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INSTITUTE FOR DEFENSE ANALYSES

Industrial Assessment on Deformable Mirrors
(Without Proprietary Information)

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PREFACE

The Institute for Defense Analyses (IDA) has established an Industrial Analyses Center (IAC) to provide the Office of the Secretary of Defense (OSD) with objective and independent analyses that characterize and assess industrial capabilities for acquisition and support military weapon systems. The IAC performs range of analyses that address industrial issues associated with changing industry structure, competition, and industrial and technology capabilities, at the prime and subtier contractor levels.

Firms reviewed in this study supply much of the information that IDA uses to perform its analyses. IDA may not be able to independently validate material supplied. As a result, future adjustments to these studies may be required to correct information provided by industry sources. The publication of this IDA document does not indicate endorsement by the Department of Defense (DoD) nor do its contents necessarily reflect the official position of that Agency.

This document reports on an analysis done by IDA to address industrial issues associated with deformable mirrors.

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EXECUTIVE SUMMARY

In 1996, the Federal Trade Commission (FTC) viewed the deformable mirror industry as a problem area with respect to vertical integration and diminishing competition. As part of a larger industrial study that the Institute for Defense Analyses (IDA) conducted during FY 1997–1998, IDA was tasked to evaluate the deformable mirror industry. The objective of the study was to determine if there were more potential deformable mirror suppliers than the one company that was identified and to identify possible alternatives to the present state-of-the-art for deformable mirrors. Because of a time constraint, the task's scope was limited to unclassified systems and U.S. deformable mirror producers.

The study had several objectives:

- Define critical components of a typical deformable mirror system using a work breakdown structure (WBS)
- Identify companies related to deformable mirrors
- Use databases to determine demands and identify government Program Management Offices (PMOs)
- Survey the companies for data not received by phone
- Survey the PMOs on issues, funding, and status of programs.

Possible component suppliers who could produce actuators or the flexible optical surfaces for the deformable mirrors were also assessed.

The overall assessment identified three deformable mirror producers (Xinetics, Thermotrex, and Raytheon) and several deformable mirror component suppliers. New technologies, including Microelectromechanical Systems (MEMS) mirrors and magnetostrictive materials for actuators, showed potential in replacing or augmenting the current technology. The study also determined that vertical integration was not an issue because of the current number of deformable mirror suppliers and the component industries available. However, it did conclude that the deformable mirror market was "thin" and could change rapidly. The final recommendation was that the deformable mirror area be re-examined as changes occur in the funding environment, the demand for deformable mirrors, and manufacturing capability of the deformable mirror suppliers.

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INDUSTRIAL ASSESSMENT ON DEFORMABLE MIRRORS

- In 1996, the Federal Trade Commission (FTC) viewed the deformable mirror industry as a problem area with respect to vertical integration and diminishing competition. According to the FTC, the Airborne Laser (ABL) program had awarded contracts to two teams: Boeing Company/Lockheed Martin Corporation and Rockwell International Corporation/Hughes. Itek Optical Systems was contracted to provide deformable mirrors to the Boeing/Lockheed team, and Xinetics was contracted to provide deformable mirrors to the Rockwell/Hughes team. However, Itek was acquired by Hughes Danbury Optical Systems. The FTC was concerned that this sale would raise prices or reduce investments in technology and quality for deformable mirrors, which were a critical component of the Air Forces' anti-missile program. An antitrust settlement was reached to ensure that competition for deformable mirrors would continue.
- In 1997, Raytheon acquired Hughes. There was concern that Raytheon did not retain Itek's deformable mirror expertise, leaving Xinetics as the only deformable mirror producer.
- The objectives of this study were to determine if there were more potential suppliers in this industry and/or possible alternatives to the present state of the art for deformable mirrors and to assess the base of suppliers for deformable mirror components.

Objectives

Investigate the availability of current and potential deformable mirror producers and determine possible alternatives to this particular technology

This slide outlines our approach to fulfilling the objectives of this study. We developed a work breakdown structure (WBS) from our understanding of the deformable mirrors and selected components critical to the deformable mirror to analyze in more depth. At one point, we had included adhesives since they must be able to withstand a variety of environments. However, given the number of adhesive suppliers, we felt that there were more critical components to address in this short study. We were provided with several databases (e.g., Carroll's Publishing R&D Database, Thomas Register, Forecast International's Contractor List) and also relied on contacts from other tasks for information on companies related to deformable mirrors. We called the main deformable mirror suppliers and questioned them about their products, their work in deformable mirrors, and issues or problems related to this technology. We sent surveys to these companies and to the component-level companies (i.e., actuator suppliers) requesting information that was either sensitive or proprietary. We also surveyed the main Program Management Offices (PMOs) on program issues, funding, and status of the defense programs.

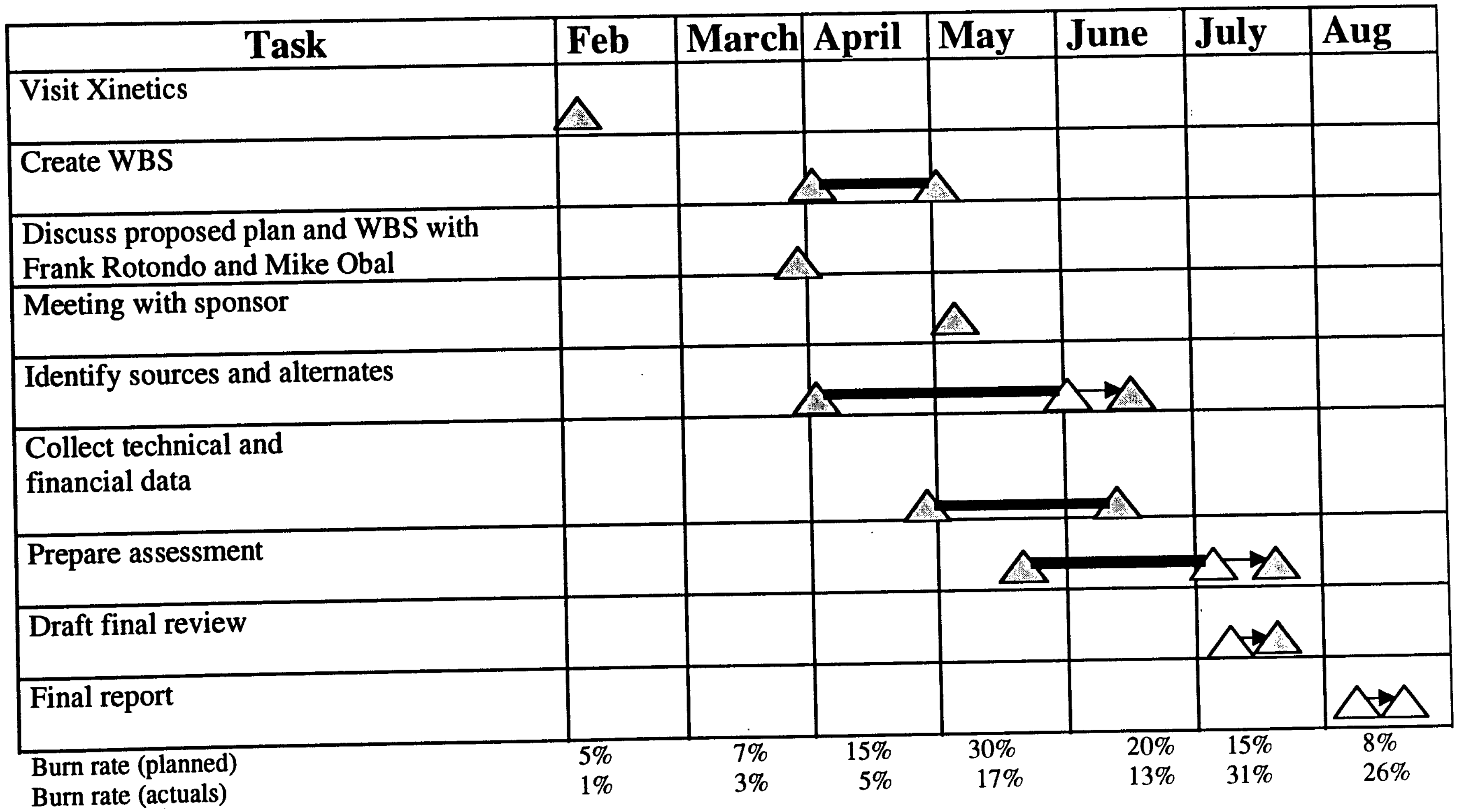
Because of time constraints, we limited the scope of the study to U.S. deformable mirror producers and potential U.S. actuator suppliers.

Study Approach

- Six-month study
- Define critical components of a typical deformable mirror system using a WBS
- Identify companies related to deformable mirrors, both primary and secondary suppliers
- Use databases to determine demands and identify government PMOs
- Survey the companies for data not received by phone
- Survey the PMOs on issues, funding, and status of programs
- Study limited to primary U.S. producers of deformable mirrors and actuator suppliers

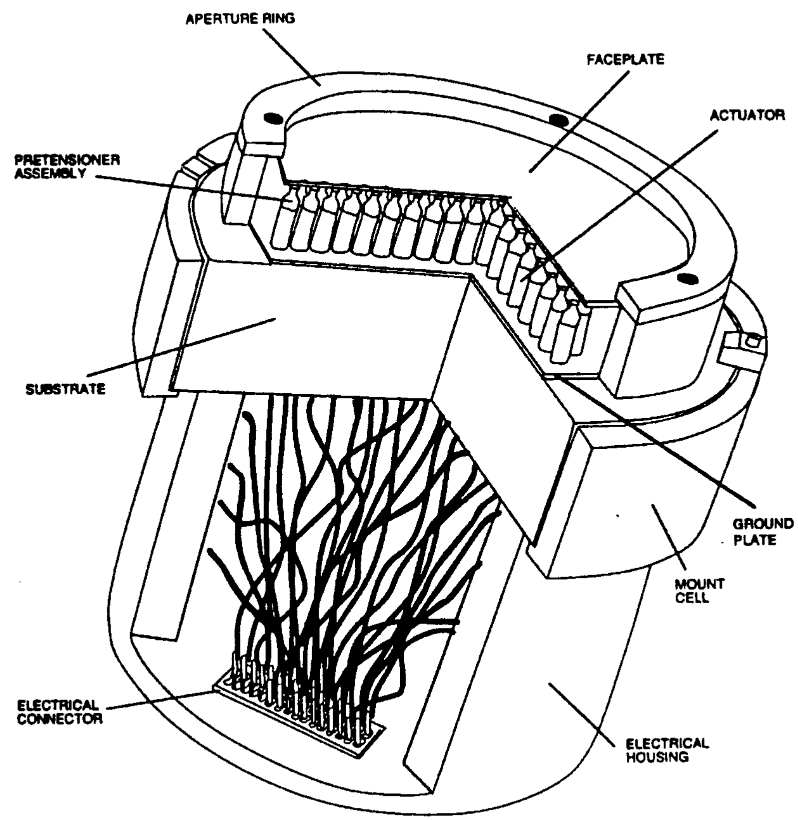
This slide is the task schedule for the deformable mirror study. A few dates slipped because meeting dates were changed or data from the surveys that were sent to the companies did not come back to us on time. Dr. Lisa Veitch and Dr. Frank Rotondo, both from IDA, and a consultant, Dr. Michael Obal, worked on this task.

Task D100-L89: Deformable Mirrors
Task Schedule



This slide is a cut-away view of a deformable mirror. The critical components we identified for the deformable mirror are the faceplate or mirror, the actuators, and the control system. This last component takes into account all the electronics and the software and controls. Systems integration and experience are also critical for the deformable mirrors to perform but are not physical components depicted in the slide.

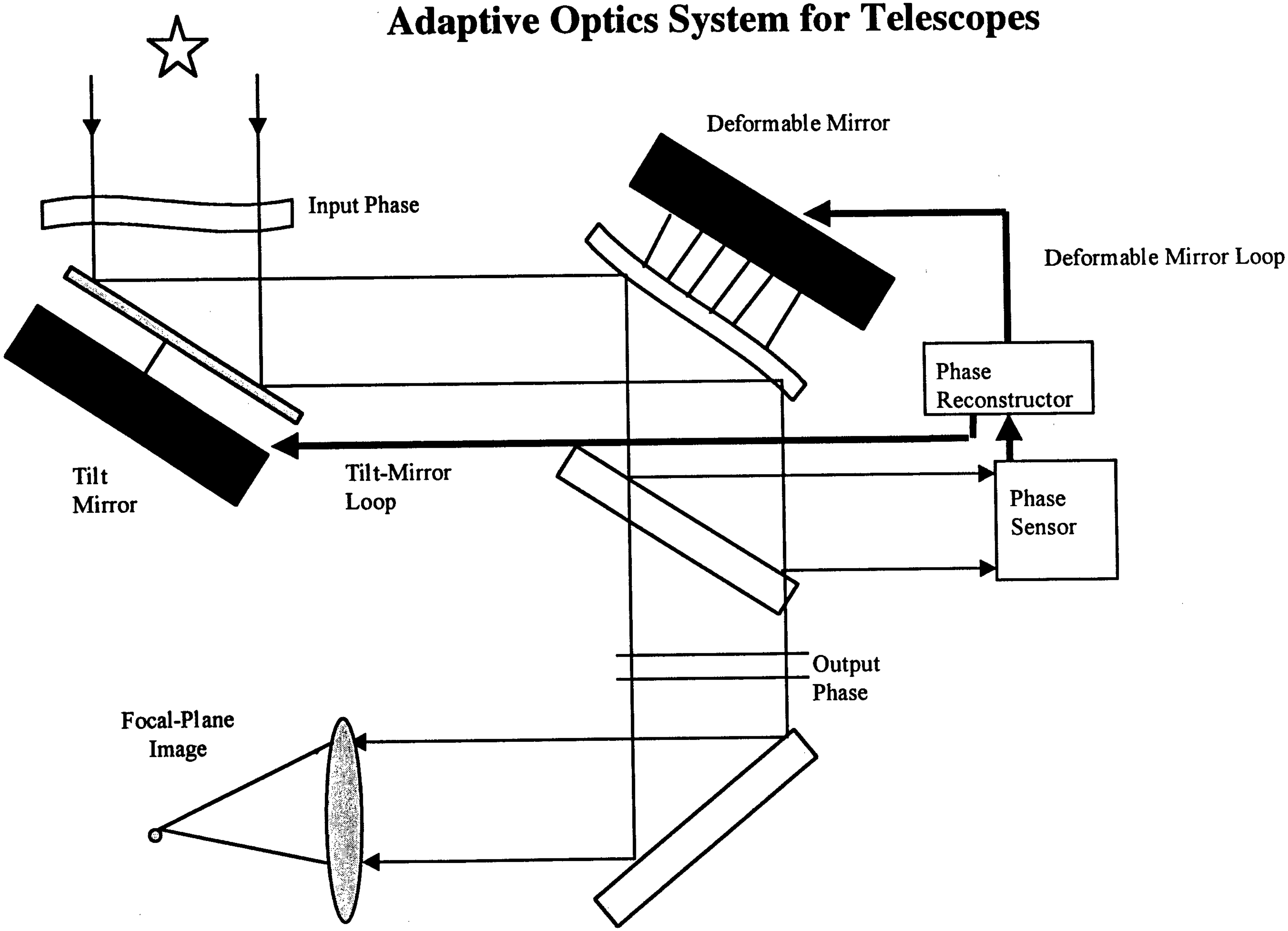
Cut-Away View of a Deformable Mirror



This slide shows the essential components of an adaptive optics phase-compensation system used in astronomy. The phase sensor measures the first derivative of the phase difference between the incoming wavefront and the surface figure imposed by the tilt and deformable mirrors. The phase reconstructor computes residual phase error and subsequently applies it to the two active optical elements.

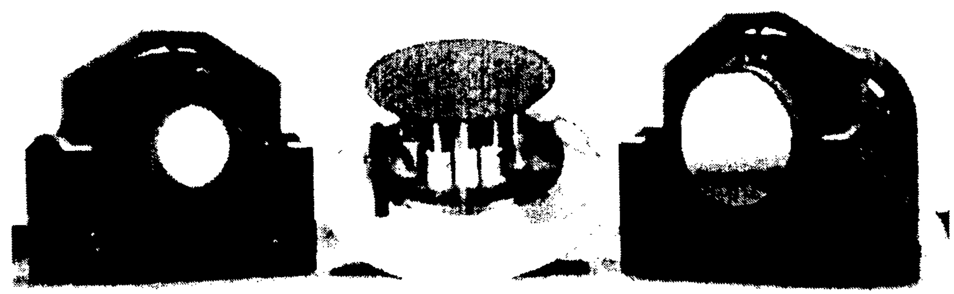
The deformable mirror is the active wavefront corrector, and its characteristics largely determine the capability of the entire adaptive optics system. The important characteristics of a deformable mirror are the actuator density, influence function, stroke, and response speed.

Adaptive Optics System for Telescopes



This slide shows finished deformable mirrors. A system can use several mirrors for correction. Most applications, however, only require one mirror.

Finished Deformable Mirrors



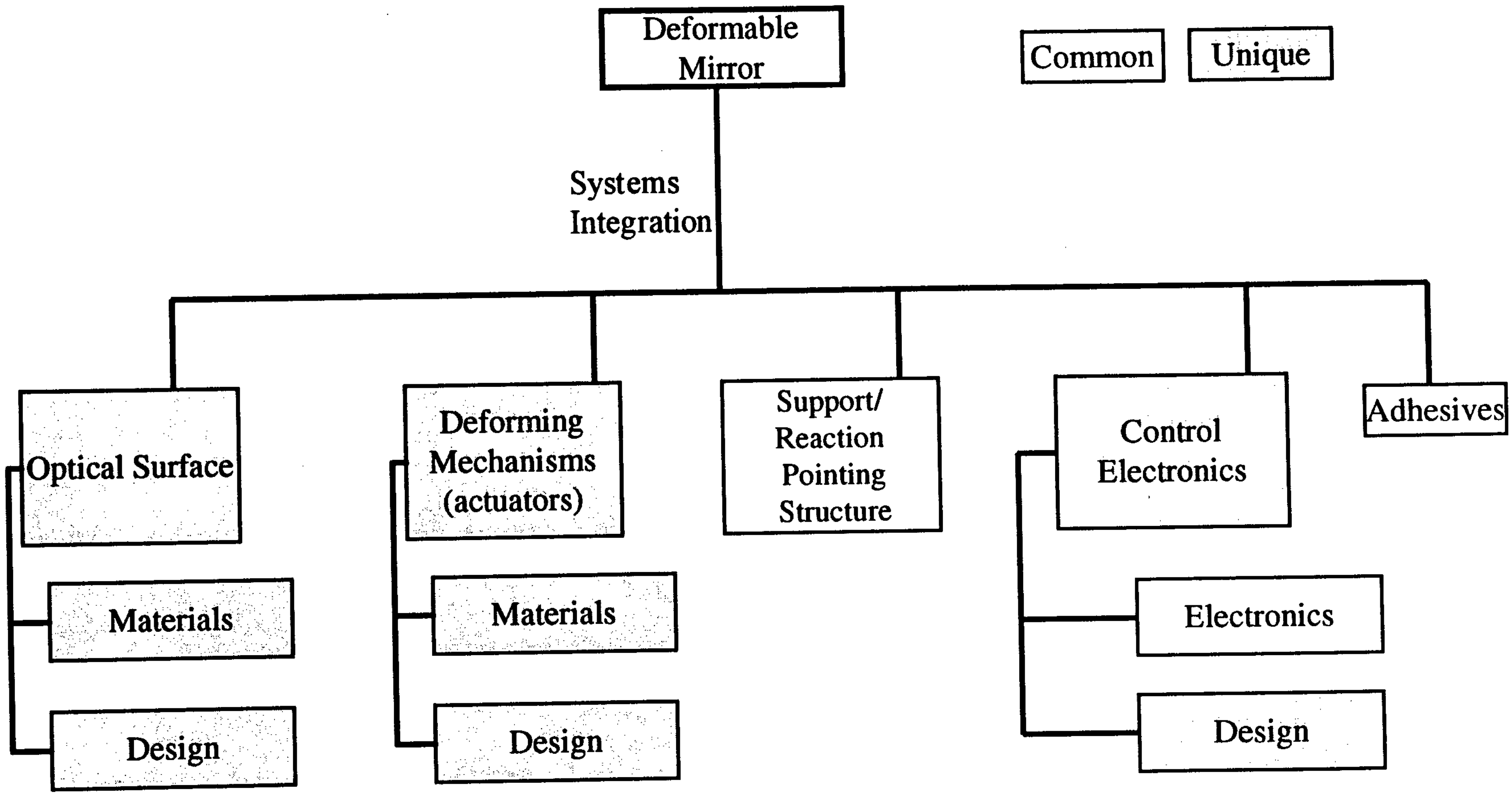
A Deformable Mirror system has the following major features:

- Optical surfaces that can be deformed in a rigid body and/or flexible manner. These optical surfaces may be unique, depending on the application. For example, specialized optical designs are required for deformable mirrors subjected to continuous high-energy radiation (Laser Weapons) or extreme short duration high-energy pulses [Department of Energy (DOE) Testbeds].
- Deforming mechanisms that consist of actuators constructed of piezoelectric or voice coils (electromagnetic coils) and usually assembled in a stack arrangement that pushes against the back surface of the mirror to create optical deformation modes. These actuators can also be used in a manner that results in rigid body rotations and displacements of the entire optical surface.
- Support/reaction hardware for mounting the deformable mirror to another platform.
- Sophisticated analog and digital electronics to sense and determine the optical system's configuration and provide drive signals and power to the deformable mirror actuators.
- Use of adhesives to attach the mirror plate to the actuator.

Although the electronics and supporting structure are off-the-shelf, the integration of the sensors, actuators, optics, and controls is critical to the operation of the deformable mirrors. Systems integration is not necessarily a "part," but the knowledge and experience is definitely a component of the deformable mirrors. **Only a few companies have systems integration expertise.**

On this slide, the unshaded areas identify the parts of the deformable mirror system that are common to precision structures and electronic manufacturing capabilities in U.S. industry. The shaded areas represent unique items for deformable mirror design and manufacturing that are restricted to a few optical systems and/or piezoelectric material/actuator manufacturers. At the beginning of this study, we thought that the adhesives to be used for deformable mirrors would be unique because of the different environments the adhesives were required to withstand. However, the large number of suppliers and formulations that exist for this application exceeds the demand for deformable mirrors. Therefore, we did not view adhesives as a critical component to study further.

Distinguishing Features of Deformable Mirrors



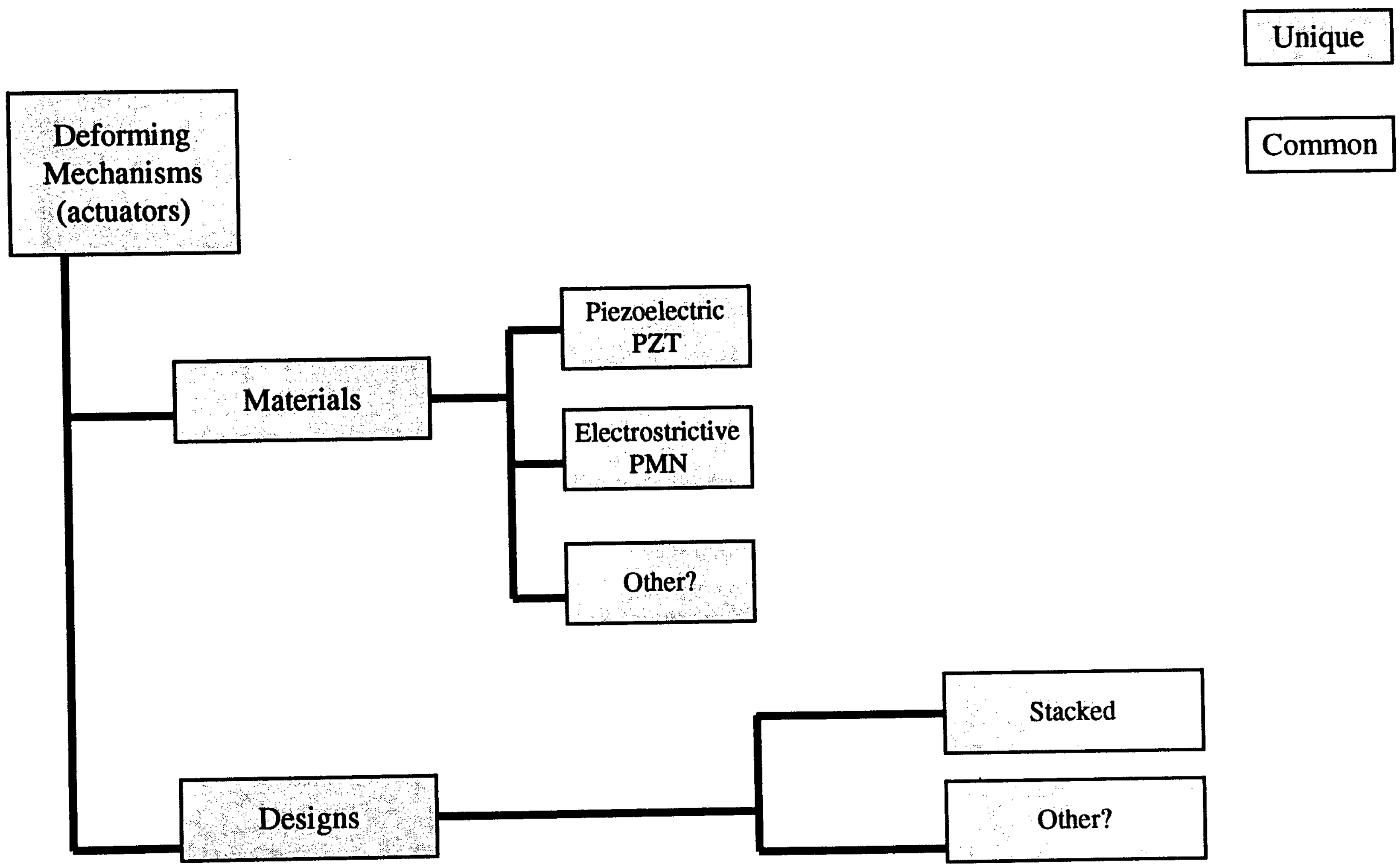
This slide details the deforming mechanisms on a deformable mirror. There are a variety of different designs for deformable mirrors. The most common type employs piezoelectric lead zirconate titanate (PZT) and electrostrictive lead magnesium niobate (PMN) actuators to rotate, displace, or deform a mirror surface. These actuators can be made out of either polymer or ceramic materials. Other materials could include single-crystal piezoelectric materials; however, this is a new area that only universities are investigating. Actuator systems and/or applications have not been developed for these new materials. Only the material properties of the single crystals are being determined at this time.

Optical surface deformations are commonly accomplished by using force actuators attached to the back of the deformable mirror's thin mirror structure. These actuators can apply a direct force to the mirror when charged by a signal.

As the number of actuators increases per mirror surface area, complex deformation patterns can be generated. For example, some deformable mirrors can employ hundreds of actuators within a 0.3-m mirror diameter. The dynamic response of the actuators can be as high as several hundred hertz.

When used in an optical system, these devices reduce the overall optical degradation of the system caused by atmospheric turbulence and other effects. The number of deformable mirror actuators per mirror surface area and the mirror system frequency response drive the control software complexity and become limiting design constraints.

Deforming Mechanisms for Deformable Mirrors



This slide details the optical surfaces on a deformable mirror. One of the most common surfaces used is single-crystal silicon. Silicon is relatively inexpensive and readily available. Although the material is inexpensive, the optical polishing and mirror coatings are expensive because of the amount of time and labor involved. Also, silicon must be cooled, and this process adds an additional weight penalty to the system.

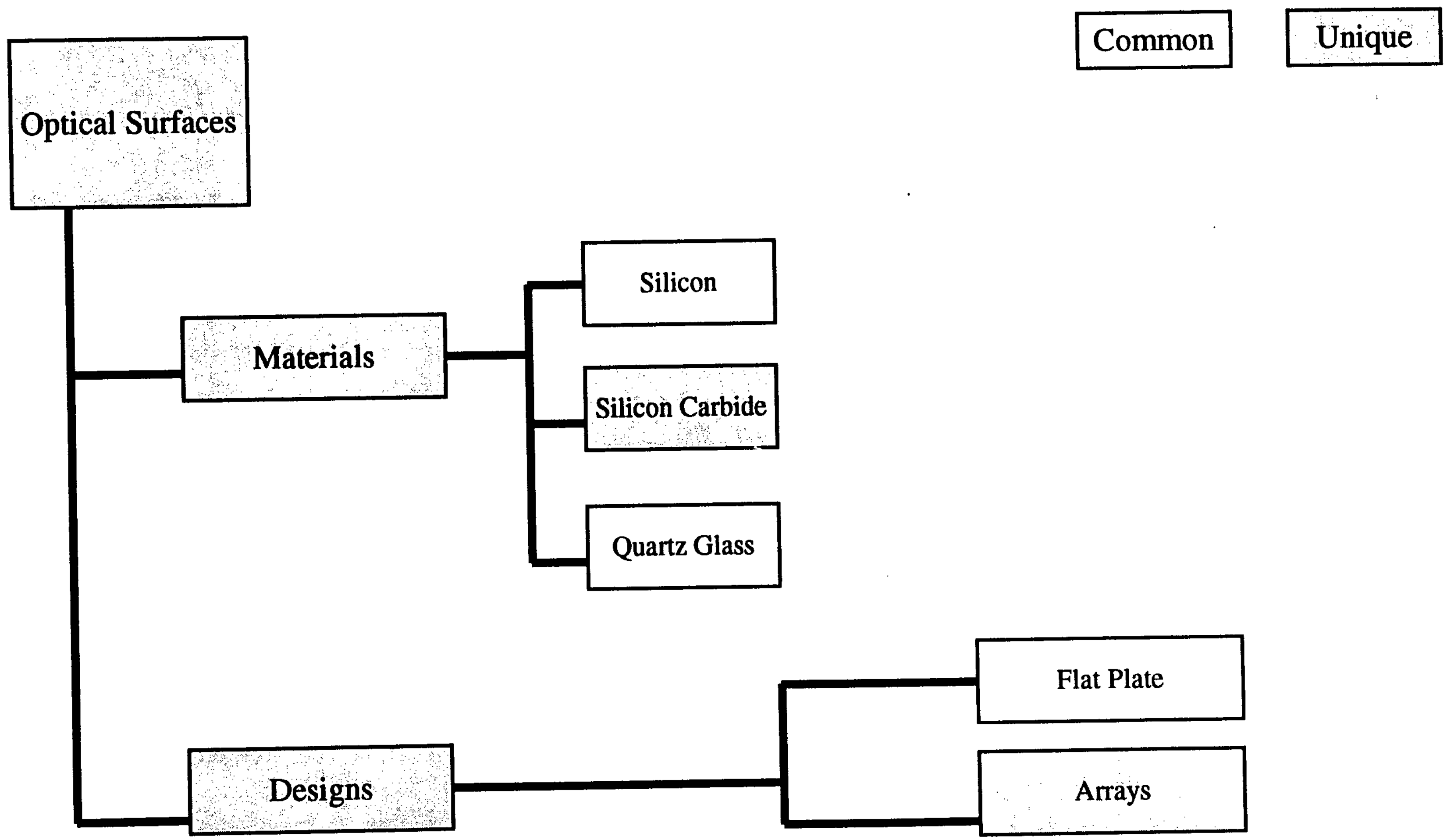
Silicon carbide (SiC) is also being used. The advantages of SiC are its light weight, its cryo optical performance of glass to visible/ultraviolet (UV) wavelengths, and its superior thermal stability over wide temperature ranges and large thermal gradients. However, when using SiC, polishing the optical surface and applying optical coatings are more difficult.

Only a few deformable mirrors that use SiC for the mirror have been produced to date. For ground telescopes, the single-crystal silicon, or even glass, is sufficient.

New designs have been explored because of the non-availability of large-diameter mirrors. For example, instead of the more traditional flat-plate, arrays of small mirrors have been considered.

Since the silicon industry is well established, we did not ask the optics companies for the amount of information that we requested from the deformable mirror and actuator suppliers. At the end of this document, one primary optic supplier and a systems control/ software supplier are given.

Basic Systems for a Deformable Mirror



Deformable mirrors can compensate for time-varying optical distortions in several areas:

- **Atmospheric effects.** Light traversing the atmosphere undergoes distortions that can blur an image or compromise the focus of an optical system. These distortions cause stars to "twinkle." Such distortions can be sensed and then corrected in real time by modifying the surface of a deformable mirror. This technology is currently used in surveillance optics, laser weapons, and astronomical telescopes.
- **Distortions in the lab.** Lab-based optical systems can be adversely affected by distortions from temperature variations and vibrations. This is especially true of high-power laser systems that are designed to produce high-energy densities at laser foci. The National Ignition Facility (NIF) and the Atomic Vapor Laser Isotope Separation (AVLIS) projects, both at Lawrence Livermore National Laboratory (LLNL), require deformable mirrors to remove such distortions. NIF will require about 200 deform-able mirror units, and AVLIS will require 10 deformable mirror units. Both of these facilities may create a long-term, low-level need for deformable mirrors.

Deformable Mirror Applications

- Ground-based telescopes
- Next-generation telescope (space)
- Surveillance
- Laser weapons systems
- Inertial confinement fusion (NIF at LLNL)
- Isotope separation (AVLIS project at LLNL)
- Laser communications

This slide attempts to show the progression of the simplest deformable mirrors to the most complex deformable mirrors. These are not quantified categories, so it is possible that different temperatures and accuracies are required for each type. Repairing ground-based systems is much easier than repairing space-based systems but reliability is still critical for any of these systems, especially when a deformable mirror can cost as much as $100,000. Most of the ground-based systems are liquid-cooled since weight is not an issue. For space-based mirrors or the ABL, other techniques are being explored to minimize the amount of heat in the system.

Deformable Mirror Comparisons

Applications	Environment Temperature Issue	Heat Dissipation	Accuracy	Bandwidth	Reliability and Repairability
Ground telescopes	No	No	Yes	High	*
LLNL NIF	No	Yes	Yes	High	*
LLNL AVLIS	No	Yes	Yes	High	*
Surveillance Satellites	Yes	No	Yes	Low	Yes
Laser Weapon Systems	Yes	Yes	Yes	Low	Yes
Laser Communications	?	?	?	?	?

* Note: Ground-based deformable mirrors are not subjected to the same vibrations and environmental conditions to which the space-based deformable mirrors are subjected. The ground-based deformable mirrors are also less expensive to replace than the space-based deformable mirrors. These areas are factored into the design and cost of the deformable mirror for a given application.

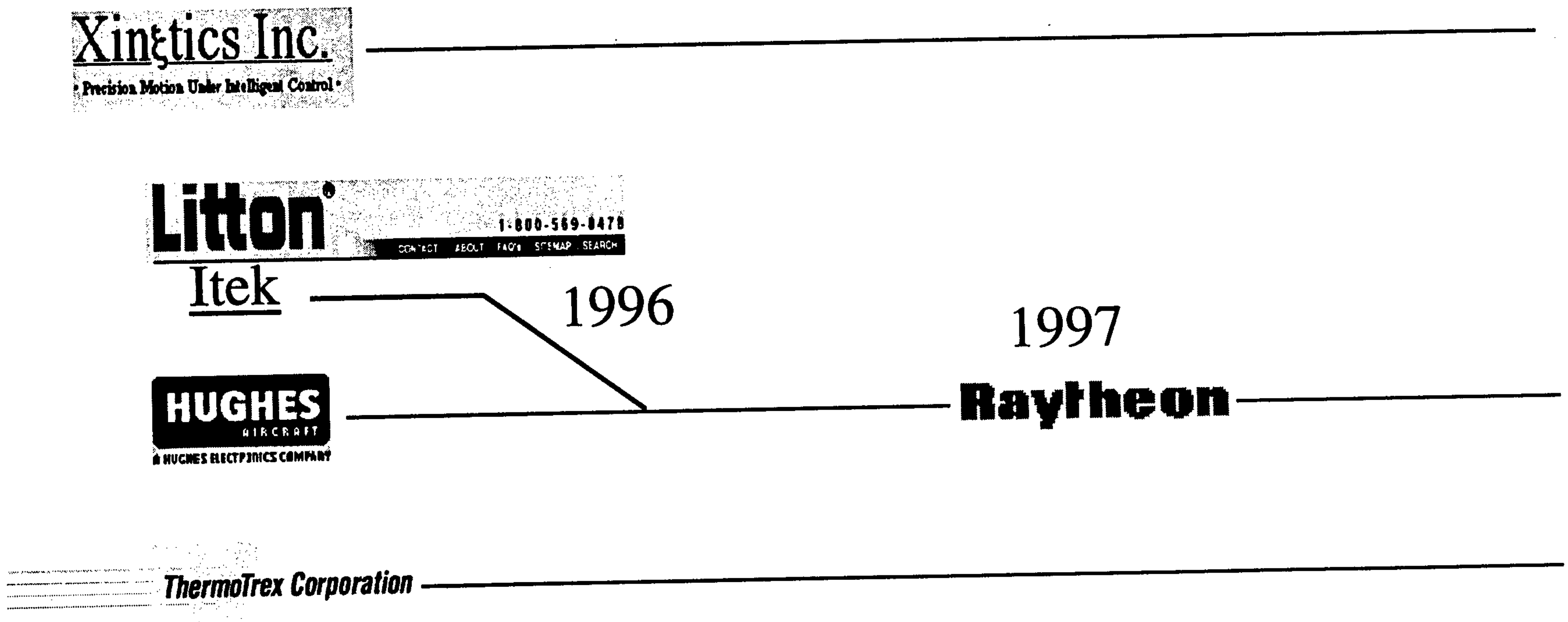
Xinetics has been producing deformable mirrors since 1993. Xinetics has developed an in-house knowledge base in assembling deformable mirrors, constructing electro-strictive actuators, and polishing SiC. Nineteen of the 25 employees at Xinetics had previously worked for Itek.

Raytheon purchased Hughes Danbury Optical Systems in 1997. The former Hughes, which had deformable mirror manufacturing capabilities of its own, merged with Itek (Litton) in 1996, making it a major producer of deformable mirrors. In addition, Raytheon's Danbury office gives their deformable mirror team great optical and engineering depth from which to draw. Raytheon relies on its Hughes Optical to provide the optics for the deformable mirrors and an outside vendor for its actuators. (Raytheon did not reveal their suppliers.) Raytheon employs four people who had previously worked for Itek.

Thermotrex, a subsidiary of Thermo Electron Corp., has made deformable mirrors for several years and is in the running for a major deformable mirror contract with the LLNL NIF facility. Two of Thermotrex's employees had previously worked at Itek.

A representative from Lockheed Martin Missiles and Space also stated that they have developed an in-house capability to build their own deformable mirrors. This capability was developed after Department of Defense (DoD) representatives recommended that Lockheed Martin not depend entirely on one source for deformable mirrors (i.e., Xinetics). We have not been able to identify specifically the DoD representatives who made this recommendation to Lockheed Martin. However, Lockheed Martin has built one mirror and intends to keep one person involved in this technology on a yearly basis. The mirror that they have built was to have been tested in July at Phillips Lab; however, to date, no results have been provided to the Institute for Defense Analyses (IDA).

Deformable Mirror Producers



Dr. Veitch visited Xinetics and talked directly with the president, Mark Ealey. Mark is a former employee of Itek Optical Systems. He started Xinetics in 1993 and has produced 26 deformable mirrors over the last 5 years, in addition to some other smaller products for military and commercial use. The company has 25 employees. Six are structural engineers, and the remainder are electro-ceramists. Xinetics manufacturing space is ~12,000 square feet and is equipped with fairly modern equipment as compared with other small ceramic processing businesses in the area. Eighty-five percent of their income results from government contracts. The remainder is from commercial develop-ment.

One strength in Xinetics operation is their ability to control raw material's purity for the deformable mirror actuators. One of the problems (which also hurt Itek's business) is the lead oxide purity needed for the PZT and PMN actuators. Most of the starting powders (lead oxide, zirconium oxide, niobium oxide, and magnesium oxide) come pre-mixed but can have purity ranges over ±20 percent. This can have a significant impact on the consistency of actuator properties. To decrease this variability, Xinetics purifies the starting powders and mixes them to yield the highest purity material for the actuators. They are then able to obtain consistent properties from run to run. One of the reasons that Itek was unable to maintain their deformable mirror business before Hughes purchased them was because they had lost a good raw material supplier and did not want to invest in purifying the starting powders. They tried other vendors of mixed powders but were not able to obtain consistent actuator properties.

Xinetics Inc.

- Private company outside of Boston
- Mark Ealey, president, started the company after leaving Itek
- 25 employees: 6 structural engineers, the rest are electro-ceramists
- At start of this study, identified as the ONLY company that was able to produce deformable mirrors
- Has produced 26 mirrors to date
- Income: 85 percent government funds, 15 percent commercial development

A listing of the deformable mirror suppliers that we identified as having produced or having the capability to produce deformable mirrors is provided under a separate cover. This list includes proprietary information regarding government sales, independent research and development (IRAD) investment in deformable mirror technology, and so forth.

Deformable Mirror Suppliers

Proprietary Information
supplied under a different cover

A list of actuator suppliers for deformable mirrors is provided under a separate cover because of proprietary information. All these companies have the capability to supply actuators for this application, but none have actually been involved in this area in recent years.

Actuator Suppliers

Proprietary Information
supplied under a different cover

This table lists Adaptive Optics Associates and SSG, Inc., as control systems and mirror suppliers, respectively. Both suppliers have participated in programs with the deformable mirror suppliers; however, they do not produce the entire deformable mirror system themselves. The main deformable mirror supplier, Xinetics, produces and integrates all the components for the deformable mirrors in-house. The two companies listed in this table rely on outside vendors for the mirror components and have limited expertise in systems integration.

CONTROL SYSTEMS AND OPTICS SUPPLIERS

COMPANY NAME	ADDRESS	CITY	STATE	ZIP	PHONE	FAX NUMBER	POC	PRODUCTS	SPECIAL CAPABILITIES/ UNIQUE PROCESSES	SUBSIDIARY RELATIONSHIP TO ANOTHER COMPANY
Adaptive Optics Associates	54 Cambridge Park	Cambridge	MA	02140	617-864-0201	617-864-1348	Martin Levine	Image Processors	Systems integration/software	United Technologies/
								Machine vision	supplier unique to DM	Hamilton Standard
								Precision motion analysis	needs	
								High-resolution line and area		
								High speed cameras		
								Adaptive optic control systems		
								Microlens arrays for HDTV		
								Laser diodes		
SSG, Inc.	65 John Spin Rd.	Wilmington	MA	01887	978-694-9991	978-694-9922	Joseph Robichaud	Mirrors for telescopes, SiC		
								mirrors for DMs		

Microelectromechanical systems (MEMS) technology offers the potential for improve-ment in deformable mirror performance, including precision of deflection and speed (or rep rate) of the mirror's adjustments.

A Boston University group recently developed a continuous membrane deformable mirror using MEMS construction techniques with 9 actuators and a stroke of 0.8 microns. A 400-element mirror with a 2-micron stroke is in development.

A Delft University group has been developing a varifocal mirror using MEMS techniques. OKO Technologies, a commercial offshoot of the Delft University group, offers 19- and 37-actuator MEMS-produced deformable mirrors with a 15-mm diameter, 500-Hz maximum frequency range, and a 9-micron maximum deflection at the mirror center.

Alternative Technology to Piezoelectric Actuators

- MEMS-produced mirrors, actuated by electrostatics
- Active research program at Boston University; related research in varifocal mirrors at Delft University in The Netherlands
- MEMS adaptive optics available from industry: OKO Technologies (Delft)

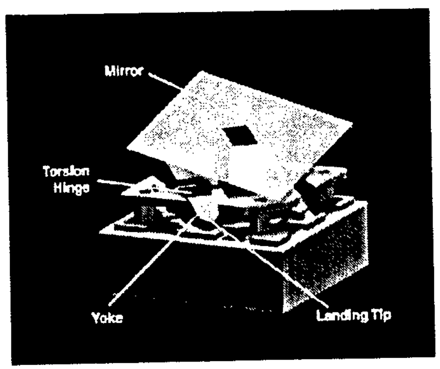
This slide shows two different approaches to using MEMS mirror technology in applications outside of deformable mirrors.

Texas Instruments is producing digital micromirror devices (DMDs), which are highly pixilated mirrors for use in high-definition television (HDTV) and video applications. Stanford University is producing tunable laser cavities using MEMS techniques.

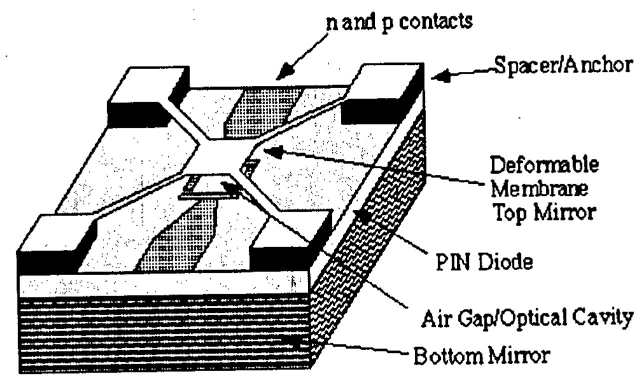
Note: While these devices are not deformable mirrors themselves, the MEMS construction techniques used to produce them may influence and improve future deformable mirror production.

Applications of MEMS Mirror Technology Outside Deformable Mirrors

- Texas Instruments' MEMS mirror technology for HDTV and video applications



- Stanford University research in tunable opto-electronic devices



Energen, Inc., is using magnetostrictive materials to develop actuators for cryogenic deformable mirrors. Magnetostrictive actuators have advantages over piezoelectric actuators because of low-voltage operation and negligible power dissipation. The magnetostrictive materials come from the family of alloys consisting of $Tb_{1-x} Dy_x Zn$, which exhibit saturation magnetostrictions of over 0.5 percent with little hysteresis, resulting in a compact and lightweight actuator. When excited with high-current density superconducting coils, the actuators provide very precise positioning capability with negligible power dissipation.

Alternative to Piezoelectric Actuators for Deformable Mirrors

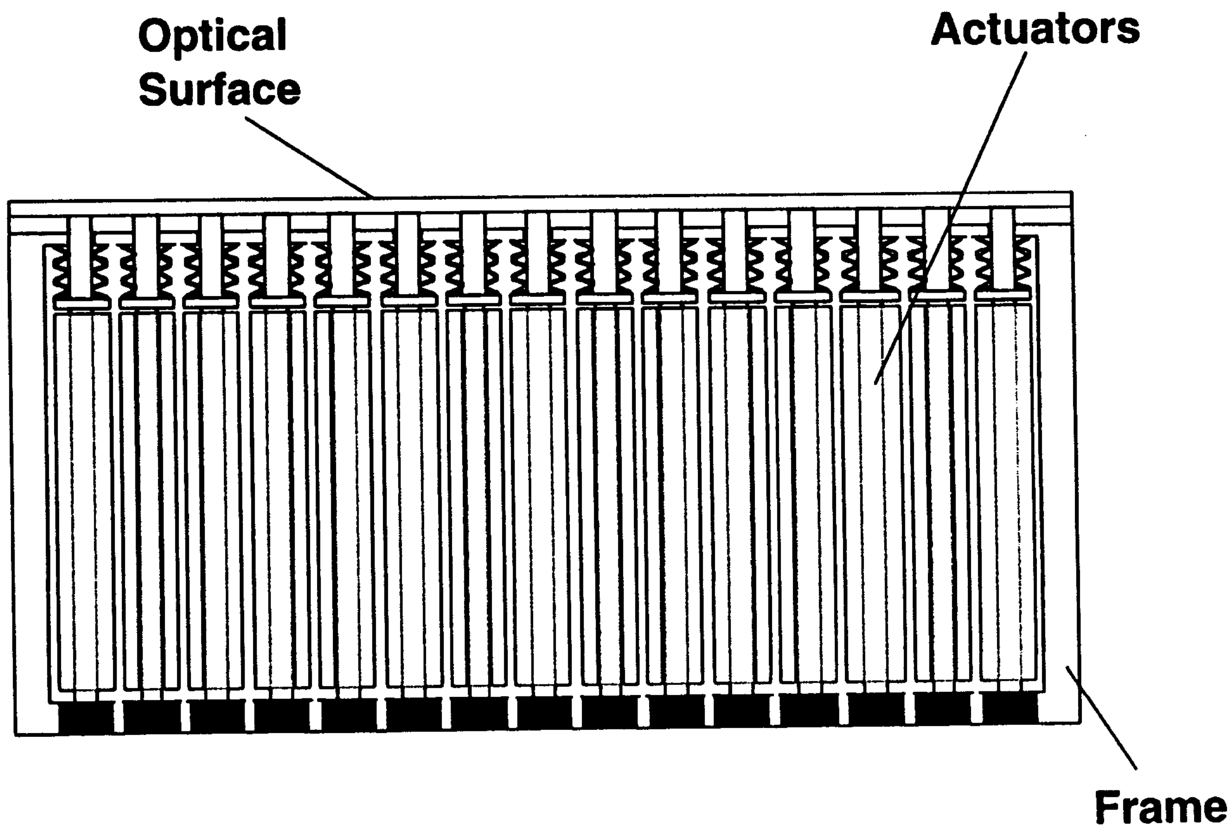
ENERGEN, INC

Magnetostrictive actuators provide:

- High spatial frequency resolution
- Greater wavefront error correction
- Low-voltage operation
- High pulling and pushing forces
- Negligible power dissipation

This slide was taken from a presentation by Energen, Inc., at the Next Generation Space Telescope (NGST) review in July 1997. Energen is pursuing a design similar to the "traditional" deformable mirror; however, instead of using piezoelectric materials for the actuators, they are developing magnetostrictive materials for this application.

Mirror Conceptual Design



The table shown on this slide is an estimate of the demand for deformable mirrors from (1999–2016):

- Space-Based Lasers (SBLs) may be deployed within the next two decades for ballistic missile defense (BMD). SBLs would propagate a high-energy laser beam from space through the atmosphere to destroy a missile during its initial stages of launch. A typical SBL design proposal would have one deformable mirror per platform. This mirror would be approximately 0.3 m in diameter, with 240 actuators per mirror. Current plans call for a fleet of about 20 to 24 satellites for complete global coverage, but only one SBL system will be built as a prototype at this time.
- Airborne Lasers (ABLs) under development by the Air Force would contain a laser weapon with sufficient capacity to destroy a tactical ballistic missile above the cloud layer. The ABL program will field seven aircraft. Each aircraft will use one deformable mirror. The ABL deformable mirrors are approximately 0.25 m in diameter. The current plan calls for a demonstration vehicle in 2002, with all seven aircraft deployed by 2008.
- Ground-Based Lasers (GBLs) are being developed by the Army for tactical missile and aircraft defense. Discussions with the Theater High-Energy Laser (THEL) office indicate that the current design does not employ deformable mirrors but that a future fielded weapon may. The actual number of deformable mirrors per platform is unknown at this time.
- Earth Surveillance Systems could use deformable mirrors; however, discussions with this community indicated that it has not yet been determined if new surveillance systems will use deformable mirrors for primary optics or laser communication systems. If deformable mirrors are incorporated, the number would be on the order of tens in the next 10 years.
- Recent applications of deformable mirrors to ground-based astronomy systems have indicated improvement in existing systems by reducing image degradation caused by atmospheric turbulence effects. A small number of deformable mirrors are planned for major NASA-sponsored telescope systems. If this community seriously embraces this technology, a large number of deformable mirrors could be required. Any organization with a telescope 1 m or larger in diameter (approximately 100 worldwide) may find it cost effective to install a deformable mirror for performance enhancement.
- Laser Communications can use deformable mirrors (required numbers not shown in the table), and discussions with the communication community indicated that deformable mirrors might improve the performance of certain types of laser communication systems. To estimate the deformable mirror demand generated by these systems, further study is needed to identify which type of laser communication system requires deformable mirrors.
- Several DOE Testbeds are currently in design and use many deformable mirrors in their optical paths. The NIF requires as many as 200 deformable mirrors. These deformable mirrors are about 15 × 15 inches with approximately 40 actuators, each operating with a 100-Hz bandwidth. These deformable mirrors are designed to handle extremely high-energy laser loads. Another DOE project requiring about 15 deformable mirrors is the AVLIS testbed that will demonstrate a new, low-cost method of making fissionable materials. The NIF and AVLIS projects are planned to be built within the next 4 years.

Estimated Demand for Deformable Mirrors

System	Year																
	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
Platforms																	
SBL			2														
ABL		1	1	1	1	1	1	1									
Army GBL																	
Surveillance	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Ground Testbeds																	
NASA Ground Telescopes					4	2											
Laser Communications																	
DOE NIF	66	66	66														
DOE AVLIS	3	3	3														
Total	69	70	72	1	5	3	1	1									

As the team obtained more data on deformable mirror technology, it became apparent that this technology was not part of a large-scale production industry. The limited demand for this specialized component and the fact that each mirror is tailored to a given application (i.e., cannot be mass produced like a semiconductor) suggest that the growth potential over the next 10 years will be small. The exception to this assess-ment may be the development of the DOE NIF and AVLIS facilities and the European (United Kingdom and France) AVLIS-type facilities.

Deformable mirrors is a "thin market"

- Low productivity
- Each mirror is dependent on an application
- Little growth in the market over the next 10 years, with the exception of the DOE facilities described

Our recommendation, based on the data to date, is that this technology area does not require close monitoring at this time.

Overall Assessment of Deformable Mirror Suppliers

- Three companies have been identified as deformable mirror suppliers
- Component suppliers (existing and potential) are in good supply
- New technologies are being developed to advance the state of the art
- Vertical integration is not an issue in this area because of the current number of deformable mirror suppliers and the component industries available. However, this is a “thin” market, and the number of suppliers could change rapidly.

We recommend that this area should be re-examined in 2 or 3 years or as the DoD and DOE funding environment, the demand for deformable mirrors, and the manufacturing capability of the deformable mirror suppliers change.

Aerospace Corporation, also a Federally Funded Research and Development Center (FFRDC), produced a report that specifically addressed U.S. contractor capabilities in producing lightweight adaptive space optics for SBL application. The Space and Missile Systems Center (SMSC) under the Air Force Materiel Command SBL PMO initiated the study based on its concern that limited sources existed for various components of the SBL. Aerospace Corporation addressed optics fabrication, optical control, and structural control technologies related to the SBL. Their report identified areas needing additional technical development: large optical components, polishing large optical components, and coating large optical components. Deformable mirror technology was not considered a show stopper for the SBL. Aerospace Corporation identified Xinetics and Raytheon as deformable mirror suppliers; however, they did comment that Raytheon might need some time to get the former Itek's capability back on line.

Assessment of U.S. Contractor Capabilities in Lightweight Adaptive Space Optics for SBL Applications

Aerospace Corporation

This table was taken from the Aerospace Corporation's report on U.S. contractor capabilities to produce lightweight adaptive space optics for the SBL.

Table 1. Contractor Capabilities

	Large Blanks	Large Optics	LightWt Space	Optical Finish	Large Coatings	Active Primary	Deploy-ment	Vib Isol Smart Struct	Beam Control	WF Sensors	Deform Mirrors	HOE's	ATP
AOA										X			
Ball							X		X				
Boeing									X	X			X
COI			X	X									
Contraves USA		X		X		X							
Corning	X												
CSA								X					
DSI					X								
Eastman Kodak		X	X	X	X	X		X		X			
Harris							X	X					
Honeywell								X					
Kaman									X				
Lockheed-Martin							X	X	X	X			X
OCLI					X								
Raytheon OSI		X	X	X	X	X	X		X	X	X	X	X
Schott	X												
SSG			X	X									
SVS						X	X		X	X			
Tinsley	X		X										
TRW							X		X				
U of Arizona	X	X		X									
Xicera	X		X										
Xinetics											X		

This slide was taken from an industrial base data overview for the SBL Readiness Demonstration. Different elements of the program were addressed in detail. These elements focused on the current industry and its ability to supply elements for the SBL. For the optical payload element of the program, specific processes and suppliers were identified. It appears as though Xinetics does provide most of the expertise in producing the deformable mirror but is still dependent on several other contractors.

Optical Payload Element

- Current ALI beam expander activities use specific suppliers
- Deformable mirror, fast steering mirror, secondary
  - Boule production: Silicon Crystals, Silicon Castings
  - Backing structure, actuators, polishing: Xinetics
  - Deposition of coatings: LPC, Star Optics, Lohnstar (DM)
  - Machining secondary center hole: Advanced Ceramics
- Wavefront sensor focal plane arrays:
  - Platinum silicide arrays: Lockheed Fairchild Imaging Systems
  - Holographic Optical Element (HOE) processing: Raytheon Optical Systems, Inc.
    - Only demonstrated source
  - Large optics fabrication: ROSI

The SBL PMO identified a limited number of sources for uncooled resonator optics elements. This slide itemizes the different components of the laser payload element and the company that has expertise for that particular component. Xinetics provides the integrating structure for the deformable mirror system. This is critical for this system because it must take into account the thermal and vibrational environment. This is not a trivial task. Xinetics' expertise in integrating all the components for a deformable mirror is just as valuable as fabricating the actuators or polishing the optical surfaces.

Laser Payload Element Technology Base Issues

- **Limited sources for uncooled resonator optics**
  - Optical coatings: Laser Power Corp. (LPC), Star Optics
  - Silicone carbide and single silicone machining: McCarter Machine and Tooling
  - Single crystal silicone boule production: Silicon Crystals, Silicon Castings
  - Silicon "brick" brazing: Scarrott
  - Silicone carbide integrating structure: Xinetics
  - Constant thermal expansion (CTE) integrating structure fabrication: Xinetics
  - Diamond turning of resonator optics: Lawrence Livermore National Lab Large Optics Diamond Turning Machine (LODTM)

This slide is an example of the survey sent to the deformable mirror suppliers.

Attachment 2
IDA Deformable Mirror Industrial Capacity Survey
Page 1 of 2
Proprietary Data
Handle Via Official Channels

General Company Data:

When was the company established? ______________________

What is the current number of employees? ______________________

How many engineers are currently employed (including consultants)? __________

Is your company a subsidiary of another firm? What is that relationship?

Does your firm have any foreign ownership? If so, by whom and at what percent?

General Sales Information:

What were the company's total sales for 1997? ______________________

What percent of total sales is for defense-related projects? ________/________

Products and Capabilities:

Please briefly describe your company's major products and any essential product development issues.

This slide is a continuation of the survey sent to deformable mirror suppliers. A similar survey with a slightly different emphasis was also sent to the component-level suppliers.

IDA Deformable Mirror Industrial Capacity Survey
Page 2 of 2
Proprietary Data
Handle Via Official Channels

DM Industrial Capacity:

What percent of total sales was for DMs? ______________________

How many engineers (including consultants) are working on DM technology? ________

Please mention any special capabilities or unique processes your company has related to the fabrication and calibration of DMs.

What is your current level of production for DMs?

Can you identify any issues regarding materials or sub-components necessary to produce a DM which may contribute to an unstable DM industrial base in the future?

Do your DM products have dual-use (defense and non-defense) potential? For what applications are your DMs used?

What is your total R&D funding for 1997 and what percent was spent on DM technology?

What do you see as the current and future market demands for DMs?

This slide is an excerpt from the *Commerce Business Daily* (CBD) dated June 2, 1998. The team contacted the primary deformable mirror suppliers and most of the actuator companies as early as February. After several conversations with the different companies and customers, the team developed a survey for the companies to complete. (The previous slide showed a copy of one of the surveys.) Each of the companies was called before the surveys were faxed or sent via overnight mail in early June. When the companies were called a week after receiving the surveys to see if they wanted IDA to sign proprietary agreements or if they had questions, most were reluctant to disclose their business information. When asked what had changed since our previous conversations, we were directed to the CBD Program Research and Development Announcement (PRDA) on June 2, 1998. All the primary and several secondary deformable mirror suppliers are in the process of submitting proposals for this PRDA. Recently, we have been able to obtain proprietary information from the deformable mirror suppliers. This information is provided under a separate cover.

[Commerce Business Daily: Posted June 2, 1998]
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SUBJECT: A--HIGH RELIABILITY DEFORMABLE MIRROR
SOL PRDA NO 98-D01
POC Barbara Steinbock,Contracting Officer, 505/846-2246; Lt Jeff Barchers AFRL/DES 505/846-5671
DESC: HIGH RELIABILITY DEFORMABLE MIRROR. PRDA NO. 98-D01. The Air Force Research Laboratory (AFRL) is seeking proposals for design and fabrication of a High Reliability Deformable Mirror.

BACKGROUND AND PRIMARY GOALS: The goal of this effort is to design and build 1000-actuator class deformable mirrors with close actuator spacing, high reliability and low cost. Innovative approaches to accomplish these goals are strongly encouraged. The deformable mirror will be used in adaptive optics systems designed to correct phase distortions created by atmospheric turbulence. The deformable mirror will be used in a closed loop servo having a control bandwith of 500 Hz (at -3 dB error rejection). The mirror must have inter-actuator spacing of less than 7.0 mm with individual actuator stroke greater than plus/minus 2.0 micrometers and adjacent actuators restricted so that differential stroke does not exceed 2.0 micrometers

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GLOSSARY

ABL	Airborne Laser
AVLIS	Atomic Vapor Laser Isotope Separation
BMD	ballistic missile defense
CBD	*Commerce Business Daily*
CSED	Computer and Software Engineering Division
CTE	constant thermal expansion
DM	deformable mirror
DMD	digital micromirror device
DoD	Department of Defense
DOE	Department of Energy
FFRDC	Federally Funded Research and Development Center
FTC	Federal Trade Commission
FY	Fiscal Year
GBL	Ground-Based Laser
HDTV	high-definition television
HOE	Holographic Optical Element
IDA	Institute for Defense Analyses
IRAD	independent research and development
LLNL	Lawrence Livermore National Laboratory
LODTM	Large Optics Diamond Turning Machine
MEMS	microelectromechanical systems
NASA	National Aeronautics and Space Administration
NGST	Next Generation Space Telescope
NIF	National Integration Facility
PMO	Program Management Office
PMN	lead magnesium niobate
PRDA	Program Research and Development Announcement
PZT	lead zirconate titanate
SBL	Space-Based Laser
SiC	silicon carbide
SMSC	Space and Missile Systems Center
THEL	Theater High-Energy Laser
UV	ultraviolet
WBS	work breakdown structure

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13. ABSTRACT ***(Maximum 180 words)***

The deformable mirror subtier task was part of the larger industrial study that the Institute for Defense Analyses (IDA) conducted during FY 1997–1998. The objective of the study was to determine if there were more potential deformable mirror suppliers than the one company that was identified and to identify possible alternatives to the present state of the art for deformable mirrors. Possible component suppliers who could produce actuators or the flexible optical surfaces for the deformable mirrors were also assessed. Because of time constraints, the scope of the task was limited to unclassified systems and U.S. deformable mirror producers. The overall assessment identified three deformable mirror producers: Xinetics, Thermotrex, and Raytheon. Several deformable mirror component suppliers were also determined in this study. New technologies including Microelectromechanical Systems (MEMS) mirrors and magnetostrictive materials for actuators showed potential in replacing or augmenting the current deformable mirror technology. It was also determined that vertical integration was not an issue in the deformable mirror area because of the current number of deformable mirror suppliers and the component industries available. However, it was concluded that the deformable mirror market was "thin" and could change rapidly. The final recommendation was that the deformable mirror area be re-examined as the Department of Defense (DoD) and Department of Energy (DOE) funding environment, the demand for deformable mirrors, and manufacturing capability of the deformable mirror suppliers change.

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