. Materials Synthesis	5	5	5	5	5	5			10	10	0.213
13. Surface Coatings	9	5	2	5	2	5			3	5	0.03
<ul style="list-style-type: none"> <li>● Gas ceramics</li> <li>● Marine paints</li> <li>● Aircraft coatings</li> </ul>											
14. Surface Coatings	5	4	4	4	4	5			5	5	0.03
<ul style="list-style-type: none"> <li>● For remote satellite detectors</li> </ul>											
15. Low Secondary Emission Yield Materials for Vacuum Tubes	2	5	7	5	7	5			5	5	0.01
<ul style="list-style-type: none"> <li>● Textured graphite</li> </ul>											

Table 3. Assessed Application Ratings for User Acceptance and Implementation (Con't)

Applicator	● Near Term Market Size ● Projected Rate of Growth ● Future Potential Markets	Economic Factors	Systems Requirements	Requirements for Acceptance by User	● Special Needs or Problems ● Further Technology Development Required	Anticipated Progress in 1981	Benefits of Application	Assessment
16. Selective Solar Absorbers	5	5	5	5	5	5	7	2.120
17. Monitor for Source for Materials Evaluation ● Controlled thermonuclear reactor (CTR) magnets	1	5	2	2	5	5	5	2.122
18. Sterilizing	7	5	5	5	5	5	5	2.125
19. Prosthetic Devices ● Dental Prostheses	7	5	3	2	5	5	5	2.126
20. Control of Surface Coatings ● Coating reactor with thermal evaporation, water separator	3	3	3	2	2	5	5	2.128
21. Thin Film Capacitor Coatings	5	5	5	2	2	5	5	2.129
22. Corrosion Barriers ● Aircraft fasteners	3	5	5	2	2	5	5	2.130
23. Stanley Corer Texturing	2	5	2	5	5	5	5	2.132
24. Conformal Coating of Electronic Components ● Dispenser ● Roll-on Coating	2	5	5	5	5	5	5	2.133
25. Solving Optical Components	2	5	5	2	2	5	5	2.134

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Table 3. Assessed Application Ratings for User Acceptance and Implementation (Con't)

Application	● Near Term Market Size ● Projected Rate of Growth ● Future Potential Markets	Economic Factors	Systems Requirements	Requirements for Acceptance by User	● Special Needs or Problems ● Further Technology Development Required	Anticipated Progress in 1991	Benefits of Application	Assessment
25. Metallizing Ceramics	3	6	6	4	2	6	4	D.1536
26. Catalyst Surface Texturing	7	4	5	5	2	4	5	D.1534
27. First Stage Ion Source for an Ion Implantation System	1	7	8	5	4	4	3	D.1577
28. Micromachining ● Razor blade sharpening ● hypodermic needle sharpening ● Biomedical probe machining	9	2	4	5	4	5	4	D.1554
29. Ion Source for Optical Emission Spectroscopy	2	4	3	5	4	4	3	D.1550
30. Liquid Crystal Display Alignment	7	2	8	3	4	4	4	D.1545
31. Polyester Fiber Processing	10	1	2	4	3	5	5	D.1542

(few collisions between bombarding particles) and little, if any, contamination of bearing surfaces.

#### Optical Components

Ion beams are being used to make optical gratings. Again, they are used in conjunction with lithographic techniques to obtain fine line resolution. Ion beam deposition of Corning 7059 glass, followed by selective etching, has been developed for making optical waveguides. Ion beam deposition is also being developed for making optical switches. Other optical component applications include ion beam etching for correction of aspheric lens surfaces.

#### Lubricating Coatings

Ion beam deposition of molybdenite onto the balls, races, and ball retainer of a precision gimbal assembly for a spacecraft mirror has been used with picture-taking instruments on weather satellites. Bearings treated this way have virtually no lubrication buildup and show little wear because of friction.

#### Coatings for Solar Cells

Ion beam deposited films of indium-tin-oxide (ITO) retain incident energy and heat on solar cells. These heat mirror coatings have been found to be superior when made using ion beam techniques.

#### Transmission Electron Microscope Sample Milling

One of the earliest applications of IBT was in thinning samples for transmission electron microscope analysis. A number of ion mills are commercially available for this purpose.

#### Biomedical Materials Texturing

Ion beam texturing of rigid implant materials, to promote tissue growth, and flexible materials, especially in blood contacting surfaces, is being investigated and clinically analyzed for a variety of applications. These include prosthetic devices, percutaneous connectors, blood pumps, neurological sensors, and a variety of biomedical instruments.

### Adhesive Bonding

Ion beam etching and texturing of surfaces is beneficial in promoting strong adhesive bonds. For example, difficult to join materials, such as Teflon and Kapton, have been treated prior to adhesive bonding. Other difficult to join materials, e.g., titanium, graphite composites, should also benefit from ion beam treatment. Bonding of composites poses a problem in structural applications for the aircraft industry. If an adhesive bonding process were developed, the bond stress could be spread over an entire surface area, instead of being localized, e.g., at rivet holes, which leads to cracking of the base material. A special application of adhesive bonding is in surface treatment prior to encapsulation of semiconductor devices. A reliable encapsulation method is actively being investigated by the military to enable use of plastic encased, rather than metal sealed, semiconductor packages where moisture resistance is important.

### In-Flight Cleaning of Spacecraft Surfaces

Ion beams may also be used aboard spacecraft for renewal of thermo-physical surface properties that have been altered by exposure to out-gassing products (and other contaminants) on the spacecraft. Also, quartz crystal monitors, which measure the minute quantities of accrued mass that deposit on the crystal, may be renewed by ion beam scrubbing.

### Materials Synthesis

Ion beam deposition of materials can be done simultaneously to form new alloys, or in the presence of various background gases, to alter the stoichiometry of the deposited film. Superconducting properties, corrosion resistance, mechanical properties, etc., of materials synthesized in this fashion have been examined. In order to be useful, it is necessary to determine film properties of ion beam deposited materials as a function of various processing parameters, such as background gases introduced during film growth.

### Surface Coatings

Ion beam deposition of conducting and dielectric materials has widespread potential. Dense, uniform surfaces are desired on gas bearings. Chromium coatings on machine tool surfaces improve tool wear characteristics. Abrasion resistant coatings for transparent aircraft canopies would significantly reduce maintenance costs. Smooth coatings for shot-peened turbine blades would improve turbine performance. New material coatings are being sought for coal gasification processes and for spacecraft charge control. Also, sputter deposited materials have been used for coating razor blades.

### Surface Cleaning

Ion beams may be used for removing surface contaminants and for exposing atomically clean layers of base material. This is advantageous in outgassing interior surfaces of neutral particle injectors, and for surface preparation prior to welding or prior to diffusion bonding.

### Low Secondary Emission Yield Materials for Vacuum Tubes

Textured graphite has the lowest known secondary electron emission yield of any material. This has potential application in manufacturing of special purpose vacuum tubes.

### Selective Solar Absorbers

Surfaces can be textured to alter their optical properties. In particular, incident light may be trapped by unusual surface morphologies produced from ion beam texturing which results in almost perfect black-body radiators. Thus, this technique may be implemented for solar energy equipment.

### Hydrogen Ion Source for Materials Evaluation

A hydrogen ion source may be used for evaluating candidate wall materials for controlled thermonuclear reactors (CTR). The source is used in determining hydrogen ion sputtering yields.

### Sterilizing

A special group of biomedical IBT applications includes sterilizing prosthetic devices, instruments, etc., prior to their actual use in practice.

### Control of Surface Coatings

In order to control the growth of surface films, and to control the stresses in the resultant surface coating, ion beams may be used in conjunction with other deposition processes, such as thermal evaporation or sputter deposition. The ion beam provides an independent means of cleaning the substrate and controlling the rate at which films nucleate and knit together.

### Thin Film Capacitor Coatings

The high quality films deposited by ion beams may be used to produce capacitors with superior performance and lifetime characteristics.

### Corrosion Barriers

Typical coatings for producing effective corrosion barriers range from 1000 to 4000 angstroms. Chromate coatings presently being used for aluminum aircraft structures are toxic to biological agents in sewage systems. Cadmium plating baths have similar environmental impact. IBT has no such environmental impact.

### Display Screen Texturing

The unusual surface morphologies produced by IBT have potential application in a variety of displays for graphically communicating information or for aesthetic novelty.

### Conformal Coating of Electronic Components

It is often desirable to conformally coat electronic components on circuit boards, but frequently these processes are limited by the allowable temperature reached during processing. IBT processing could be used to deposit conformal coatings directly, or to initiate low temperature polymer curing by irradiation.

### Polishing Optical Components

An ion beam may be directed across the face of a flat surface in order to polish its irregularities. Some work has been done in this area, but more development is needed to demonstrate its feasibility for specific applications. Very smooth surfaces are needed to advance the state of the art, but even polishing plastics to an optically shiny condition prior to their coating operation would be advantageous.

### Metallizing Ceramics

Ion beam deposition of metallic coatings on ceramic substrates can be used to metallize the ceramics prior to brazing or other joining operations. A typical application would be for ceramic vacuum chamber feedthrough insulator assemblies.

### Catalyst Surface Texturing

Ion beams may be used to texture catalyst surfaces, either to increase surface area, or to alter surface properties.

### First Stage Ion Source for an Ion Implantation System

Ion implantation equipment accelerates the ions of interest to energies of  $\sim 100$  keV, far greater than the nominal 500 eV used for etching, texturing, and deposition processes. The source used, however, for these processes, also has potential application as a first stage ion source in an accelerator used for implantation purposes.

### Micromachining

IBT provides a means for removal of minute amounts of material in a controlled fashion. Fine surface features may be machined by implementing this technique. Applications include sharpening of blades, needles, or probes, and machining of interconnecting holes in miniature electronic components.

### Ion Source for Optical Emission Spectroscopy

Special gauges have been developed for comparing the partial pressure of nitrogen to the total pressure in a vacuum system. The ion source in these gauges could be improved by incorporating IBT features.

### Liquid Crystal Display Alignment

Ion beam etched electrodes have been used to align liquid crystals. These electrodes tend to produce high tilt angles. At low tilt angles, alignment tends to be nonuniform over the surface. Electrode etching in production is usually done by wet chemical or plasma sputtering. Both of these alternative techniques suffer from Government regulations on chemical disposal.

### Polyester Fiber Processing

Altered fabric surface properties, via IBT processing, are beneficial for:

- Moisture resistance, retention, or transport
- Static losing properties
- Sensitivity to oil pickup
- Sensitivity to dirt pickup
- Change of fabric feel
- Fabric treatment

The fiber could be processed in either yarn, fabric, or textile form.

## 6. RECOMMENDED DIRECTIONS FOR IBT TECHNOLOGY DEVELOPMENT

Section 5 described an IBT applications list with an associated assessment for the various applicational groups. This section outlines a series of recommended directions for IBT technology development, within the specific context of the IBT effort at NASA-LeRC and their associated grantees.

The rating system in Section 5 does not necessarily identify the specific (recommended) technology development directions described in this section. The notion will be advanced here that technology development goals within NASA will respond to a different series of criteria than those used in the probability of user acceptance and implementation. For example, the use of IBT for material removal in microelectronic devices appears as both a condition of high likelihood and a condition of high level return on investment. But this use of IBT will probably proceed, irrespective of NASA action. A considerable amount of work remains to be done in the physics of ion cutting and in process control on IBT actions here. This work will best be carried out, however (and at this time), within the specific framework of the various microelectronic devices needing this technology.

The recommended areas for NASA technology development will be, in point of fact, those areas in which there are significant outstanding questions to be answered by research and for which user acceptance will probably proceed after extensive review of the IBT product and of alternate methods for the development of this product. The suggested directions for the research capabilities of NASA are, thus, precisely those directions which pose the greatest present challenges and for which the eventual likelihoods of success are the most difficult to estimate. In many of the specific applications, however, the return for a successful application can be of major importance.

Table 4 contains a list of recommended directions for IBT technology development. Placement in the table is somewhat arbitrary. A brief discussion is given for each of the items in the table.

Table 4. Recommended Directions for IBT Technology Development

1. Neural coaxial electrode
2. "Bottoms-Up" Ion Implantation
3. Neural sensor/stimulator
4. Spacecraft surface scrubber
5. Artificial tendon/ligament
6. Artificial knuckle
7. Textured cannulae
8. Textured quick connect (artificial heart)

The neural coaxial electrode, developed by Bunshah and coworkers and produced through other manufacturing techniques, is currently in use for insertion into the human brain. In this application area the role of IBT would be to utilize both cutting and deposition processes with the goal of producing a superior coaxial electrode. The recommended course of action specifically focuses IBT development into those areas in which the manufacturing process calls for precise fabrication of very small scale devices. The recommended course of action is also to focus IBT development into the challenging (but, possibly, highly rewarding) area of neural research and rehabilitation. The course of action also moves IBT into the developmental area of small (and smart) sensors of internal body processes, such as may be required in blood sugar level determinations for the (proposed) artificial pancreas.

The "bottoms-up" ion implantation is a recommendation for a demonstrated material synthesis in which the dopant ion is placed into the material during the period of material growth through the addition of surface layers. A specific synthesized material is not suggested here, but possible directions for an initial experiment would be in either amorphous or polycrystalline materials, used, perhaps, as corrosion barriers or for improved surface lubrication properties.

The neural sensor/stimulator may be a single connecting conductor (as distinguished from the coaxial electrode above) whose purpose is either the stimulus of neural action or the sensor of neural action. The primary use here would be in neural research, but eventual applications could include neural prosthetic devices to correct areas of neural dysfunction. IBT technology development in this area would focus attention on precise cutting and deposition with, again, an emphasis on very small scale size objects.

The recommended IBT development as a spacecraft surface scrubber is in more traditional working areas for NASA. It is now apparent from a variety of in-orbit spacecraft behavior that low solar absorptivity surfaces (which are vital for spacecraft performances) tend to become more absorbing for continued in-space operation. It is hypothesized that this surface deterioration results from the accumulation and photolysis of contaminant layers. The specific recommended action for IBT development here is the surface cleaning by ions of representative low  $\alpha$  surfaces bearing representative contaminant layers. The principal question here is the degree of recoverability of the low  $\alpha$  condition, following ion cleaning. A successful demonstration of surface scrubbing here should be followed by the development of a miniaturized IBT source for use on specific spacecraft which must maintain low  $\alpha$  surfaces over prolonged periods of space operation.

The recommended development of artificial tendons and artificial ligaments calls for a use of IBT texturing in the biomedical device area. This specific area has been chosen because the major requirement for acceptance would appear to be improved attachment to tissue. The grant effort of Gibbons at Case-Western is currently examining the attachment of IBT textured surfaces, implaced in rats. In this overall application area of tendons and ligaments the growth of scar tissue might be tolerated (there are fewer demands on the tissue response), provided only that superior attachment is obtained. The material to be textured will not be specified here, but some attention in this device area is being directed toward carbon fibers.

A recommended course of action for the development of an IBT textured artificial knuckle has followed from a series of contact discussions relative to IBT textured knee and hip prostheses. The expressed view that the predominant attachment problem is one of differential stiffness between the device and the bone (for artificial knees), and the desire to continue PMMA use into drilled cavities indicates that IBT textured devices and sculpted enclosures will have a low likelihood of user acceptance. For device injection into the bones of the hand, however, a sculpted approach may be preferable (less material removal in (now) smaller bones) and immobilization of the hand until the bone attaches into the textured regions can be carried out with less patient distress than for the (large) bone attachment case.

A recommendation has been given for the use of IBT to develop textured cannulae for blood access. The successful development of an "attached" device here has been questioned by some workers in the field in view of the continued outward growth of the skin which leads, in principle, to the eventual upward dislocation of an attached device. Because of the considerable level of pain associated with blood access for dialysis, however, and because of the large scope of this national health care problem, the attempted development of IBT in this area is recommended in full face of the acknowledged difficulties.

A final recommended area for IBT development is in the use of ion texturing for the interior surfaces of the quick connect devices on artificial hearts. Tissue growth has been observed to proceed along the quick connect inner surface and into the interior of the artificial heart causing the blockage of the valves. It has not been demonstrated that tissue response to a textured surface (or to a textured-grading-to-smoothed surface) will be significantly different from the present response to the quick connect smooth surfaces. In view of the possible benefits for a successful demonstration and application, however, this area will be a recommended area of action.

## 7. ACKNOWLEDGEMENTS

During the course of this study, the members of the Study Group enjoyed many discussions with workers in the field of IBT and in possible applicational areas. The Study Group wishes to acknowledge the valuable assistance and insights into potential IBT applications from these discussions. The Study Group specifically wishes to acknowledge the guidance and assistance of the study program technical monitor and the Section Head in charge of IBT applications development, Mr. Ed Wintucky and Mr. Bruce Banks, of NASA-Lewis Research Center.