1 HISTORY

1.1 Glass, Lenses, Spectacles and Mirrors
By 1500BC, in the E Mediterranean, colourless glass was being produced, (including water-filled blown spheres which could focus) and quartz crystal was also available [1,2]. In 212BC Archimedes defended Syracuse from the attacking Roman fleet using ‘a burning glass’ [3] (a translation error for polished metal shields?).

In 11thC Alexandria, scholar Abu Al Hasan of Baghdad, (also referred to as ‘Al-Hazen’) recorded geometrical theory of concave mirror focusing [2]. This was followed in the late 13thC by ophthalmic correction lenses (spectacles) due to English cleric-inventor Roger Bacon [2] and soon ‘opticians’ were making them across Europe. However, rough grinding and fine polishing of small glass optics to spherical form and fine finish (to 10s of nm) remained more accepted than understood.

1.2 The Telescope
The first utility telescope using two lenses is credited to Lippershey, a Dutch spectacle maker, in 1608. Hearing of it, Galileo in Padua made a telescope for the merchants of nearby Venice (to give advance knowledge of ships arriving).

In 1668, Newton [5] constructed the first reflecting telescope using a 34 mm (1.33 ins) diameter primary mirror of focal length 155 mm (6 ins) made from ‘bell metal’ (bronze). Being brittle, the established artisan spectacle-makers’ glass-working techniques obtained its intrinsic metallic reflection. Not suffering the chromatic aberration of contemporary refractor telescopes, the instrument had much shorter focal length and so was considerably more compact with higher resolution.

Newton pioneered use of a pitch-polisher tool charged with abrasive, (‘putty’ in his case: finely powdered calcium carbonate and linseed oil)[5]. The mirror was made from the brittle bronze eutectic comprising 67% copper and 33% tin with an added doping of arsenic to ‘whiten’ the metal [2]. Known as ‘speculum’ in optical sciences, this alloy readily tarnishes, requiring re-polishing to maintain adequate reflectivity (63%). It was used in ever larger telescope mirrors over the next two hundred years, taking diameters to 1.8m.

1.3 Mirrors vs Lenses
It is worth comparing the lens and mirror as primary focusing elements.

In a reflecting telescope, the secondary mirror causes obstruction but there is little resulting loss in light or resolution.

A lens requires two surfaces coaxially aligned on a single blank which demand precision manufacture, including their mutual orientation in four degrees of freedom. Being effectively a ‘curved prism’, the single lens dispenses colours (wavelengths) differentially to foci along the optical axis. To reduce the effects, telescopes were made with (ungainly) long foci and tubes until the advent of the two-lens (doublet) ‘achromat’ in the 18thC which brought the foci for two colours (blue and red) into coincidence. However, the two extra surfaces add considerably to manufacturing costs.

Definitively, a mirror requires only one surface, involving no transmission, refractivity or dispersion. However, an error e in its surface causes a reflected (air) path error 2e. In a refracting glass surface the error e is desensitised by a factor of 3 as the resulting path change involves exchange of glass (index 1.5) with air (index 1.0). This applies to both surfaces (or all four in an achromatic doublet). However, form errors in a doublet can be offset to some extent by mutual rotation.

Glass transparencies (>90%) considerably exceed reflectivities of most metals and a lens does not tarnish. However, larger lens thicknesses (proportional to aperture) incur temperature-gradient stress and refractivity problems resulting in index-differences, scatter and micro-cracking. Metal mirrors suffer fewer thermal problems and are considerably more rugged. Thermal defocus is the main disadvantage with advantages of improved mirror ‘micro-seeing’ and thermal emissivity.

2 LARGER APERTURE OPTICS
2.1 Needs
There are two fundamental drivers for increasing the aperture of objective focusing elements:
1. Finer image resolution, which is directly proportional to wavelength and inversely proportional to aperture diameter.
2. Increased light flux energy, ie brightness at the focus (proportional to the area of the optic, and diameter squared).
2.2. The 48 inch (1.2m) Mirror of Sir Wm Herschel (1738-1622)

William Herschel [4,6] was a musician-tutor in Bath when he took up astronomy. Unable to obtain satisfactory mirrors, he set about making them himself, including casting speculum blanks (at some personal risk) and learning to grind and polish their surfaces. Soon he produced mirrors considerably superior to those of the established instrument makers (enabling him to resolve objects hitherto unseen).

Herschel experimented with the alloy ratio, the grinding and polishing abrasives and the pitch materials. For rough form grinding, he used Naxos emery with iron or brass tools; they were then cleaned to become the backing for polishing pitch charged with rouge abrasive. For larger mirrors, he developed a series of polishing machines with crank-handle drives and ratchet and pawl systems to rotate the mirror and tool at preset differential intervals and rates with figure of eight motion.

Herschel undertook the first systematic observations of the night sky and in 1781 discovered Uranus. Appointed personal astronomer to King George III, he moved to Slough (to be near Windsor Castle for royal astronomical soirees). There he progressed mirror-making capability to a diameter of 1.22 m (48 in) and 12.2m (40ft) focal length.

2.3 The 72 inch (1.8m) Mirror of William Parsons, 3rd Earl of Rosse (1800-1867)

At Birr Castle, Co Offaly, Ireland, Lord Rosse investigated production of cast speculum mirrors [3,4]. He also investigated lightweight mirrors comprised of a thin-walled backing structure soldered to a faceplate could detect no optical differences between this blank and a monolith cast disc. However, for unspecified reasons, he reverted to the monolith casting for his telescopes.

His work culminated in a telescope 1.83m in diameter and 16m long which remained the world’s largest from 1845 to 1917. The 150 mm (6 in) thick primary mirror (weighing 3.5 tonnes) took eight casting attempts. Twyman [2] reports that Rosse polished it with a pitch tool using rouge with ammonia soap and water (the ammonia retarded and removed tarnishing). The instrument has been rebuilt in recent years (see 5.3).

2.4 Chemical and Electrolytical Enhancement of Ablation. (Henry Draper 1837-1882)

Draper produced speculum mirrors, based on alloy proportions obtained on a visit to Lord Rosse [3,4]. He perfected techniques of figuring with acid and experimented with electrolytic action for figuring, (making the speculum the positive pole of a voltaic circuit with acidulated water as electrolyte). Such techniques are currently employed in the semiconductor industry to speed the polishing of sawn wafers.

3. REFRACTOR VS REFLECTOR

By the end of the 19thC, lens apertures approached a plateau culminating in 40 inches (1.01m) for the objective of the Yerkes Observatory refractor designed by G E Hale [3,4]. As chemical silvering had become available [4], on moving to Mt Wilson Observatory, he redirected his efforts toward larger glass mirrors: first a 50 inch instrument followed by the 100 inch (2.5m) Hooker Telescope of 1917 and then the 200 inch (5m) completed on Mt Palomar in 1948. This work set the scene for a number of 4m aperture instruments using glass or glass-ceramic mirrors.

Doubings in aperture require proportionate scaling of required associated technologies. During chemical silvering, the 3 tonne 100 inch mirror was agitated successfully but, when the 25 tonne 200 inch mirror was attempted, the building agitated instead. Fortunately, at Harvard Observatory Lab., John Strong presciently demonstrated the viability of aluminium vapour deposition [3] which now sees extensive use for reflecting optics, multiple thin film filters and VLSI microelectronics fabrication.

Monolith glass mirror technology continued to 8m apertures based on the rotating furnace [13] which considerably reduced roughing requirements for faster aperture ratios in more compact instruments. These offered improved performance and the considerable economies of shorter tube length (to the cube of which, the building volume is proportional).

4 PRODUCTION OF LARGE ASPHERIC OPTICS

4.1 Special Issues in Polishing Aspherics

The well-tried techniques of convergent (spherical) optical polishing for spectacle manufacture requires the polishing tool and optical surface to ‘nest’ throughout maintaining close contact for all overlapping (shearing) mutual positions when subjected to the relevant two degrees of translational freedom and one of rotation [7]. A spherical optic is ‘stigmatic’ (ie yields best focus) only for auto-focussing a point source.

Alternate conic sections of rotation apply to other required optical geometries: the paraboloid focuses collimated parallel light (including from a point source at infinity), the ellipsoid focuses light diverging from a point source at one of its foci so as to converge at the other and the hyperboloid will refocus an already convergent light beam to a different focus (and reciprocity applies).

In aspherics, radius of curvature varies with radial position so the polishing lap must either be small enough or sufficiently flexible not to impose unacceptable departure from the required form; even so, force and dwell must be carefully controlled to achieve the required local ablation. For aperture ratios >10, the difference between spherical and requisite aspheric form is deemed negligible and the lap can be full size. As the aperture ratio reduces below this value, then so must the lap-size unless it is has form-adaptable capability.
4.2 Machining to Form plus Fine Polishing
A novel process for aspheric optics' manufacture was devised by Dr Reason pre 1950 at the Taylor Hobson Company, Leicester [1]. The form was generated with a diamond tool (either single point or high speed rotating burr) on an ultra-precision machine tool to within the requisite aspheric form error specification whilst accepting (grey) surface finish equivalent to traditional free abrasive roughing. With a soft bag-polisher, the time is established for removing subsurface damage and the resulting induced ('parasitic') spherising error measured. Production of the required aspheric then requires machining of the prepolished form so as to include a correction-term for the unwanted spherisation incurred in polishing.

Horne [1] describes a similar approach employed contemporarily by the Bell and Howell Co, Chicago. These facilities were used to produce aspheric aerial camera and projection lenses of up to 175mm (7 inch) aperture and Schmidt correctors to 275mm (11 inches).

4.2 Ion Beam and Magnetoholographic Finishing
Over the last thirty years, new processes such as ion beam ablation and magnetoholographic polishing have been developed. For new telescope designs requiring very fast (short focus) optics, traditional methods of production cannot produce the required surface quality for the optical performance necessary. With the aid of computer control, production techniques have been developed to produce the latest generation of large telescopes [12].

4.3 Metrology
At apertures below about 0.4m, standard interferometric wavefront metrology and other full aperture tests can be employed using commercial instrumentation. Traditional tests, such as Foucault’s arrangement [2] amenable to larger apertures, are restricted to the stigmatic focusing condition. In the case of perfect spherical mirror, a point source at its centre of curvature will return a stigmatically focused beam there.

However, for paraboloidal objectives used in most astronomical telescopes, stigmatic focusing requires a (bright) point test source at infinity or a full-aperture well-collimated input source light beam which in turn requires a collimator optic of the same or greater aperture. An alternative is a ‘contrived null’ test based on an appropriately (conjugally) distorted source wavefront from a conjugate focal point, the nominated ‘centre’ of curvature in the case of a mirror. Using this, a perfect test-optic shows stigmatic focus but the Hubble Large Space Telescope illustrated difficulties incurred in this approach.

Other tests for large apertures include the Shack-Hartmann point source array test [1-3] which is particularly suited to electronic areal image detectors and can be enhanced using Foucault’s test [1]. The Ronchi test [1] can be modified by predistorting the line pattern either optically or by computer generation.

Testing large convex secondary mirrors is particularly troublesome at full aperture as it is difficult to access a focus other than in a completed instrument.

5 DEVELOPMENTS
5.1 Large Arrays and High Volume Production
With current conceptions of large telescopes employing primary focusing elements with apertures in the 20m+ range and areas of 100s of m², the manufacture of tessellated multi-mirror arrays is encouraging further interest in metal optics. During production, storage and installation, of such large numbers of (1-2m) optics, ruggedness during handling becomes an issue. An accident with a malleable metal mirror will usually result in some minor damage but the optic will be still repairable and usable. However a glass (or brittle metal) optic is very susceptible to fracture rendering it unusable. In the last few decades, around 6% of large optics produced have been lost through accidents during handling [14].

Development of beryllium, silicon carbide and aluminium lightweight substrates enables construction of adaptive and active metal optics with low inertia characteristics, capable of withstanding high momentary loads [11]. They also enable rapid tilting accelerations for infra-red astronomy and high frequency-response in adaptive secondary mirrors. However, there are (different) issues of manufacturing process costs and handling for both beryllium and silicon carbide.

Soft metals like aluminium and beryllium cannot themselves be optically polished due to factors including their ananmorphous grain structure. Since 1944, the development of electroless autocatalytic ‘Kanigen’ nickel-phosphide coating [1] has enabled a regular hard layer of nickel to be deposited on such metallic substrates. Although it offers only 63% intrinsic reflectivity, it can be polished using classical (glass-working) techniques to take a vapour deposited aluminium coating [1].

5.2 Aluminium Mirrors
As a result of the development of high precision externally pressurized gas and liquid bearings over recent decades, single-point diamond lathe turning enables aluminium mirrors to be machined to form (1/4) and to near-finishes (2nm Rs) for astronomical telescope mirrors.

Aluminium has merits of ease of casting, machining and ruggedness of handling which makes it attractive in competing with other materials such as glasses, glass ceramics, beryllium and silicon carbide.

The European Southern Observatory (ESO) investigated constructing the primary mirror of their ‘New Technology Telescope’ (NTT) from aluminium although it was eventually made from zero expansion
glass. This in turn led to the 'Large Active Mirrors for Astronomy' (LAMA) programme, which examined the possibility of manufacturing the 'Very Large Telescope' (VLT) primary mirrors from aluminium. The LAMA programme concluded with the construction of two 1.8 meter diameter nickel coated aluminium mirrors [8]. A 23 feet diameter aluminium collimating mirror was made for the JPL Solar Space simulator [9] in 1967. It was highly polished to 1200 inch radius of curvature but did not require astronomical form quality.

5.3 Reconstruction of the Rosse 1.8m Telescope at Birr Castle
In 1996, funding was obtained through various sources to rebuild the Rosse 1.8m telescope at Birr Castle [10]. The original speculum mirror, (on exhibition at the Science Museum, S Kensington, London) was deemed too fragile so it was decided to make the required replacement of aluminium with a nickel coating to be polished to optical quality [11] and overcoated with a vapour deposited aluminium layer. The Optical Science Lab., University College London, undertook the work to reconstruct the optics. This included supplying the paraboloidal primary and flat secondary aluminium mirrors, two eyepieces and their mounts, the mounting trolley with whiffle tree support system for the primary and support leg mount for the secondary. These were successfully installed on the telescope in 1999 [11].

6 SUMMARY
Current plans for new larger telescopes extend demands beyond previous manufacturing capabilities in terms of scale, materials and processes. Reviews of these indicate that metal mirrors (in particular, aluminium) may provide for the way forward.

7 REFERENCES