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Design of Lightweight Primary Mirrors for Optical Imaging Devices

by

Cory J. Hamelin, B. Eng.

A thesis submitted to the faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of

Master of Applied Science

Ottawa-Carleton Institute for Mechanical and Aerospace Engineering
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January 2002

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of the thesis

Design of Lightweight Primary Mirrors for Optical Imaging Devices

by

Cory J. Hamelin

in partial fulfillment of the requirements for the degree of Master of Applied Science

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January 2002

Abstract

The development of lightweight optics through material and structural design has been under investigation over the past several decades: of this work, the greatest achievements have been realized in primary mirror design. A wide variety of mirror materials and structural layouts have been proposed for a range of applications. This thesis describes in detail the major trends in optical light-weighting. Materials and structural designs are discussed such that a database outlining advantages and disadvantages of current approaches has been established. Using this data, materials have been chosen that are best suited for production-scale airborne optical systems: these include aluminum, Zerodur, and a proprietary CANMET metal matrix composite. A test case for traditional mirror configurations has been established using finite element analyses and compared to interferometric data. Peak-to-valley error predicted theoretically was found to deviate less than $1.0\text{ }\mu\text{m}$ from experimental data for the Zerodur mirror, falling within acceptable limits. Using this model, structural light-weighting of the Zerodur mirror was analyzed using circular pockets. It was found that a multiple-pocket design that focused on mass reduction through pocket depth was most advantageous.

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Nomenclature

W	Vertical mirror deflection at a given radius
w	Vertical mirror deflection at the mirror centre
R or r	Mirror radius
α	Coefficient of thermal expansion (CTE)
R_S	Mirror radius of curvature
T	Temperature soak change
I	Energy focused (I_0 = without quilting, I_I = with quilting)
δ_c	Quilting peak-to-peak error
λ	Wavelength
E	Young's modulus
E_f	Faceplate Young's modulus
h_f	Faceplate thickness
ν	Poisson's ratio
ν_f	Faceplate Poisson's ratio
P	Polishing pressure
b	Inscribed circle diameter (for open-back and sandwich-core structures)
ψ	Geometric constant
G	Shear modulus
ρ	Density
d	Grain diameter

σ_y	Yield strength
σ_o	Frictional stress resisting the motion of gliding dislocations
K	Hall-Petch slope (measure of grain boundary resistance to slip transfer)
k	Direction of planar wave propagation
ψ	Phase of planar wave
PV	Peak-to-valley surface error
rms	Root mean square surface error
x	Average fringe spacing
Δx	Fringe width
P or Q_r	Transverse load
D	Flexural rigidity
t	Mirror thickness
a	Mirror outer radius (from centre)
c	Radius of mirror support location (from centre)
M_C	Bending moment at support location
D	Mirror outer diameter
e	Element length
r_1	Radius of light-weighting pocket
r_2	Radius from the mirror centre to the centre of the light-weighting pocket
t_0	Depth of light-weighting pocket
DI	Increase in deflection
MR	Mass reduction

Chapter 1

Introduction

1.1 Optical Imaging Devices

Since the studies of light by Euclid circa 300 BC, the field of optics has become an ever-expanding, increasingly complex topic. One of the first devices used to implement theories on refraction and magnification occurred near 1590 AD, when Zacharius Jensen constructed a compound microscope using a pair of shaped lenses [1]. After that point, several additional microscopes and eventually telescopes were made using the same principles of refractive optics. Further research resulted in the suggestion that replacing lenses with shaped mirrors would increase the precision of such imaging devices, and thus the area of reflective optics began with Isaac Newton's reflecting telescope in 1668 [1]. Although refractive optics are still used in many areas, reflective optics have proven advantageous in a majority of optical imaging applications – a case where this is especially true is in reflective telescope technology [2]. Table 1 lists several advantages of reflective optics over refractive optics in this field [3]. For this reason, the remainder of this thesis will focus on the area of reflective optics only, and any mention made of optical imaging devices will refer directly to those involving reflective optics.

Since their introduction, reflective optical imaging devices have undergone dramatic improvements in image quality while experiencing few changes to their original configuration. Apart from applications involving refractive optics (such as microscopy or traditional photographic equipment), there are three main areas of influence for optical imaging devices:

- (1) ground-based systems (mainly telescopes),

(2) airborne systems (telescopes, ground surveillance), and

(3) spaceborne systems (deep-space telescopes, earth-based imaging).

Regardless of the imaging system, the basic configuration of the mirrors used to gather images has been available in one of two arrangements, as depicted in Figure 1 [4]. The first is the Newtonian telescope, which features a concave primary mirror that focuses incoming light onto a flat plate, used to redirect the converging beams to a point outside the telescope tube. This allows the imaging device (in the case of Figure 1, the human eye) to be placed at the focal point without inhibiting the incoming light. In a similar fashion, the Cassegrain telescope uses a primary and secondary mirror; however, the secondary mirror in this case is a convex mirror used to redirect the converging beams through a hole in the centre of the primary mirror to the imaging device. This configuration is beneficial for large ground-based telescopes in particular, since the imaging device may be placed conveniently near the ground instead of up in the air as would be the case for the Newtonian telescope [4]. In fact, the Cassegrain telescope configuration is one of the most commonly used in the optics industry.

1.2 The Primary Mirror

While several different variations of the aforementioned optical configurations exist, there is a common element in each that is vital for an effective imaging device: the primary mirror. The main purpose of this mirror is to focus the incoming light onto an imaging device: these devices may range from photographic instruments and charge-coupled-device (CCD) cameras, to spectrographs for temperature or atomic composition

readings, to the naked eye. There are several factors that must be considered when designing a primary mirror, but one of the most important issues regarding its design is the mass of the mirror used. The desire exists in most optical devices currently produced to decrease the overall weight of the system. This is due primarily to the environment commonly associated with such devices: in airborne or spaceborne systems, these systems need to be optimized to reduce payload weight, thereby reducing the overall cost of operation. For ground-based systems, relatively large apertures are required such that the self-weight of the primary mirror becomes an issue. In previous studies, it has been found that one of the largest contributions to the overall weight of an optical system is the weight of the primary mirror used [5]. It is for this reason that the opto-mechanical design of the primary mirror is of paramount concern when creating an optical imaging device.

1.3 Methodology of Light-Weighting

There are currently two methods used to reduce primary mirror weight. The first is performed via a geometry standpoint, whereby the shape of the mirror is chosen to reduce its weight while enhancing its overall stiffness. Traditionally, primary mirrors have been constructed of solid material with little or no light-weighting involved. Primary mirrors were fabricated with a concave front contour and a flat back contour (concave-plano): with the progression of optical performance and design, several concepts emerged that proved to successfully enhance stiffness-to-weight characteristics in these mirrors. This will be discussed further in Section 2.2.

The second method of light-weighting is through a materials standpoint. Over the past 40 years, continuous advancement in the design of new lightweight optical materials has been experienced. While conventional mirrors were constructed of aluminum, trends began in the design and fabrication of materials such as low-expansion glass, beryllium, and silicon carbide – Figure 2 shows a rough timeline of the progression of these materials [6]. The use of aluminum has given way to beryllium, Zerodur, Ultra-Low Expansion (ULE) glass, silicon carbide, and metal-matrix composites (MMCs) in many of today's state-of-the-art optics.

In considering which material is ideal for a given situation, several different aspects of each material must be examined. Such aspects include the mechanical, physical, optical, metallurgical, and fabrication properties of the material [7]. Table 2 lists specific data necessary in each category to make a proper material selection. Not only must the performance of the material be taken into account, but the availability of the material must also be considered. While one material may perform far better in comparison to another, it is useless to select this material if there is no easy way to deal with suppliers or if the material itself is too expensive. The cost of processing is yet another issue to be examined: some materials will require unconventional machinery for mirror fabrication, the cost of which may be enough to turn a company away. In terms of Canadian reflective telescope manufacturing, materials such as aluminum and Zerodur have been selected for mirror fabrication [3]. Some beryllium mirrors have been produced for

military applications, but these projects are based primarily on foreign engineering design knowledge and not the type commonly undertaken by a commercial optics manufacturer.

1.4 CANMET/APS/Carleton University Joint Project Overview

Through a combination of both methods of light-weighting, an optimization of the primary mirror for a given application becomes apparent. With an optimum mirror shape chosen, the selection of the appropriate material can further reduce the weight of the system such that a combination of both geometry and materials can provide a much-improved end product. Unfortunately, the time and cost of producing multiple test specimens to determine the best combination available is not feasible, and so an alternate means of analysis is required. As such, a joint initiative has been undertaken that will attempt to provide a method of accurately predicting primary mirror behaviour without specimen fabrication. The institutions involved are given below, along with the goals and responsibilities of each:

- (1) Carleton University: by using advanced Finite Element Analysis (FEA) software, the deflection of a primary mirror of given geometry and material will be predicted and compared to experimental data for model calibration. Light-weighting of this model is then carried out to explore the benefits of various easily fabricated lightweight designs.
- (2) Applied Physics Specialties (APS): a Canadian optical component manufacturer, APS is responsible for producing the primary mirror specimens and providing the facilities for model calibration.

(3) Canada Centre for Mineral and Energy Technology (CANMET): the Advanced Materials division of CANMET is currently testing new materials that could in time replace those currently used for primary mirrors. In addition to the development of these materials, the material properties associated with each are provided to Carleton as a preliminary testing ground. The information is added to the finite element model, and compared to results from mirrors using existing materials, thus providing CANMET with a detailed comparison of their material(s) to those currently used, without the delays associated with fabrication and testing.

This thesis project attempts to combine all aspects of the initiative, yet focuses primarily on the work performed at Carleton University – the work contributed by the other institutions is referred to when necessary. The outcome of the project should give APS the ability to analyze potential mirror designs without the need for fabrication. The following chapter provides background information into current primary mirror design, including mirror geometry, material, manufacturing procedures, and inspection techniques. Chapter 3 details the specific objectives and methodology of this thesis, while Chapter 4 provides analytical results for both traditional and light-weighted mirror specimens. These results are discussed further in Chapter 5, and conclusions to the project and recommendations for further work are given in the final chapter.

Chapter 2

Review of Optical Imaging Technology

The following review covers the areas essential to primary mirror design. The first section deals with the most common applications of reflective optical systems, and the environmental conditions associated with each – this results in a customization of mirror design. The following three sections deal with primary mirror geometry, materials, and manufacturing techniques, respectively. The last part of the review focuses on inspection techniques, particularly interferometry methods used to determine the surface conditions of the mirrors tested – these are the methods involved in gathering the experimental data offered in Chapter 4.

2.1 Application of Optical Imaging Devices

For an optical component to perform according to specifications, it is vital that the mirrors used be robust under the environmental conditions experienced; however, depending on the application, primary environmental concerns may be varied. As previously mentioned, there are three main areas of application that provide three unique environmental conditions: these are ground-based, airborne, and spaceborne systems. Before each type of system is discussed, it should be noted that there are two types of environmental loading conditions that are prevalent in each system, i.e. gravitational loading and thermal loading. While both types of loading are present in each system, the terms in which they are applied may vary greatly, and it is this variation that leads to customization of primary mirror design.

2.1.1 Ground-Based Imaging Systems

The primary application of ground-based imaging systems is the use of telescopes. Be it small-scale amateur telescopes or large-scale observatories, the focus on high-quality primary mirrors is evident. In terms of small-scale telescopes, environmental loading does not noticeably affect the mirrors' performance. The gravity and thermal conditions are nearly identical to the conditions experienced upon fabrication and testing, such that any performance issues would have been encountered upon manufacturing. It is not until large-scale primary mirrors are used that loading conditions must be accounted for.

Examples of such mirrors exist at observatories throughout the world. In Hawaii for example, three large telescope arrays are used for space imaging: the Gemini telescopes, the Subaru telescope, and the Keck telescopes. While the Keck telescopes use several actively controlled mirrors to simulate one large primary mirror, the Gemini and Subaru telescopes use single primary mirrors to focus incoming light [8][9]. The Gemini mirrors (two telescopes are used) are 8.1 m in diameter with a mass of over 22,000 kg each, while the Subaru primary mirror is 8.3 m in diameter with a mass of over 24,000 kg. Figure 3 shows the size of the Gemini and Subaru telescopes, while Figure 4 allows a view of the primary mirror used for the Gemini (prior to application of its reflective coating). Another project using large-diameter primary mirrors is the Very Large Telescope (VLT) project located in Chile that uses four telescopes, each with 8.2-m mirrors [10]. One of these telescopes is shown in Figure 5, thus giving an idea of the size and weight of these mirrors (each VLT mirror weighs over 23,000 kg).

With mirrors of this magnitude, size and weight issues become more important. Gravitationally, the self-weight of the mirrors becomes so great that the mirror surface can tend to sag and distort, thus hampering the optical performance of the imaging device [5]. Thermally, concave mirrors such as those used here with a high diameter-to-depth ratio must be tolerant of both thermal gradients and thermal soaking. Even small changes in temperature across the large surface area can cause the material expansion to vary enough to create noticeable distortions, and thermal soaking can lead to sagging of the mirror in a fashion similar to gravitational loading. The corresponding surface sag due to thermal loading is given by [5]:

$$W = \frac{\alpha T R^2}{2 R_s} \quad (1)$$

where W is the vertical deflection in the mirror at any given radius R , α is the coefficient of thermal expansion (CTE), R_s is the radius of curvature of the mirror, and T is the temperature soak change. The changes experienced by these effects are usually compensated for by a matched thermal expansion of the metering structure (i.e. the mounting structure for the primary and auxiliary mirrors expands to ensure the sag is accommodated for, regardless of the type of support – be it continuous or discontinuous).

Apart from telescopes there are several other imaging systems that are ground-based; these are used primarily as surveillance or targeting systems in military applications. For

example, tank fire control systems such as that used on the Leopard I rely on precise imaging devices for target acquisition [11][12], whereas the United States army incorporates lightweight, portable collimators that locate distant objects of known position [13]. Fortunately, the diameter of the primary mirrors in these imaging devices range from approximately 10 to 30 cm, and issues concerning self-weight and thermal loading are not a concern with these relatively small systems.

2.1.2 Airborne Imaging Systems

A majority of airborne imaging systems are used for ground surveillance. Photographic and infrared-based devices have been used on unmanned aerospace vehicles (UAVs) such as the Predator during military operations. There are three main differences between large ground-based optics and airborne optics [5][14]:

- (1) airborne optics are much smaller than large-scale ground systems (i.e. they are similar in size to the smaller scale surveillance equipment previously mentioned – approximately 10-30 cm), and as such are not concerned with gravitational loading through self-weight alone,
- (2) airborne optics are exposed to varying degrees of gravitational force, as many of these systems are equipped on aircraft capable of high-g maneuvers, and
- (3) dramatic changes in elevation and location result in temperature variations that cause thermal loading to the mirror through thermal soak.

A second, more demanding application in the area of airborne optics is in the use of large-scale airborne telescopes. A good example of this is the Stratospheric Observatory for Infrared Astronomy (SOFIA) telescope [15][16][17][18][19]. The telescope uses a Cassegrain configuration with a 2.5-m diameter primary mirror, mounted inside an open cavity in a modified Boeing SP 747 aircraft. It is intended to replace the existing Kuiper Airborne Observatory (KAO), which uses a 0.91-m aperture telescope. Figure 6 shows how the telescope is to be mounted within the aircraft. The main advantage of such a telescope over conventional ground-based telescopes is that the SOFIA may climb above most of the Earth's atmosphere – which interferes with the images received by ground-based telescopes – while eliminating the high cost of launching a space-based telescope. Unfortunately, with such a large primary mirror diameter the SOFIA telescope must endure loading conditions faced by both airborne and large-scale ground-based imaging devices.

2.1.3 Spaceborne Imaging Systems

Spaceborne imaging systems serve three main purposes: Earth-based observation (i.e. remote sensing), planetary observation, and deep-space observation. Most of the current Earth-orbiting satellites are involved with the first group of applications. Instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS) view the entire surface of the Earth within one to two days (acquiring data in 36 spectral bands), further developing various fields of Earth sciences [20]. In terms of planetary observation, satellites have been launched over the past several decades to provide important

information about other planets within the solar system. Instruments such as the Mars Orbiter Laser Altimeter (MOLA II) are used to obtain surface profiles and atmospheric data of distant planets [21]. Finally, deep-space telescopes such as the Hubble Space Telescope (HST) provide a unique look into distant galaxies. The success of the HST has led to future NASA endeavours for deep space imaging, such as the Next Generation Space Telescope (NGST) [22].

Gravitational and thermal loading are quite different for space-based systems. Primary mirrors are designed in a 1-g environment, yet must operate within microgravity conditions. Mirror designers must make the proper adjustments to the mirror to ensure optimum performance in a near-weightless environment, while ensuring the mirror is stiff enough to endure a high-g launch cycle – this is no small task [5]. At the same time, thermal loading can be severe in an environment outside the Earth's atmosphere. During the trip to Mars, the primary mirror on the MOLA II was exposed to temperatures ranging from -30°C to $+50^{\circ}\text{C}$, and operating temperatures from $5-26^{\circ}\text{C}$ [21]. Severe temperature gradients are also experienced on the MOLA II, as the temperature may vary up to 1.7°C across the mirror due to solar flux or other equipment on the satellite.

Another type of thermal loading is common on many spaceborne imaging systems, as well as some ground-based and airborne systems. The load is in the form of an extremely cold thermal soak, brought about as a result of using infrared (IR) imaging systems [5]. In order for IR imaging devices to accurately read incoming infrared radiation the

radiation emitted from the surrounding “warm” equipment must be eliminated, and so the entire device is usually subjected to cryogenic temperatures using liquid helium or nitrogen [23]. For these applications, the mirrors must be tested at near-absolute zero temperatures to ensure dimensional stability during operation.

2.2 Primary Mirror Geometric Design

Primary mirrors have traditionally been constructed of solid material with little or no light-weighting. These mirrors were fabricated concave-plano, meaning the front surface used for reflecting light is machined into a concave shape while the back surface – used generally for mounting – is kept flat. With the progression of optical performance and design however, several concepts have been introduced that proved to successfully enhance stiffness-to-weight characteristics in these mirrors, which is paramount in mirror design. These so-called lightweight mirrors were defined as any mirror that is lighter than a solid mirror of the same diameter and stiffness. Of the concepts proposed, five different types of lightweight mirror structures are currently in use [24]:

- (i) contoured back designs, with the backing tapered or curved,
- (ii) radially ribbed structures, with a thin faceplate and radial/circumferential ribs for support,
- (iii) open-back structures, with a faceplate and a regular array of reinforcing ribs (rectangular, triangular, and hexagonal patterns are the most common),
- (iv) sandwich structures, which are the same as open-back structures with the addition of a reinforcing backplate, and

- (v) foam core structures, where the sandwich core is replaced with a low-density foam core. As in sandwich structures, the core carries the shear loads between faceplate and backplate.

Currently, open-back and sandwich structures are the most common of structural light-weighting procedures, although contoured mirrors have been used (this is the type of light-weighting currently employed by APS).

2.2.1 Open-Back and Sandwich Mirrors

2.2.1.1 Open-Back Mirrors

Open-back mirrors are commonly manufactured by machining holes out of the back of a solid piece of material. This process has proven to be expensive and risky (roughly one third to one half of the mirrors are destroyed during fabrication), but the stiffness-to-weight benefits are significant. Another important feature to open-back mirrors is that the stiffness or flexural rigidity is always less than a solid mirror of the same thickness, although open-back mirrors can have a much higher stiffness at the same weight as a solid mirror [24]. This characteristic may be important if size and stiffness limitations exist such that an efficient open-back mirror cannot be produced.

Figure 7 shows the self-weight deflection of an open-back mirror with the parametric variation of the faceplate thickness and rib support structure [24]. From this figure it has been shown that the flexural rigidity increases with increasing rib thickness: rib thickness also dictates the sensitivity of the flexural rigidity to the faceplate thickness used. For

thinner rib supports, the faceplate thickness required to achieve acceptable stiffness values becomes increasingly small, to the point at which current fabrication methods are not possible [25].

2.2.1.2 Sandwich Mirrors

Unlike open-back mirrors, sandwich structures can have better stiffness over solid mirrors of the same thickness in response to gravitational loading. Figure 8 shows this in a manner similar to that of the open-back structure, such that the same dependencies may be observed. Due to the fact that both a faceplate and a backplate exist, further restrictions on faceplate thickness become apparent. It is for this reason that a transitional faceplate thickness exists, at which the optimum mirror structure changes from sandwich to open-back as the thickness is increased (this will be discussed in greater detail in Section 2.2.1.4).

Quilting is also a factor affecting both open-back and sandwich mirror performance – this effect can be described as the deflection of the faceplate between the supporting ribs during polishing, due to the application of a significant polishing pressure. The permanent deformation results in a loss of focused light, with a reduction in energy due to quilting given by [26]:

$$\frac{I_1}{I_0} = 1 - \frac{4\pi^2 \left(\frac{\delta_c}{2\lambda} \right)^2}{\left[1 - 2\pi^2 \left(\frac{\delta_c}{2\lambda} \right)^2 \right] \left[1 - 4\pi^2 \left(\frac{\delta_c}{2\lambda} \right)^2 \right]} \quad (2)$$

where I is the energy focused (0 = without quilting, 1 = with quilting), δ_c is the quilting peak-to-peak error, and λ is the wavelength of light focused. Consequently, the quilting error is given as [27]:

$$\delta_c = \psi \frac{Pb^4}{\left[\frac{E_f h_f^3}{12(1-\nu_f^2)} \right]} \quad (3)$$

where E_f is the faceplate modulus, h_f is the faceplate thickness, ν_f is the faceplate Poisson's ratio, P is the polishing pressure (usually ranging from 1.4-6.9 kPa), b is the inscribed circle diameter of the unit cell of the mirror core (shown in Figure 9 for different rib patterns), and ψ is a geometric constant determined by the shape of the unit cell (0.00151 for triangular cells, 0.00126 for square cells, 0.00111 for hexagonal cells). Using simplified formulae derived for small-diameter sandwich mirrors [28], Figure 10 demonstrates the dependence of faceplate thickness on polishing pressure, denoted q in the figure. As polishing pressure is increased, the required faceplate thickness increases with any given rib spacing. The trade-off between reducing polishing pressure is that it takes longer to polish the mirror to specifications, which in turn increases the cost to manufacture.

2.2.1.3 Weight Savings and Thermal Response

From similar simplified theory as above, weight savings in open-back and sandwich mirrors range from a 70-80 % reduction in weight with similar stiffness characteristics. More detailed work by Pepi [5] indicates that for an open-back structure, a 25 % increase

in mirror depth will result in 85 % less weight than a solid mirror with the same optical performance. Subsequently, a 25 % *reduction* in mirror depth for a sandwich mirror will result in the same optical performance at 85 % less weight than a solid mirror using the same materials. This comparison was performed using gravitational loading characteristics with the optical axis in the vertical.

Another important characteristic is thermal response, which is directly related to thermal loading. There are two primary aspects to thermal response: the length of time it takes for a mirror to return to its original shape after thermal perturbation, and the time it takes to reach thermal equilibrium with the surrounding air – both of these qualities affect optical performance during transition to equilibrium. For open-back and sandwich structures, the faceplate thickness governs thermal response. Conservative estimates show the response time for these structures to be about 15 % the time it would take a solid mirror to respond to these types of thermal conditions [5]. This fast response time is very important considering a normal response time for a 12.7-cm thick solid mirror is approximately 3 hours, during which the optical performance of the mirror is severely inhibited.

2.2.1.4 Transition Faceplate Thickness

Using Figures 7 and 8, it can be seen that extremely small values of faceplate thickness lead to a reduced self-weight deflection in open-back mirrors, where the same effect causes high self-weight deflection using the sandwich-core design: however, a slight

increase in this thickness results in restoration of sandwich mirror stiffness and a loss of stiffness in open-back mirrors due to gravitational loading. Thus, a transitional faceplate thickness is realized, whose exact value depends on the physical properties of the material as well as the density of the core. A detailed analytical study performed by Mehta [25] shows that for almost all conventional light-weighted mirrors (with an areal density of 10-30 kg/m²), the transitional faceplate thickness ranges from 0.89-4.45 mm – at a faceplate thickness less than this value, greater stiffness would be reached using an open-back structure, whereas a sandwich structure would be preferred for values greater than this. Unfortunately, the current state-of-the-art in faceplate fabrication limits the thickness of faceplates produced: Table 3 shows the minimum faceplate thickness for most of the materials commonly used currently in lightweight mirror production [25]. While thicker faceplates imply preference to sandwich mirror construction, this thickness is still small enough to result in little difference between the performance of the two designs: Mehta showed the flexural rigidity of an optimized sandwich structure would only be 13.9-15.7 % higher than for an open-back system of equivalent depth [25]. It is therefore more realistic with current fabrication methods to produce open-back structures, which are much easier to manufacture and are therefore less costly.

2.2.2 Foam-Core Mirrors

Foam-core mirrors present an attractive alternative to open-back and sandwich structures for three main reasons [24]:

- (1) the use of a foam core eliminates distortions through quilting of the faceplate,

- (2) foam density can be reduced to less than 2 % that of a solid mirror with the same depth and material, and
- (3) fabrication of a foam core is much easier and more economical than for a ribbed structure (fabrication concerns with low-density thin ribs are currently an issue in open-back and sandwich mirror construction).

Additional testing by Cho et al. [29] has shown that the foam weight is very small compared to the weight of the faceplate and backplate. Current foam-core materials include aluminum foams from Energy Resources and Generation (used in heat exchangers and gas attenuators), aluminum oxide foams from Astro Met Co. (used as a filter material in metal refining), nickel foams being researched at the University of Arizona, SXA MMC foams made by Advanced Composite Materials Corp. (also investigated at the University of Arizona), and fused silica foams used in experimental mirrors as far back as 1962; at that time, foam cores were thought to be too fragile and were not again studied until the 1980s with aluminum foam core mirrors.

The main inhibitor of current foam-core research is the lack of knowledge concerning shear modulus derivation. One of the most important parameters of the foam core for mirror applications is its shear modulus, as it determines the efficiency by which the loads are transferred from the faceplate to the backplate. Most of the experimental work done to date has relied upon Ashby's relationship, which states [30]:

$$\frac{G_{foam}}{G_{solid}} = \left(\frac{\rho_{foam}}{\rho_{solid}} \right)^2 \quad (4)$$

Unfortunately, experiments performed at the University of Arizona disprove the validity of such a relationship [24]. It has been suggested that the lack of interest in foam-core technology that has been established in the past may be a direct result of the incorrect theoretical assumptions about the shear modulus of the material, primarily due to the use of this equation. Figure 11 shows measured shear modulus data compared to theoretical predictions using Ashby's relationship.

Other areas of concern exist when considering foam-core mirrors. First, the attachment of the foam core to the faceplate has proven difficult. Adhesive bonding has been used in aluminum oxide foam/Pyrex faceplate mirrors, but for limited temperature ranges. Dip brazing has also been considered for aluminum core/aluminum faceplate bonds. For nickel foam-core mirrors with SXA faceplates, electroplating of the faceplate has also been used with some success. With a new interest in foam-core mirrors, these techniques will undergo further evaluation. Another problem that has arisen is in the plating operation normally performed on the faceplate to enhance its optical performance [24]. Damage of the foam has been experienced in aluminum foam-core mirrors using aluminum faceplates: it is important to note however, that subsequent mirrors were constructed successfully, with an overall mass of 2 kg – this compares to a 3-kg mass for an aluminum sandwich mirror with the same optical performance.

2.2.3 Contoured Back Mirrors

Although not as widely used as open-back and sandwich mirrors, contoured mirrors have been studied and applied in industry. Parametric design studies were carried out at the Optical Sciences Center at the University of Arizona concerning contoured mirror shapes and support conditions [29]. The study comprised of establishing FEA models of different mirror contours, and using the finite element program NASTRAN – as well as the FRINGE post-processor – the optical performance of each was examined. Design criteria for the study included minimization of self-weight, optimization of optical performance, and the maximum efficiency of support conditions.

Mirror back surfaces tested include a concave flat-back, meniscus, double-concave, tapered-back, convex back with parabolic contour, and single and double arch back mirrors with parabolic contours: these shapes are shown respectively in Figure 12. The mirrors were subjected to self-weight, and their deflections analyzed both with the optical axis vertical and horizontal, representing the extreme loading conditions. From this study, it was shown that single arch mirrors resulted in the lowest mass, with the lowest optical error at horizontal orientation and the second-lowest error in the vertical. Results of this report are given in Table 4.

It is also important to note that in this study, comparison of a solid SXA composite mirror was made with both a nickel foam-core and an SXA foam-core mirror, the results of which are also in Table 4. From this, it can be seen that while the foam-core mirror

offers a considerable weight savings, optical performance is degraded, such that stringent demands on optical performance may prohibit the use of this design. Comparison of nickel foam-core and SXA foam-core mirrors shows that the higher shear modulus in the SXA foam ($G = 44.8 \text{ MPa}$) compared to that of the nickel foam ($G = 13.8 \text{ MPa}$) has a direct impact on the optical performance of the system. Thus, performance of foam-core mirrors depends on both the flexural rigidity of the faceplate/backplate as well as the shear modulus of the foam.

2.3 Material Candidates

As mentioned, the selection of materials is as important as structural optimization. Over the past 40 years, continuous advancement in the design of new lightweight optical materials has been experienced. In selecting the appropriate candidate(s) however, a certain group of properties must be considered in order to find the material that best suits a given application. Such properties have been summarized in Table 2 [7]. From this chart, all candidate materials should be placed into one of two categories: metals and glasses/glass-ceramics. This is done because the two different types of materials contrast greatly.

One of the largest differences between metals and other mirror materials is thermal conductivity. Since the valence electrons in metals are free of the influence of individual atoms and can move much more freely than in other materials, metals possess a much higher thermal conductivity than glasses, thereby providing a higher degree of thermal

stability [31]. For example, solid glass has a thermal conductivity of 1.0 W/m-K (at 273 K), while that of pure copper is 400 W/m-K at the same temperature. Even as the temperature is varied from 300 K to absolute zero (near the temperature for cryogenic IR applications), the thermal conductivity of metal is always higher than that of glass, as shown in Figure 13 [7].

Whereas metals have a much higher thermal conductivity, many glasses and glass-ceramics benefit from having a near-zero coefficient of thermal expansion, as seen in Table 5 for such materials as ULE glass and Zerodur. This proves advantageous for the construction of large optics – since any small change in temperature would result in significant expansion of a large piece of material – which is why much of the current use of these materials is focused on primary mirrors in the 8-m class. However, the figure of merit commonly used to compare thermal control characteristics of various materials is the thermal distortion coefficient, defined as the coefficient of thermal expansion (CTE) divided by the thermal conductivity of the material [31]. From Table 5, it is clear that metals such as aluminum and beryllium are still competitive with glasses and ceramics due to their high thermal conductivity, although it is difficult to measure thermal distortion for ULE and Zerodur since the CTE used is so close to zero.

A secondary importance of the CTE of the material deals with issues regarding bimetallic distortion. As will be discussed, the inability of some metals to achieve desirable level of surface roughness (less than $\sim 10 \text{ \AA}$) results in plating of the mirror surface with an

electroless nickel-phosphorus (EN) metal, which can be polished to a roughness similar to that of glass [3]. Unfortunately, the CTE of this material is about 12.1 ppm/K (can vary depending on phosphorus content), which may differ enough from the mirror material that internal stresses and distortions develop upon thermal loading [13][32]. This problem is not observed in glass because EN plating is not needed for the low surface roughness values required.

The elasticity of metals and glasses/ceramics are also quite different. Metals generally consist of rows of atoms that can readily slip over each other in close packed directions, hence dislocations and other imperfections move quite freely if the density of the dislocations is small. However, when the dislocation density becomes large, the interference in dislocation motion makes it difficult for slip to occur. Vitreous glass has a disordered structure that can be thought of as an overwhelming concentration of dislocations [31]. The interatomic bonds in this material are also strong yet flexible, which has led many to the conclusion that glasses are in general the most perfectly elastic material known [31].

The same cannot be said of metals. In fact, very few metals are truly Hookean in nature (i.e. perfectly elastic); as such, the presence of dislocation motion at low stresses leads to small distortions that affect optical performance [33]. Deformations in the micrometre range can have deleterious results, and consequently the use of a 0.2 % offset yield stress is not adequate enough to ensure quality control. Thus, the micro-yield stress (MYS) is

used for metals to determine their suitability for an optical application: MYS is defined as the stress required to produce 1 part per million permanent strain. Table 6 lists some typical MYS values for aluminum, magnesium, and several types of beryllium [7].

An additional characteristic worth mentioning here is the crystallographic structure of the material. While most symmetric (e.g. cubic) structures are subject to randomness in the crystalline makeup, materials having a degree of non-symmetry in their unit cell may have anisotropy on the macroscopic level. An example of this is the hexagonal structure of beryllium – Figure 14 shows the anisotropic CTE distribution that occurs as a result of this cell structure.

Currently, several key materials are used in the field of lightweight optics. These include [3]:

- (1) monolithic aluminum,
- (2) optical grade beryllium,
- (3) ULE glass,
- (4) Zerodur,
- (5) metal-matrix composites, and
- (6) reaction bonded silicon carbide.

A summary of the typical properties associated with these materials is given in Table 5, along with the preferred characteristics of each. What follows is a more detailed look at

each of these materials, with the advantages, disadvantages, and current applications of each.

2.3.1 Aluminum

One of the first materials to be used for optical mirrors, aluminum is attractive primarily due to the cost benefits relative to alternate materials. Mirror fabrication using 6061 Al has been observed since the late 1960s, and has gained recognition as being one of the traditional optical materials, having been used in hundreds of mirror applications [34]. While 6061 was chosen initially due to its history in gyro manufacture, it has proven one of the best choices for long-term stability in comparison to other popular types of aluminum such as 7075 and 2024. Apart from low cost due to its high availability, aluminum is also easy to manufacture given current optical machining equipment (e.g. diamond tooling). Unfortunately, bare aluminum cannot be polished to a high degree of precision, and electroless nickel (EN) plating is used to allow easy polishing to the desired tolerance. As a consequence of both the plating and the aluminum itself, the properties of aluminum mirrors are inferior to similar optical materials used currently (see Table 5). Low specific stiffness and a coefficient of thermal expansion that is twice that of the EN plating used indicates a high degree of dimensional instability at varying temperatures due to bimetallic distortion [3]. A second source of instability comes from fabrication from solid billet stock through casting, welding, and machining operations. This produces material inhomogeneity and residual stresses that lead to dimensional instability of the mirror [24][35]. It is also important to note that the incorporation of

aluminum into complex mirror designs adds significantly to the overall cost of mirror production, such that light-weighted mirrors using aluminum loses its low-cost attractiveness.

One current application involving an aluminum primary mirror is the space based visible (SBV) reflective telescope designed by the Lincoln Laboratory at MIT (MIT/LL). The telescope consists of a three-mirror optical configuration (see Figure 15), with all mirrors fabricated from 6061-T6 aluminum [36]. The primary mirror has a 6-in. aperture, with the root-mean-square (rms) surface error ranging between $0.345\text{--}0.640\lambda$ (λ refers to the wavelength of the light used for interferometric surface testing – refer to Section 2.5). Maximum operating temperature range was anticipated to be between -55 and $+40$ °C. An additional benefit of the SBV is that the metering structure used to mount the mirrors is also fabricated of 6061-T6 Al, which means the overall structure is both very conductive and athermalized to minimize the system's reaction to thermal loading [36].

While aluminum has been a controversial choice for applications requiring a surface precision greater than 630 nm RMS, the use of an Al foam-core is quickly becoming a valid alternative to solid aluminum mirrors [35]. This eliminates some of the dimensional instability associated with fabrication from solid billets, and provides a large weight reduction without the need for costly light-weighting procedures. Foamed Al can be produced with densities as low as 4 % of the parent material, is low in cost, easily fabricated, and can be easily brazed to Al sheet (for faceplate/backplate use) [37].

Unfortunately, there have been difficulties in predicting the behaviour of foam-core mirrors (see Section 2.2.2) such that analytical deflections vary greatly from experimental results. For example, the predicted optical performance using FEA of an aluminum foam-core mirror with aluminum faceplates joined by dip brazing was found to differ by as much as a factor of two from experimental results [35]. This is due to both the lack of information on foam cores, as well as the dimensional instability that is inherent in aluminum for applications requiring such high surface precision.

2.3.2 Beryllium

As seen in Table 5, beryllium holds optimal material properties in several categories. It enjoys the highest specific stiffness of all optical materials, and its CTE is almost equivalent to that of the EN plating used for most applications. Also advantageous is the fact that beryllium mirrors can be machined using the same equipment as that used for traditional aluminum mirrors, which eliminates the cost of purchasing expensive new machinery to facilitate beryllium mirror production [34]. Beryllium is also stable over a large temperature range, making it suitable for almost any environment.

Several specific types of beryllium may be used as it is supplied from Brush-Wellman in a variety of grades [34]. These include:

- *I-70A*: optical grade, low oxide content, moderate micro-yield strength, usually used when no coatings permissible.

- *S-200*: standard grade, medium oxide content, moderate micro-yield strength. can be bare polished but usually plated.
- *I-220*: structural grade, medium oxide content, moderately high micro-yield strength, generally plated.
- *I-400*: instrument grade, high oxide content, difficult to polish directly (usually replaced by I-220).

One point to note here is the effect oxide content has on the polishability of the material. BeO is much more brittle than pure Be, making it difficult to directly polish – for this reason, beryllium grades with a higher oxide content are generally coated with EN plating to minimize polishing time and cost.

One of the main inhibitors to widespread beryllium use in primary mirror fabrication is the cost involved in materials acquisition and production [3]. While the cost associated with beryllium has been reduced over the years, its price still remains high relative to similar optical materials. Further difficulties are presented within Canada, where there are no direct suppliers of beryllium. The beryllium powder used (and created during machining) is toxic, although this hazard has been minimized with quality control and safety precautions in recent years.

As with aluminum, problems arise in the stability of beryllium mirrors: the cause of this instability is quite different in beryllium however, due mainly to the anisotropy of the Be crystal. A 37 % difference in CTE between the crystal axis and the basal plane (Figure

14) promotes the use of powder consolidation instead of wrought processing to better randomize the CTE distribution [32][38]. Micro-yield and micro-creep behaviour is also very important: micro-yield is strongly dependent on powder grain size and geometrical properties, while micro-creep is dependent on chemical composition, powder characteristics, and consolidation processes. Usually, attempts to improve one of these qualities will introduce unwanted results in the other – for example, initiating a pre-strain into the system will increase the MYS, but can increase the sensitivity to micro-creep due to the induced stress [38].

During thermal loads, localized yielding may also occur due to a complex interaction between crystal anisotropy, mis-orientation between adjacent crystals, the MYS and imposed temperature changes [33]. Armstrong and Borch [39] have produced a specific model for thermal loading of HCP crystal structures such as that found in beryllium. It has shown that in cooling beryllium from room temperature to 4 K (required for cryogenic applications) a thermal stress of approximately 49.6 MPa is generated, which is over the MYS of I-220 Be. The model thus demonstrated a need for a beryllium grade with a higher MYS than that seen in the strongest structural grades. Research by Marder [33] examined a new type of beryllium, designated I-250. It was shown that since the yield strength σ_y is governed by the Hall-Petch relationship

$$\sigma_y = \sigma_o + Kd^{-\frac{1}{2}} \quad (5)$$

(where d is the grain diameter, σ_o is typically rationalized as the frictional stress resisting the motion of gliding dislocations, and K the Hall-Petch slope – considered to be a

measure of the resistance of grain boundary to slip transfer), and the offset yield strength was found to relate to the MYS, the micro-yield characteristics of the beryllium used could be improved by reducing the grain size. Table 7 shows that I-250 has higher UTS and MYS values over all other grades of beryllium, with no sacrifice in ductility. The higher oxide content does mean that this type of beryllium is not suited to bare-mirror applications as previously mentioned, and should be EN plated.

Current applications of beryllium mirrors include the primary mirror for the Mars Orbiter Laser Altimeter (MOLA II) [21], and the secondary mirror for the Very Large Telescope (VLT) [32]. The MOLA II telescope is constructed entirely of Brush Wellman S-200F vacuum hot pressed (VHP) beryllium, with EN and electrolytic gold plating. It has a 508 mm diameter, and was designed for operational temperatures between 5 °C and 26 °C (cruise temperatures range from -30 to +50 °C, although this is not what the mirror experiences due to internal heating and cooling). In comparison, the VLT mirrors are 1.12 m in diameter, hyperbolic, and actively controlled, operating in visible and IR wavelengths. Each 42-kg mirror experiences an operational temperature of 0 to 15 °C – this was predicted to produce bimetallic distortions and internal stresses in the mirror structure and the Ni layer, such that optimization of the plating process was required.

2.3.3 ULE Glass and Zerodur

Both ULE and Zerodur are glasses that have the advantage of a near-zero thermal expansion coefficient. Their surfaces can be polished with the smallest degree of error

compared to all other optical materials, meaning there is no need for any plating to improve optical surface quality. While this is ideal in most cases, both ULE and Zerodur suffer from a poor thermal conductivity that is inherent in most glasses [35]. For example, the thermal diffusivity of aluminum is 83 times that of Zerodur, which means it is nearly two orders of magnitude faster in reaching thermal equilibrium than glass optical materials. As previously mentioned, it is the thermal distortion figure of merit that is important, and glasses do remain competitive with metal candidates.

Ultra-Low Expansion glass is a titania-silica glass manufactured by Corning Incorporated. Available as Corning glass code 7971, it exhibits virtually zero thermal expansion at room temperature [40]. The material is commonly fabricated into “facets” or individual mirror pieces that can subsequently be fused into mirrors of various sizes: this makes ULE ideal for the construction of large optics. Unfortunately, inhomogeneity of the CTE is a well-known characteristic of ULE glass, such that Corning defines the material to have a thermal expansion coefficient of $0 \pm 0.029 \text{ ppm/}^\circ\text{C}$ [41]. The material is therefore well suited for applications where the mean operating temperature is relatively constant while the thermal gradients are more severe [41]. Alternatively, fused silica has a much higher CTE but with less variation, such that it is better suited for applications with larger isothermal temperature changes (e.g. cryogenically cooled IR telescopes).

The main types of deformation that may exist as a result of the CTE mismatch are summarized in Figure 16. These include [41]:

- (1) *Lateral growth of facets*: caused by bulk CTE differences between facets, finite element analyses (FEA) show this error to be highest near the centre of the mirror.
- (2) *Bending of the facets*: caused by axial CTE variation between facets, shown to be relatively small.
- (3) *Direct thickness expansion*: also caused by bulk CTE differences between facets, this type of error is shown to be the smallest (approximately 0.01λ)

Currently, a combination of inspection techniques and FEA are used to successfully assemble large monolithic ULE mirror blanks. Advanced methods of CTE evaluation for process control and product certification include nondestructive ultrasonic procedures, which can predict local CTE values with an accuracy of ± 0.24 ppb/ °C [40]. FEA can then determine which arrangement of facets will minimize thermal distortions within the mirror.

There are many examples of mirrors constructed from ULE glass to date. One of the most popular of these has been the Hubble Space Telescope (HST) primary mirror, although many other large mirrors have been produced. The Gemini telescope features an 8.1-m diameter primary mirror fabricated from ULE [8]. This mirror has a meniscus

contour with a hexagonal core open-back arrangement, which demonstrates the feasibility of a lightweight ULE mirror.

Zerodur is a glass ceramic that also possesses a near-zero CTE. Developed by Schott Glaswerke in West Germany, this effect is produced by a combination of 70 % crystalline phase and 30 % residual glass phase within the material [10]. The negative CTE of the crystal phase is used to cancel the positive CTE of the glass phase, causing a net expansion that is virtually zero. Like ULE glass, Zerodur may be designed for mirrors of various sizes, although large mirrors are the current focus of the material due to the current lack of feasibility in large metal mirrors. Table 8 lists past and current applications, not including the primary mirrors of the VLT [10].

2.3.4 Metal-Matrix Composites

Metal-matrix composites (MMCs) have proven beneficial to many industries, including mechanical, recreational, and aerospace. Incorporation of MMCs provides structural weight savings that reduce system loads, increase component life, imply a direct reduction in both launch and on-orbit operating costs (for space systems), and permit new applications that were previously unobtainable with existing materials [42]. Its use in the optics industry is still in its infancy, although several experiments and prototypes have been designed [43].

Continuous-fibre composites are rarely used, even though continuous graphite fibre MMCs have very high strength and stiffness characteristics without sacrifice to weight, with exceptional thermal conductivity and thermal distortion qualities. The limiting factor in continuous fibre usage results from the cost and difficulty of fabrication: it is easy for fibre damage to occur at the microstructural level, which can have more of a deleterious effect with continuous fibres over discontinuous fibres or particulate. Discontinuous fibre composites have marginal improvements in strength but are used mainly for improved stiffness and fatigue strength characteristics, as well as improved CTE (proportional to the amount of reinforcement used) and superior wear characteristics [42]. Another benefit of discontinuous reinforcement is that the resulting MMC is isotropic in nature, whereas continuous fibre reinforcement results in significant anisotropy.

The largest database currently available for MMCs is for silicon carbide (SiC) reinforced aluminum, in both particulate and whisker reinforced varieties. Particulate SiC/Al composites first infiltrated the automotive industry through companies like Alcan International, as the MMC offered both an increase in strength (up to 50 %) and in stiffness (up to 100 %) over monolithic Al [42]. Cost is one of the major disadvantages, with raw materials costing nearly double that of conventional metals, and fabrication costs ranging from equivalent to an order of magnitude increase. This cost is also associated with whisker reinforced MMCs, although they possess superior properties over particulate reinforced composites. The whiskers typically have an aspect ratio

(length:diameter) of 50:1 to 150:1, while they are arranged randomly to retain isotropic qualities [42]. Whisker reinforced MMCs have the highest tensile strength of all discontinuous fibre MMCs, while the ductility of the whisker is up to 70 % lower than that of the metal matrix. Table 9 shows some typical applications of SiC/Al MMCs, both with particulate and whisker reinforcement [42].

One of the most used composites in the optics industry has been a material known as SXA, produced by Advanced Composite Materials Corporation (ACMC). SXA Optical Grade Composite is a high-strength aluminum alloy reinforced with 30 volume percent (30 % v/o) fine particulate silicon carbide which has been optimized for use as a mirror substrate [12]. As seen in Table 5, many material characteristics of SXA show improvement over aluminum, including the specific stiffness. Another important property is the dynamic response of the material, a ratio of the MYS to material density: SXA has a dynamic response parameter three times higher than that of aluminum, and seven times higher than beryllium [43]. As seen in Figure 17, the micro-creep characteristics are also improved without sacrifice to the MYS. Another important advantage of SXA is that it can match the CTE of the EN plating used to significantly reduce surface error due to bimetallic distortion [43]. This can be done through a combination of adjusting the percentage of particulate and adjusting the phosphorus content in the plating (12 % phosphorus gives the best surface for optical polishing, although this can be altered slightly). Unfortunately, limited experimental evidence of

the MMC at lower temperatures indicated surface distortion may become large due to non-linearity of the CTE variation of both nickel and SXA due to temperature.

Several examples of SXA can be cited. One of the most prominent applications came when the fire control system for the Leopard I tank had its Zerodur unit replaced with an SXA mirror on the existing mount [11][12]. The MMC was used to create a lightweight mirror with excellent stability and optical performance, EN plating, and a high-reflectance, laser-hard coating. The mirror was designed with a larger diameter, which meant the specific stiffness had to be larger to maintain the same mass specifications. Of the materials that were considered (beryllium, aluminum, and SXA), SXA proved the most attractive, having superior optical performance over aluminum at a much lower cost than beryllium (the SXA mirror was less than two-thirds the cost of the Be prototype). Structurally, the mirror was radially ribbed, which meant the use of conventional diamond tools on a CNC mill to form the light-weighting pockets [11].

Unfortunately, some studies suggest that incorporation of SXA results in little weight reduction of the overall system. For example, efforts at producing a lightweight portable collimator for the U.S. Army looked at four candidate materials: aluminum, beryllium, silicon carbide, and SXA [13]. Originally, the collimator was a combination of aluminum and SXA, but the CTE mismatch between the aluminum and the EN coating prohibited the collimator from operating within a useful temperature range. This CTE mismatch ultimately led to the elimination of the material from the feasibility study.

Beryllium was deemed advantageous due to well-developed machining technology and the success of EN plating – however, the cost factor was enough to discourage its use. Silicon carbide proved to be the worst of the possible solutions: brittle characteristics, differential thermal expansion with the support structure, extreme tool wear during machining and cost were all disadvantages to the material. SXA was chosen due to successful machining and matching of the support structure with the mirror material such that no differential thermal expansion was experienced [13]. A one-third-scale model of a full SXA collimator was developed and analyzed. Table 10 shows the results of a comparison between this model and that of other materials. It was found that the complete SXA collimator would be slightly lighter than the Al/SXA combination, but still relatively heavy to an all-beryllium structure, and fabrication costs for the prototype proved severe (a significant cost reduction was suggested if mass production of the collimators was adopted).

As with ceramics and metals, SXA is also available in foam known as Stablcel, also produced by APMC. Stablcel foam is a metallic matrix closed cell material, with many of the same properties as SXA at a fraction of the weight [43]. One of the main drawbacks to using this foam lies in the lack of efficient joining techniques suited to the useful temperature range, particularly on space-based missions. Currently, adhesion and soldering remain the best way of joining the foam to the faceplate/backplate.

2.3.5 Silicon Carbide

Initially intended for water-cooled optical mirrors, silicon carbide fabrication has improved sufficiently over the years to warrant its use in non-cooled systems [6]. Silicon carbide (SiC) is favourable because it is competitive with beryllium as a structural material, yet with a surface quality similar to glass. The use of a ceramic material poses several advantages, the most important being the thermal distortion qualities (see Table 5). SiC mirrors also enjoy a high specific stiffness. Disadvantages to silicon carbide include the relative cost associated with manufacturing, and the inherently brittle nature of the material.

Significant advancement has been made in SiC mirror production in the last twenty years [6]. From 1982-86, research focused mainly on the use of silicon carbide in cooled high-energy laser mirrors. However, work from 1986-88 on open-back mirrors and from 1988-90 on sandwich mirrors made from SiC meant applications in non-cooled systems became feasible [6]. The structures can be formed with flat, contoured, or tapered surfaces to allow further light-weighting of the system. However, limitations of lightweight mirror production remain, including [6]:

- (1) a minimum rib thickness of 0.38 mm, with an aspect ratio as large as 250:1,
- (2) a minimum facesheet thickness of 1.02 mm, with an aspect ratio as large as 50:1, and
- (3) a minimum peripheral wall thickness of 1.02 mm.

Nevertheless, research into SiC mirror fabrication continued in 1990-93 for production-class scanning mirrors. After that time however, defense cut-backs in the United States ceased production of optical grade SiC, and the company originally responsible for its production (SSG, Incorporated) sold the intellectual property to a new company, Xinetics, Incorporated [6]. This property included information pertaining to a now-popular optical grade of SiC known as CERAFORM.

CERAFORM contains 30 % free silicon in a SiC matrix, located approximately 300-700 Å below the surface [44]. It has been found that varying the silicon content and grain size/distribution of the SiC can affect optical and structural characteristics. To optimize optical smoothness, minimizing the silicon content and using a multimodal distribution of small grains has proven beneficial [44], and CERAFORM seems to have a good combination of high optical quality with superior structural characteristics, as seen in Table 5. Table 11 also compares material producibility for various lightweight optical materials: cast substrates such as CERAFORM are quite competitive with mirrors made conventionally [45].

SiC mirrors are currently used in a variety of cryogenically cooled IR applications of various sizes, as well as some non-cooled missions [6]. Several lightweight mirrors have been produced in the past by SSG, Inc., including [46]:

- (1) a 9 cm diameter mirror weighing less than 30 g,
- (2) a 23 cm diameter “egg-crated” mirror weighing less than 400 g,

- (3) a 0.6 m diameter primary mirror less than 6 kg, and
- (4) several aspheric SiC/Si mirrors.

Much interest has been expressed in using SiC mirrors for space-based applications. The Marshall Space Flight Center has performed studies into using SiC for 1-m class space telescopes, due to the high thermal stability inherent in SiC that is required for such missions. Testing has shown that surface changes of less than 0.1λ are observed when the temperature drops from room temperature to -150°C [2].

2.4 Manufacturing Techniques

Closely related to the selection of a candidate mirror material is the selection of an appropriate fabrication process. The type of fabrication cycle needed is strongly dependent on the type of material considered, so that it may have a definite influence on which material will ultimately be the most feasible to use in a given application. To examine the fabrication cycle, it may be separated into five distinct processes [7];

- (1) *Blank Manufacture*: for most optics manufacturing, this consists of fully machined, cast, forged, electroformed or brazed/welded options. Any manufacturing through machining can be included here.
- (2) *Stress Relief*: appreciable levels of residual internal stress develop in the blank from blank production, machining, and some heat treatment operations. As the stress levels usually reach a maximum near the external surface of the mirror, the relief can usually be carried out through chemical etching, heat treatments, or a combination of the two.

- (3) *Plating Requirements*: plating is selected based on the machinability of the substrate, refractory characteristics of the substrate, surface quality requirements, and cost.
- (4) *Optical Finishing*: finishing can be achieved through mechanical polishing (conventional method using a slurry on a shaped lap), chemical polishing (through immersion in a chemical solution), electrolytic polishing (deplating of the mirror in an electrolytic solution), submerged polishing (substrate and lap completely submerged in a diluted slurry), ion polishing (bombardment of the surface in a vacuum with heavy ions such as argon), and single point diamond turning.
- (5) *Optical Coating*: applied to improve optical performance without changing the surface figure. In some cases, the bare material can achieve the desired reflectivity and this process is not required.

As previously mentioned in Section 2.3, the variety of optical materials used results in significant variation of material behaviour, and thus the processes needed in mirror fabrication are equally diverse. For example, rough machining different material types gives different results. When grinding glass, the pressure of a hard lap on loose abrasive grains causes conchoidal fractures to propagate from the surface of the glass, as shown in Figure 18 [31]. Material removal is then facilitated through the intersection of a large number of these fractures. In comparison, using the same procedure on a metallic surface will result in plastic deformation, work hardening, and embedding of the abrasive in the

surface, all of which result in little material removal. These same difficulties can also be seen in the finishing process: while polishing has been performed successfully for years on glass mirrors, using the same procedures on metals has not proven as successful [31]. Polishing rates have been found to be dependent on crystal orientation, and grain boundaries respond differently to the polishing action; grain boundary inclusions may fall out leading to pits and large scratches in neighbouring areas. Overall, a discontinuous surface may be produced.

Research into overcoming these difficulties has led to the use of such things as EN plating on metallic substrates [31]. A combination of mechanical and chemical polishing of EN plating can produce a surface comparable to that of glass (RMS surface errors of about 10 Å), which is why it is so commonly used in most of the metallic primary mirror applications. This is an example of the many difficulties that may be encountered when selecting a fabrication cycle; the unique qualities of each candidate material discussed previously are enough to warrant discussion of the processing of each material individually, as given in the sections following.

2.4.1 Aluminum Mirror Fabrication

With aluminum being one of the most traditional mirror materials to date, experience in aluminum mirror fabrication has been thoroughly established. Hundreds of product tests and years of research has led to a process cycle that best suits the material and can easily

be adapted to a given application. What is detailed here is the process used after fabrication of the initial aluminum billet.

First, the mirror blank is rough machined to within 12.7 mm of final tolerances [34]. A variety of methods have been proposed to carry this out, but one of the most common is the use of a roughing machine that has a rigid spindle and a heavy transverse cutter bar [47]. A carboloy tool is attached, and used to remove the aluminum: in the example illustrated by Cooke [47], the material removal rate is 0.38 mm per cut. Once this has been carried out the blank is heat-treated to 520 °C, then water-quenched [34]. The aluminum is sometimes age hardened at 180 °C for 6-8 hours: this entire heat treatment is performed to relieve any internal stresses that may have occurred during the rough machining process (as well as to increase yield strength, in the case of the age hardening process).

The next stage after the initial heat treatment is the final machining to tolerance, commonly performed through fine grinding or polishing. This assures no see-through of the tool marks in the final product. Since the aluminum is soft and ductile, ordinary lapping techniques result in the impregnation of the abrasive into the surface: for lapping, a dirt-free lead tool made of round pellets has been found to be satisfactory when used with a solution of kerosene and garnet, for example [47]. Final polishing of the aluminum can then be carried out on a hard pitch lap covered with beeswax, using a Lanide C mixture [47].

With the mirror figured to tolerance, plating of electroless nickel may be applied to ensure minimum surface error. Since EN deposits as platelets on the surface, sharp slope errors from tooling can lead to microscopic changes in hardness and surface texture if a sufficiently thick plating is not applied [34]. EN plating 0.102-0.152 mm thick allows for final mirror polishing – this plating is deposited at 90 °C and unlike electrolytic nickel, is deposited stress-free. Stress relief is once again performed through 5-10 thermal cycles from 180 °C to liquid nitrogen [34]. Final figuring and polishing are then completed.

In some cases, application of an electrolytic coating (gold, rhodium, etc.) is necessary. In the case of the SBV telescope in Section 2.3.1, the mirror is gold plated to enhance reflectivity and protect the surface from corrosion [36]. The coating must be thin as these coatings can produce high internal residual stresses if applied too thick, and if possible, the coating should be applied to both the front and back to balance stresses and reduce distortion. Once this final coating has been applied, the mirror undergoes a final thermal cycling stage and is ready for use.

Although aluminum mirror fabrication has not changed drastically over the years, there are new processes that may improve upon its original success. One example of this is the single-point diamond turning of aluminum, where the mirror is rotated by a highly precise air spindle [48]. Also available is a precision generator that can perform both

rough machining and polishing applications directly from one machine, further reducing time and cost.

2.4.2 Beryllium Mirror Fabrication

Researchers began mirror fabrication with vacuum pressed beryllium in the early 1980s: however, the toxic nature of the material made it difficult to do so cost-effectively [3]. As a result, the acceptance of beryllium as a feasible mirror material did not come about until the use of near net forming techniques such as hot and cold isostatic pressing, which reduced production costs dramatically. The beryllium must still be provided in a powder; this can be done using impact grinding, ball milling, or attrition [32]. Impact grinding is usually preferred as it produces a more equiaxed powder with fewer tendencies towards crystallographic orientation during consolidation.

The three major consolidation techniques used currently include Vacuum Hot Pressing (VHP), Cold Isostatic Pressing (CIP) and Hot Isostatic Pressing (HIP). VHP is a uniaxial process that can lead to anisotropy during consolidation: however, examples of its use are available, such as the MOLA II primary mirror [21]. While CIP and HIP produce near net shape isotropic materials, HIP produces mirrors with higher mechanical properties than that of CIP. HIP is also advantageous over VHP, due to [49]:

- (1) efficient material utilization and reduced machining,
- (2) improved material properties (50-100 % improvement in mechanical properties),

- (3) rapid, cost-effective production,
- (4) demonstrated cryogenic figure stability (ie. the surface does not deform at near-absolute zero temperatures), and
- (5) current potential to fabricate monolithic mirrors up to 1.5 m x 2.5 m (although presses of this size are not yet seen in industry).

Figure 19 shows a typical HIP process for lightweight beryllium mirrors. It can be seen that the light-weighting can be performed during the consolidation process, eliminating the need for costly machining operations later in fabrication. Both open-back and sandwich core mirrors may be produced using this technique [24]. The HIP process is carried out at approximately 840 °C and 103 MPa, and has produced mirrors within ± 0.5 mm in all directions and a radius of curvature (for concave/convex mirrors) within 2 % of the target [49].

Machining of beryllium differs from aluminum primarily due to the higher machining stresses required [34]. Blanks are generally machined to within 0.76 mm of the final tolerances (as opposed to 12.7 for aluminum), then heat-treated at 900 °C to relieve internal stress. Progressive machining brings the part within 0.076-0.102 mm of the final dimensions. Acid etching is used to reduce residual internal stress along with the heat treatment after each rough machining operation, then with thermal cycling (usually from -40 to +100 °C) after each surface grinding operation [32][34]. After a final heat treatment of 680-790 °C, the mirror can then be plated to allow a smoother finish (note

that for extremely thin substrates, this final heat treatment may be too severe – warping of the surface has been observed – and the temperatures must be reduced).

The plating of a beryllium substrate is similar to that of aluminum. The only care that must be taken is in cases of cryogenic application, where the CTE mismatch may lead to significant instability. While the EN plating has a lower CTE than that of aluminum, the CTE of beryllium may be slightly higher than that of the plating – this will cause tensile stresses to be induced that can lead to cracking of the mirror at cryogenic temperatures [34]. Additional coatings may be added as required: for example, visible and near infrared (NIR) operations use gold or silver coatings plus a MgF or SiO₂ layer to enhance surface reflectivity, while bare optical grade beryllium is suitable for long-wave infrared (LWIR) applications as the BeO layer that forms is stable and highly durable.

2.4.3 ULE Mirror Fabrication

Figure 20 shows the hex seal process that is used by Corning Incorporated to fabricate large aperture mirrors [40]. The ULE glass is first formed into boules, up to 1.5 m in diameter and typically 13-15 cm thick. The boules are then stacked according to offsetting CTE values in the stacking direction: this direction is determined using ultrasonic inspection techniques, thus eliminating (or significantly reducing) expansion in that direction. The stacked boules are machined into hexagonal facets for mirror assembly, which is then performed using a high-temperature fusion process and is optimized using FEA to minimize surface distortions that arise during heating. For

curved mirror surfaces, the mirror is again heated and subjected to a sagging process until the desired shape is achieved [41].

This type of mirror fabrication is ideal for mirror diameters between 4-10 m, although the upper limit to the size produced through this process is quantified only by transportation and handling concerns [8]. This may not be said of small-aperture mirrors, where facet assembly may not be a feasible option – compared to traditional aluminum mirrors, glass mirrors are relatively expensive due to the material costs and fabrication time [35]. However, for smaller applications ULE can be cast to near-net shape in both open-back and sandwich configurations, reducing the need for complex assembly while increasing the chance of CTE variation through the material.

2.4.4 Zerodur Mirror Fabrication

Fabrication of Zerodur mirrors is similar to that of ULE glass. Conventionally, the material is produced through a casting process that is monitored to ensure the proper crystallographic mix is attained (see Section 2.3.3). The mirror blank may then be machined using equipment customary to the optics industry (e.g. diamond turning) and polished in a manner appropriate for any optical glass [50]. Light-weighting of these mirrors may also be accomplished through drilling and grinding, resulting in a feasible weight reduction of up to 60 % [10].

In recent years however, new fabrication techniques have allowed an alternate means of Zerodur mirror production. The three main types of processes include fusion techniques, slumping techniques, and spin-casting techniques [10]. In a manner similar to large ULE mirror production, fusion techniques involve the fusion of individually prefabricated components into complex lightweight structures. This can be done either by generating a rib structure through fusion of prefabricated thin plates with subsequent fusion of front and rear plates, or by machining the rib structure from a fabricated disc by abrasive waterjet (AWJ) cutting, ultrasonic cutting or traditional diamond tooling with subsequent fusion of front and rear plates. Weight reductions exceeding 85 % of an equivalent solid mirror have been reached using the fusion technique, compared to the 60 % of conventional light-weighting techniques. Slumping techniques may also be used to fabricate the appropriate contours for faceplates and backplates if necessary, prior to fusing each to the rib structure (the rib structure must be machined to the appropriate contour) [10]. Spin-casting techniques, used primarily for large mirrors, involve the formation of a thin meniscus by rotating a casting mold with a bottom that has the desired contour. This process is more expensive as it requires a melting tank, unlike the other processes that can use stock castings.

One of the main differences in fabrication of Zerodur mirrors over ULE mirrors is the feasible range of mirror diameter using these production techniques. While fusion techniques limit ULE mirror production to larger mirrors, they allow the production of smaller, thinner Zerodur mirrors. This is shown in Figure 21, that identifies the most

economical technique over a large range of mirror diameters [10]. The use of the slumping process for faceplate/backplate fabrication, with subsequent fusion of the plates to a rib structure, is feasible for mirrors from less than 0.25 m to greater than 4 m in diameter. This makes Zerodur an appealing choice for small glass mirror manufacture.

2.4.5 MMC Mirror Fabrication

As SXA is the most commonly used MMC in the optics industry, it is the fabrication techniques of this material that shall be discussed here. The two most common methods of SXA billet production involve either powder metallurgy (P/M) or liquid metal infiltration (LMI) [42]. P/M is costly and tedious, but provides superior mechanical properties. Whiskers or particulate are mixed with particulate matrix in solid state in an alcohol solution to ensure uniform dispersion. The solution is then cleaned, degassed and consolidated using HIP, or hot extrusion and die pressing [42]. On the other hand, LMI is simpler but does not produce consistently precise composites. The reinforcement is held together with a binder to form a preform that is infiltrated with molten metal subjected to pressure in a mold. Most discontinuous MMCs including SXA are fabricated into billets similar to monolithic metals. After this, secondary processes may be performed; these include rolling, extrusion, casting and forging. For aluminum-based MMCs such as SXA, the composite is then age hardened in a manner similar to that used for monolithic aluminum [42].

Structural grade SXA is manufactured using vacuum hot pressing of a filled die [43]. After undergoing thermal treatment, the product is machined into billet form and sonic inspection is performed. The billets are then extruded, forged or rolled: extruded SXA can provide a weight savings of 15-30 % over the same volume of monolithic aluminum, and up to 60 % of SXA may be removed until equal stiffness is reached [43]. As has been discussed earlier however, this effect does not necessarily hold true for optical applications.

Economical fabrication of MMC materials into lightweight mirror structures requires unique machining and heat treatment methods. Since SXA is reinforced with SiC particulate it is extremely abrasive, causing high tool wear in most common cutter materials. The only exceptions to this are polycrystalline diamond cutting tools and some non-conventional methods such as abrasive water jet (AWJ) cutting and chem milling [43][11].

A good example of SXA mirror fabrication is the primary mirror of the Leopard I tank firing system [43][11]. Forgings were produced by the Optical Corporation of America (OCA) from billets made by the Advanced Composite Materials Corporation (ACMC) – the SXA billet was made from 2024-T6 aluminum with 30 % (by volume) silicon carbide particulate reinforcement. The forging was done on hot-pressed billets to yield more efficient use of the material and to reduce machining time [11]. A flowchart for the fabrication of the mirror is presented in Figure 22. The hot deformation experienced by

the mirror did not induce anisotropy in the material, which means the mirror surface will not be severely affected by temperature changes due to particle alignment. Once forging is completed, heat treatment of the mirror is introduced. Originally, a process was recommended by APMC involving a liquid nitrogen quench, re-equilibration to room temperature in air, heating to 90 °C for 15 min, then air cool to room temperature. The process was found to be ideal for structural parts but not for optical substrates, as it could not strengthen the mirror enough to withstand high temperatures in the coating stage of production [43]. A new proprietary heat treatment was then introduced that involved thermal cycling from -200 to +180 °C. The blank was then rough machined using diamond tooling and once again stress relieved.

Due to the usage of the mirror in visible and NIR conditions, EN plating was applied. Prior to plating, the mirror surface was loose-abrasive ground to 0.005 mm. The mirror had a plating 0.076 mm thick over its entire surface (with the exception of the mounting hub) to minimize the possibility of surface distortion due to bimetallic effects [43][11]. In addition, the phosphorus content of the EN plating was adjusted so the CTE of the plating closely matched that of the SXA [11]. The mirror was then polished on a continuous polisher, with lead shot in the pockets of the light-weighted mirror back to obtain uniform polishing pressure. Polishing was performed using 1- μ m alumina powder for the initial stage, and 0.1- μ m powder for final polishing [11]. After this a final coating was applied to satisfy surface requirements. In the end, the mirrors exhibited excellent

optical performance and stability and are currently used in the tank fire system, proving the feasibility of SXA-based optical mirrors.

2.4.6 Silicon Carbide Mirror Fabrication

The primary fabrication of optical grade silicon carbide may be performed in one of three ways: reaction bonding (RB), hot pressing, and chemical vapour deposition (CVD). CVD SiC provides the mirror with a high survivability to radiation, which is desired particularly for space-based missions, yet is limited in the size of mirror that can be produced and is relatively expensive [6]. Hot pressed SiC results in a mirror with the highest strength and elasticity, as the SiC powders are combined with additives that serve as hot pressing aids and grain growth inhibitors. Unfortunately, this process is inhibited by high pressure and temperature conditions during fabrication that ultimately lead to size restrictions as well [6]. Designs using this process must also be relatively simple.

Reaction bonding provides the most flexibility and is the easiest to produce complex shapes with [6]. Fabrication of “green bodies” is carried out using isostatic pressing, press molding, or slip casting, and are pre-sintered prior to silicon infiltration. Silicon infiltration then occurs at high temperatures: in this process the silicon enters the green body, filling porous regions with silicon to produce a material density near 100 % [44]. This is why the microstructure consists of bonded SiC with regions of free silicon compromising 10-30 % of the structure – this bimodal structure results in tailorable thermal and mechanical properties [6]. Tailoring can be carried out through the addition

of carbon into the green body prior to silicon infiltration, thus increasing the amount of bonded SiC and reducing the percentage of free silicon. One downside of this bimodal structure is that inhomogeneity of the mirror results, and the boundaries between the two materials are a source of damage during finishing.

Machining of a RB SiC mirror can be carried out using standard hard diamond tooling. Generating the mirror shape is performed using diamond on composite laps, while figuring of the mirror is performed with diamond slurry on pitch laps [44]. Grinding of the surface is done to remove the subsurface damage induced during fabrication. This is carried out using progressively reduced abrasive sizes, from 30 to 1 μm at 1-3 $\mu\text{m}/\text{hour}$ (with subsurface damage up to 3 μm). This damage must be minimized to optimize the final surface finish. Polishing is then carried out to reduce the subsurface damage caused by grinding [44].

Problems are more likely to occur with cost-effective polishing techniques. Elastic modulus and hardness are key to polishing the mirror surface, and a good understanding of brittle mode fracture is needed to assess the underlying subsurface damage [44]. Finishing with submicron diamonds is the final step, with subsurface damage in the submicron range. A 15-hour polishing cycle is used, with 12 hours using a 1- μm abrasive size (producing 15- $\text{\AA}$ surface finish), then 3 hours using a 0.5- μm abrasive size (producing finish below 10 $\text{\AA}$). Continued finishing will degrade the surface due to intergranular damage: removal rates can be increased via tool pressure, but this can lead

to an increase in fractures along the free silicon-SiC interfaces. Chemical etching of the silicon phase is also detrimental to the optical surface, such that acetic acid must be carefully added to the solution to keep the pH at 5.5-6.5 for all operations [44].

While the advances that have been made to polish bare SiC have resulted in surface finishes as good as 7 Å RMS, current efforts have focused on using a PVD Si cladding for cost-effective optics that do not operate over a broad temperature range [6]. These mirrors have surface finishes as good as 5 Å RMS, and reduce the time and cost needed to finish (the time needed to get the same finish for cladding is 25 % of that required for bare SiC [44]). The cladding allows for diamond turning of the mirrors with savings in cost, especially for aspheric mirrors. Unfortunately, the temperature range is reduced due to decreased thermal stability, a property that is in many cases the reason for which silicon carbide is chosen as a mirror material. Figure 23 shows the CTE values for SiC and Si, which are close enough over a wide temperature range to permit Si cladding, yet restrict the optimum temperature range of operation (only the useful temperature range is shown) [46].

For light-weighting of SiC mirrors, the CERAFORM process was developed to enable direct casting of ribbed cores with integral backplates – these designs are 70 % the weight of other open-back mirrors, while the core stiffness exceeds that of beryllium [6]. The process involves mixing SiC grains ranging from 1-10 µm with a binder to form a slip, then cast into a mold and solidified by freezing. Water in the system is removed by

freeze-drying at -70°C , and the mold is then removed by leaching out the core prior to thermal operations [6]. The green body is sintered at 1650°C and the silicon is infiltrated at a temperature of 1750°C to form a near-100 % dense structure. Finish machining and polishing are carried out as previously mentioned. The benefit of using this type of process is that near net shape structures are created when using the RB SiC, which shrinks less than 0.5 % [6]. This, along with the fact that there is no need to machine the lightweight core structure, means that lightweight SiC mirrors are among the fastest mirrors to produce and machine.

2.5 Inspection Techniques: Interferometry Methods

Once a primary mirror has been manufactured, it is essential to determine its optical performance prior to installation and operation. The cost of replacing or repairing a primary mirror during service is quite high – one of the best examples of this is the problem encountered with the primary mirror on the Hubble Space Telescope, where extra equipment and shuttle missions were required to remedy the defective mirror that was already in orbit. The defective mirror resulted in millions of dollars in repair costs, due primarily to the fact that the defect had not been observed during ground testing.

As a result, the field of optical metrology – measurement of the static and dynamic displacement of solid surfaces used for the optics industry – is a vital tool for determination of the optical performance of a mirror. There are four main techniques that may be employed for this task [51]:

- (1) interferometry,
- (2) moiré techniques,
- (3) speckle methods, and
- (4) photoelasticity.

Of these techniques, interferometry is the most widely used for practical application in industry, and shall be the focus of the experimental analysis presented within this thesis.

2.5.1 Interferometry Fundamentals

In its simplicity, interferometers operate by observing the interference pattern created between two sets of beams to gather information about the surface tested [52]. Figure 24 shows the basic setup of a typical interferometer: for the type of analyses carried out in this thesis, a flat reflective surface (denoted the test optic) is positioned in front of a beam of light transmitted from the interferometer. Between the two is a transmission flat, which is used to allow only a portion of the light to pass through to the test surface (the remaining light is reflected back into the interferometer). As a result, two beams are produced: the reference beam created by the light reflected off the transmission flat, and the light reflected off the mirror surface. The two beams consequently overlap, and the interference of these beams is analyzed to determine the surface quality of the mirror sample tested [52][53].

In order to fully comprehend this method, an example of its use is warranted. Consider a plane wave such as that emitted by a light source used in an interferometric device.

These waves are not two-dimensional but rather three-dimensional, such that points of equal phase lie on parallel planes that are perpendicular to the direction of propagation. Figure 25 shows such a wave, with the direction of propagation denoted $\mathbf{k}$ and the phase of the wave denoted ψ [51]. Using this planar representation results in a type of “grating pattern” (referred to as a moiré pattern) as seen in Figure 26(a), where the wavelength of the propagating light is equivalent to the distance between the “grating lines” [54]. Consider now a second beam of light travelling at an angle 2α to the first: the superposition of these beams results in bands of constructive and destructive interference, as shown in Figure 26(b). Since these are planar waves, this effect will be identical in the direction perpendicular to the figure, such that an image from the observation plane shown in Figure 26(b) would look similar to that shown in Figure 27. This example illustrates one of the most common observations in interferometric analysis: tilt. Tilt is observed when the reflective surface under analysis is tilted slightly from the transmission plate, and therefore the reference beam. The bands of constructive and destructive interference are referred to as fringes, and it is these fringes that are the essence of interferometric analysis.

In addition to tilt, several other surface errors exist that may cause serious deleterious effects to imaging devices. These include [55][56][57]:

- *Spherical Aberration*: occurs in all spherical optics, as the rays that reflect near the edge of the mirror converge in front of rays that reflect near the centre of the mirror. Figure 28 shows this aberration: the paraxial focus shown in the

figure is used as a reference to determine the extent of the aberration [58].

The paraxial region pertains to an infinitesimal threadlike region about the optical axis, the focal point of whose rays determine the paraxial focal point.

- ***Coma***: caused by zones of differing magnification on the surface of a lens, the image produced is deformed in such a way that it is shaped like a comet with a small bright head (hence its name). Figure 29 shows the ray diagram for this concept: it can be seen here that some of the rays converge at a given point, thus providing the bright head that is seen [58].
- ***Astigmatism***: a variation in focal point due to surface variation, this causes rays that are in one plane to focus at a different location than rays in another plane – an example of this is shown in Figure 30[59]. Here, the terms *tangential focus* and *sagittal focus* are introduced: rays in the meridional (or vertical) plane are said to be in the tangential plane, whereas rays in the plane normal to this (the horizontal) are said to be in the sagittal plane. The focal points of these sets of rays differ when astigmatism occurs.
- ***Defocus***: occurs in spherical optics as a variation in radius of curvature between the test piece and the reference (here, a transmission sphere). Figure 31 shows that the rays reflecting off mirrors with different curvatures will have different focal points, i.e. the incoming rays from the test sample will be at an angle from those of the reference. This is analogous to the tilt error, only for spherical optics.

Figure 32 shows typical interferometric readings of tilt, defocus, spherical aberration, coma, and astigmatism [55]. It should be noted that tilt and defocus are not actually surface errors on the mirror tested, but are instead variations between the mirror and the reference piece used. This type of error may be remedied by adjusting the orientation of the mirror (in the case of tilt) or adjusting the radius of curvature of the transmission sphere used for the testing of spherical optics (in the case of defocus): however, it is common practice to tilt the mirror slightly so as to introduce a few fringes across the field. This allows for the measurement of surface errors less than a wavelength, since these errors would not be produced otherwise (i.e. the error would not produce a fringe as it is smaller than a wavelength) [60].

Conversion of fringes to surface data follows a direct mathematical correlation: a sample of such an analysis is shown in Figure 33. If the average fringe spacing is denoted x and the width of the fringe denoted Δx , the peak-to-valley error (PV error) is given as [60][54]:

$$PV = \left(\frac{\Delta x}{x} \right) \left(\frac{\lambda}{2} \right) \quad (6)$$

where λ is the wavelength of light used by the interferometer. PV error is a worst-case error statistic: it is merely a calculation of the high and low points on the surface relative to the reference. In contrast, the root-mean-square (rms) error is an area-weighted statistic, calculated as the standard deviation of the height of the test surface relative to the reference at all data points along the interferogram [61]. Figure 34 gives an example

of the difference between the two errors: while there is no specific proportionality between the two, PV errors are typically 3-5 times greater than rms errors for polished optical surfaces [61]. In the experimental data that is given in following sections, the PV error data is used as it is a conservative estimate of mirror quality.

2.5.2 Fizeau Interferometers and the ZYGO GPI XPS

There have been many variations in optical interferometers over their lifetime. Many of these variations have been introduced as a result of different light sources: these may be categorized as single-beam interferometers (Fizeau and Twyman-Green, eg.), two-beam interferometers (Rayleigh and Michelson, eg.), multiple-beam interferometers (Fabry-Perot, eg.), and holographic interferometers [60]. One of the most popular of these configurations is the single-beam Fizeau interferometer, depicted in Figure 35. This type of configuration is beneficial as Fizeau interferometers have fewer optical components, greater accuracy, and are easier to use than with other configurations [62].

One state-of-the-art interferometer using this configuration is the ZYGO GPI XPS system [63]. This system is equipped with a helium-neon laser, which is beneficial over normal light for two reasons [60]:

- (1) lasers provide an intense source of light, resulting in bright, crisp interferometric images, and
- (2) lasers offer a high degree of spatial and temporal coherence, which allows for the placement of the test sample away from the reference flat: this

eliminates the risk of damage to the test specimen without loss of image clarity, as would be the case with traditional light sources (eg. a mercury vapour lamp).

The ZYGO GPI XPS is the interferometer that has been used for the experimental analysis within this thesis. The schematic of this brand of interferometer is presented in Figure 36: here, it can be seen that the image is received by a TV camera, allowing for easier visibility of the fringe pattern on a television screen [64]. The data is also sent to the Zygo MetroPro computerized data analysis software. This software greatly increases the capability and usefulness of the interferometer by providing accurate quantitative measurements, eliminating the subjectivity of fringe inspection by the human eye [63]. A sample application screen can be seen in Figure 37, which illustrates the thorough analysis performed by the software, including surface profiles, topographic maps, and isometric surface plots [65]. With this software, experimental data acquisition has been carried out at APS and is given in Chapter 4.

Chapter 3

Thesis Objectives and Methodology

As previously mentioned in Chapter 1, this thesis is an attempt to combine all aspects of the CANMET/APS/Carleton University Joint Project, the ultimate goal of which is the optimization of lightweight primary mirror design for optical imaging devices. In order to achieve this, several objectives have been established for this thesis, including:

- (1) Establishment of a materials database containing candidate mirror materials for analysis, so that the material selection can take into account physical properties, fabrication techniques, availability, and cost.
- (2) Construction of a finite element model that will successfully predict the behaviour of traditional mirror designs (ie. plano-plano mirrors with no light-weighting involved) for each of the candidate mirror materials. For this, a parametric study is used to establish mesh dependence on material and mirror size (if any), and model accuracy is evaluated through comparison with calibration data. This calibration data is provided in the form of interferometric analyses carried out at APS.
- (3) Examination of the benefits of structural light-weighting, carried out using the calibrated finite element models. Various lightweight designs are modelled and analyzed to determine weight savings and stiffness characteristics for each of the candidate mirror materials selected.

The outcome of the project should allow APS the ability to analyze potential mirror designs, and CANMET the ability to compare new materials to those traditionally used in the optics industry, without the need for fabrication. As such, Chapter 4 begins with a preliminary thin-plate bending analysis using all feasible mirror materials to determine

which candidates perform best optically. From this – and from the literature of Chapter 2 – final material selection is carried out. The sections following material selection are associated with the development and calibration of finite element models for both the traditional and lightweight geometry, with variation in material and structural design. The results of this are then discussed in Chapter 5.

Chapter 4

Analytical Results

4.1 Initial Parametric Studies Involving Thin-Plate Bending Assumptions

This section provides a comparative analysis of materials suited for primary mirror application. Materials considered include aluminum, beryllium, ULE glass, Zerodur, MMCs, and silicon carbide. Comparisons are made based on both the size of the mirror necessary to achieve a certain level of optical performance, and conversely the level of optical performance reached assuming size restrictions. Results are given for solid mirrors subjected to mechanical loading: thermal loading would require several additional independent variables and would not take into consideration issues such as bimetallic distortion.

The problem of a mirror subjected to mechanical loading is one of a plate in pure bending. For simplicity it is easiest to assume the load – which is applied along the optical surface of the plate – is directed transversely, such that no forces result along the mirror plane (see Figure 38) and the analytical equations required are fewer [66]. The problem may be further simplified by assuming the plate to be axisymmetric (as most primary mirrors are) and flat (i.e. no curvature to the optical surface, so that all loads are applied perpendicular to the plane – this is typical of many optical mirror designs). For a simply supported case as in Figure 39, the equations governing the deflection of the mirror can then be reached using a variety of analytical methods.

The easiest method of approaching this type of problem is through the use of thin plate bending theory. Compared to thick plate theory it is a much simpler approach, due

primarily to the fact that the distribution of stresses through the thickness of the plate are assumed constant and deformation due to transverse shear strain is considered zero. These assumptions do result in a small degree of error, but this has been shown to be negligible for diameter-to-thickness ratios as large as those used herein (as discussed by Roark and Young, thin-plate assumptions are valid provided the diameter-to-thickness ratio remains larger than 4:1 [27] – the most common ratio produced for traditional optics is 6:1 [24]). Detailed analysis of thin plate bending theory has been presented by Timoshenko [67], and will be used for a first-order approximation of the relative performance of the optical materials considered for investigation.

From the loading condition given in Figure 39, the case of a plate – simply supported at a radial distance c from its centre – subjected to a concentrated load along the axis of symmetry must be studied. The solution for this type of problem is determined using the governing equation

$$\frac{d}{dr} \left[\frac{1}{r} \frac{d}{dr} \left(r \frac{dw}{dr} \right) \right] = -\frac{Q_r}{D} \quad (7)$$

where r is the radial distance from the centre of the plate, w the transverse deflection, Q_r the transverse load, and D the flexural rigidity, defined as

$$D = \frac{Et^3}{12(1-\nu^2)} \quad (8)$$

with E being Young's modulus, ν Poisson's ratio, and t the thickness of the plate [68].

Both Equations (7) and (8) will be used in the parametric study that follows. First, the bending characteristics of plates of different materials will be compared, with the size of the plates held constant. Second, a comparison of plate thickness for mirrors of different materials will be examined, given identical bending characteristics. These bending characteristics are used as a measure of optical performance: if a mirror experiences a higher degree of bending, the light rays that are reflected off the mirror become scattered and unfocused, greatly affecting image quality.

4.1.1 Bending Characteristics Given Size Constraints

Several fundamental cases have been established from Equation (7), and have been published in reference material. Cook and Young provide a short catalogue featuring most of the commonly encountered loading cases [66], such that solutions to more complicated problems may be solved by means of superposition. In this instance, the loading problem described by Figure 39 may be divided into two smaller problems, shown in Figure 40. Separation of the problem requires the acquisition of the bending moment at the support location (M_C), which is found using proposed boundary conditions. The value of M_C is thus expressed as

$$M_C = - \frac{\frac{P}{8\pi} \left[1 - \frac{3+\nu}{1+\nu} \right]}{\frac{1}{1+\nu} + \frac{c}{a^2 - c^2} \left[\frac{c}{1+\nu} + \frac{a^2}{c(1-\nu)} \right]} \quad (9)$$

where c is the radial distance of the supports to the centre of the plate and a is the plate radius. Once this value has been determined, the central deflection of the plate can be evaluated using

$$w = \frac{Pc^2}{16\pi D} \left[\frac{3+\nu}{1+\nu} \right] - \frac{a^2 c^2 M_c}{D(1-\nu)(a^2 - c^2)} \ln\left(\frac{c}{a}\right) \quad (10)$$

where w is the central plate deflection, found by superposition of the problems depicted in Figure 40. It can be seen from this equation that as the supports reach the outer radius of the plate, the central deflection equation reduces to

$$w = \frac{Pa^2}{16\pi D} \left[\frac{3+\nu}{1+\nu} \right] \quad (11)$$

Table 12 lists the critical information of the mirrors for this investigation. The support location is at a distance 89.9 % that of the outer radius, so that using Equation (11) yields actual deflections that are 14-15 % higher than those calculated using the exact equation – Equation (10) – and no more than 1 % higher when the deflections are normalized as will be discussed. Since the exact equation has been determined however, it is used for this analysis.

Seven different mirror materials are considered in this investigation. These include:

- aluminum,
- beryllium,
- Ultra-Low Expansion (ULE) glass,
- Zerodur,

- SXA (a metal-matrix composite),
- silicon carbide, and
- a proprietary MMC manufactured at CANMET.

For this study three material properties are required: the modulus of elasticity (E), Poisson's ratio (ν), and material density (ρ). These quantities are listed in Table 13. Using Equation (10) along with the material properties in Table 13 and the fixed dimensional characteristics in Table 12, the central deflection of each plate may be easily obtained. This has been done for two cases: first using an arbitrary external load, then with a gravitational load acting through the centre of gravity (i.e. the centre of the mirror). The reason for distinguishing between these two loading cases is that external loading is more likely to occur during manufacturing, while the gravitational loading will be encountered in service (e.g. maneuvering loads). While the external loads are independent of the mirror material, gravitational loads will depend upon the material density, such that a lighter material will result in reduced loading during service.

Figure 41 shows the results of this analysis. Central plate deflections have been normalized such that deflections are shown relative to that of the aluminum sample. It can be seen that with the exception of ULE, all other materials deflect less than the aluminum. It is also apparent however, that the type of loading can also influence the relative deflection. For example, while ULE deflects more than aluminum when external loads are applied, it deflects less for the same g-load. A similar pattern is also seen when comparing beryllium and silicon carbide, the two materials that were found to deflect the

least during loading (and therefore the two materials found to produce the greatest resistance to mechanical loading of all mirror materials studied).

4.1.2 Relative Mirror Thickness Given Identical Bending Characteristics

Three things may be done to take advantage of one material's superior bending characteristics over another. One is to remove material from the mirror without changing its overall dimensions (light-weighting): this will create a lighter mirror, but will sacrifice some of the optical performance. A second option is to take advantage of the increased optical performance of the mirror and do nothing else. A third option is to reduce the thickness of the mirror without light-weighting; this has similar effects to light-weighting, yet is advantageous in that the overall size of the mirror is reduced as well.

To determine the thickness of one mirror relative to another of a different material with the same optical performance, the deflection characteristics outlined in Equation (10) must be further examined. It has been suggested that these equations are weakly dependent on the Poisson's ratio of the mirror material, such that relative thickness can be derived directly from a comparison of the flexural rigidity (see Equation (8)) of the materials used [69]. In doing so, the following equation results:

$$\frac{t_2}{t_1} = \left[\frac{E_1 \left(\frac{1 - \nu_2^2}{1 - \nu_1^2} \right)}{E_2} \right]^{\frac{1}{3}} \quad (12)$$

From this, the thickness of any candidate mirror material can be compared to any other material to achieve the same flexural rigidity and therefore the same bending characteristics. Table 14 is a summary of these comparisons for each of the materials studied.

Note that Equation (12) does not include a term for density, in that the equation only holds true for externally applied loads. As before, gravitational loads require this density term to see its effects on required mirror thickness. The resulting equation for thickness comparison of two plates during gravitational loading concentrated along the centre of gravity is

$$\frac{t_2}{t_1} = \left[\frac{E_1}{E_2} \left(\frac{1-\nu_2}{1-\nu_1} \right) \left(\frac{3+\nu_2}{3+\nu_1} \right) \frac{\rho_2}{\rho_1} \right]^{\frac{1}{2}} \quad (13)$$

Table 15 lists the relative thickness values necessary to achieve similar bending characteristics during gravitational loading. As previously observed, the influence of density is noticeable in many of the materials used. For example, an aluminum mirror would need a thickness 58 % larger than that of beryllium during external loading, while during gravitational loading, that thickness is increased to over 125 %.

4.1.3 Summary

The bending characteristics for several different material candidates have been evaluated and compared. Using similar mirror geometry and loading conditions, relative bending characteristics showed the resistance of some materials to bending (beryllium, silicon

carbide), while others were much more flexible (aluminum, ULE). Knowing the relative performance of these materials, the opposite effect – varying mirror thickness according to a similar level of optical performance – has been recognized. Again, materials such as beryllium and silicon carbide were found to be much thinner than aluminum and ULE while achieving the same level of optical performance, with Zerodur, SXA, and the CANMET MMC coming out somewhere in between. The bending characteristics are ultimately important in each case, and have been found to depend on the type of loading condition studied.

For external loads such as those seen in manufacturing, these bending characteristics are indicative of the type of stresses that are developed within the mirror. These stresses may be found to exceed the micro-yield stress of the material, leading to warping and micro-tears in the system that result in loss of optical performance later on in service – this phenomenon is known as dimensional instability. The same is true for gravitational loads such as those encountered during high-g maneuvers, although in this case there may be sufficient bending during the load cycle to reduce image quality without permanent deformation, if the device is in operation at that time. It is true that this type of loading is not concentrated as has been studied here, but distributed along the mirror surface, and that the loading values used (both external and gravitational) were chosen arbitrarily to permit comparison. Use of a concentrated gravitational load at the centre of gravity has been established merely as a means of comparison with external loads, so that the effects of material density may be examined. As shown in the parametric studies, gravitational

or in-service loads differ noticeably from mechanical or manufacturing loads. This quality may be beneficial to mirror design, based on which quality is most desirable.

4.2 Material Candidate Selection

Before analyzing the benefits of structural light-weighting, it is necessary to select a group of materials that best reflect the future trends in high-performance mirror materials. Unfortunately, an optimum material cannot be chosen solely on its optical performance: several key issues must be considered in addition to this, some of which are currently more important. Ideally, a material must be chosen that will best satisfy the material aspects shown previously in Table 2. More specifically (and for the requirements of this thesis), priority must be given to those aspects which are of primary importance to APS, as it is APS that will attempt to implement the results of this project into future primary mirror fabrication endeavours.

After several discussions with APS, it became clear that the most important material aspects were as follows:

- (1) *Cost/Availability*: the primary concern of many industrial applications, both cost and availability can seriously affect implementation of a superior material. It has been observed in the past that high-performance optical mirror materials have not been used in full-scale production until the price of the material had dropped to levels more competitive with relatively inferior

products [6]. At that point demand would increase, as would its supply; thus, commercial availability of a material would also increase.

(2) *Ease of manufacture*: this is closely related to cost for two reasons. First, the complexity of the fabrication cycle impacts fabrication time – simpler manufacturing procedures require less time, and will therefore result in a cheaper product. Second, a new or different type of manufacturing procedure may require the acquisition of new facilities, which results in theoretically unnecessary expenditures.

(3) *Optical performance*: implies superior material properties in several areas – mechanical, physical, optical, and metallurgical.

Using this as a template for material selection, it is possible to select a group of candidates that will be the best suited for future use at APS.

Seven materials are considered as possible candidates: these have been discussed throughout the literature review. Aluminum, beryllium, ULE glass, Zerodur, SXA, silicon carbide, and a proprietary CANMET metal-matrix composite are all materials that must be compared; however, a final group of candidates can be reached through a process of elimination. Looking first at availability and cost, it is clear to see why a material such as aluminum has been used for so long as a primary mirror material. In comparison to the wide availability and low cost of aluminum, the availability and cost of materials such as beryllium and silicon carbide are not acceptable for a regular production schedule. The excellent performance of these materials in service does allow for its use in unique

applications (such as the MOLA II), and the price of both materials has been undergoing a steady drop since their introduction, but dedicating a large portion of a company's products to the use of these materials is simply not feasible at this time. This is reflected in the number of companies currently involved in the manufacture of optical-grade beryllium and silicon carbide in North America: one company (Brush-Wellman) is involved with optical beryllium production, and one company (Xinçtics) is associated with optical silicon carbide production. Considering SXA, ACMC has in recent years halted its production of the optical MMC – however, the raw materials required for its production (aluminum, silicon carbide particulate) are commonly available relative to beryllium and silicon carbide. As for the remainder of the products, the cost associated is cheaper than the beryllium and silicon carbide, yet none can compare to the availability of aluminum.

In terms of manufacturing, many companies today rely on traditional tools used for aluminum mirrors. As discussed in Section 2.4, such machines include grinders, polishers, and furnaces. These fabrication tools can be used for materials other than aluminum, however: it is possible for all of the other mirror materials to be machined using these components. Unfortunately, the quality of the product and the time involved may not be satisfactory. In terms of beryllium, it would be very difficult to machine a mirror blank due to the safety measures that must be taken to deal with the toxic beryllium powder that results. For silicon carbide, the wear resistance of the material is so great that both grinding and light-weighting through machining would be both time

consuming and costly, as the wear rate of the diamond tooling would be much greater relative to traditional aluminum production. For both beryllium and silicon carbide, it is possible to produce near-net shape, light-weighted mirrors using HIP processes, but this would require the acquisition of a press. Similarly, mirrors constructed from Corning's ULE glass require high-temperature fusion processes and precise CTE matching that has only been performed at Corning Incorporated to date. Therefore, in-house manufacturing of the mirror blank would not be feasible, and the additional cost of having Corning produce a line of APS mirrors is not a feasible expense at this time. The remaining materials – Zerodur, SXA, and the CANMET MMC – can be manufactured using the tools currently at APS. It should be noted however, that the ceramic reinforcement used in the metal-matrix composites increase wear resistance significantly, and problems with machining time and tool wear are present.

Finally, optical performance of each material must be compared. As has been discussed in the previous section, the materials with the best optical performance during both external and gravitational loading conditions include beryllium and silicon carbide. Aluminum and ULE glass perform poorly, while Zerodur, SXA and the CANMET MMC range between the extremes (see Figure 41). It should be noted that the relative performance of these materials are affected by light-weighting, specifically the extent of light-weighting possible for each material.

To narrow the list of candidates, each of the three material characteristics described must be examined at once. Table 16 summarizes the qualities of each material in the areas of cost/availability, ease of manufacture, and optical performance. From this table, it is apparent that beryllium and silicon carbide are not logical candidates for multiple-mirror production runs. The same can be said of SXA, primarily because it is no longer produced by ACOM. Corning's ULE glass is also a poor selection, with poor optical performance and the higher cost associated with purchasing a complex mirror blank that must be produced off-site. As such, a final list of candidates consists of aluminum, Zerodur, and the CANMET MMC. Each of these materials performs well in at least two of the three categories, with no major drawback of using each. It is therefore these materials that will be used in the analyses following, as these materials are the best candidates for APS to employ in future mirror design.

4.3 Traditional Mirror Analyses

Before an examination of the benefits of structural light-weighting can be performed, it is essential that analyses for traditional mirrors be performed. This is done both to establish a reference point for comparison, as well as to validate the methodology used for analysis. In this case, the finite element method (FEM) is used to theoretically predict the optical performance of traditional, plano-plano mirrors subjected to mechanical loading. The results of these analyses are compared to the data acquired experimentally via interferometric examination of mechanically-loaded samples, and a sense of accuracy – both in the theoretical and experimental results – may be assessed.

4.3.1 Finite Element Analysis (FEA)

Over the past four decades, the finite element method of analysis has become a powerful tool in most engineering fields. With its origins in the area of structural mechanics, the finite element method (FEM) has evolved considerably, and appropriate analyses involving truss, beam, plane stress, plane strain, axisymmetric, three-dimensional, plate and shell elements are now possible. In essence, FEA involves the discretization of a continuous problem such that a solution may be reached using algebraic equations [70]. With the advent of the electronic digital computer, numerical formulation and solution of these idealized FEA problems can be carried out at a fraction of the time it would take to reach exact solutions of continuous problems (if these could be reached at all).

In recent years, several commercial software packages have been produced that utilize FEA procedures to solve many types of engineering problems. Some of the most popular of these are NASTRAN, ANSYS, and I-DEAS. Both NASTRAN and I-DEAS have been used in cases involving optical performance evaluation [29][36][35][21][41][8]. While each of these programs would prove advantageous for FEA of the mirrors under investigation for this thesis, it is the I-DEAS package that has been chosen for several reasons.

One principal advantage of the I-DEAS software package is that it is the package currently used by APS for solid model construction of the imaging devices they produce.

As a result, APS already has experience operating within the I-DEAS environment, and the time required to learn the FEA program would be minimal. I-DEAS also has an intuitive graphical user interface (GUI) system, which would also aid in the adoption of the FEA program. A second advantage of the I-DEAS package is that it is currently available at Carleton University, where all of the theoretical analyses are produced for this thesis. This results in a time and cost savings when compared to the installation of a new commercial FEA package. Finally, I-DEAS proves advantageous as it is possible to move from solid modelling and meshing operations to FEM operations without having to export files or change environments. A person interested in the modification and testing of a model (as has been done many times through the course of this work) can do so therein with as little modification or upkeep of the model as possible, i.e. having to export the model from a solid modelling package to a finite element package often results in a loss of relevant data, such that model re-definition may be required.

Solid models for the traditional mirrors have also been constructed within the I-DEAS modelling environment. For a detailed look at commands and techniques used in modelling these mirrors within I-DEAS, refer to Appendix A. These models have been produced using the same diameter and loading conditions found in the previous first-order parametric study (see Section 4.1 and Table 12), for two reasons:

- (1) it provides a valid comparison of the two analyses (i.e. FEA and thin-plate bending theory), and

- (2) these are the dimensions of the mirrors tested by APS, which also allows for a proper comparison of theoretical and experimental data.

As will be shown, the maximum load applied experimentally at APS is 36.95 N; consequently, it is the load applied during FEA. The mirrors are supported by a ring mount a radial distance of 48.64 mm from the mirror centre, and the boundary conditions have been applied to reflect this. Figure 42 shows the restraints applied to the mirror: first, the ring mount is represented by a z-axis restraint whereby no deflection is allowed in this direction (i.e. the direction of the loading), and to ensure all degrees of freedom have been constrained in the model, deflections in the x- and y-axis (as well as rotations about all axes) have been assigned a constant value of zero at the central node of the mirror. The depth or thickness of the mirror has been varied to determine its effects on mirror performance: these values range from a diameter-to-thickness ratio ($D:t$) of 4:1 (the upper limit for which thin-plate bending assumptions are still accurate) to a ratio of 20:1 (the minimum thickness for the mirrors produced is at or around this value, given the materials used and the diameter chosen). Seven ratios in total were examined: 4:1, 6:1, 8:1, 10:1, 12:1, 16:1, and 20:1. Figure 43 depicts the variation in depth of the models.

To these solid models a variety of finite element meshes were added to determine mesh dependence. Solid elements were used instead of plate elements, as the lightweight models under analysis (see Section 4.3) are more complex than those used here (i.e. these models form the basis for the lightweight models to follow, in which plate elements could

not be modified to accurately predict model behaviour). For similar reasons, the inherent symmetry of the mirrors was not taken advantage of to reduce the model size, as light-weighting of the model may result in an asymmetric design. The need for establishing a generic model for potentially diverse structural light-weighting designs also has an impact on the type of element used. Figure 44 shows some typical meshes that were studied: significant variation from coarse-mesh to fine-mesh models can be observed. Within the I-DEAS FEA package exist three different types of solid elements [71]: these are brick elements, wedge elements, and tetrahedron elements (Figure 45 displays a list of all I-DEAS element types). Of the three, it is the tetrahedron element that will provide the most flexibility of design in three dimensions. For example, rounds or fillets in the light-weighted structure, and even the curvature of the cylindrical mirror itself warrants the use of tetrahedrons. Thus, the bulk of the simulations shown herein use 10-node tetrahedron elements (as opposed to 4-node tetrahedrons, which give a lower order strain interpolation along the element).

Having established the numerical model, the surface deflection data for each mirror – varying in size, material, and mesh – was recorded and examined to determine an acceptable element size for the FEA work that followed. 147 models were produced in total, taking into account the three candidate mirror materials (aluminum, Zerodur, and the CANMET MMC), seven mirror sizes per material (shown above), and seven element lengths per mirror size. The element lengths were normalized to the mirror's thickness (defined e/t), that being the smallest dimension in the model and as such the most critical

design parameter. Normalized element lengths ranged from 0.4 to 1.0 – this range allowed a diverse number of elements within each model of a given size to predict how many elements would be sufficient for model accuracy. In addition to the deflection data, elapsed time to reach a solution for each model was recorded: this information allows for trade-off between model accuracy and time to reach solution.

The results of the deflection data found using varying element sizes are presented in Figures 46 to 51. Figures 46 to 48 highlight the effects of altering the mirror size given identical material properties (in this case, aluminum). Here it is apparent that at any mirror thickness, little variation in top surface deflection occurs when the size of the element is altered. The deflection calculated along the bottom surface of the mirror appears more sensitive to element size: this is because a point load has been applied at the bottom centre of the mirror. As the element length decreases, the increasing number of elements near the centre of the plate works to amplify the stress concentration at this point: this location however, is not of direct importance to the investigation, as it is only the deflection data of the top surface – the surface used to reflect light – that are required. Figures 49 to 51 highlight the effects of altering the mirror material given identical size constraints (in this case, a $D:t$ of 6:1 is shown, as it is the most common in industry). It can be seen here that material properties such as Young's Modulus have no effect on the accuracy of the mesh.

Examination of these figures results in the conclusion that variation of element size does little to affect the deformation results along the top surface of the mirror, regardless of mirror material or size (provided the element length is proportional to the thickness) – top surface deflections varied less than $0.01\text{ }\mu\text{m}$ in all cases as element size was varied. Selection of an appropriate element size is therefore dependent on the time to solve the finite element model, as well as the projected complexity of the lightweight design under consideration. Figure 52 shows how the number of elements increases as element length (denoted e) decreases. As such, the time required to solve – given in Figure 53 – follows a similar pattern. It is for this reason that the $D:t$ ratio is indirectly related to element length selection, through the number of elements used and the required time to solve.

The traditional mirrors under investigation at APS have a thickness of 6 mm. Given a diameter of 108.2 mm, this results in a $D:t$ ratio of approximately 18:1. Examination of analyses in the literature suggest the number of elements range into the low thousands: for example, FEA of the Gemini primary mirror in I-DEAS used 3 720 elements [8]. This model however, was referred to as a coarse mesh model, and the mesh was also designed for one specific model instead of one for parametric study. As such, the number of elements was increased to 11 305, corresponding with an element length of 3 mm (and therefore, $e/t = 0.5$). Examination of Figure 53 suggests the time to solve the model is approximately 30 minutes.

Having established appropriate mesh sizing, loading parameters and boundary conditions, 3 additional models were constructed to reflect the bending behaviour of the APS test models. These three models varied in material only: properties for aluminum, Zerodur, and the CANMET MMC were entered into each of the models, and the simulations were run. Note that while in most cases, the deflection data for one model could simply be scaled as

$$w_2 = \left(\frac{E_1}{E_2} \right) w_1 \quad (14)$$

where w is the deflection at the mirror centre and E is the Young's Modulus. This relationship however, does not take into account Poisson effects that, due to the small deflections encountered, have a noticeable effect on the final deflection value. Table 17 gives deflection data and time to solve for each of the three models. Values agree with data presented in determining mesh independence. Figure 54 shows the deflection contour on the top surface of the aluminum mirror: similar contours exist for the Zerodur and CANMET MMC mirrors, while the values associated with the contours change accordingly.

4.3.2 Interferometric Data Acquisition

Interferometric analyses were carried out at APS for several mirror materials. Figure 55 shows the general layout of the GPI XPS interferometer used at APS. A specialized mirror mount was used to place the specimens in front of the incoming laser beam: a close-up of this apparatus is given in Figure 56. Figure 57 shows how the mirror is

mounted and loaded on the interferometer. A thread is attached to the back of the mirror via a strong epoxy adhesive – the free end of which is placed over a pulley and loaded with a variety of weights.

The most important of these tests involved a Zerodur mirror, but tests were also carried out for aluminum, fused silica, and BK7 mirrors (these latter two materials are glasses displaying similar properties to Zerodur). As for the tests involving the aluminum sample, it was found that the unloaded mirror had noticeable deformation due to the inherent difficulty in machining ductile metals (see Section 2.3). In contrast, the harder glass candidates – including Zerodur – showed less initial deformation. Figures 58 and 59 show the results of the initial unloaded tests for aluminum and Zerodur mirrors, respectively. Errors are given as a function of wavelength, specifically the wavelength of the helium-neon laser light used (632.8 nm): as such, a peak-to-valley (PV) error of 4.089λ (shown in Figure 58) corresponds to an error of approximately $2.588 \mu\text{m}$, while an error of 0.157λ (shown in Figure 59) corresponds to an error of approximately $0.099 \mu\text{m}$.

As a result of its increased dimensional stability, the Zerodur mirror specimen was the focus of the interferometric analysis. Increasing loads of 1.5 kg, 2.4 kg and 3.8 kg were applied to the harness attached to the back of the mirror. The loads used were relatively small for tests commonly conducted at APS, but due to weight restrictions imposed by the mount used the maximum force successfully applied was 36.95 N (just under 3.8 kg). It should be noted that this factor also resulted in the use of such a large D:t ratio (18:1),

allowing for sufficient deflection of the mirror surface and a high level of confidence in the results.

Figure 60 illustrates the deflection data for the Zerodur mirror subjected to a 36.95-N load. From this analysis, a PV deflection of 3.345 μm was recorded. However, the Zygo MetroPro software used in conjunction with the GPI XPS has a filter that can be used to “remove” certain effects from the results displayed. For example, *tilt* and *position* filters are used throughout the set of analyses to account for any errors that occur as a direct result of off-axis mounting concerns. In a similar fashion, a *power* filter can be used to compensate for sag or spherical aberration in the mirror. The use of this filter gives the results shown in Figure 61: here, the PV deflection is reduced to 1.948 μm .

4.3.3 Correlation of Analyses

Results predicted using the fine-mesh FEA model in I-DEAS closely resemble those values reached experimentally. Table 18 gives a brief comparison of these values. It can be seen that the theoretical prediction of deflection lies between the experimental values, given with and without filtration. It is believed that the *power* filter does eliminate the effects of concavity that appear as an initial condition or state of the mirror: however, the load application at the centre of the mirror will produce deflection effects similar to natural concavity without loading. Thus, the fact that the deflection results of the FEA study lie between the two experimental values is beneficial, as this would be the approximate deflection of a defect-free Zerodur mirror under the same loading

conditions. Regardless of this hypothesis, the error between either of the experimental results and the FEA-determined values is satisfactory.

While the error percentage is high, the deflection data that has been acquired experimentally is at a value so low that APS cannot be fully confident of the results. Readings of over 1.0λ are deemed accurate, but existing deformation in the mirror surface make it difficult to ascertain what percentage of the deflection during loading is contributed by the natural shape of the mirror. In addition, modelling of the loading and boundary conditions prove simplified and inaccurate, due partially to the variation in load and mount conditions experimentally. In terms of loading, the thread used to transfer the load to the back of the mirror is affixed using an epoxy resin: therefore, the loading distribution on the mirror changes for each case as epoxy application is not an exact procedure (i.e. it is done by hand, and will vary for each new specimen). As for boundary conditions, the mirror rests on a rubber tube that sits between the mirror and the mount. As the load is increased the contact area between the two surfaces is increased, which is an effect that has not been taken into consideration within the model. For these reasons, load and boundary conditions have been simplified and may affect the resultant deformation, although it is believed that these contributions are negligible compared to errors reached experimentally.

Nevertheless, the FEA deflection data does lie within $1.0 \mu\text{m}$ of the readings taken – an accuracy that seemed unattainable at the outset of this research. With modifications to

the experimental setup such that higher loads may be applied, FEA-predicted deflections should deviate no further from experimental data than what has already been observed. As a result, the error percentage will drop significantly and the analyses will appear to be more successful. An alternate means of proving this theory is to experimentally test some of the lightweight designs given in the following section: as will be shown, the deflection of these mirrors under the same load is noticeably greater, and should lead to greater apparent accuracy of the FEA work.

4.4 Lightweight Mirror Analyses

After discussions with APS, it was determined that the logical first step in structural light-weighting was to create circular pockets in the back of the mirror. APS has confirmed that this would be the easiest way for them to remove material for the structure – whether or not this is the optimum method has yet to be proven, but it does provide a suitable starting point. The work following is a detailed FEA parametric study, which examines the effects of multiple circular pockets with variations in pocket depth and diameter. A set of over 100 simulations have been used to analyze the parameters that are most effective in structural light-weighting, and which of these parameters are sensitive to others used. The analyses first involve three circular light-weighting pockets, then move on to four, five, and six pockets. In all cases, material properties for Zerodur are used as the best data for traditional mirrors has been given for this material, and it serves as the best means of comparison.

4.4.1 Three Circular Lightweight Pockets

Figure 62 shows an example of the structure imposed on the back of the mirror for a three-pocket design. Variations to this model appear in two forms: first, the diameter of the mirror is varied, then the depth of the pocket is varied for each diameter. In each case – given a specified pocket depth and diameter – the mass of the mirror and the mirror deflection are recorded. The deflection results from a 36.95-N load applied to the back surface, thus allowing for a comparison of the deflections between traditional and lightweight designs. Figure 63 shows the variation in mass and deflection as the radius of the light-weighting pockets (denoted r_1) is increased. The term r_2 refers to the radius from the mirror centre to the centre of the light-weighting pocket: for all models, r_2 is equal to one quarter the mirror diameter, or 27.05 mm. In this example, a pocket depth (denoted t_0) of 3 mm is used: this would correspond to a t_0/t of 0.5, as the thickness of the mirror (t) is 6 mm. As would be expected, a similar pattern is exhibited when the pocket depth is increased and the pocket radius is held constant. Figure 64 shows this correlation. It is also possible to examine the sensitivity of mass reduction and deflection of the lightweight mirror to both pocket depth and diameter. Figure 65 shows mass reduction and deflection data for the three-pocket design, as both pocket depth and diameter is varied.

Further examination of the deflection contours for the three-pocket design led to adverse results. It was observed that for large pocket diameters at sufficient depth (i.e. for large percentages of mass removal), deflection values were greater along the directions where

the pockets were situated. Figure 66 shows loading effects of this design: it can be seen that the deformation is no longer axisymmetric. In most active systems, axisymmetric deformation can be accounted for through variation of secondary mirror position or the location of the imaging device, as the main consequence of this deformation is a relocation of the focal point. If the deformation is not axisymmetric, rays of incoming light are focused in different locations and the image becomes distorted (see *astigmatism*, Section 2.5, to illustrate). The need to better distribute the mass reduction has thus been identified: to do this, the number of light-weighting pockets has been increased to four, five, and six. The deflection contours in these instances have been analyzed, as have the mass reduction and deflection data, in a manner similar to the three-pocket design.

4.4.2 Four-, Five-, and Six-Pocket Designs

Once the solid models for the four-pocket design were established, the deflection contour for the case most susceptible to deformation (i.e. the case with the highest mass reduction) was observed. It can be seen in Figure 67 that the deformation during loading is once again axisymmetric, meaning the mass reduction has been sufficiently distributed about the back of the mirror. Therefore, the five- and six-pocket designs would also produce an axisymmetric deformation, and the validity of producing these models was confirmed.

To allow a comparison of the four designs, sets of 25 analyses were carried out for each configuration. As with the three-pocket design, variations were made to both the pocket

depth and diameter. In all cases, the finite element models were composed of approximately 10 000 – 12 000 elements. Figures 68 to 70 show the mass reduction and deflection data for the four-, five-, and six-pocket designs, and Table 19 gives specific examples of each that warrant comparison. Looking at this data, one can see that as the number of pockets used is increased, the deflection at a given mass is noticeably reduced. Also included in Table 19 is a brief comparison of two different cases in the four-pocket design, where the mass reduction is nearly identical but the pocket depth and diameter is varied, and as a result the deflection data is remarkably different.

One final characteristic to note is in the stress concentrations that appear on the top surface of the mirrors, as shown in Figure 71. This effect occurs for large values of t_0/t , and may be eliminated by reducing the pocket depth, or by filleting the interior edges of each pocket. Similar contours can be seen for all other multiple-pocket mirrors with large pocket depths.

Chapter 5

Discussion of Findings

Although it appears to be a simple process, the candidate material selection results given in Table 16 have involved a great deal of background research and attention to every detail, as shown by the literature review contained herein. In this instance, the primary factors involved in the material selection focus on the availability and cost associated with the candidate. As this may not always be the case, many aspects of current mirror material candidates have been included in one written work. With the current priorities for material selection given by APS however (i.e. availability and cost), it is felt that aluminum, Zerodur, and the CANMET MMC are viable mirror materials. In each case, the material was proven both readily available and cost-efficient while maintaining a certain level of optical performance: however, it should be noted that this is for APS specifically, and such statements may not be true for other optics manufacturers worldwide.

Subsequent construction of traditional mirror models within the I-DEAS environment led to several conclusions about mesh dependence and the selection of an appropriate element size. Figures 46 to 51 show that the deflection of the top surface varies within $0.01\text{ }\mu\text{m}$ as the normalized element length is varied. This is regardless of material property specifications and mirror thickness. The use of a normalized element length is important as the dependence of element length on mirror thickness has already been recognized, i.e. the use of large elements in relatively thin models will result in significant element distortions that may lead to solve errors in the subsequent analysis. It then became apparent that the factors dictating element size were the time required to

solve the model and the predicted complexity of the light-weighted mirror structure to be analyzed. While the latter is dependent on future light-weighting procedures that cannot be realized here, an examination of the former was possible. Figures 52 and 53 have shown that reduction in normalized element length led to an increase in the number of elements, which thereby results in an increase in time to solve. What is important to note is that the sensitivity of the number of elements to the normalized element length is strongly dependent on the D:t ratio of the mirror. Thus, a large D:t allows for large increases in the number of elements as e/t is reduced.

As for model calibration, an adequate summary has been provided in Section 4.1.3. It is felt that most of the deviation that has occurred between experimental and theoretical data has resulted from inaccuracies in the interferometric data acquisition. A good example of this can be seen in comparing the interferometric data of the aluminum and Zerodur samples (Figures 58 and 59, respectively). Both unloaded mirrors should have zero PV surface error, yet the Zerodur mirror has an error of $0.099\text{ }\mu\text{m}$ and the aluminum mirror an error of $2.588\text{ }\mu\text{m}$. Most of this error arises due to aforementioned difficulties in producing a perfectly smooth surface during manufacturing. What this data shows is that the resultant errors between the FEA data and the interferometric data (shown in Table 18) are less than the apparent accuracy of the experimental procedure used. This means that even if the accuracy of the model were improved, it would do little to predict the actual mirror behaviour. For the purposes of this work the model accuracy is more than sufficient, especially considering the fact that most of the structural light-weighting

analyses presented highlight relative differences in various processes, not absolute deflection values. The dimensions, load, and boundary conditions imposed on the mirror are not typical of most mirrors used in industry, and are used mainly as a means of establishing benefits and drawbacks to a different material or light-weighting scheme.

This traditional mirror study also points out the advantages of Zerodur in terms of manufacturing accuracy, something that has also been referred to in the literature review. What this means is that predicting mirror behaviour when the mirror is made from Zerodur or some other low-expansion glass becomes more accurate when compared to aluminum, beryllium, MMC, or other similar types of mirrors that require EN plating for surface accuracy. This EN plating could be modelled, given the thickness of the plating used and its composition, and assuming uniform distribution along the mirror surface. In fact, this has been used to study the effects of bimetallic distortion and other effects on current imaging devices [21].

Preliminary results on structural light-weighting have given much insight into which procedures are better suited to a lightweight design. Examination of the number of circular pockets machined from the back of the mirror has shown that material removal must be sufficiently distributed about the mirror back to allow for axisymmetric deformation upon loading. In terms of the circular pockets used here, the number of pockets had to be increased to more than three: however, this is not the only way to evenly distribute the mass reduction about the mirror surface. Several different

lightweight geometries exist (as shown in Section 2.2) that can provide axisymmetric deformation – it was the ease in manufacturing that attracted APS to the idea of circular pockets for light-weighting.

Parametric variation of pocket depth and diameter led to similar conclusions about effective light-weighting procedures. Increasing the pocket diameter resulted in both mass reduction and greater mirror deflection when compared to the traditional mirror (see Figure 63); the same is true for increasing pocket depth (Figure 64). However, comparison of these two techniques reveals that for the same degree of mass reduction, the increase in deflection that arises due to pocket diameter increase is greater than that shown when pocket depth is increased. There is a limit to the depth of a light-weighting pocket however, and as such a suitable pocket diameter must be chosen. Table 19 substantiates this theory: in comparing two lightweight, four-pocket designs with nearly identical values in mass reduction, it was found that the design with a smaller pocket diameter and a larger pocket depth resulted in less mirror deflection under the same loading conditions. This characteristic is invaluable when attempting to reduce the mass of a mirror by a given amount – if the maximum extent of light-weighting were requested, one would simply use the largest pocket depth and diameter permissible, but this is not usually the case. In most cases, the optical performance of the mirror dictates how much a mirror can be light-weighted, and such trade-off studies as this allow for a greater reduction in mass while meeting target performance restrictions.

The advantages of using a smaller pocket diameter is further exemplified by comparisons of three-, five-, and six- pocket designs, shown in Table 19. Here, the increase in the number of pockets has forced the pocket diameter to be reduced, and any loss of mass reduction that has occurred as a result of this has been compensated for by an increase in pocket depth. Conclusively, the six-pocket design, having similar mass reduction values to the other two designs shown, deflects far less under the same loading conditions – the deflection is almost half that of the three-pocket design. It is therefore quite beneficial to increase the number of light-weighting pockets in the mirror design, provided this number is not excessive: a large number of pockets will increase the manufacturing time and decrease the structural integrity of the design (i.e. more pockets spaced closely together result in an intricate web-like structure similar to an open-back design, and must be handled with great care). Trade-off studies must be conducted to establish an optimum number of circular pockets for the design.

Chapter 6

Conclusions and Proposals for Future Research

6.1 Summary

A detailed materials database containing information on all state-of-the-art mirror materials has been established. This database includes physical properties, fabrication techniques, availability and cost information for materials suited to all types of mirror applications. This data has been used to select candidate materials for airborne optical systems under manufacture at APS. Aluminum, Zerodur, and a proprietary CANMET MMC have been selected as the most promising materials to pursue lightweight mirror fabrication.

With these materials chosen, traditional mirror analyses were carried out using both FEA data from models produced in the I-DEAS modelling environment, and interferometric data from mirrors produced at APS. The mirrors studied had a D:t ratio of approximately 18:1. Mesh dependence was established, and FEA models were produced that consisted of 11 305 tetrahedron elements; each model took approximately 23 minutes to solve. Due to inaccuracies in experimental data for the aluminum mirror, and a lack of experimental data for the CANMET MMC mirror, model accuracy was established using data from the Zerodur analyses. Here, the PV deflection of the mirror centre was found to deviate less than 1 μm from the deflection found using interferometric data, given the same loading and boundary conditions: this accuracy falls well within acceptable limits.

Having established the validity of the model, studies were conducted on the benefits of structural light-weighting. As only the Zerodur mirror model had been calibrated, this

material was the focus of the investigation. Structural light-weighting was conducted using a series of circular light-weighting pockets located on the back of the mirror. Three-, four-, five-, and six-pocket designs were produced, and a parametric study was conducted whereby the depth and diameter of these pockets were varied. It was concluded that while both pocket depth and diameter contribute to mass reduction of the mirror, mass reduction through increases in pocket depth was more advantageous than increases in pocket diameter, as the mirror stiffness of the former was higher at a given mass. This characteristic was taken advantage of through the use of multiple light-weighting pockets, such that the six-pocket designs performed much better than the three-pocket designs.

It is felt that the work contained herein provides a strong foundation for the selection of lightweight optical materials and structural designs. It is a guideline that validates and promotes the investigation of lightweight optics through finite element analyses, a technique that would save both time and money when compared to the alternative of manufacturing test specimens for interferometric analyses. With this work, CANMET may be able to compare how well materials they produce compare to materials currently available in lightweight mirror designs, and APS may be able to optimize structural designs for a given project.

6.2 Future Research

Establishing a materials database and validating the finite element models used has been fully realized and leaves little to be desired. Should a new material be introduced into the field of optics, it is felt that it would be beneficial to include the properties of this material alongside that of its competition. Additionally, it would be beneficial to validate finite element analyses with interferometric data for different mirror materials, including metals such as aluminum and beryllium, and ceramics such as silicon carbide. Other than this however, it is felt that this work has reached completion.

In the area of structural light-weighting, several opportunities exist to further develop the work initiated here. Only the benefits of using circular pockets for structural light-weighting have been examined: looking at the various methods of structural light-weighting discussed in Section 2.2, there remains a vast array of possibilities that could be studied. First, the work involving circular light-weighting pockets could be extended. This includes the aforementioned optimization of pocket number, size, and location, as well as the benefits of using fillets to alleviate stress concentrations that affect the mirror surface. Also, further validation of the finite element analyses with interferometric data for a mirror with circular light-weighting pockets would be beneficial.

From this, an examination of light-weighting using a radially ribbed structure should be conducted. This form of structural light-weighting is currently used by APS in several mirror designs, and should be compared to the use of circular pockets in terms of mass

reduction, optical performance, and ease of manufacture. This may provide immediate benefits to APS in some of their current design philosophies. Once this has been conducted, examination of open-back and sandwich structure designs should be analyzed to examine the feasibility of such designs for APS mirrors.

It should also be noted that the analyses carried out in this work have only been for plano-plano mirrors: although the relative simplicity of these types of mirrors allows for a more thorough initial parametric study, the use of such mirrors for primary mirrors in optical imaging devices is limited. The reflective surface of almost all primary mirrors are concave in nature, and so analyses of a concave-plano structure would be advantageous. It is therefore proposed that the structural light-weighting techniques applied to plano-plano mirrors for initial study be then applied to concave-plano mirrors for greater industrial relevance.

Finally, the acquisition of an appropriate optical post-processor for the I-DEAS deformation output should be looked into. In terms of post-processors, the FRINGE program developed at the Optical Sciences Center of the University of Arizona can provide PV and rms errors for complex FEA models. It can also identify complex surface errors such as coma and astigmatism that may arise due to complex loading scenarios or boundary conditions – this has not been the case thus far due to the relative simplicity of these conditions in the analyses conducted. Currently, the FRINGE post-

processor works in conjunction with NASTRAN output files, but perhaps the I-DEAS output can be modified to resemble the former.

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Tables

Table 1.
A comparison of reflective and refractive optics using several parameters vital to telescope quality [3].

<i>Telescope Characteristic</i>	<i>Reflective Design</i>	<i>Refractive design</i>
<i>Mass</i>	Ultralight	Moderate
<i>Envelope</i>	Comparable to or somewhat larger than refractor	Compact relative to aperture and focal length
<i>Athermal Performance Range</i>	Wide operating range (> 100 °C)	Low to moderate (10 to 40 °C)
<i>Spectral Response</i>	Ultrawide visible to LWIR	Limited to single band visible, NIR or SWIR, etc.
<i>Radiation Sensitivity</i>	None	Radiation hardened glasses or adequate shielding must be provided
<i>Polarization Sensitivity</i>	Very low reflectivity-induced polarization	Depends on the number of elements and coating. Typically, 5 to 10% polarization can be introduced

Table 2.
Consideration of properties for optical materials [7].

<i>Aspect</i>	<i>Properties</i>
Mechanical	Elastic modulus, strength, micro-yield strength (MYS), creep strength, hardness, ductility
Physical	CTE, density, thermal conductivity, specific heat, neutron cross-section, melting point, electrical conductivity, vapor pressure, corrosion potential
Optical	Reflectivity, absorption, complex index
Metallurgical	Crystal structure, phases present, voids and inclusions, grain size, recrystallization temperature, stress relief temperature, heat treatment, texture
Fabrication	Machinability, polishability, plateability
Other	Temperature sensitivity of properties, availability (size and cost)

Table 3.
Minimum faceplate thickness for common lightweight materials given current fabrication capabilities [25].

<i>Material</i>	<i>Minimum faceplate thickness (mm)</i>	<i>Minimum core density (%)</i>	<i>Core or rib fabrication process</i>
ULE	6.35	6.0	Fritting
Zerodur	3.05	7.5	Fusing
Fused Silica	3.05	4.0	Extrusion tubing
Beryllium	2.03	7.5	HIP

Table 4.
RMS wavefront errors for various contoured mirrors [29].

Mirror shape	Mass (kg)	Surface error (RMS wavelength – ring support)	
		Vertical	Horizontal
1.02-m diameter mirrors			
Concave-flat	247	0.017	0.028
Meniscus	281	0.071	0.009
Double-concave	212	0.282	0.002
Single arch	61	0.175	0.226
Double arch	137	0.036	0.007
0.41-m diameter mirrors			
Single arch: solid	7.35	0.012	0.003
Single arch: SXA foam core	3.18	0.148	0.025
Single arch: Nickel foam core	2.90	0.218	0.048

Table 5.
Mechanical and thermal properties of lightweight materials [3].

<i>Material</i>	ρ kg/m ³	<i>CTE</i> ppm/K	<i>Specific Heat</i> J/kg-K	<i>Thermal Conductivity</i> W/m-K	<i>E</i> GPa	<i>Thermal Distortion Coefficient</i> $\mu\text{m/W}$	<i>Specific Stiffness</i> MH/kg 10 ⁶
<i>Preferred</i>	<i>low</i>	<i>low</i>	<i>high</i>	<i>high</i>	<i>high</i>	<i>low</i>	<i>high</i>
Al	2.7	25	899	237	70	0.105	28.1*
Be	1.85	11.4	1880	216	303	0.053	164
ULE	2.20	0.03	708	1.3	67	0.023	30.4
Zerodur	2.55	0.15	820	6.0	90	0.025	35.3
SiC/Al MMC	2.96	12.2	-	120	130	0.102	40
SiC	3.21	2.4	700	250	466	0.010	145

Table 6.
Micro-yield strength characteristics of commonly used optical metals [7][31][33].

<i>Material</i>	<i>MYS</i> MPa	<i>Yield Strength (0.2 % offset)</i> MPa
Aluminum A356-T6	66.9	165
Beryllium	I-70	303
	I-220	345
	I-400	550 (UTS: brittle fracture)
	HP-21	not available*
	HP-40	not available*
	HP-81	not available*
Magnesium AZ31B	41.4	170

* data not available as Kawecki-Berylco ceased beryllium manufacture in 1979.

Table 7.
Comparison of I-250 to other types of beryllium [39].

<i>Material</i>	<i>Grade</i>	<i>MYS</i> MPa	<i>UTS</i> MPa	<i>Grain Size</i> μm	<i>Elongation</i> %	<i>% BeO</i>
I-250	Optical	96.5	655	2.5	3	2.0
I-70	Optical	11.7-12.4	n/a	10	3	0.7
I-220	Instrumental	49.6	n/a	6-8	2	2.1
S-200F	Structural	n/a	365	8-10	3	1.7

Table 8.
Past and current applications of Zerodur mirrors [10].

<i>Project</i>	<i>Year of Delivery</i>	<i>Dimensions (mm)</i>
MPIA/Calar Alto	1975	Ø 3602 x 593
Mount Korrek/Irak	1981	Ø 3600 x 592
ESO/NTT/La Silla	1986	Ø 3580 x 241
MPIA/Calar Alto	1970	Ø 2302 x 337
MPIA/ESO/La Silla	1971	Ø 2302 x 336
Madras/Indien	1974	Ø 2360 x 380
RGO/I. Newton T.	1975	Ø 2600 x 400
Lawrence Berkeley Laboratory	1983	Ø 2036 x 107
Nordic Optical Telescope, La Palma	1985	Ø 2560 x 190
Keck Telescope/Mauna Kea	1986-90	Ø 1900 x 76

Table 9.
Aerospace applications for SiC/Al MMCs [42].

<i>Material</i>	<i>Application</i>	<i>Comments</i>
SiC _p /Al	<ul style="list-style-type: none"> • electronic housings • gearbox housings, hinges, guide vanes, compressor housings, brackets, joints • gears (low load) • support extrusions 	<ul style="list-style-type: none"> • economical • detailed castings/ extrusions • tailorable CTE • high temp strength/stiffness • reduced fracture toughness
SiC _w /Al	<ul style="list-style-type: none"> • support extrusions • plate and sheet • shafts, cranks, brackets • housings • booms, casings 	<ul style="list-style-type: none"> • lowest fracture toughness • enhanced properties from extrusion, rolling, forging, etc. • high stiffness • tailorable CTE, conductivity

Table 10.
Mass comparison of collimators constructed of various materials (in kg) [13].

<i>Component</i>	<i>Al/SXA</i>	<i>SXA</i>	<i>Be</i>	<i>SiC/SXA</i>
Primary mirror	6.7	4.9	1.1	2.3
Secondary mirror	0.6 (SXA)	0.6	0.2	0.5
Structure	1.4 (SXA)	1.4	0.7	1.4 (SXA)
Baseplate	6.8	5.4	1.1	5.4 (SXA)
Total collimator weight	15.5	12.3	3.1	9.6

Table 11.
Producibility of various lightweight optical materials [45].

<i>Property</i>	<i>Al</i>	<i>Be</i>	<i>CERAFORM</i>	<i>Silicon</i>	<i>ULE</i>
Size Limitation	> 2.0 m	1.2 m	1.2 m	0.5 m	8.1 m
Joining Methods	Braze and Weld	Braze	Frit and Fusion	Frit and Braze	Frit and Fusion
Machining Fine Details	Conventional	Conventional and HIP	Cast, Ultrasonic and Diamond Mill	Ultrasonic and Diamond Mill	Ultrasonic and Diamond Mill
Polishability	30 Å RMS	15-20 Å RMS	7 Å RMS	5 Å RMS	< 3 Å RMS
Cost	Low	High	Low	Medium	Medium

Table 12.
Critical information of the mirrors under investigation.

<i>Property</i>	<i>Description</i>
Materials	Aluminum, beryllium, ULE glass, Zerodur, SXA composites, silicon carbide
c (mm)	48.64
a (mm)	54.10
t* (mm)	6.00
P** (N)	100

* t is the thickness used for the cases where mirror size is held constant

** P is the load applied for external loading only (i.e. not gravitational loading)

Table 13.
Physical properties of candidate mirror materials [6][25].

<i>Material</i>	<i>E (GPa)</i>	<i>ν</i>	<i>ρ (kg/m³)</i>
Aluminum	68.3	0.33	2710
Beryllium	303	0.07	1850
ULE	67.6	0.17	2120
Zerodur	93.8	0.24	2519
SXA	110	0.30	2768
Silicon Carbide*	364	0.14	2950
CANMET MMC	125	0.3	2200

* Properties were taken for CERAFORM silicon carbide, one of the common types of SiC used in mirror fabrication

Table 14.
Thickness comparisons of candidate mirror materials having identical bending characteristics due to external loads. Values given are in the form t_2/t_1 .

		t_2						
t_1	<i>Material</i>	Al	Be	ULE	Zerodur	SXA	SiC	CANMET
	Al	n/a	0.63	1.03	0.92	0.86	0.59	0.82
	Be	1.58	n/a	1.64	1.45	1.36	0.94	1.30
	ULE	0.97	0.61	n/a	0.89	0.83	0.57	0.80
	Zerodur	1.09	0.69	1.13	n/a	0.94	0.64	0.90
	SXA	1.16	0.74	1.20	1.07	n/a	0.69	0.96
	SiC	1.69	1.07	1.75	1.55	1.45	n/a	1.39
	CANMET*	1.21	0.77	1.25	1.11	1.04	0.72	n/a

* implies CANMET proprietary MMC.

Table 15.
Thickness comparisons of candidate mirror materials having identical bending characteristics due to gravitational loads. Values given are in the form t_2/t_1 .

	t_2							
t_1	<i>Material</i>	Al	Be	ULE	Zerodur	SXA	SiC	CANMET
	Al	n/a	0.44	0.99	0.86	0.81	0.50	0.68
	Be	2.25	n/a	2.22	1.95	1.83	1.12	1.53
	ULE	1.01	0.45	n/a	0.88	0.82	0.50	0.69
	Zerodur	1.16	0.51	1.14	n/a	0.94	0.58	0.78
	SXA	1.23	0.55	1.22	1.07	n/a	0.61	0.84
	SiC	2.01	0.89	1.98	1.74	1.63	n/a	1.36
	CANMET*	1.48	0.65	1.45	1.28	1.20	0.73	n/a

* implies CANMET proprietary MMC.

Table 16.
Comparison of optical materials for final candidate selection.

<i>Material</i>	<i>Cost/Availability</i>	<i>Ease of Manufacture</i>	<i>Optical Performance</i>
Aluminum	Very good	Very good	Poor
Beryllium	Poor	Very poor	Very good
ULE glass	Good	Poor	Very poor
Zerodur	Good	Good	Good
SXA	Very poor	Poor	Good
Silicon carbide	Poor	Very poor	Very good
CANMET MMC	Good	Poor	Good

Table 17.
Central-point deflection data (on the top surface) and time to solve for mirrors under investigation by APS.

<i>Material</i>	<i>Deflection (μm)</i>	<i>Time to Solve (min)</i>
Aluminum	3.125	23.12
Zerodur	2.492	22.59
CANMET MMC	1.763	23.38

Table 18.
Comparison of deflection data between FEA-produced results and those reached experimentally.

<i>Power Filter Status</i>	<i>FEA Deflection (μm)</i>	<i>Experimental PV Deflection (μm)</i>	<i>Deviation (μm)</i>	<i>% Error</i>
On	2.492	3.345	+ 0.853	+ 34
Off	2.492	1.948	- 0.544	- 22

Table 19.
Comparison of selected deflection data for multiple-pocket designs.

# pockets	t_0/t	r_1/r_2	Mass Reduction (% of traditional mirror)	Increase in Deflection (% of traditional mirror)
3	0.50	0.75	21.1	120.7
5	0.67	0.55	25.2	101.5
6	0.75	0.45	22.8	67.4
4	0.50	0.70	24.5	155.4
4	0.67	0.60	24.0	95.4

Figures

Figure 1. Ray diagrams comparing the two main types of reflective telescopes: (a) the Newtonian telescope, and (b) the Cassegrain telescope [4].

Figure 2. Trends in optical commercialization [6].

Figure 3. Photo of one of the Gemini telescopes (left) and the Subaru telescope (right) (courtesy the National Schools' Observatory).

Figure 4. Photo of a Gemini primary mirror prior to application of its reflective coating (courtesy the Gemini Observatory Photo Gallery).

Figure 5. Photo of one of the telescopes from the VLT project (courtesy the National Schools' Observatory).

Figure 6. Installation of the SOFIA in the aft section of a Boeing 747 SP aircraft [15].

Figure 7. Self-weight deflection for open-back lightweight mirrors [24].

Figure 8. Self-weight deflection for sandwich-core lightweight mirrors [24].

Figure 9. Inscribed circle (denoted b) for various rib patterns [25].

Figure 10. Minimum faceplate thickness of a sandwich mirror exposed to polishing loads assuming visible light and a 1 % allowable light loss [28].

Figure 11. Measured values (data points) of the shear modulus of structural foams compared to Ashby's relationship [24].

Figure 12. Contoured mirror shapes [29].

Figure 13. Thermal conductivity of different materials at varying temperature [7].

Figure 14. CTE anisotropy in beryllium [7].

Figure 15. Optical configuration of the SBV telescope [36].

Figure 16. Distortions in a ULE mirror due to CTE discontinuities [41].

Figure 17. Microcreep behaviour of SXA composites [43].

Figure 18. Material removal through loose abrasive fracture of glass [31].

Figure 19. HIP process used for lightweight beryllium mirrors [49].

Figure 20. Corning Hex Seal process used for mirror fabrication [40].

Figure 21. Most economical fabrication techniques for Zerodur mirrors as a function of diameter and thickness [10]:

Area I: Conventional casting/machining.

Area II: Slumping and fusion techniques.

Area III: Spin-casting.

Figure 22. Flowchart for the fabrication of SXA mirrors [11].

Figure 23. CTE variations for silicon carbide and free silicon over temperature [46].

Figure 24. Setup for a typical interferometer analyzing the surface flatness of a primary mirror [53].

Figure 25. A plane wave propagating in the k -direction [51].

Figure 26. Zones of constructive and destructive interference caused by superimposing two plane waves. A single plane wave is represented in (a), while its overlap with a second “tilted” wave is shown in (b), highlighting the formation of a fringe pattern [54].

Figure 27. Resulting fringe pattern from Figure 26(b), as seen from the observation plane.

Figure 28. Ray diagram of a spherical aberration in a simple reflective optic [58].

Figure 29. Ray diagram depicting coma in a converging lens. The bright head would be situated at the top of the aberration in this case [58].

Figure 30. Ray behaviour in the presence of astigmatism [59].

Figure 31. The principle of defocus, whereby the rays of the reference piece (transmission sphere, shown using dashed lines) will be at an angle to those of the test piece [59].

Figure 32. Typical interferometric readings of tilt, defocus, spherical aberration, coma, and astigmatism [55].

Figure 33. Determination of peak-to-valley error using fringe analysis [60].

Figure 34. Difference between PV and rms errors [61].

Figure 35. Configuration of a single-beam Fizeau interferometer [60].

Figure 36. Schematic of the ZYGO GPI series of interferometers [64].

Figure 37. Application screen for the Zygo MetroPro software [65].

Figure 38. Transverse loading of a circular plate, simply supported [66].

Figure 39. Loading conditions used in preliminary theoretical analysis for a thin circular plate.

Figure 40. Solution of the plate bending problems in Figure 39 (a) through superposition of two easier problems, (b) and (c).

Figure 41. Central deflection of loaded mirrors.

Figure 42. Boundary conditions applied to the mirror model. *From left:* the partitioned model, the model with a ring mount restraint, and the fully restrained model.

Figure 43. Solid models of the mirror specimens created within the I-DEAS modelling environment. Dashed lines represent partitions used for FEA operations.

Figure 44. Various meshes used to determine the effectiveness of coarse-mesh (*left*) and fine-mesh (*right*) models.

Family	Order			Topology	
Lumped Mass					
Spring					
Damper					
Gap					
Constraint					
Rigid					
Rigid Surface					
Rod					
Beam	<u>Linear</u>		<u>Parabolic</u>
Pipe					
Plastic					
Axisymmetric Shell					
Membrane					
Plane Stress					
Plane Strain					
Thin Shell	<u>Linear</u>	<u>Parabolic</u>	<u>Cubic</u>	<u>Quad</u>	<u>Triangle</u>
Thick Shell					
Axisymmetric Solid					
Solid	<u>Linear</u>	<u>Parabolic</u>	<u>Cubic</u>	<u>Brick</u>	<u>Wedge</u> <u>Tetrahedron</u>

Figure 45. I-DEAS element types [71].

Figure 46. Comparison of central deflection for an aluminum mirror, $D:t = 20$, using plate bending theory and FEA.

Figure 47. Comparison of central deflection for an aluminum mirror, $D:t = 10$, using plate bending theory and FEA.

Figure 48. Comparison of central deflection for an aluminum mirror, $D:t = 4$, using plate bending theory and FEA.

Figure 49. Comparison of central deflection for an aluminum mirror, $D:t = 6$, using plate bending theory and FEA.

Figure 50. Comparison of central deflection for an Zerodur mirror, $D:t = 6$, using plate bending theory and FEA.

Figure 51. Comparison of central deflection for an CANMET MMC mirror, $D:t = 6$, using plate bending theory and FEA.

Figure 52. Number of elements as a function of element length, given various $D:t$ ratios.

Figure 53. Required time to solve as a function of element length given various $D:t$ ratios.

Figure 54. Deflection contour for the top surface of the aluminum APS test model. Scale shown is in mm.

Figure 55. The GPI XPS interferometer installed at APS. (1) The laser light is emitted from the main unit, where some of the light is reflected back. The remaining light is sent to the mount (2), where the mirror specimen is mounted. The resulting interferometric pattern is displayed on the computer monitor (3).

Figure 56. A close-up of the specialized mirror mount used. The mirror is placed on the mount plate (1), while the thread holding the load applied to the back of the mirror is passed through the hole and over the pulley (2).

(a) Prior to mounting.

(b) Mounted and loaded.

Figure 57. Mirror specimen mounted and loaded on the interferometer.

Figure 58. Initial unloaded test for the aluminum APS test specimen.

Figure 59. Initial unloaded test for the Zerodur APS test specimen.

Figure 60. Zerodur mirror subjected to a 36.95-N load.

Figure 61. Zerodur mirror subjected to the same 36.95-N load, but with the *power* filter activated.

Figure 62. Lightweight mirror, consisting of three light-weighting pockets on the back of the mirror. Dashed lines represent partitions used for FEA operations.

Figure 63. Reduction in mirror mass and increase in mirror deflection as a result of increasing pocket diameter (three-pocket design, t is constant at 3 mm).

Figure 64. Reduction in mirror mass and increase in mirror deflection as a result of increasing pocket depth (three-pocket design, r_1/r_2 is constant at 0.5).

Figure 65. Sensitivity of the three-pocket design to pocket depth and diameter.

Figure 66. Deflection contour for the three-pocket design. The top surface of the mirror is shown, as is the location of the light-weighting pockets.

Figure 67. Deflection contour for the four-pocket design. The top surface of the mirror is shown, as is the location of the light-weighting pockets.

Figure 68. Sensitivity of the four-pocket design to pocket depth and diameter.

Figure 69. Sensitivity of the five-pocket design to pocket depth and diameter.

Figure 70. Sensitivity of the six-pocket design to pocket depth and diameter.

Figure 71. Stress analysis of a six-pocket design, $t_0/t = 0.75$. Regions of concentrated stress are light blue. Top surface of mirror shown.

Appendix A

Procedures for Finite Element Modelling in I-DEAS

The following appendix outlines the procedure followed when setting up and conducting finite element analyses within the I-DEAS modelling environment. It is assumed the reader has knowledge of the basic I-DEAS solid modelling package, such that a model of desired geometry may be produced without aid. Instructions cover partitioning of such a model, application of boundary conditions, development of a finite element mesh, carrying out an analysis, and post-processing. These instructions are given as they pertain to the study followed in this thesis, and it must be noted that several variations to this type of analysis exist.

A1.1 Establishment of Appropriate Solid Model Parameters

Assuming the solid model used for FEA has been constructed, this model must be partitioned such that element nodes are located at points of interest (ie. they must be placed at points of load application, and along boundary conditions). In the analyses conducted in this thesis, the main areas of interest include the centre point of the mirror – where the load is applied and deflection data is taken directly – and a circular band indicating the location of the ring mount used to constrain the system.

To properly partition the model, first sketch out the partition locations on the mirror surface. The *Master Modeler* task must be selected to do this; choose the *Sketch in place* command and select the mirror surface to sketch the desired partition design. Once this has been completed, partitioning can be carried out using the *Extrude* command. In the *Extrude Section* menu, select the parameters *Partition* and *Thru All*. This will ensure the

division of the model will carry through its entire thickness. Figure A1 shows this menu selection, and Figure A2 shows partition formation in its simplicity.

Figure A1. Partition menu.

Figure A2. Partitioning of a traditional mirror. *From left:* the solid model, the model with the desired partition sketched on the surface, and the fully partitioned model.

With this complete, the model has been partitioned and is ready for boundary condition application. Note however, that the presence of light-weighting geometry may have an impact on the partition design: for instance, the lightweight mirror design shown in Figure 62 of the text incorporated three light-weighting pockets, the position of which warranted redirection of the partition lines. Partitions may also have to be redirected if they are close to other geometric entities and gross element deformation occurs during meshing operations.

A1.2 Application of Boundary Conditions (Geometric)

Boundary condition application requires the user to switch from *Master Modeler* to *Boundary Conditions* tasks. First, apply mount restraints to the model using the *Displacement Restraint* command and selecting the appropriate geometric entities (in this case, the circular partition). This will bring up a screen allowing the creation of a finite element model, shown in Figure A3: this is required as the boundary conditions will eventually be applied to the finite element mesh constructed at a later stage. From this screen, a name and part number is assigned to the model, as well as any additional characteristics. Figure A3 also shows the form used to specify boundary conditions on the geometry; in this case, the ring mount is assigned a fixed z-deflection, with all other degrees of freedom set free. Then at the centre of the mirror, the same procedure is followed, except this time the z-deflection is set free and all other degrees of freedom (x-deflection, y-deflection, etc.) are fixed. Figure A4 shows how the partitioned model becomes geometrically restrained.

FE Model Create

Bin

Main

Part or Assembly

Mirror

Get...

Part Material

6061 ALUMINUM

Select

FE Model Name

Model

FE Model Part #

m1

☐ All Sections

☐ P Element Analysis

☐ Geometry Based Analysis Only

Assembly Configuration

Define Assembly FEM

OK

Reset

Cancel

Displacement Restraint and Edge

Restraint Set

Restraint Set 1

Time

Graphics

Coordinate System

CS1

Select

Combine

	Amplitude	Type	Name
X Translation	0	free	
Y Translation	0	free	
Z Translation	0	constant	
X Rotation	0	free	
Y Rotation	0	free	
Z Rotation	0	free	

Set As Defaults

Use Defaults

Set All Free

Set All Constant

OK

Apply

Reset

Cancel

Figure A3. The FE Model creation screen (above) and boundary condition form (below)

Figure A4. Placement of geometric boundary conditions. *From left:* the partitioned model model, the model with a ring mount restraint, and the fully restrained model.

A1.3 Meshing Operations

The addition of a finite element mesh to the solid model must be performed within the *Meshing* task. From here, select the *Define Solid Mesh* command: when prompted to select the desired volumes, the user may simply select the entire model. This will bring up a *Define Mesh* form, where the element length, type, and family may be selected (see Figure A5). Solid, ten-node tetrahedrons have been used in this work, with an element length of 3.0 mm. Free meshing has also been selected over mapped meshing, as the latter would require further model subdivision – this would contribute to additional work, particularly in parametric studies where variation of the model geometry will require variation of the model subdivisions. At this point, preview the mesh to see if it is satisfactory. If it is, the user must then return to the *Boundary Conditions* task and set the geometric boundary conditions to the finite element model (i.e. the mesh). This can be performed using the *FE from Geometry* command: if prompted to apply to current sets only, select *No*. This is because the restraints that have been created have not formally

been set to the model: I-DEAS will therefore search through all boundary conditions and will transfer any geometric data to the relevant nodal points on the finite element mesh. In the end, a finite element model such as that shown in Figure A6 will be created. Note that the *Convert FE from Geometry* command will also convert forces (which have also been applied to the geometry), such that nodal forces result.

Define Mesh

Mesh Type
☒ Free ☐ Mapped

Free Options Mapped Options

Element Length 3.0

Element Family Solid

Element Type

Element Color GREEN

Physical Property SOLID1

Beam Options

Material 6061 ALUMINUM

☒ Part ☐ Other

Material Selection

Set As Defaults Use Defaults

OK Apply Reset Cancel

Figure A5. Mesh definition form.

Figure A6. Finite element model, consisting of over 11 000 elements. Geometric boundary conditions are shown.

A1.4 Model Solution

The first step in creating a solution file is to apply all relevant boundary conditions to the model. From the *Boundary Conditions* task, select the *Boundary Condition* command. This will allow the user to select the FE-based restraints and loads as the boundary condition set for the analysis. Once this has been completed, it is possible to establish a solution set. Under the *Model Solution* task, select the *Solution Set* command: from the *Manage Solution Sets* form that appears, create a new solution set. It is important to note that the boundary condition set specified for the solution set matches the boundary condition set created previously – it is possible to have more than one boundary condition set applied to the model, so making sure the desired conditions are applied is essential. Select the *Solve* command once this is complete, thereby beginning the model solve. Time to solve for a model of the size used here would be approximately 25 minutes.

A1.5 Post-Processing

Having solved the finite element model, examination of the deflections, stresses, and strains resulting from the problem can be observed using the *Post Processing* task. Selecting the *Results* command allows for the selection of whatever type of result the user wishes to be displayed on the viewport. Figure A7 shows the *Results Selection* form: here, the deflection countour, stresses, strains, and reaction forces that result may be chosen for display.

Figure A7. Results selection form.

Once the desired results have been selected, they may be viewed using the *Display* command, and selecting the elements the user wishes to have displayed (normally, the entire model is selected). Figure A8 gives an example of this analysis, showing the deflection contour as well as a legend providing the quantitative deflection data associated. Should more detailed information be required, using the *Report* command will allow results for specific nodes. Once the command has been selected, the user is prompted to select the nodes of interest from the viewport. Relevant data for each node selected is then given in the *I-DEAS List* window located at the bottom left of the screen. Note that the information is usually given for a number of nodes, so the actual node number (which can be acquired from the viewport by highlighting the node) is required.

Figure A8. Deflection contour of the mirror under loading.