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Scaling laws for light-weight optics.

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ABSTRACT

Scaling laws for light-weight optical systems are examined A cubic relationship between mirror diameter and weight has been suggested and used by many designers of optical systems as the best description for all light-weight mirrors A survey of existing light-weight systems in the open literature has been made to clarify this issue Fifty existing optical systems were surveyed with all varieties of light-weight mirrors including glass and beryllium structured mirrors, contoured mirrors, and very thin solid mirrors These mirrors were then categorized and weight to diameter ratio was plotted to find a best fit curve for each case A best fitting curve program tests nineteen different equations and ranks a "goodness of fit" for each of these equations The resulting relationship found for each light-weight mirror category helps to quantify light-weight optical systems and methods of fabrication and provides comparisons between mirror types

1. INTRODUCTION

Understanding light-weight optics has become an important issue for many optical systems Many systems are weight limited including space optics and pointing and tracking systems In many cases the weight of the optics is the primary influence on the system weight as well as the cost Although these light-weight mirrors are often more costly to produce, their decreased weight often can produce a savings in the mounting Various scaling laws for light-weight optics have previously been used Generally, a cubic relationship has been assumed between weight and diameter [1] Another proposed generic equation commonly used for all light-weight mirrors is cited by Hamill[2] :

$$W = \frac{k\,D^{2\,6}}{\frac{D}{t}} \tag{1}$$

Where: D = diameter; k = constant; t = mirror thickness; W = mirror weight

It is suggested that for advanced space optics, this constant k should be reduced by a factor of 2 Many authors have developed other scaling relationships of interest including cost scaling laws developed by Meinel[3] and weight scaling relationships for the total tube moving weight developed by Rule [4] To continue this interest in scaling and preferred mirror types for systems, a survey of existing light-weight systems was proposed

Once weight to diameter ratio for these mirrors is known it is necessary to quantify these ratios mathematically It was proposed to use a best fit curve program developed by Myung Cho of the Optical Sciences Center The nineteen different mathematical equations that were used to fit the data are listed in Table 1

2. MIRRORS STUDIED

The literature search of existing light-weight systems also included a few famous conventional systems for comparison In each case, mirror dimensions, material, configuration, and weight were tabulated Table 2 lists the conventional or solid mirror systems studied It should be noted that for future analysis, a very thin solid mirror with an aspect ratio (thickness/diameter) of less than 0 1 was considered as a light-weight mirror Listed in Table 3 are the light-weight systems studied These mirror types include structured mirrors, contoured mirrors, and beryllium mirrors Mirrors referred to as structured mirrors contain ribbed cells such as openback and sandwich mirrors Contoured mirrors are mirrors that have been light-weighted by cutting contours in the back of the mirror; i e single arch and double arch

3. RESULTS

After data compilation was completed and the mirrors were categorized, both the best fitting function and the power function for weight vs diameter were found for each category The power function represents the common weight to diameter relationship used for both solid and light-weight mirrors Figure 1 illustrates the functions found for solid mirrors with conventional aspect ratios (diameter to thickness) as well as very thin solids with small aspect ratios Although conventional solids are best described with a parabolic function, the power function using a nearly cubic exponent also describes the data well as expected The very thin solid mirrors are best described by a hoerl function and in the case of the power function have an exponent slightly smaller than that of conventional solids

All light-weight mirrors are represented in Figure 2 In this case the power function was the best fitting function with an exponent of approximately 3 This would indicate that in general, a cubic relationship between weight and diameter is a good rule of thumb for light-weight mirrors Figure 3 illustrates both the solid curves and the light-weight curve for comparison

Specific light-weight mirror types were next investigated The weight to diameter relationship for structured mirrors, contoured mirrors, and beryllium mirrors are shown in Figures 4, 5, and 6 respectively Upon examination of the power functions fit to the data, it is apparent that each specific type has a significantly different coefficient and exponent. It is also interesting to note the difficulty in achieving a good data fit for the beryllium mirror category This category contains a variety of unusual optical designs including innovative space optics

Finally the mirrors were categorized using the weight relationship cited earlier (equation 1):

$$W = \frac{k\,D^{2\,6}}{\frac{D}{t}}$$

The constant k was calculated for each mirror and optics with roughly equivalent constants were grouped together The category of traditional mirrors, shown in Figure 7, is comprised of solids and heavier light-weights (primarily contoured mirrors) and has an average k of 2560 The light-weight mirror category consisting of commonly configured light-weights has an average k of 802 (see Figure 8) The smallest average k value belongs to the ultra-lightweight mirror category This group, shown in Figure 9, includes the very unusual light-weight designs and the majority of the beryllium mirrors Figure 10 illustrates the weight to diameter relationship of all 3 of these categories on a single graph for comparison It is noteworthy that light-weight mirrors fit the power law the best and the ultra-lightweights came the closest to satisfying the 2 6 exponent of the light-weight equation (1)

4. CONCLUSIONS

A sample size of approximately 50 light-weight mirrors was used to examine the relationship between weight and diameter Table 4 summarizes the results found for each mirror category and includes both the best fitting function and the commonly used power function

While 50 samples is not a definitive data base, it is sufficient to draw a few conclusions It appears that a cubic relationship between weight and diameter for both solids and light-weights is a reasonable rule of thumb:

Solid Mirrors: $W = 246\,D^{2\,92}$
Light-weight Mirrors $W = 82\,D^{2\,95}$

For specific mirror types however, a more precise relationship can be used to scale weight as a function of diameter:

Structured Mirrors $W = 68\,D^{2\,90}$
Contoured Mirrors $W = 106\,D^{2\,71}$
Beryllium Mirrors $W = 26\,D^{2\,31}$

Mirrors may also be described using the light-weight relationship of equation 1:

Traditional $k_{avg} = 2560$ $W = 192\,D^{2\,76}$
Light-weight $k_{avg} = 802$ $W = 120\,D^{2\,82}$
Ultra-lightweight $k_{avg} = 387$ $W = 53\,D^{2\,67}$

With a better understanding of the weight to diameter relationship of specific mirror types, more informed choices can be made for candidate light-weight mirrors and more accurate weight estimations can be made for weight sensitive systems

5. ACKNOWLEDGEMENTS

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I.D.	NAME OF CURVE	EQUATION OF CURVE
1)	Linear	Y =a +bX
2)	Recip Linear	Y =1/(a +bX)
3)	Linear Hyperbola	Y =a +bX +c/X
4)	Hyperbola	Y =a +b/X
5)	Recip Hyperbola	Y =X/(aX +b)
6)	2nd Hyperbola	Y =a +b/X +c/X**2
7)	Parabola	Y =a +bX +cX**2
8)	Cauchy Distribution	Y =1/(a +(X +b)**2 +c)
9)	Logarithmic	Y =a +b lnX
10)	Recip Logarithmic	Y =1/(a +b lnX)
11)	Power	Y =a +X**b
12)	Super Geometry	Y =a +X**(bX)
13)	Mod Geometry	Y =a +X**(b/X)
14)	Hoerl	Y =a b**X X**c
15)	Modified Hoerl	Y =a b**(1/X) X**c
16)	Log Normal	Y =a EXP ((b - lnX)**2/c)
17)	Modified Power	Y =a b**X
18)	Root	Y =a b**(1/X)
19)	Normal Distribution	Y =a EXP ((X - b)**2/c)

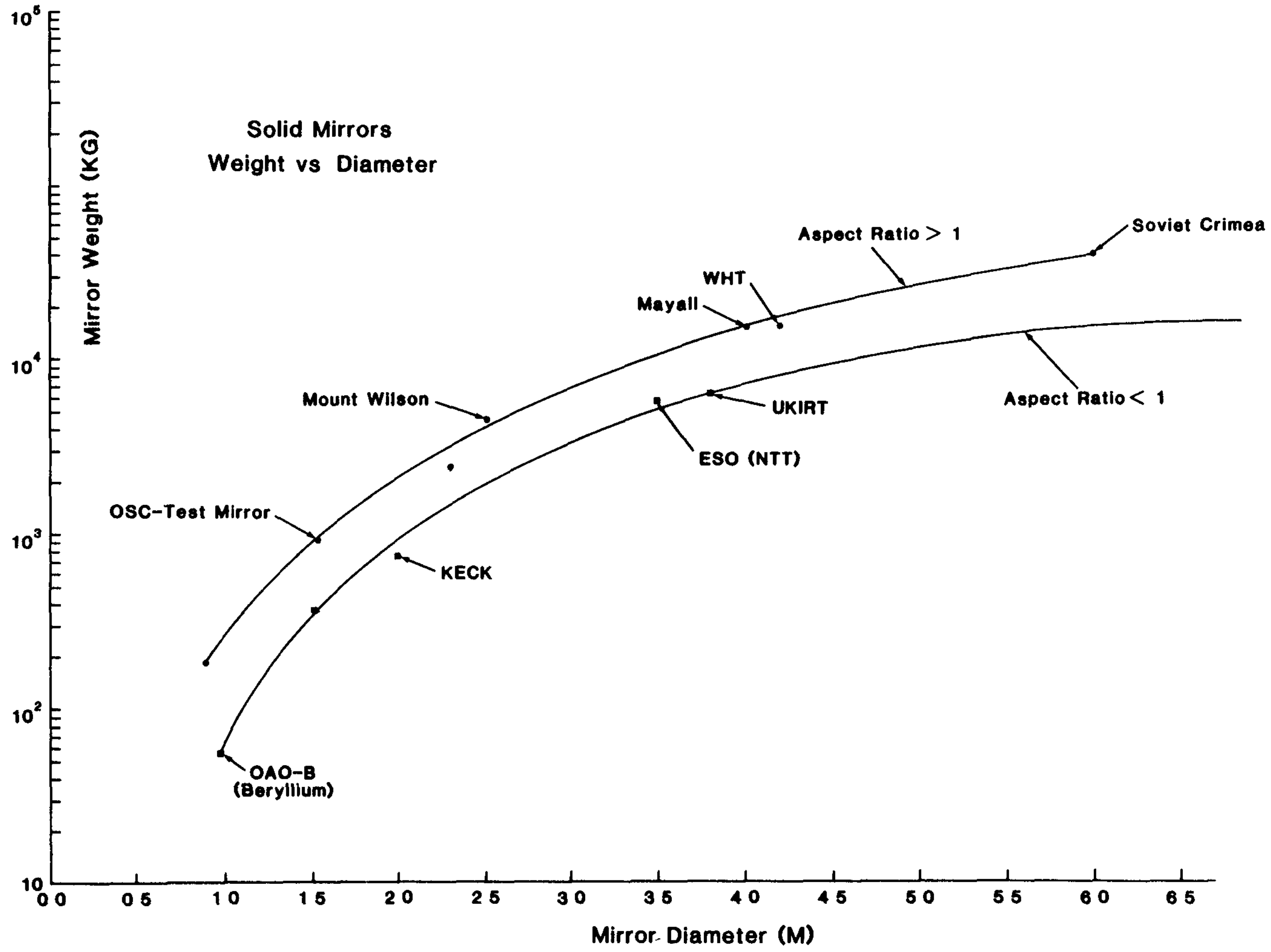
Table 1 List of Curve Fit Options

MIRROR	REF	YEAR	DIA (M)	THICK (M)	WEIGHT (KG)	MATL	CONFIG	MISC
Mount Wilson	5	1918	2 5	0 33	4083	glass	solid	Aspect ratio=13
Mayall	6	1973	4 0	0 56	15880	quartz	solid w/ 66M hole	Aspect ratio=14
UKIRT	7	1979	3 8	0 24	6500	Cervit	solid w/1 0M hole	Aspect ratio=06
KECK	8	1990	2 0	0 08	763	Zerodur	solid 36 hex seg	Aspect ratio=03
Stratascope II	9	1965	0 91	0 13	181	F silica	solid	Aspect ratio=14
Steward Stellar	10	1972	2 3	0 33	2340	Cervit	solid w/ 7M hole	Aspect ratio=14
P-E 60 inch	11	1979	1 52	0 09	380	ULE	solid w/.25M hole	Aspect ratio=06
WHT	12	1988	4 2	0 52	16000	Cervit	solid	Aspect ratio=12
Soviet Crimea	13	1976	6 0	0 65	42000	Pyrex	solid w/ 36M hole	Aspect ratio=11
OAO-B	14	1970	0 97	0 04	57	Beryllium	solid meniscus	Aspect ratio=04
ESO NTT	15	1988	3.5	0 24	6000	Zerodur	solid w/ 58M hole	Aspect ratio=06
JNLT	16	1983	7 5	0 2	17236	ULE	solid w/hole	Aspect ratio=03
OSC Test mirror	16	1972	1 54	0 25	910	------	solid	Aspect ratio=16

Table 2 Solid Mirrors Surveyed

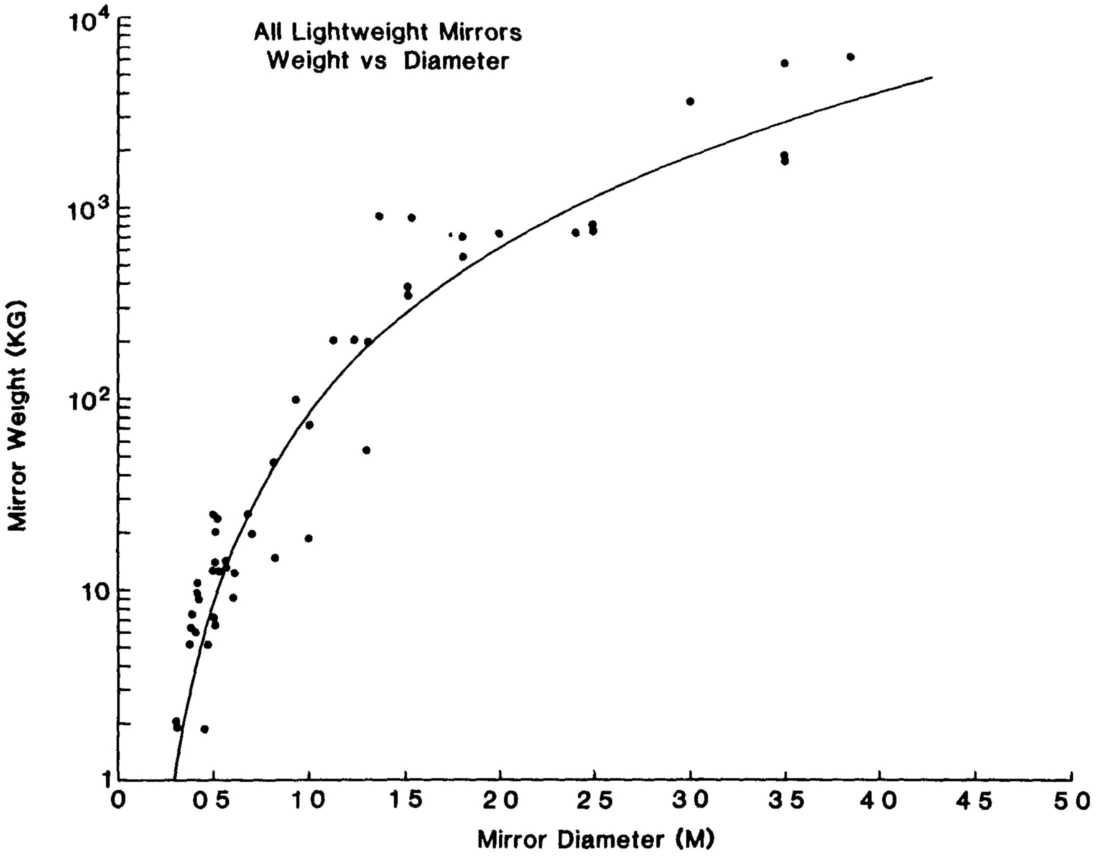
MIRROR	REF	YEAR	DIA (M)	THICK (M)	WEIGHT (KG)	MATL	CONFIG	MISC
IRAS	17	1983	0 60	0 09	12 6	Beryllium	Openback	annular ribs
Ball Relay	18	1989	0 60	0 06	9 07	Beryllium	Openback tri cells	Hip process
P-E 40 inch	19	1989	1 02	0 05	18 14	Beryllium	Sandwich hex cells	2 265 in cells
P-E Scan	20	1975	86x 81	0 08	14 52	Beryllium	Openback sqr cells	Flat λ/20
P-E second	20	1975	1 65x1 02	0 08	53 5	Beryllium	Openback sqr cells	f/0 67
Thematic Map	21	1972	406x 508	0 04	1 86	Beryllium	Sandwich sqr cells	Brazed
P-E 9 5 inch	22	1984	0 24	0 05	0 98	Beryllium	Sandwich hex cells	HIP process
P-E Test	23	----	0 57	0 04	13 25	Beryllium	Double arch	------
P-E test	23	----	0 51	0 05	6 51	Beryllium	Double arch	1 in circ cores
Hale	24	1950	5 0	0 60	13158	Pyrex	Openback	- ----
MMT	25	1979	1 8	0 30	567	F silica	Sandwich sqr cells	6 mirrors
RCT	26	1965	1 3	0 15	200	Aluminum	Single arch	---- -
Spacelab UV	27	1979	0 92	0 15	100	Cervit	Double arch	------
Hubble	28	1990	2 48	0 30	773	ULE	Sandwich sqr cells	-- ---
Teal Ruby	29	1980	0 50	0 08	7 3	F silica	Sandwich hex cells	------
OAO-c	30	1972	0 82	0 13	48	F silica	Sandwich sqr cells	-----
U of Colorado	31	1979	0 41	0 05	9 98	Cervit	Double arch	f/2.5, 1/4λ
Steward Obs	32	1985	1 8	0 36	703	Borosilicate	Sandwich hex cells	f/1.0
LDR test	33	1985	0 38	0 13	6 24	Borosilicate	Sandwich hex cells	sand-hexing
LDR test	33	1985	0 15	0 05	0 53	Vycor	Sandwich hex cells	air pressure
UTRC	34	1985	0 30	0 06	1 1	Glass TSC	Sandwich	Frit bonded
Ft Apache	35	1986	3 5	0 46	1893	Borosilicate	Sandwich hex cells	--- --
Nasa	36	1983	2 48	0 30	771	Glass	Sandwich sqr cells	------
Los Alamos	37	1982	1 1x1 1	0 20	204	Tempax	Openback sqr cells	------
SIRTF test	38	1983	0 51	0 089	16-25	quartz	Single arch	------
SIRTF test	38	1983	0 51	0 102	19-29	F silica	Double arch	f/4
Landsat-D	39	1979	0 42	0 07	9	ULE	Sandwich sqr cells	-----
GIRL	40	1985	0.50	0 074	25	Zerodur	Double taper	-- --
ISO	41	1985	0.64	0 075	20	F silica	Sandwich	machined
Hextek	42	1989	1 0	0 15	73	Borosilicate	Sandwich hex cells	f/0 5, meniscus
Hextek	42	1989	0 46	0 086	5 17	Borosilicate	Sandwich hex cells	------
Hextek	42	1989	0 38	0 076	7 71	Borosilicate	Sandwich hex cells	-----
Shane 3 M	43	1959	3 0	0 406	3856	Pyrex	Openback tri cells	f/5
NASA 2 4 M	44	1981	2 4	0.305	748	ULE	Sandwich sqr cells	f/2 35
Milan 54 inch	45	1968	1 37	0 20	907 2	Aluminum	Single arch	- ---
Steward 68 cm	46	----	0 68	0 10	25 4	Pyrex	Sandwich hex cells	-----
Soviet test	47	1977	0 506	0 076	13 7	quartz	Openback hex cells	54mm cells
Soviet test	47	1977	0.50	0 065	12 5	quartz	Sandwich hex cells	54mm cells
Soviet test	48	1977	0.37	0 052	5 2	F silica	Sandwich hex cells	28mm cells
Soviet test	49	1983	0 52	0 053	12.4	F silica	Sandwich	70mm cells
Soviet test	49	1983	0.57	0 057	13 2	F silica	Sandwich	71mm cells
Soviet test	49	1983	0.42	0 059	11 2	F silica	Sandwich	73mm cells
Soviet test	50	1985	0 70	0 10	20	Al alloy	Openback	annular ribs
Schott test	51	----	1 143	0 159	204 12	F silica	Sandwich	- ----
OSC 16 in scope	52	1989	0 406	0 076	6.17	SXA	Single arch	- - -
OSC 12 in scope	52	1988	0 305	0 064	2 04	Aluminum	Double concave	Al foam core
OSC 12 in scope	52	1988	0 305	0 043	1.95	Aluminum	Double concave	Al foam core
AFCRL	53	1972	1 524	0 165	363	Cervit	Single arch	-- -

Table 3 Lightweight Mirrors Surveyed



	Aspect Ratio h/D < 1	Aspect Ratio h/D > 1
BEST FIT FUNCTION	HOERL FUNCTION $Y = (117\ 7)\ 5457^{X}\ X^{4\ 738}$	PARABOLA FUNCTION $Y = 2279\text{-}3721X+1721X^{2}$
GOODNESS OF FIT	9951	9974
POWER FUNCTION	$Y = 98\ 78X^{2\ 867}$	$Y = 246\ 1X^{2\ 917}$
GOODNESS OF FIT	9452	9957

Figure 1 Weight vs Diameter of Solid Mirrors



		GOODNESS OF FIT
BEST FIT FUNCTION	POWER FUNCTION $Y = 81\ 89X^{2\ 949}$	9459

Figure 2 Weight vs Diameter of All Light-weight Mirrors

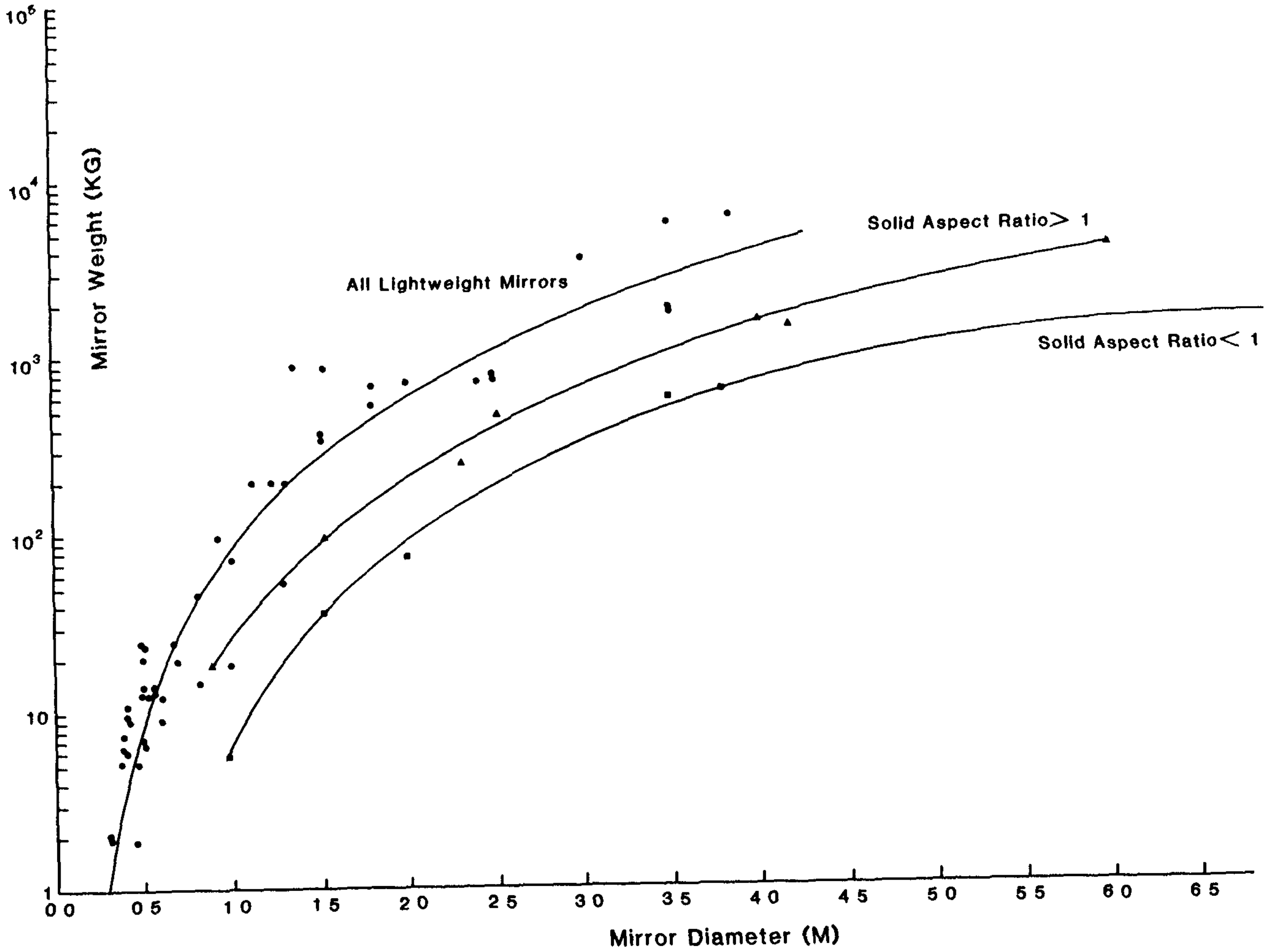
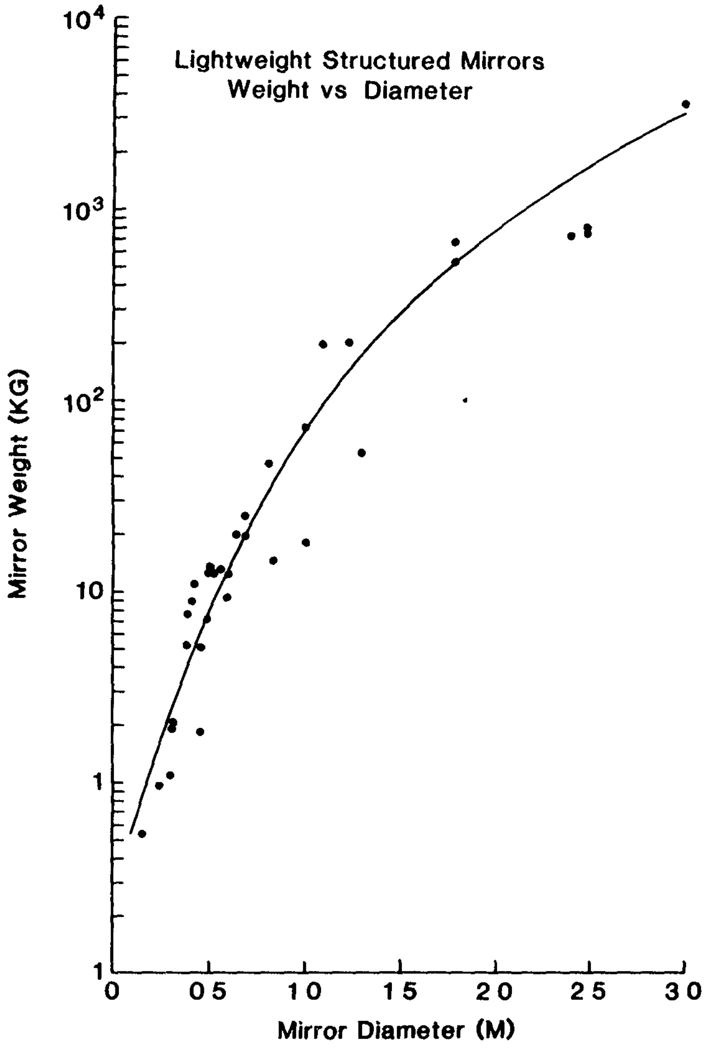
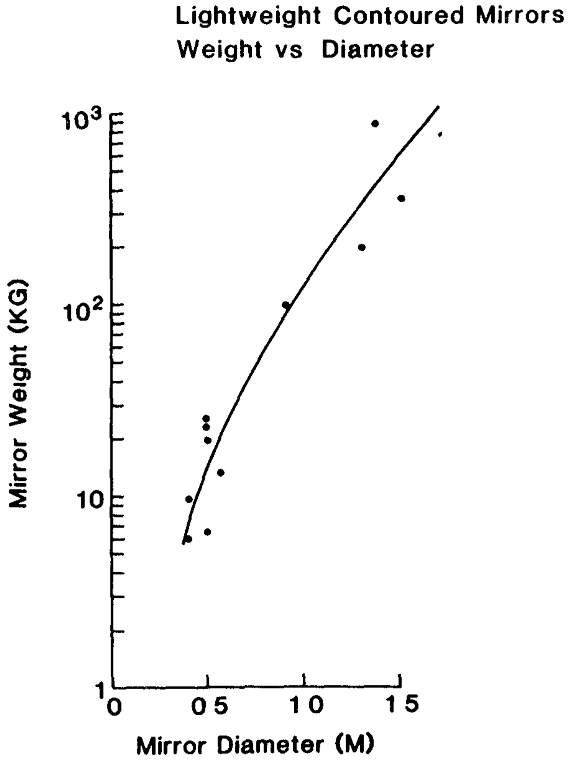


Figure 3 Weight vs Diameter of Solids and Light-Weight Mirrors



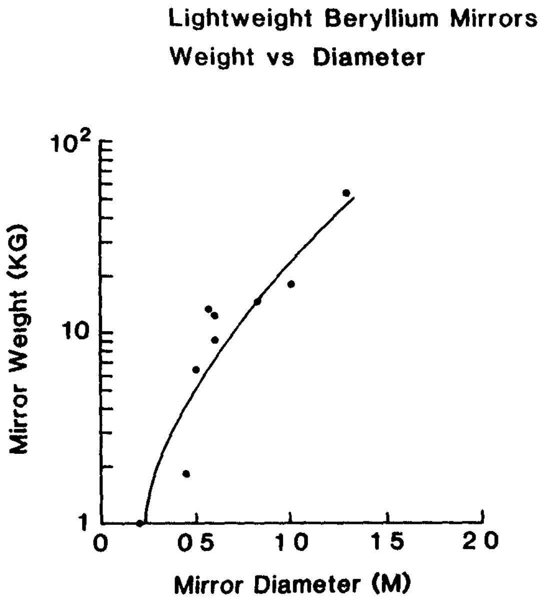
		GOODNESS OF FIT
BEST FIT FUNCTION	LOG NORMAL $Y = 177 \times 10^{-3} \exp\left[(-8\ 739-\ln X)^{\frac{2}{5\ 996}}\right]$	9512
POWER FUNCTION	$Y = 106X^{2\ 712}$	.9499

Figure 4 Weight vs Diameter of Structured Mirrors



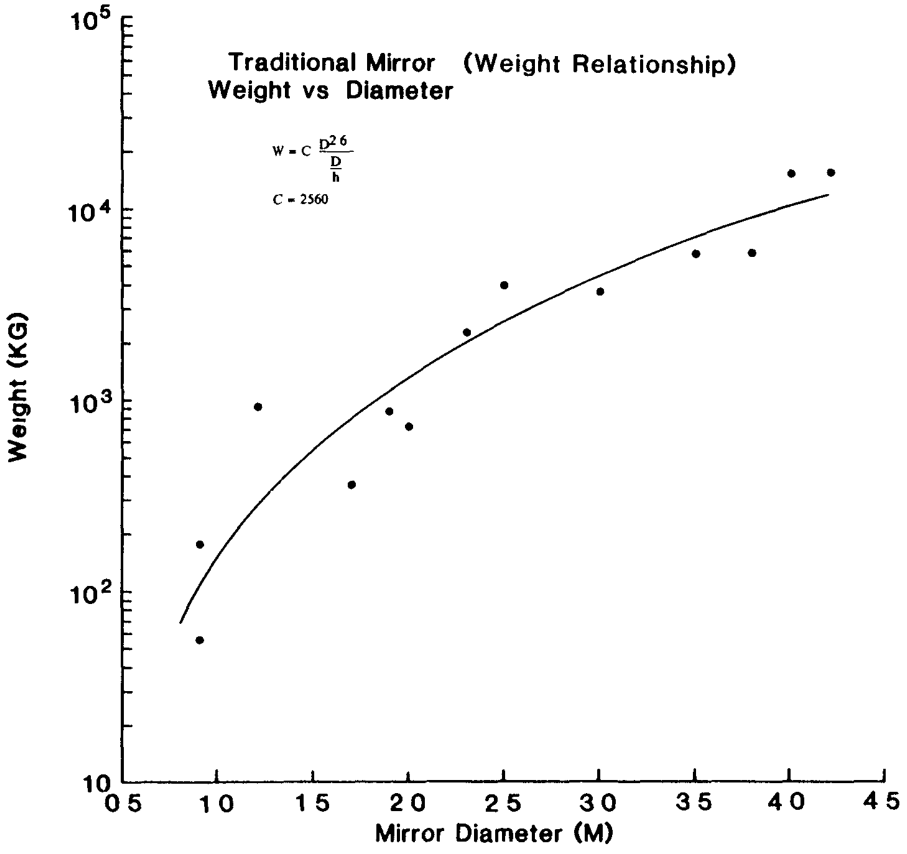
		GOODNESS OF FIT
BEST FIT FUNCTION	LINEAR HYPERBOLA $Y = -4409+2854X+1439/X$	9967
POWER FUNCTION	$Y = 106X^{2\ 712}$	9728

Figure 5 Weight vs Diameter of Contoured Mirrors



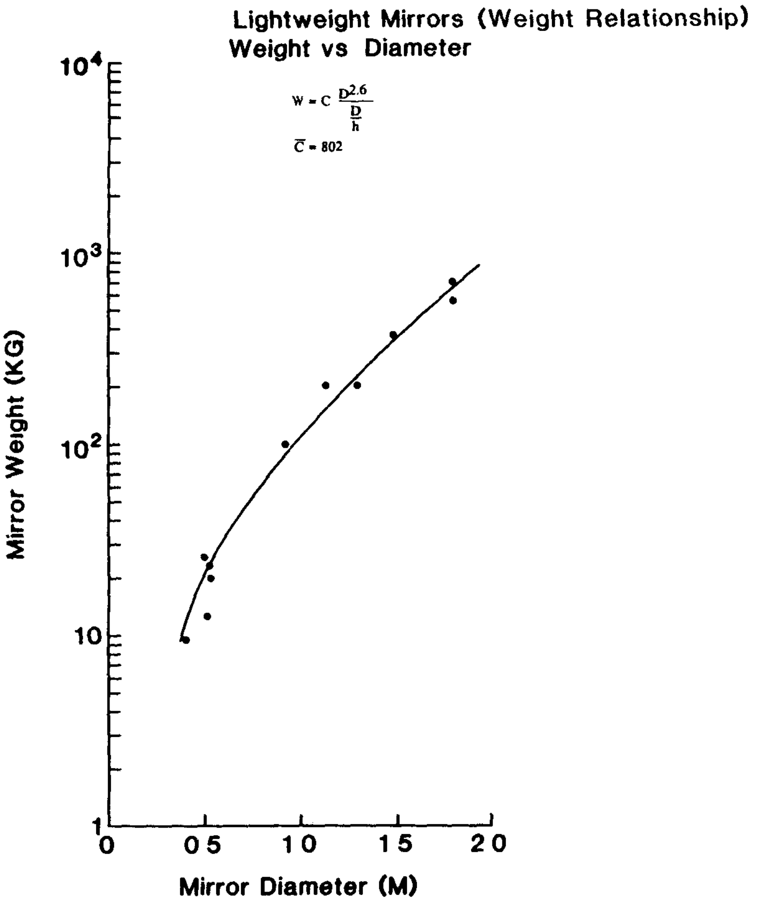
		BEST FIT FUNCTION
BEST FIT FUNCTION	PARABOLA FUNCTION $Y = 7\ 75-27\ 12X+45\ 41X^2$	8784
POWER FUNCTION	$Y = 26\ 19X^{2\ 305}$	8566

Figure 6 Weight vs Diameter of Beryllium Mirrors



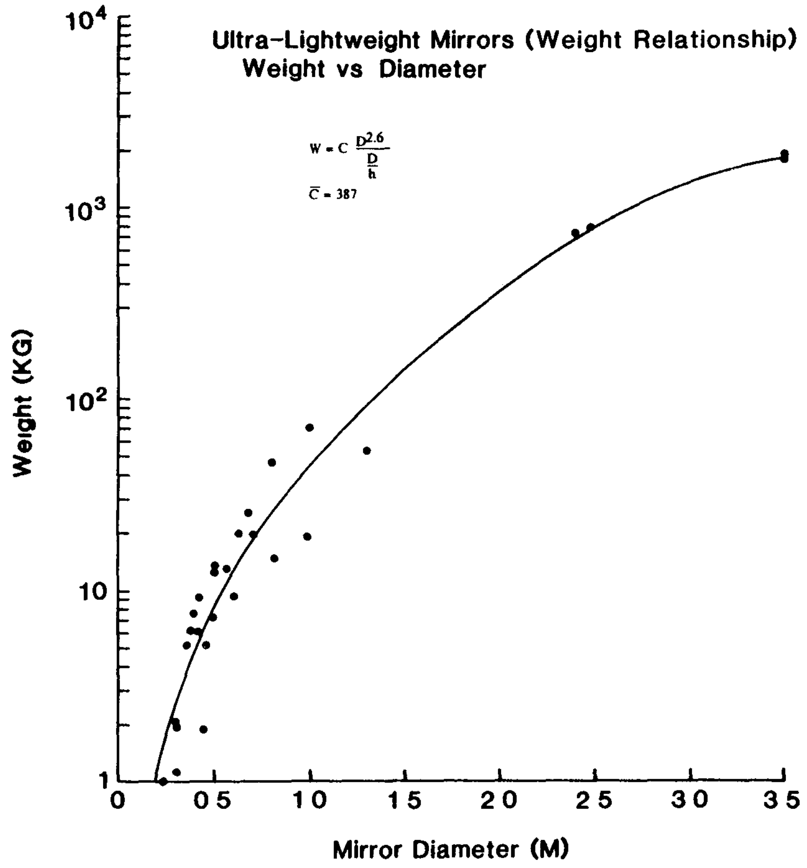
		GOODNESS OF FIT
BEST FIT FUNCTION	HOERL FUNCTION $Y = (232\ 9)\, 6359^{X}\ X^{4\ 037}$	.9249
POWER FUNCTION	$Y = 191\ 8X^{2\ 763}$	9097

Figure 7 Weight vs Diameter of Traditional Mirrors (weight dependent)



		GOODNESS OF FIT
BEST FIT FUNCTION	PARABOLA FUNCTION $Y = 95.2-332.2X+349.4X^2$	.9707
POWER FUNCTION	$Y = 120\ 4X^{2\ 820}$	9707

Figure 8 Weight vs Diameter of Light-Weight Mirrors (weight dependent)



		GOODNESS OF FIT
BEST FIT FUNCTION	PARABOLA FUNCTION $Y = 62.76 - 229\ 3X + 211\ 4X^2$	.9977
POWER FUNCTION	$Y = 53\ 15X^{2\ 666}$	9423

Figure 9 Weight vs Diameter of Ultra-Lightweight Mirrors (weight dependent)

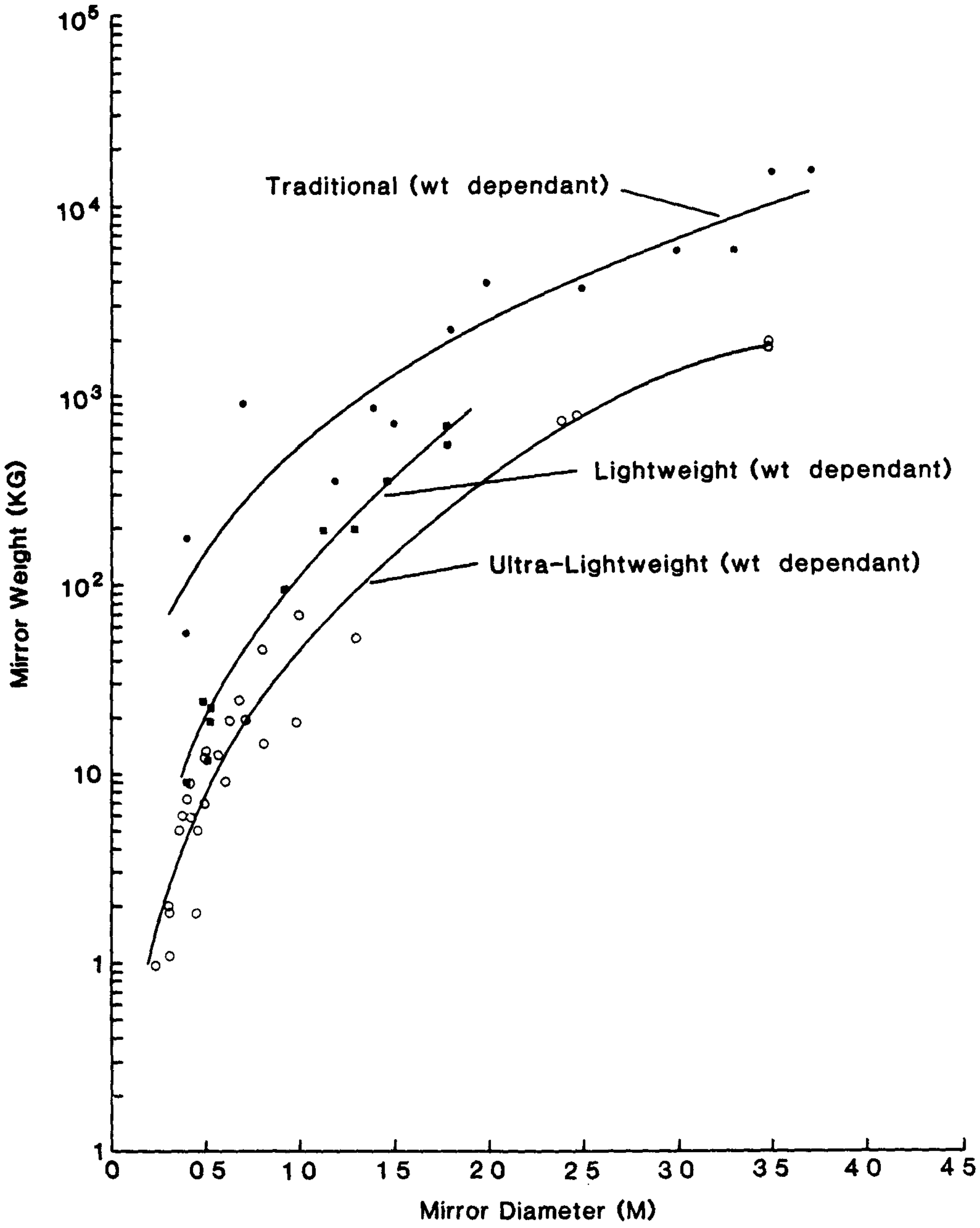


Figure 10 Weight vs Diameter of Traditional, Light-weight, and ultra-lightweight Mirrors (weight dependent)

MIRROR CATEGORY	BEST FIT CURVE	GOODNESS OF FIT	POWER FUNCTION CURVE	GOODNESS OF FIT
Solids with large aspect ratios $\frac{h}{D}$	Parabola Fcn $Y = a + bX + cX^2$ a=2279, b=-3721 c=1721	9974	$Y = aX^b$ a=246 1 b=2 917	9957
Solids with small aspect ratios $\frac{h}{D}$	Hoerl Fcn $Y = ab^X X^c$ a=117 7, b= 546 c=4 74	9951	$Y = aX^b$ a=98 78 b=2 867	9452
All lightweight mirrors	Power Fcn $Y = a + X^b$ a=81 89 b=2 949	9459	$Y = aX^b$ a=81 99 b=2 949	9459
Structured mirrors	Log Normal Fcn $Y = aEXP(b - \ln X)^{\frac{2}{c}}$ a= 18E-3, b=-8 74 c=5 996	9512	$Y = aX^b$ a=67 97 b=2 898	9499
Contoured mirrors	Linear Hyperbola $Y = a + bX + \frac{c}{X}$ a=-4409, b=2854 c=1439	9967	$Y = aX^b$ a=106 0 b=2 712	9728
Lightweight beryllium mirrors	Parabola Fcn $Y = a + bX + cX^2$ a=7 75, b=-27 12 c=45 4	8784	$Y = aX^b$ a=26 19 b=2 305	8566
Traditional mirrors ($C_{avg} = 2560$) $W = \frac{CD^{2\ 6}}{\frac{D}{h}}$	Hoerl Fcn $Y = ab^X X^c$ a=232 9, b= 636 c=4 037	9249	$Y = aX^b$ a=191 8 b=2 763	9097
Lightweight mirrors ($C_{avg} = 802$) $W = \frac{CD^{2\ 6}}{\frac{D}{h}}$	Parabola Fcn $Y = a + bX + cX^2$ a=95 2, b=-332 2 c=349 4	9707	$Y = aX^b$ a=120 4 b=2 820	9707
Ultra lt wt mirrors ($C_{avg} = 387$) $W = \frac{CD^{2\ 6}}{\frac{D}{h}}$	Parabola Fcn $Y = a + bX + cX^2$ a=62 76, b=-229 3 c=211 4	9977	$Y = aX^b$ a=53 15 b=2 666	9423

Table 4 Curve Fitting Summary